

Hydrogen and Fuel Cell Technologies

Cathy Padró

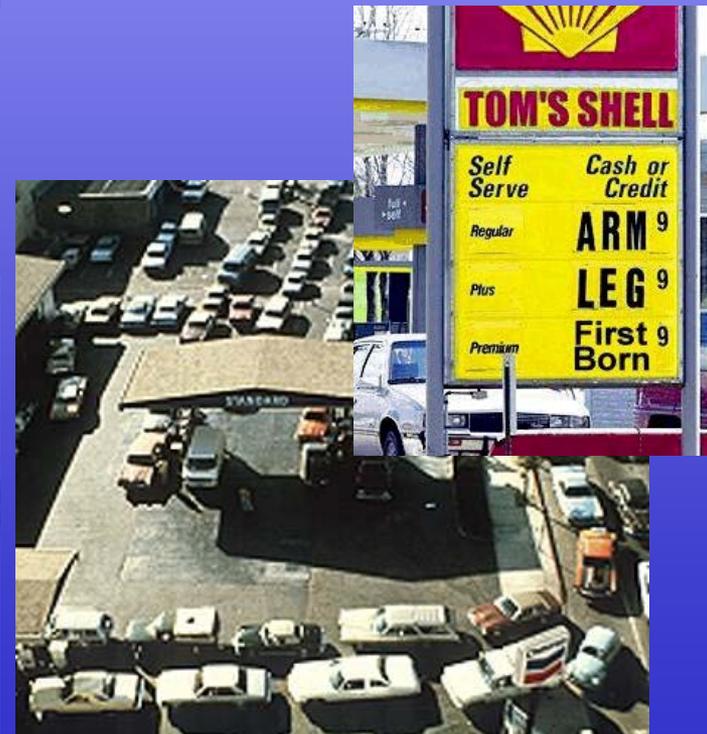
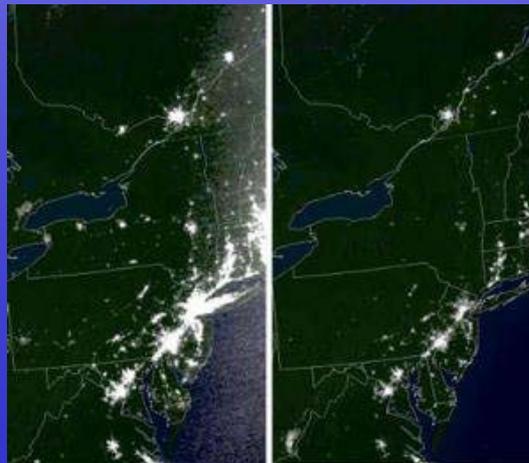
Los Alamos National Laboratory

Pre-Quiz

Part I: Hydrogen Energy System Basics

What we need from our energy system

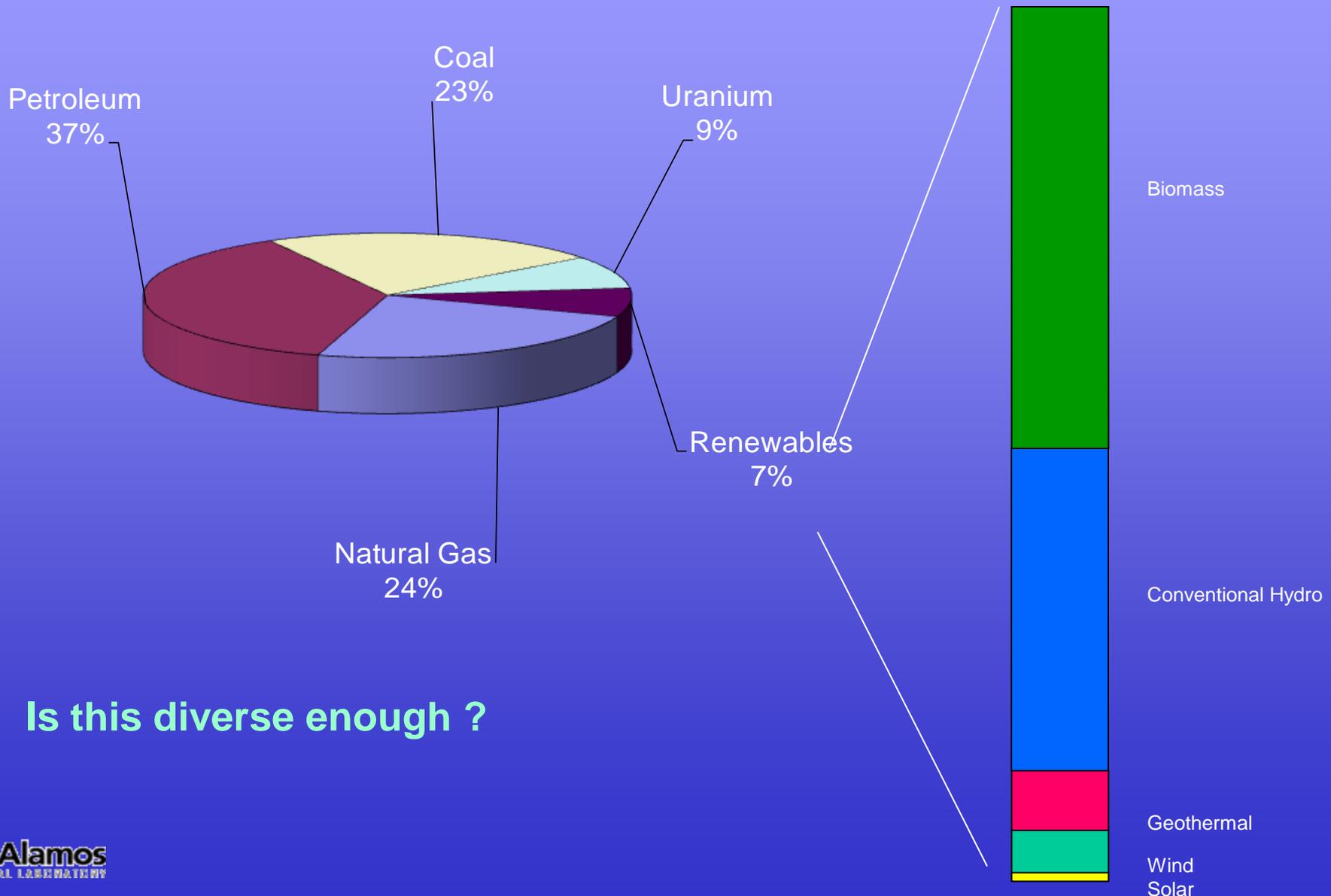
- Most Americans do not think about energy unless the lights go out or the price at the pump skyrockets
- BUT, access to clean, reliable, affordable and sustainable energy is vital to maintaining and enhancing our standard of living



What we need from our energy system

- Any energy system, including our current one, needs to have certain characteristics
 - Security of supply
 - Domestic production
 - Flexibility of sources
 - Sustainability
 - Environmental quality
 - Reduced harmful emissions (smog, particulates)
 - Low GHG emissions
 - Sustainability
 - Economic benefits
 - Efficient and reliable
 - Accessibility
 - Stable prices
 - Job creation

Current US Resource Base

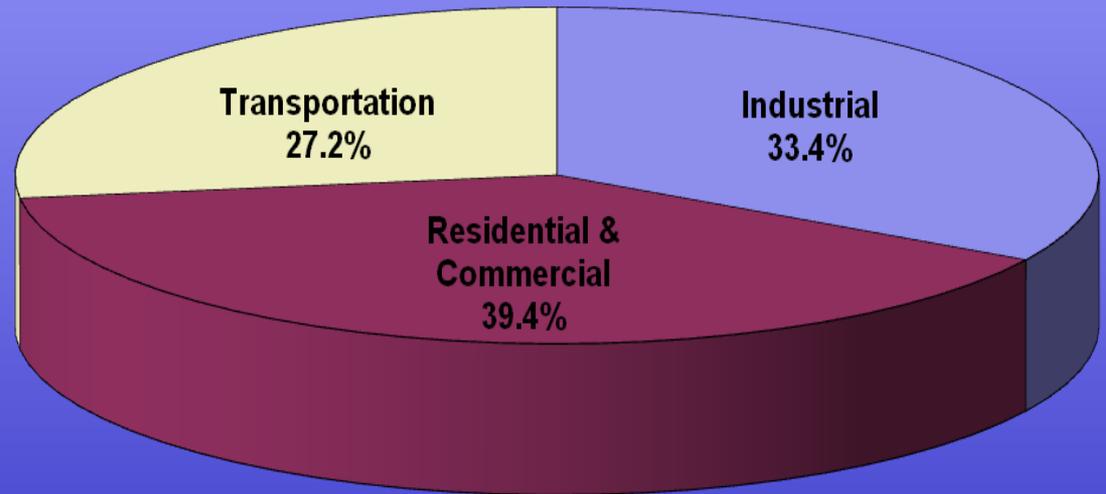
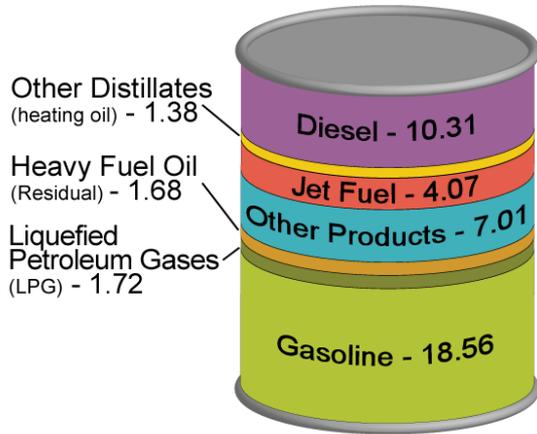


Is this diverse enough ?

Energy Consumption by Sector

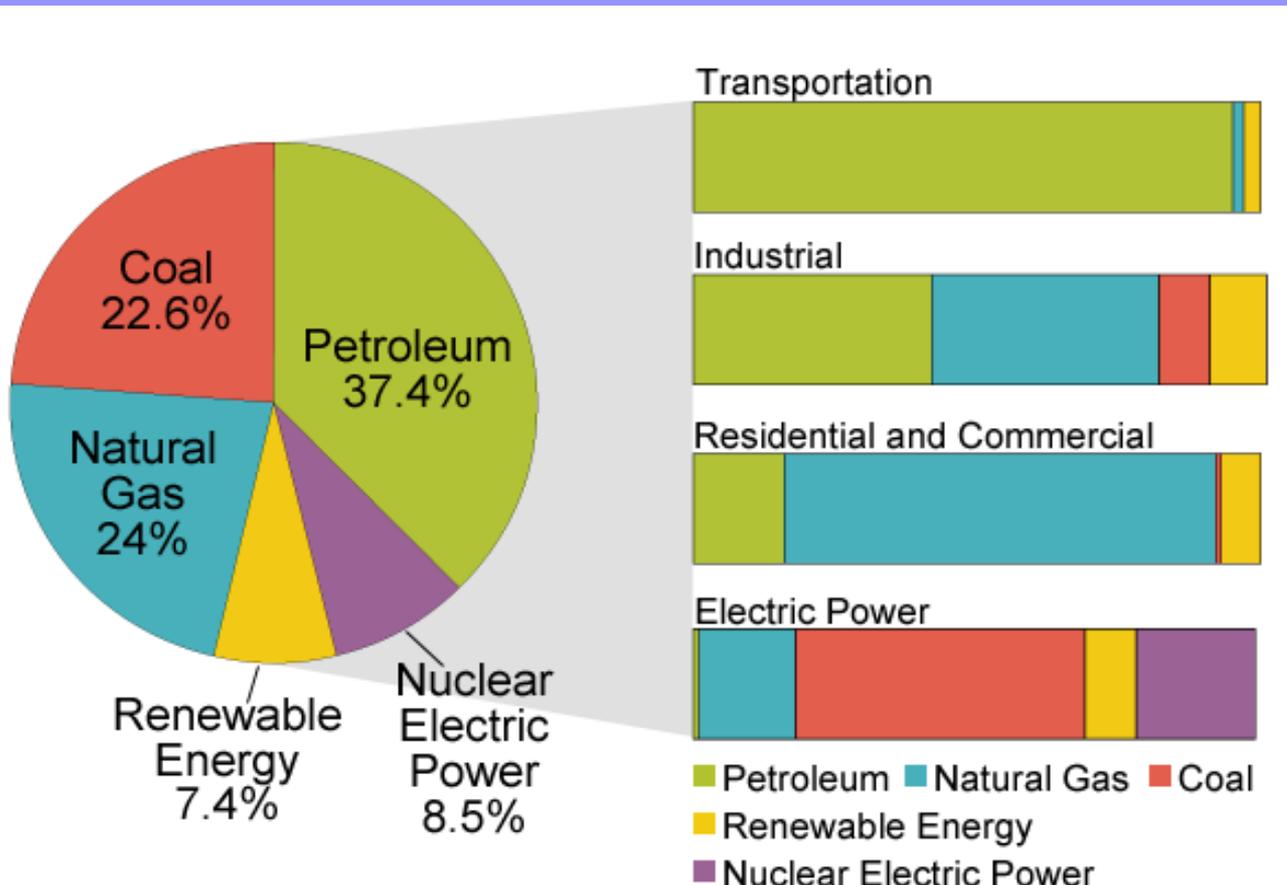
Two-thirds of oil is used in Transportation Sector
The rest is used to produce chemicals (Industrial Sector) and heating oil (Residential & Commercial)

Products Made from a Barrel of Crude Oil (Gallons)



Electricity for energy services
(lighting, cooking, ventilation,
cooling, computing, etc)
Natural gas for heating, cooking

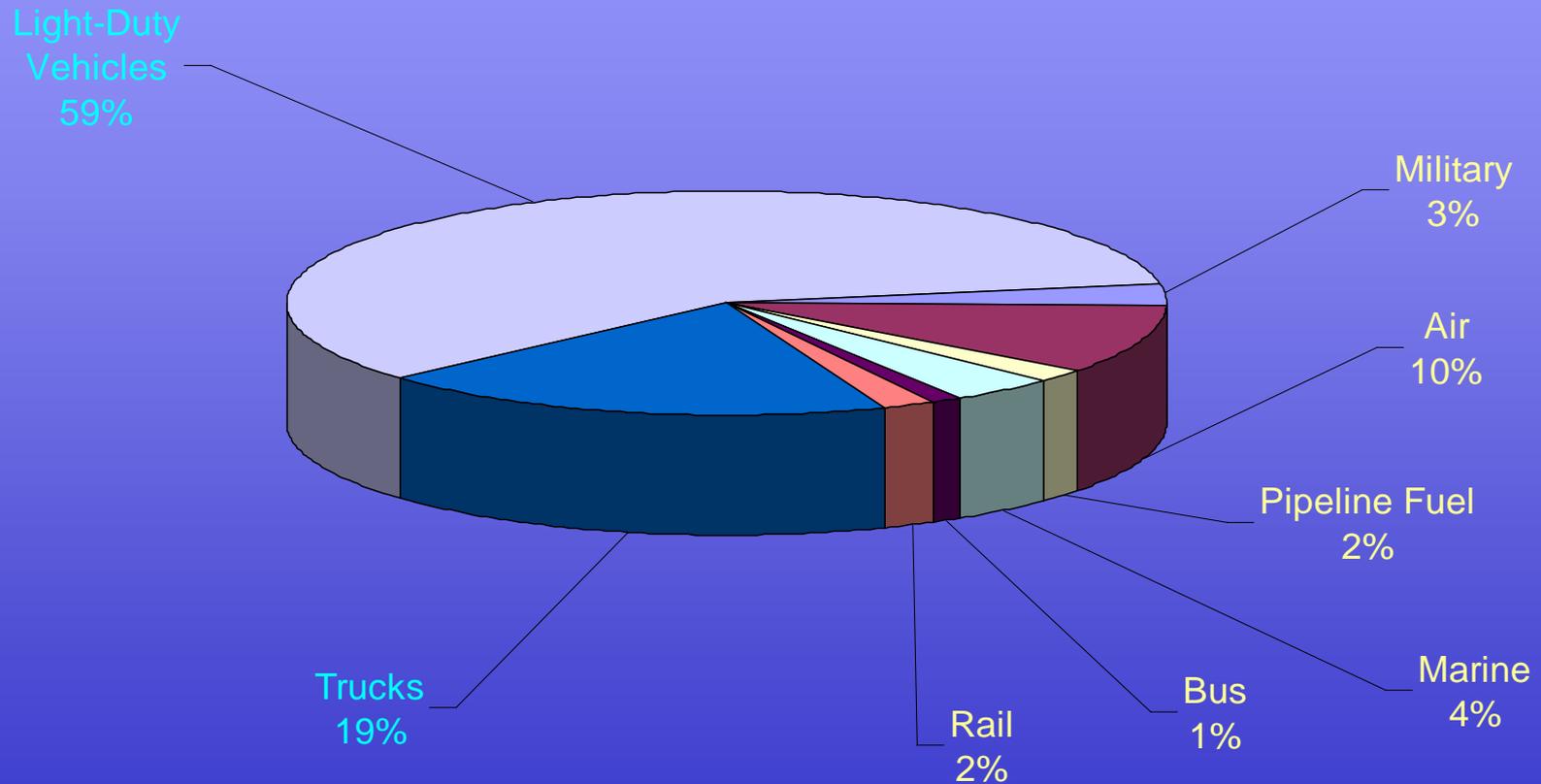
US Primary Energy Consumption



Total U.S. Energy = 99.3 Quadrillion Btu

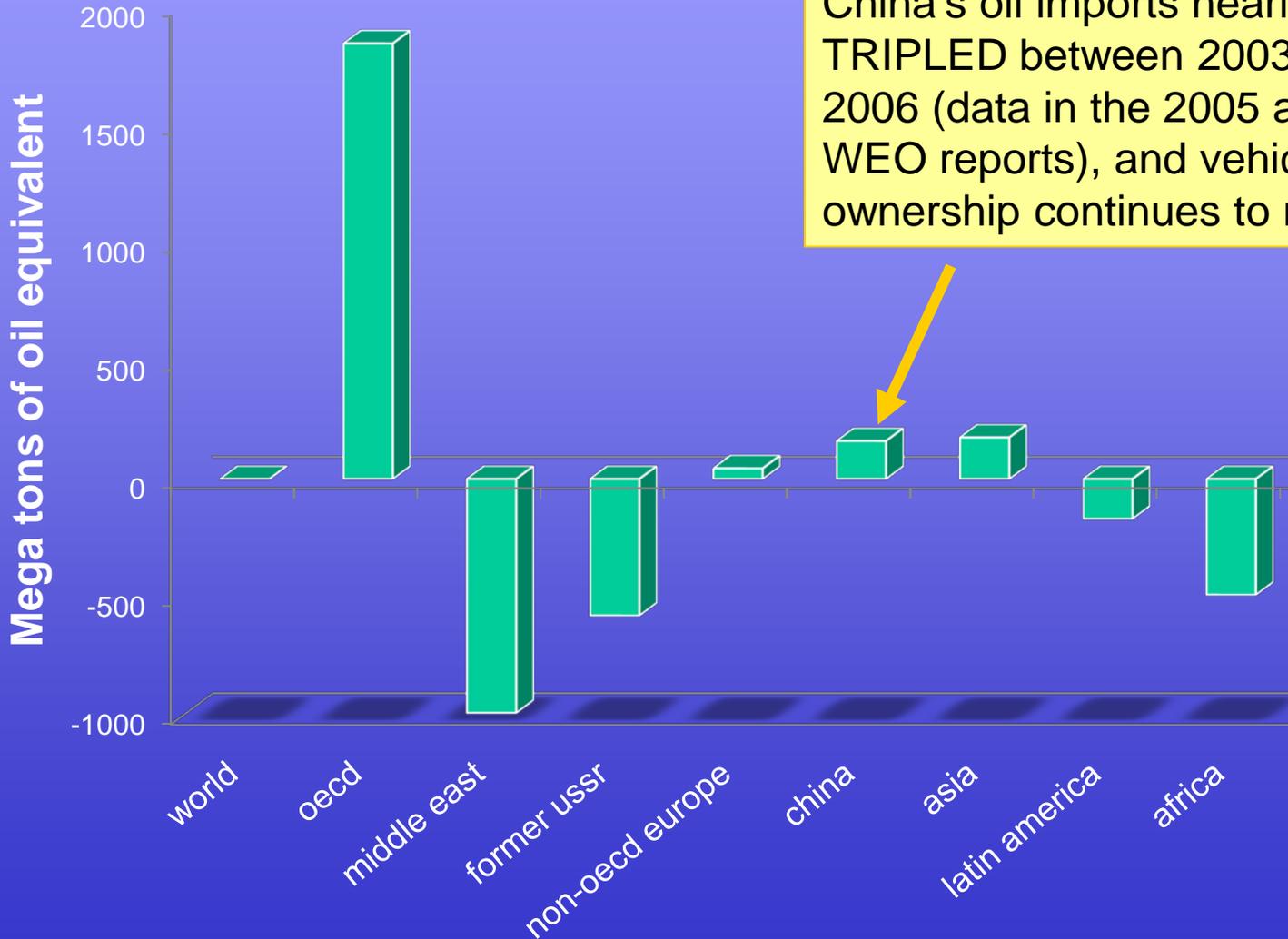
Source: Energy Information Administration, *Annual Energy Review 2008*, Tables 1.3, 2.1b-2.1f, 10.3, and 10.4.

Transportation Energy Use



Transportation Sector is 97% petroleum-based
60% of the petroleum we use is imported, and the gap is growing every day

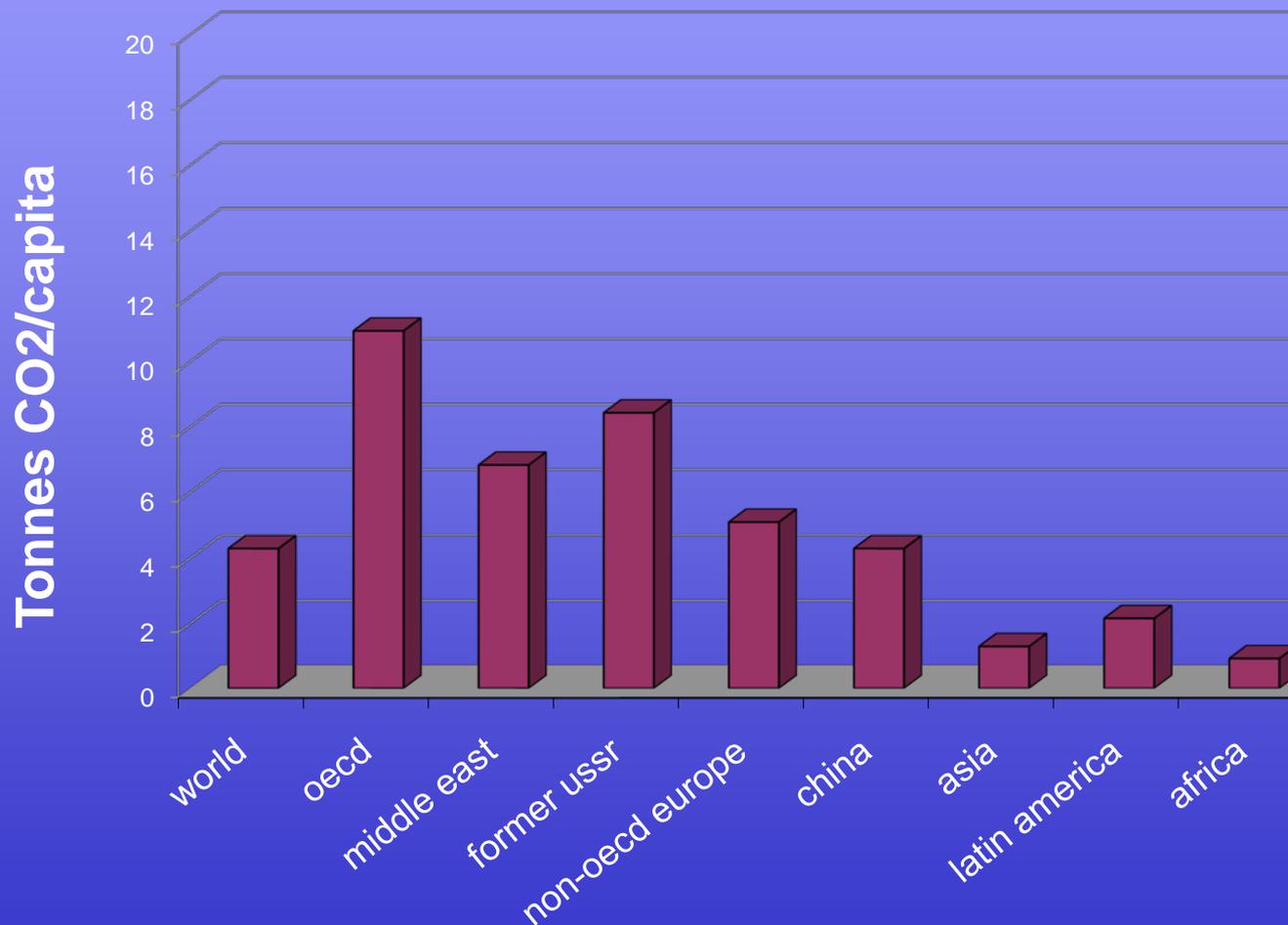
Imports



China's oil imports nearly **TRIPLED** between 2003 and 2006 (data in the 2005 and 2008 WEO reports), and vehicle ownership continues to rise

Notes: Taken from IEA 2008 Key World Energy Statistics (2006 data)
USA included in OECD – also plotted separately to show contribution

CO₂ Emissions per Capita



Notes: Taken from IEA 2008 Key World Energy Statistics (2006 data)
USA included in OECD – also plotted separately to show contribution

Why Hydrogen?

- Flexibility of source: can be produced from a wide variety of domestically-available resources at any scale
 - Could reduce price instabilities in the energy market
 - All regions of the world are “in the game”
 - Energy security is actually possible through increased domestic energy production
- Significant, positive environmental impacts are possible
 - Remove energy production and consumption from the environmental equation, both locally and globally
 - Potential for very-low impact throughout energy chain
 - Urban air quality
 - Global climate change
- Flexibility of use: only energy carrier that can (effectively) provide all energy services for all energy sectors

What is Hydrogen?

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	Ac	Unq	Unp	Unh	Uns	Uno	Une	Unn								
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu				
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr				

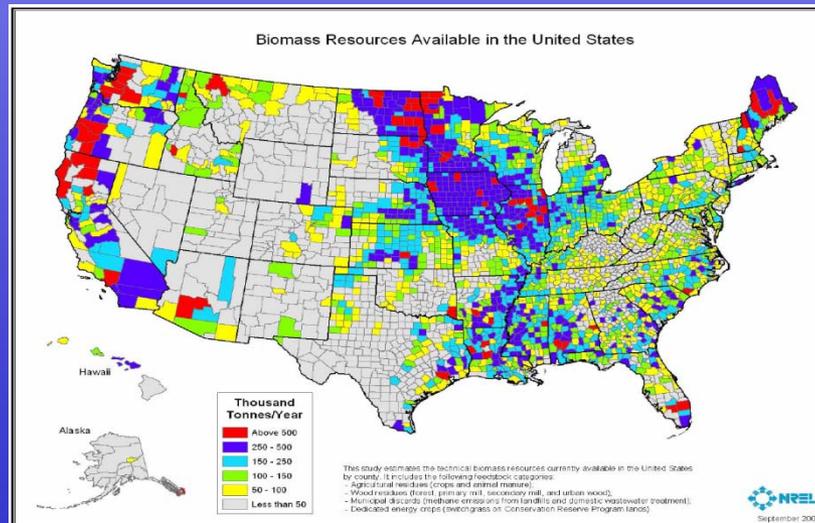
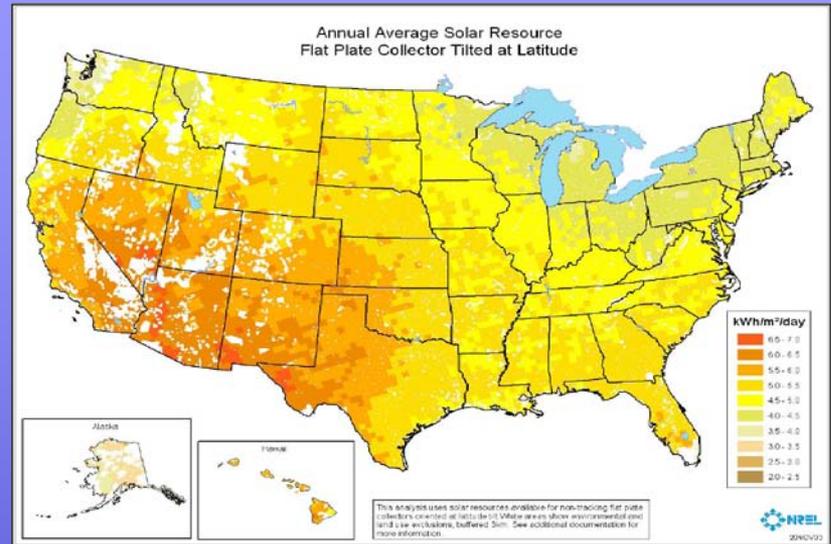
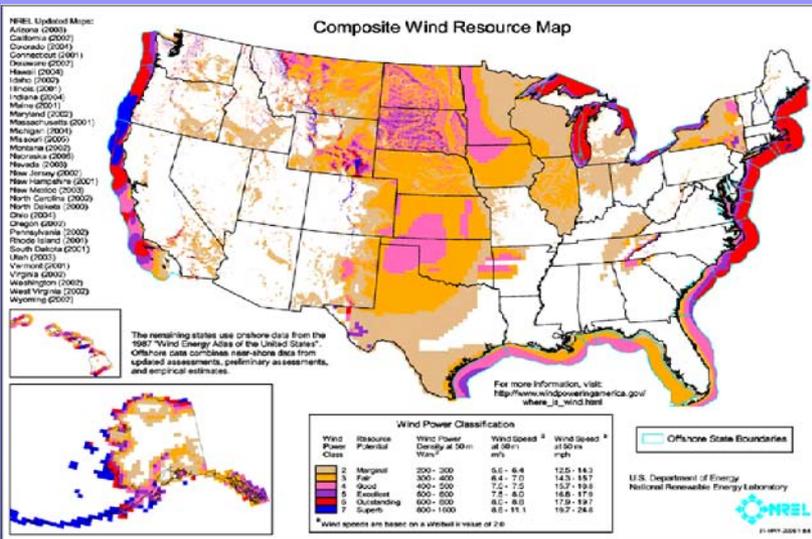
- Element 1 on the Periodic Table
 - 1 proton, 1 electron
- Diatomic molecule (H₂)
 - 2 protons, 2 electrons
- Highest energy content of common fuels on a WEIGHT basis
- Lowest energy content of common fuels on a VOLUME basis
- “H” is abundant on earth, but usually bound to carbon (such as CH₄) or oxygen (H₂O) or both (organic matter – “carbohydrates” – C₆H₁₂O₆)
- H₂ is not found in nature in large quantities (although there are some underground gas deposits that have relatively high concentrations of H₂)

Flexibility of Source

- Hydrogen can be produced from water; from carbon-containing materials (usually reacting with water); as a byproduct of chemical processes
- Every region has some indigenous fossil or renewable resource that can be used to make hydrogen
 - Regional variations in traditional energy resources are no longer (as critical) economic, political, or security issues

	Biomass Hydro Wind Solar Geothermal
	Nuclear
	Oil Coal Natural Gas

Renewable Resources



Production Potential from Domestic Resources

- As an example, how could the US fuel half of the current fleet with hydrogen?
 - Current annual consumption in the light-duty market is 16 quads of gasoline
 - Quad is short for Quadrillion (10^{15}) BTUs
 - One quad is about 8 billion gallons of gasoline, or about 230 million barrels of crude oil (making current consumption ~3.7 billion barrels of oil annually, for light-duty vehicles only)
 - Assume a 2x increase in efficiency with hydrogen fuel cell vehicles
 - For half of the fleet, we need 4 quads
 - This is 36 (let's call it **40**) **million tons** of hydrogen per year (~4 times the current domestic hydrogen production, mostly from natural gas)
- Using only **ONE** domestic resource, can we make this much hydrogen?
 - We will, of course, use a combination of resources, but this is an interesting and eye-opening exercise

Production Potential from Domestic Resources

For 40 million tons/year of hydrogen, we would need:

95 million tons of natural gas (current consumption is around 475 million tons/year in all energy sectors)

OR

280-560 million tons of coal (current consumption is around 1,100 million tons/year)

OR

400-800 million tons of biomass (availability is 800 million tons/year of residue plus potential of 300 million tons/year of dedicated energy crops with no food, feed or fiber diverted)

OR

The wind capacity of North Dakota (class 3 and above)

OR

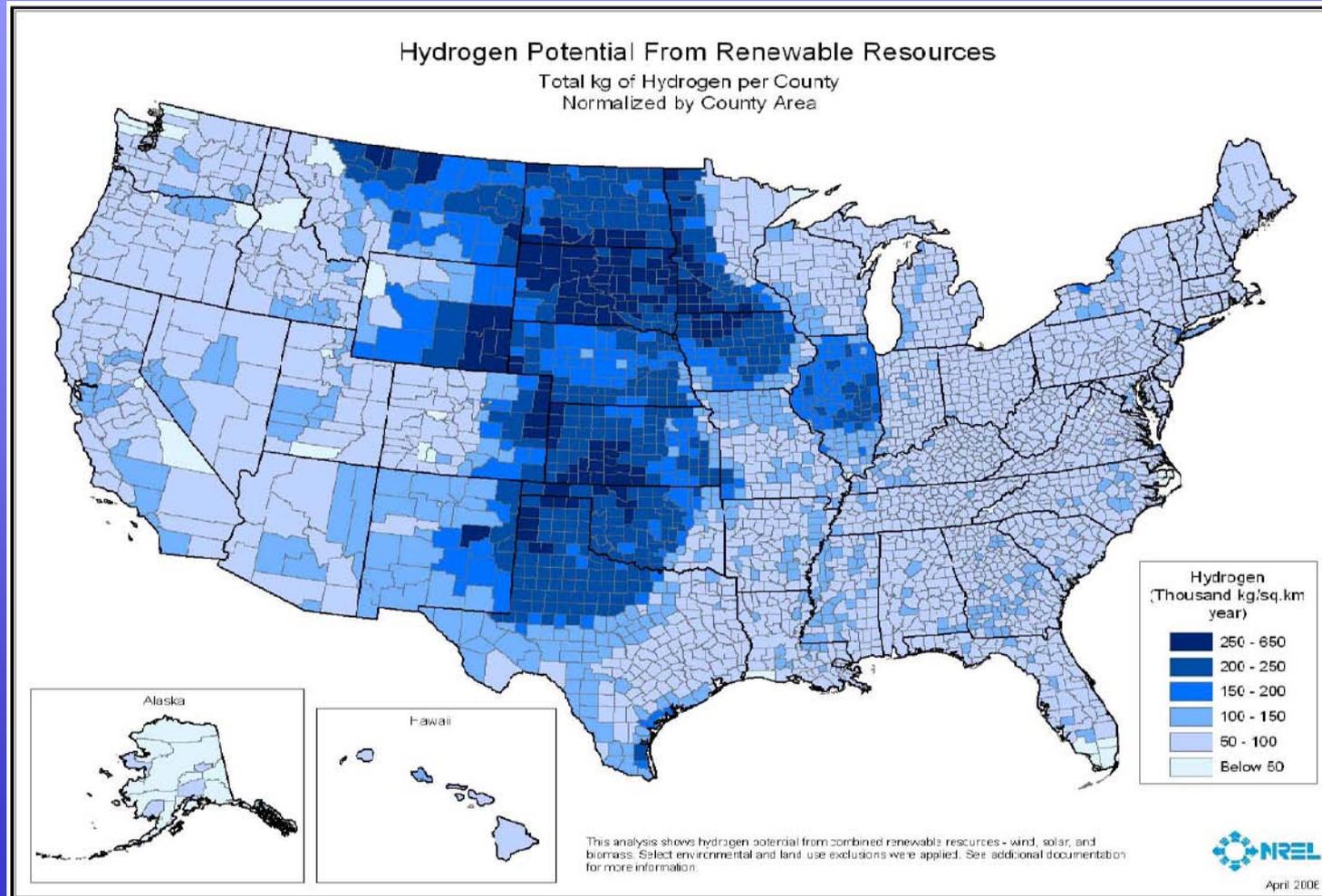
3,750 sq. miles of solar panels (approx. footprint of the White Sands Missile Range)

OR

140 dedicated conventional nuclear power plants

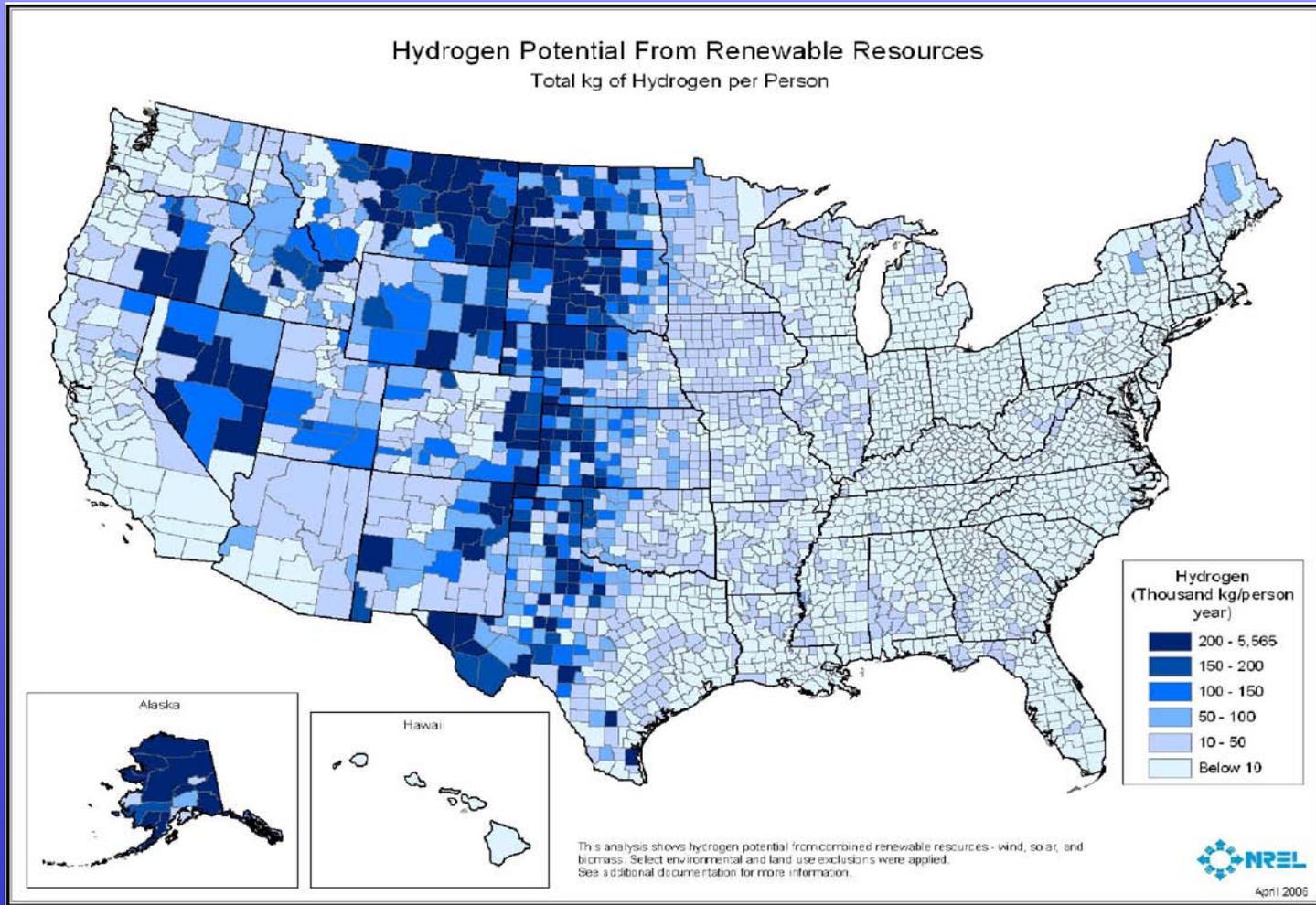
Hydrogen from Renewables

Per Area Potential



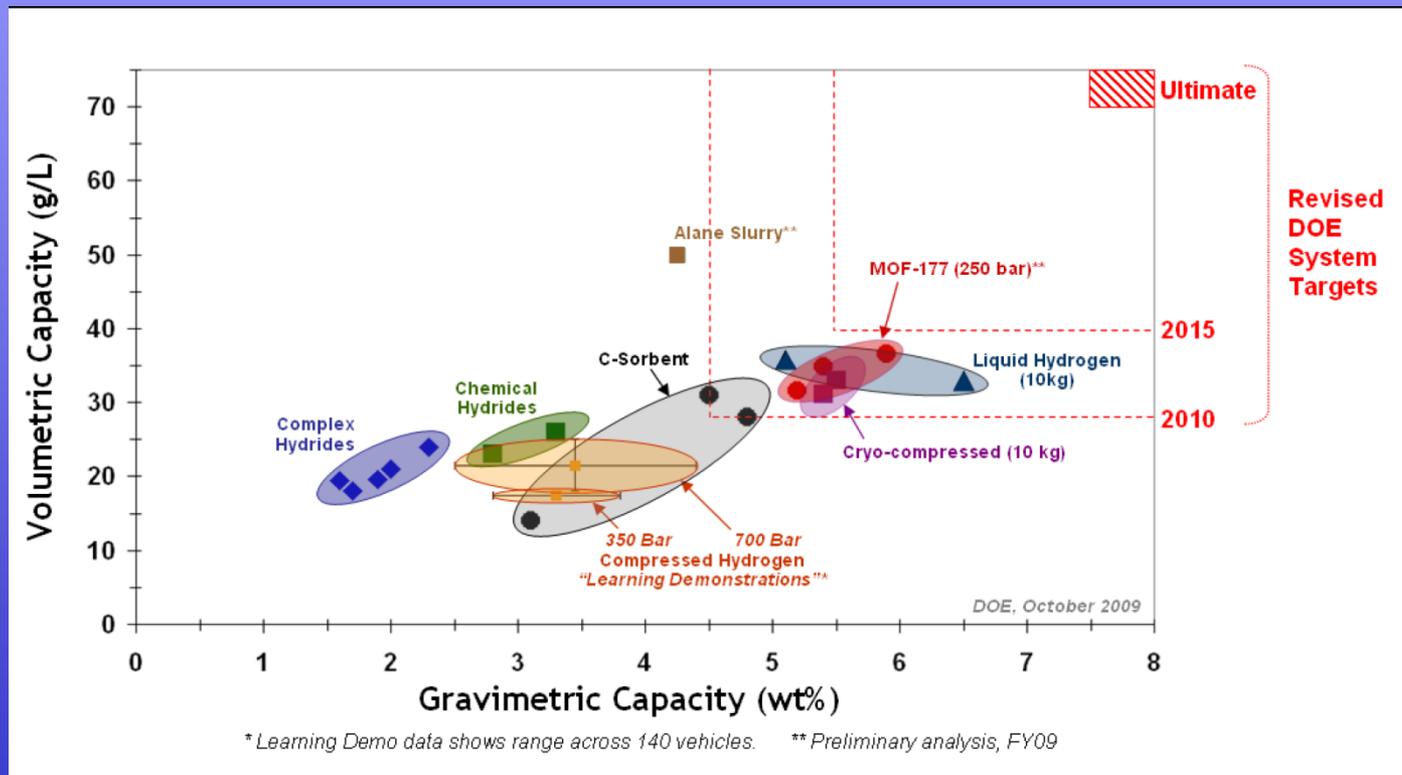
Hydrogen From Renewables

Per Person Potential



So We Can Produce Hydrogen - Now What?

- Storage of hydrogen on board is a tough technical challenge



Where do you think gasoline fits on this chart?

Answer:
It doesn't
~180 g/L
and 26 wt%

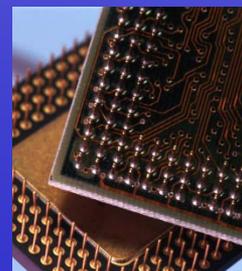
So We Can Produce Hydrogen - Now What?

- Installation of a hydrogen delivery and dispensing infrastructure is an expensive proposition (maybe)
 - Hydrogen pipelines exist in some industrial areas (around the Gulf Coast, for example)
 - Most merchant hydrogen is delivered as a liquid in cryogenic tanker trucks or as a compressed gas in tube trailers (depending on demand)
 - Electrolysis is a great option if the user needs a relatively modest amount of extremely high-purity hydrogen
- To realize the benefits of a hydrogen economy, we actually have to put a value on energy security and environmental impacts, and bear some incremental cost



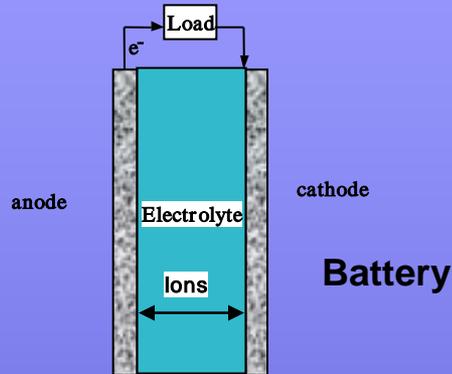
Flexibility of Use

- In the Transportation Sector
 - Desired range can be achieved with on-board hydrogen storage (unlike BEV – let's talk about this later)
 - Can be used in ICE (with modification, very low emissions); preferred for fuel cell (no emissions); APUs
 - Trains, automobiles, buses, and ships
- In the Buildings Sector
 - Combined heat, power, and fuel
 - Reliable energy services for critical applications
 - Grid independence
- In the Industrial Sector
 - Already plays an important role as a chemical
 - Opportunities for additional revenue streams



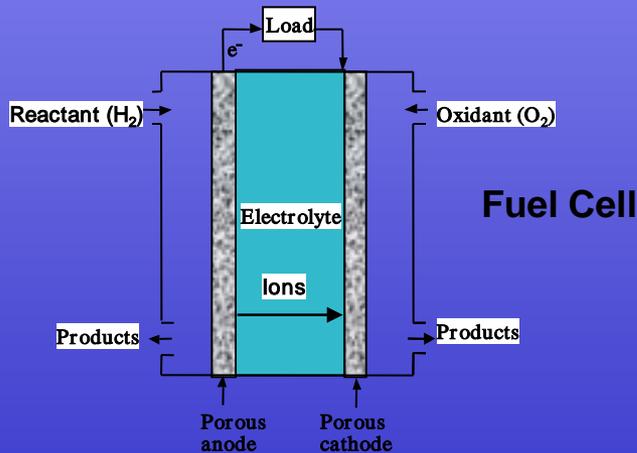
Part II: Fuel Cell Technology

Battery vs Fuel Cell



Similarities: half reactions, separation of ionic and electronic pathways, direct conversion of chemical energy into electrical energy

Differences: breaking of covalent bonds (battery) versus addition and removal of reactants and products (fuel cell); closed (battery) versus open (fuel cell) system



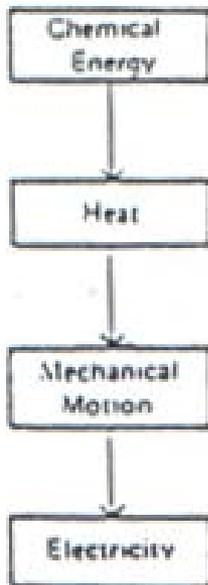
Advantages: fuel cell energy density is up to >6000 Whr/kg based on fuel versus battery energy density is up to 150 Whr/kg; refuel (fuel cell) versus recharge (battery)

Disadvantages: fuel cell cost, reliability, fuel storage

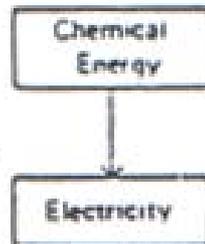
Combustion vs Fuel Cell

Fuel cells do not operate through a Carnot Cycle (they are not heat engines) and can therefore be more efficient than processes that directly involve combustion. Pollution is typically greatly reduced.

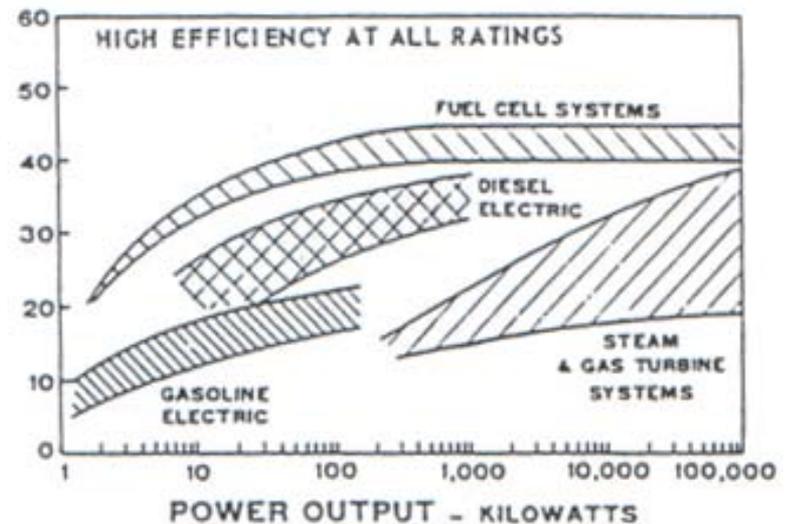
Heat Engine Generator



Fuel Cell



EFFICIENCY *
PERCENT



Hydrogen Fuel Cell Types

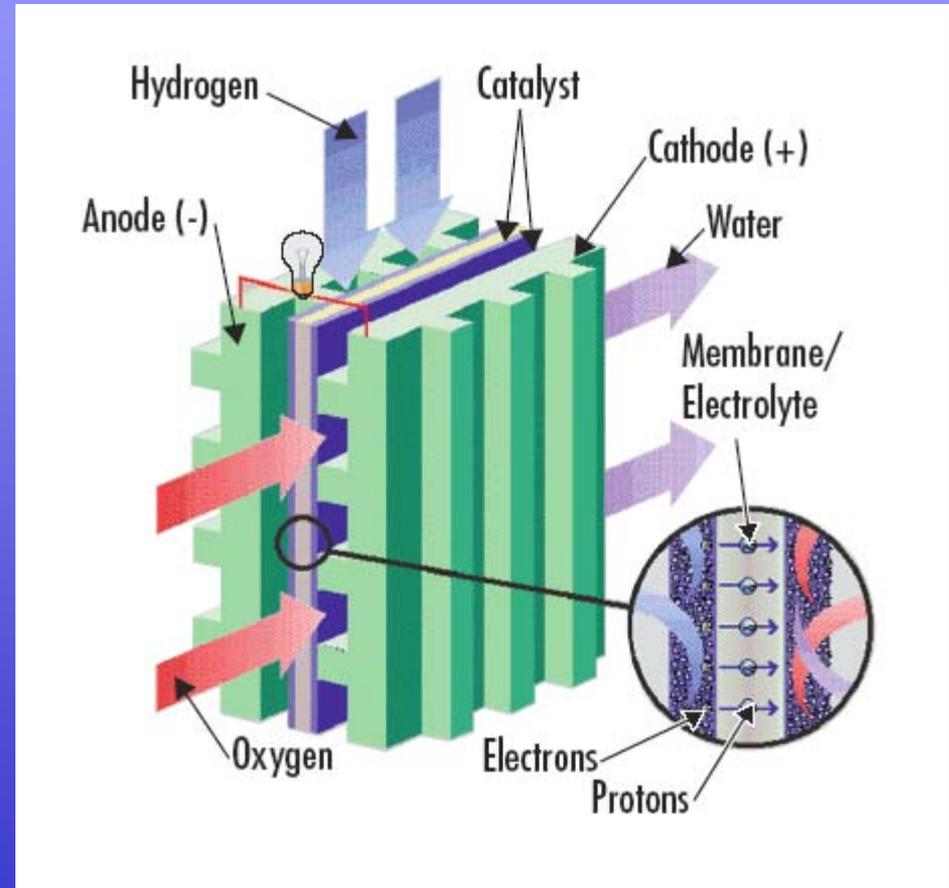
Type	Mobile Ion	Temp of Operation	Uses	Benefits	Issues
Alkaline (AFC)	OH ⁻	150-200C	Manned space flights (starting w/ Apollo missions) Some interest in vehicle use	Produces drinking water for astronauts and heat for the spacecraft Highly reliable	Extremely sensitive to CO ₂
Phosphoric Acid (PAFC)	H ⁺	150-200C	Stationary power Combined Heat and Power (CHP)	Electricity-only efficiency of ~40% Improved efficiency with CHP Reliable operation Commercial history	Cost reductions have stagnated (\$3500-4500/kW)
Molten Carbonate (MCFC)	CO ₃ ²⁻	~650C	Stationary power CHP	Electricity-only efficiency of ~60% High efficiency (80-85%) with CHP Fuel flexibility Noble metal catalyst not required	Long startup time Durability Cost
Solid Oxide (SOFC)	O ²⁻	800-1000C	Stationary power CHP Auxiliary Power Units (APUs)	Electricity-only efficiency of 50-60% 80-85% efficiency for CHP Fuel flexibility Noble metal catalyst not required Solid electrolyte	Long startup time Durability Cost
Polymer Electrolyte Membrane (PEMFC)	H ⁺	50-80C	Vehicles Portable appliances Stationary power	Fast startup High power density	Cost Durability Sensitivity to CO and H ₂ S

Polymer Electrolyte Membrane (PEM) Fuel Cells

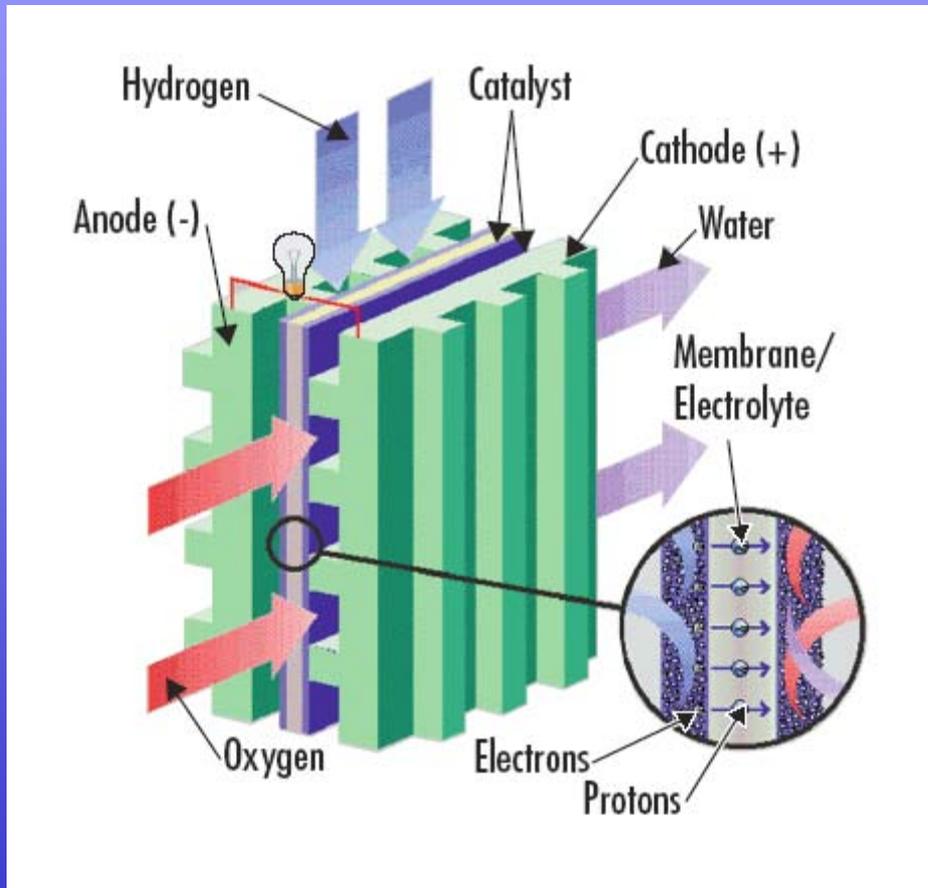
- The PEM fuel cell was initially developed for the first Gemini spacecraft, but did not meet the reliability requirements of NASA
- Development languished for decades, until improvements made at Los Alamos National Laboratory led to a resurgence of interest in the late 1980s and early 1990s
- The centerpiece of the PEM fuel cell is the solid, ion-conducting polymer membrane.
 - Typically made from a tough, Teflon-like material invented by DuPont called Nafion™
 - This material is unusual in that, when saturated with water, it conducts positive ions but not electrons
 - Exactly the characteristics needed for an electrolyte barrier

Schematic of PEM Fuel Cell

The membrane is sandwiched between the anode and cathode electrode structures, which are porous conducting films, about 50 micrometers thick. The electrodes consist of carbon particles that have nanometer-size platinum particles bonded to them, in a porous matrix of recast Nafion™. The carbon particles provide the electron-conducting path, while the Nafion™ provides an ion-conducting path to the membrane.



Schematic of PEM Fuel Cell



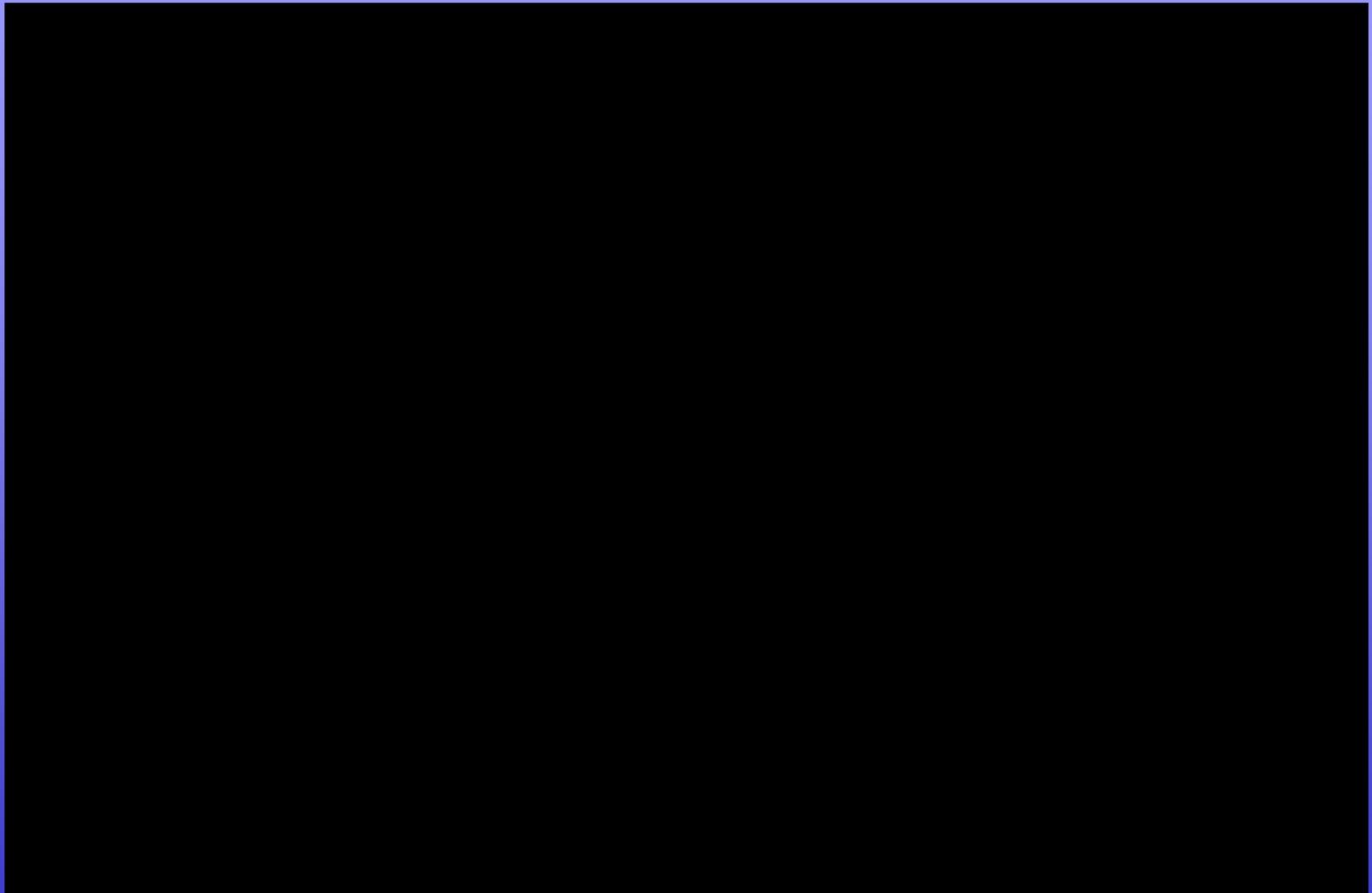
In addition to having catalytic, electric- and ion-conducting properties, the electrodes and the supporting backing material are crucial to water management. This, and the control of gas flows in and out of the cell, are key to efficient cell operation:

- too little water at the cathode, the membrane begins to lose the ability to conduct ions.
- too much water, it floods the porous electrodes and prevents oxygen from diffusing to the catalytically active sites.

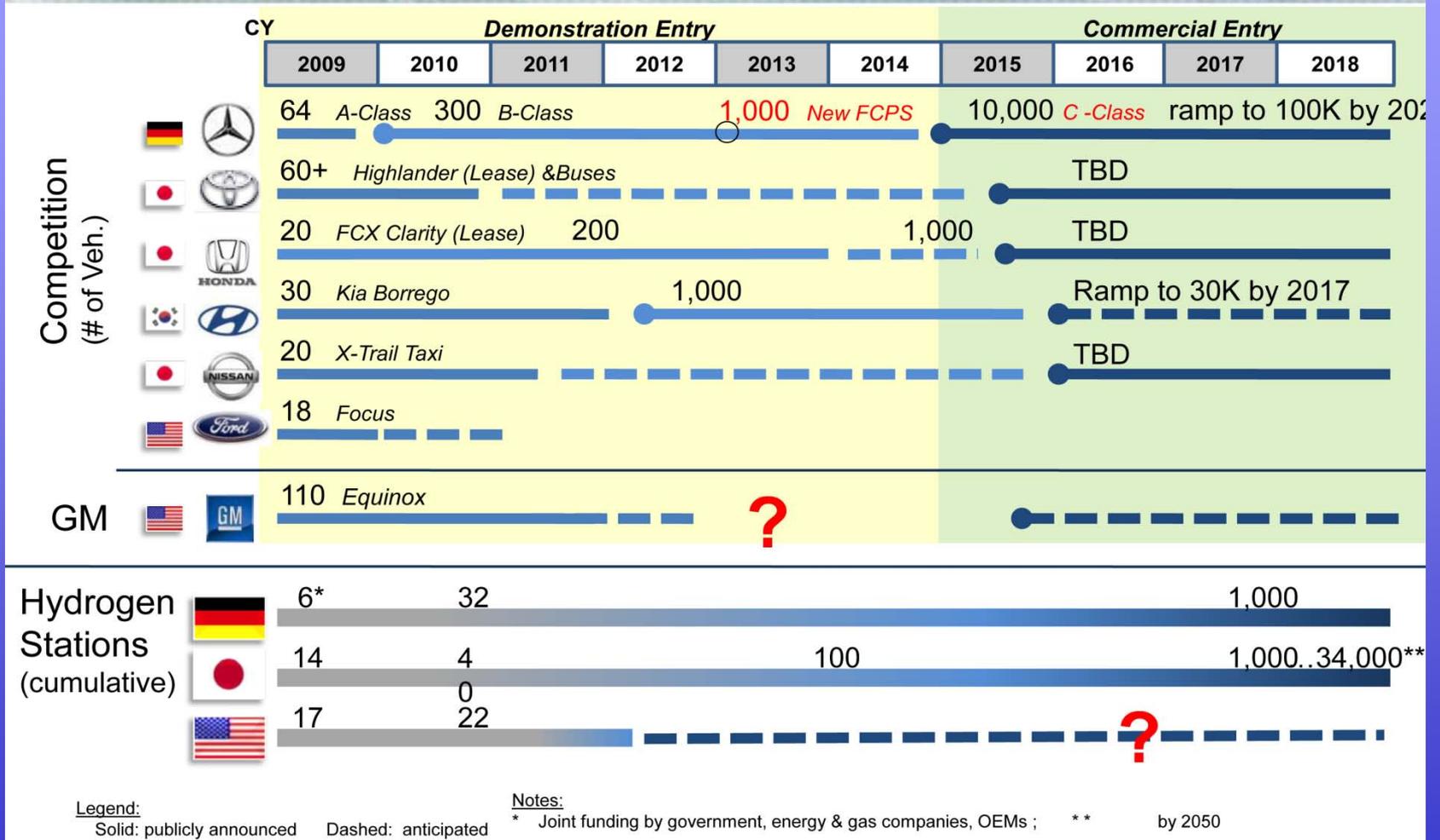
PEM Fuel Cells

- Transportation is the key target/focus area of efforts to develop and commercialize PEM fuel cells, although not the only area of interest
- Low temperature ($\sim 80^{\circ}\text{C}$) PEM fuel cells
 - Less “waste” heat, and higher electrical efficiency
 - Limits CHP applications compared to other fuel cell types
 - Quick startup, lower thermal stresses
- Efficient at low loads (typical operating region for vehicles)

How PEM Fuel Cells Work



Competitive Landscape - Summary



GM Confidential

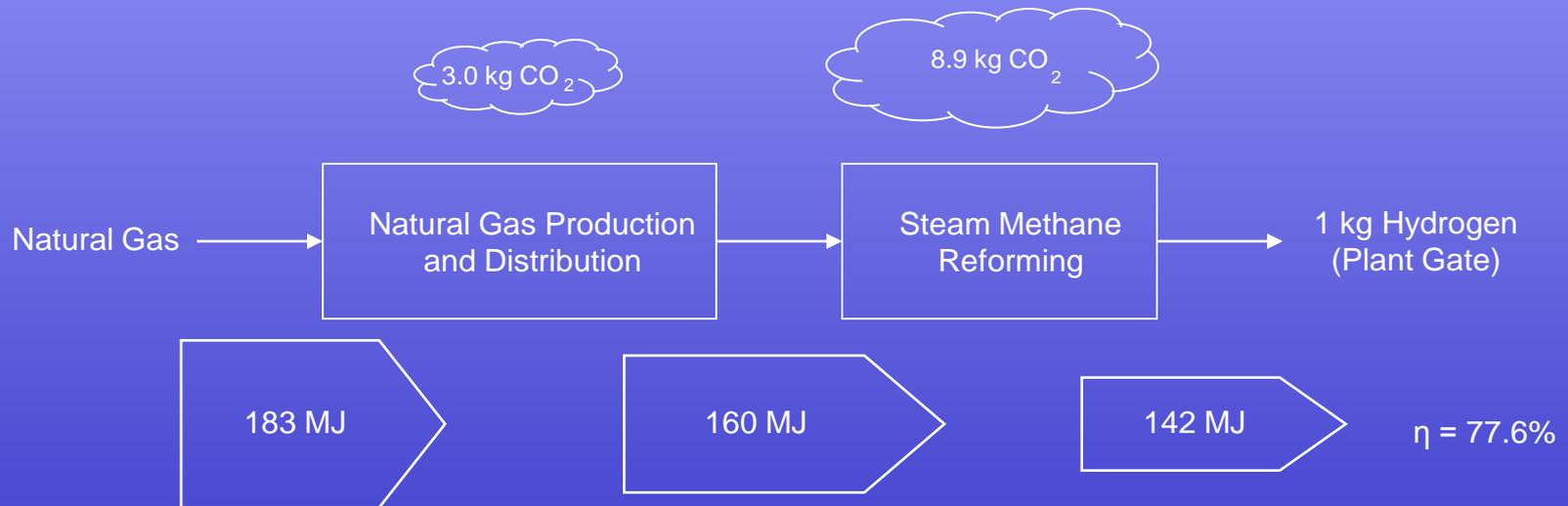
BREAK!!!!

Part III:
Environmental, Energy
and Economic Implications

Environmental, Energy and Economic Implications

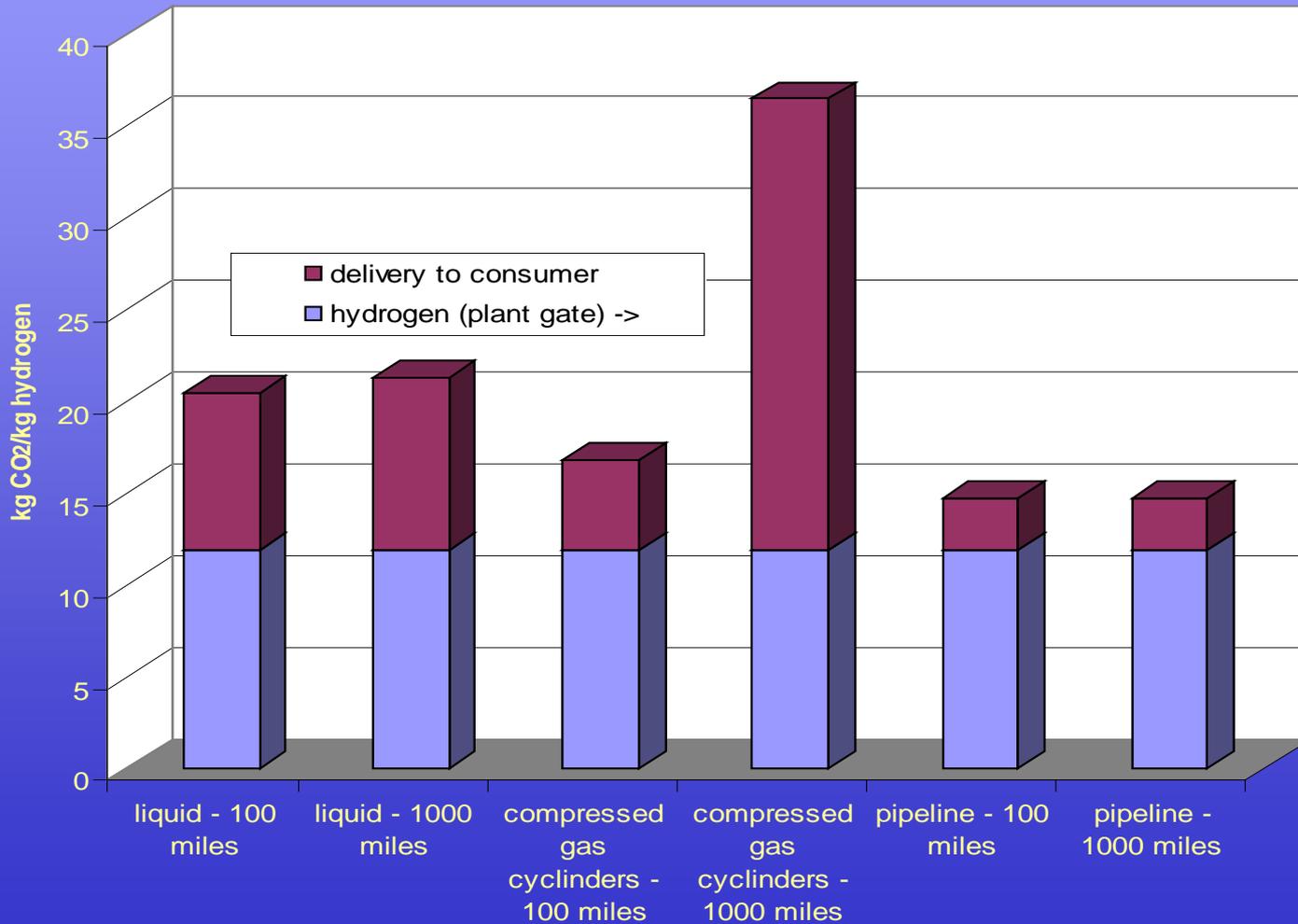
Current Technology:

Central Station Hydrogen from Steam Methane Reforming

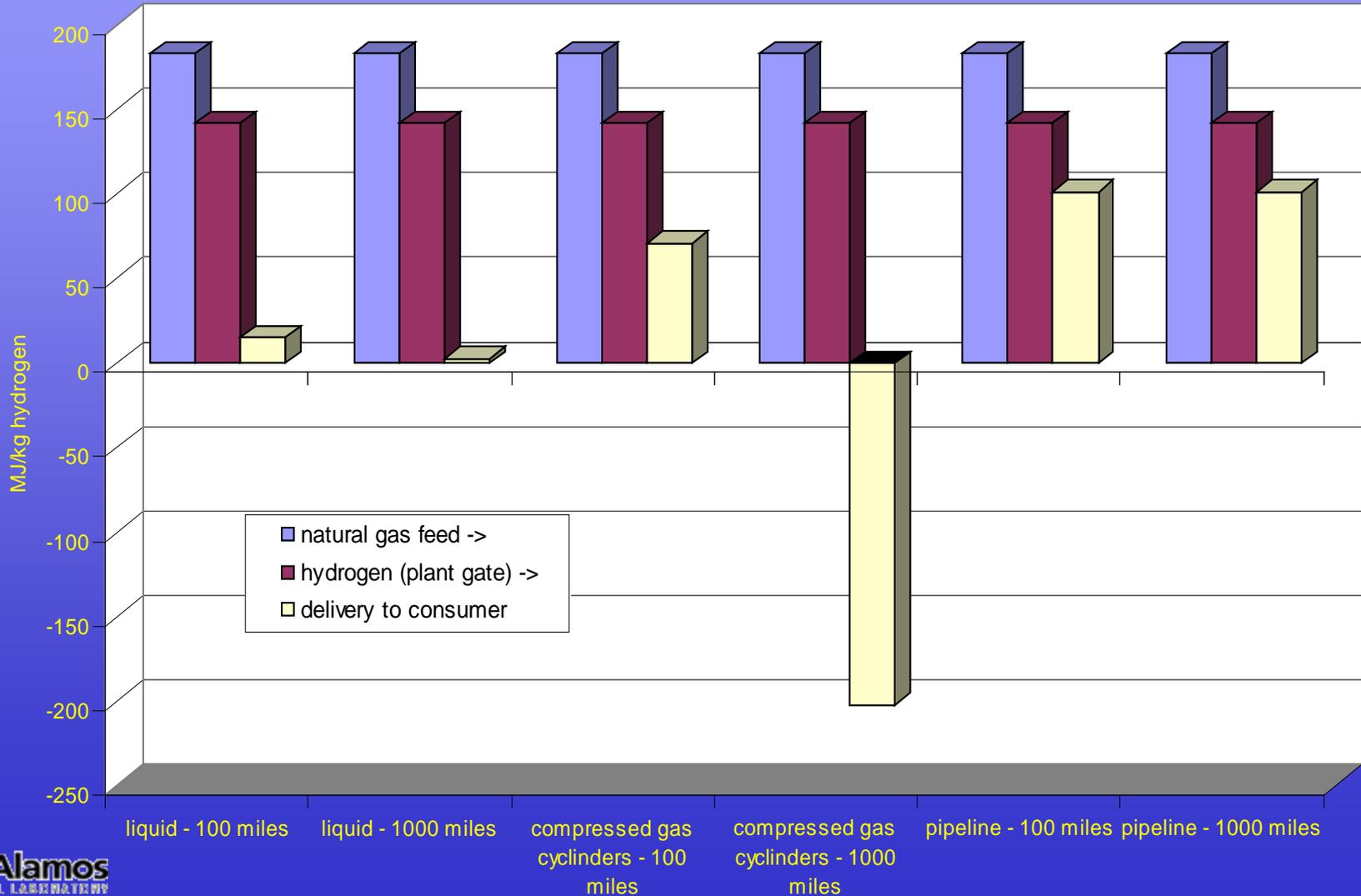


1 kg hydrogen produces 11.9 kg CO₂-equivalent emissions (stoichiometry says 5.5 kg CO₂)

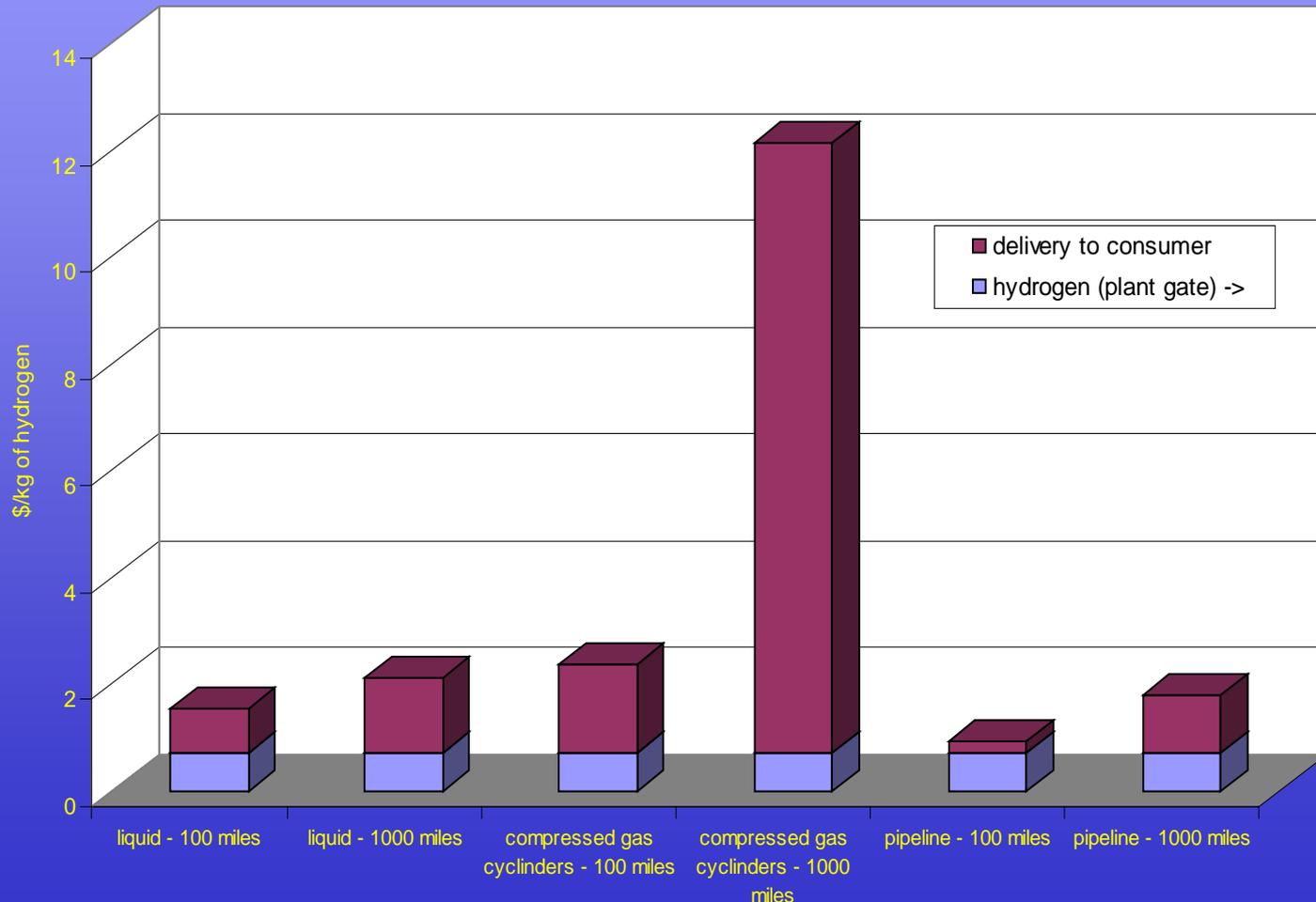
Environmental Implications



Energy Implications



Economic Implications

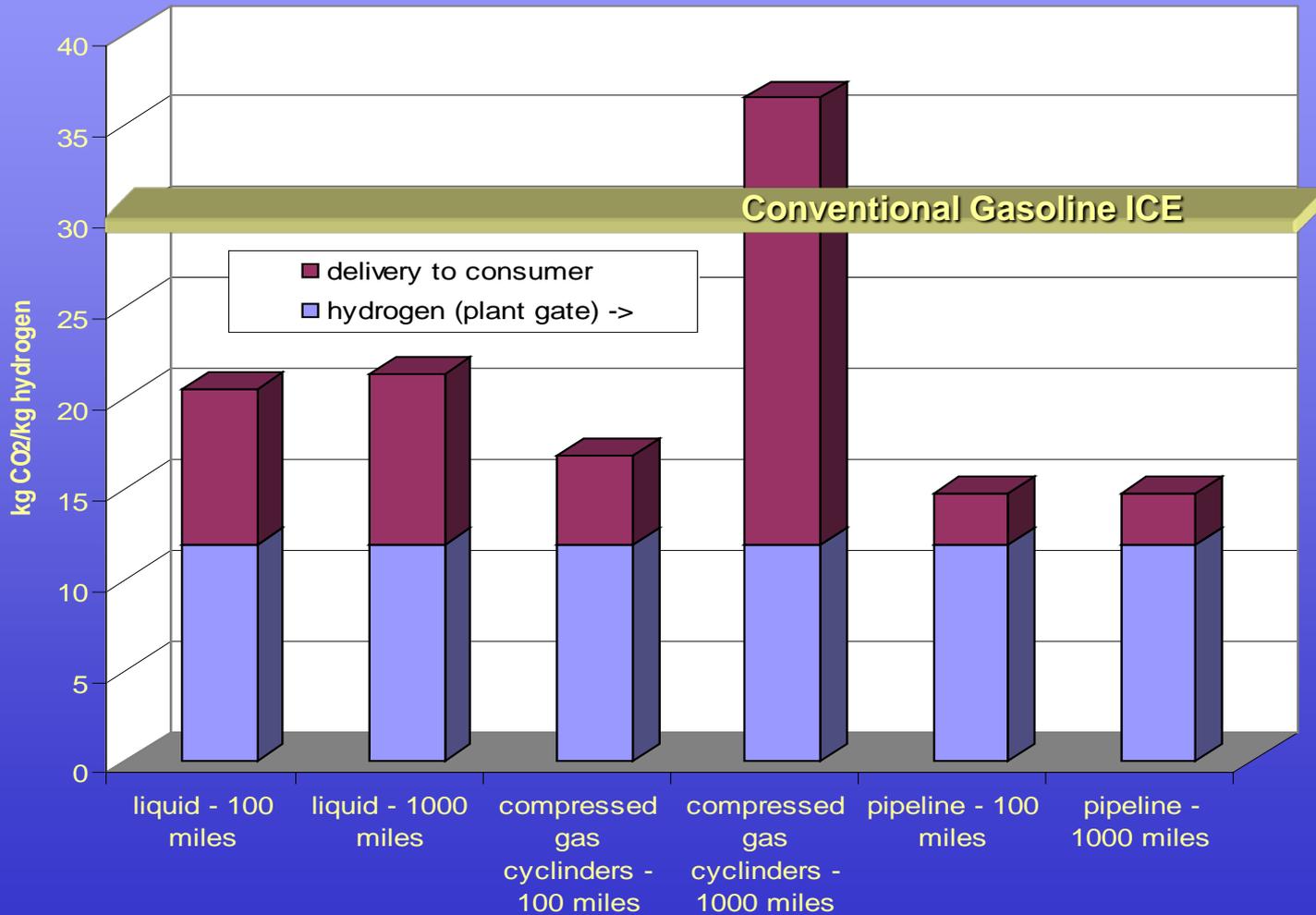


Environmental Implications

- Conventional Gasoline ICE
 - Well-to-Wheels:
 - Car similar to Chevy Malibu (2010 fuel economy and emission numbers from www.fueleconomy.gov)
 - 0.5 kg CO_{2-equivalent}/mile driven, for fuel economy of 22 mpg (combined driving), full fuel cycle basis
 - For 15,000 miles driven per year: 7,545 kg CO_{2-equivalent}/year
- Hydrogen FCV: zero tailpipe CO₂ emissions
 - Well-to-Wheels:
 - At 60 mpgge (~60 mpkg): 250 kg hydrogen needed yearly
 - No CO₂ from the tailpipe
 - only need to do better than 30.2 kg CO_{2-equivalent}/kg hydrogen for production *and delivery* (if we compare to conventional technology)

Environmental Implications

Conventional Gasoline Vehicle and Hydrogen Fuel Cell Vehicle

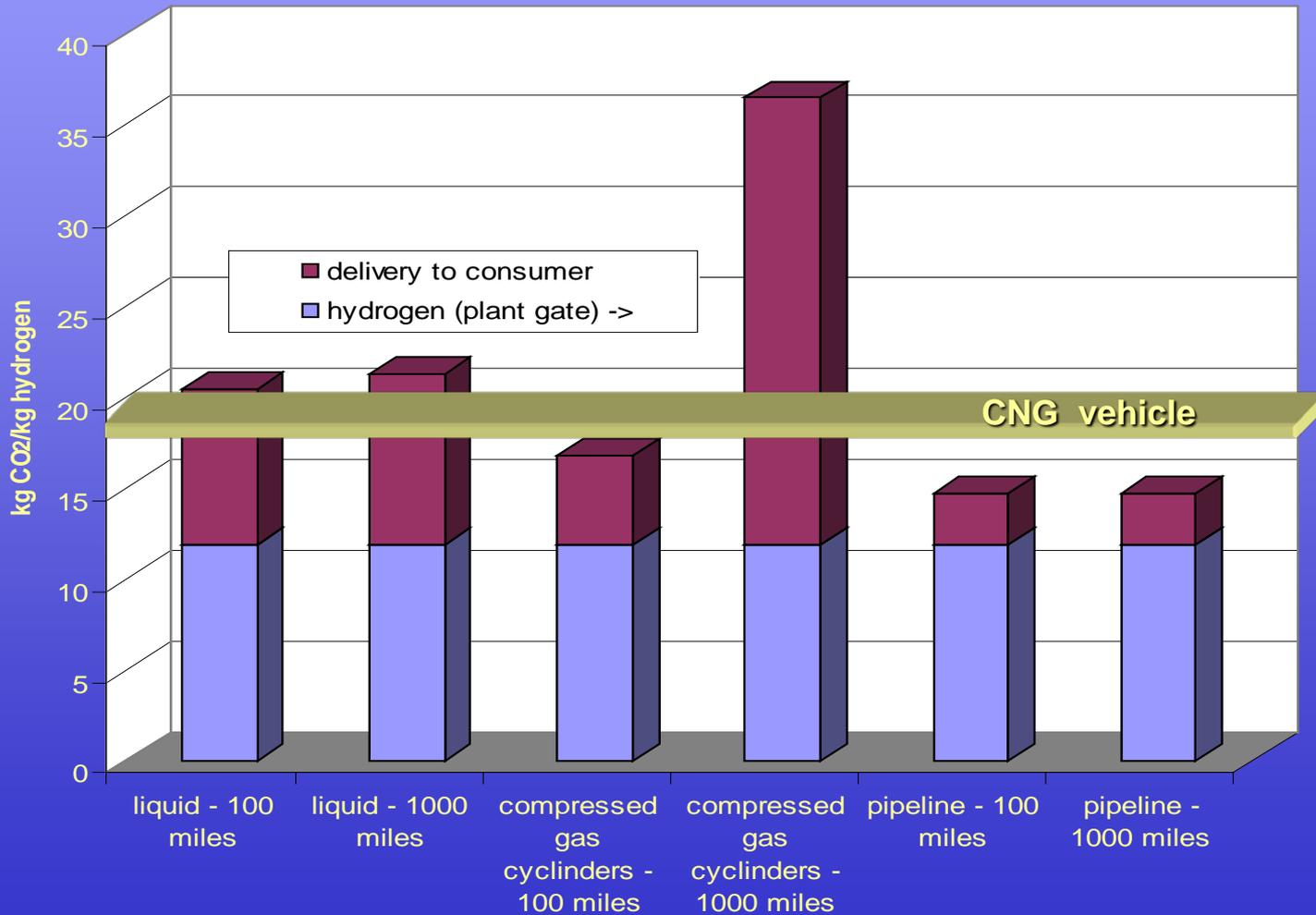


Environmental Implications

- Compressed Natural Gas ICE
 - Well-to-Wheels:
 - Car similar to Honda Civic CNG (2009 fuel economy and emission numbers from www.fueleconomy.gov)
 - 0.33 kg CO₂-equivalent/mile driven, for fuel economy of 28 mpg (combined driving), full fuel cycle basis
 - For 15,000 miles driven per year: 4,909 kg CO₂-equivalent/year
- Hydrogen FCV: zero tailpipe CO₂ emissions
 - Well-to-Wheels:
 - At 60 mpgge (~60 mpkg): 250 kg hydrogen needed yearly
 - No CO₂ from the tailpipe
 - only need to do better than 19.6 kg CO₂-equivalent/kg hydrogen for production *and delivery* (if we compare to conventional technology)

Environmental Implications

CNG Vehicle and Hydrogen Fuel Cell Vehicle

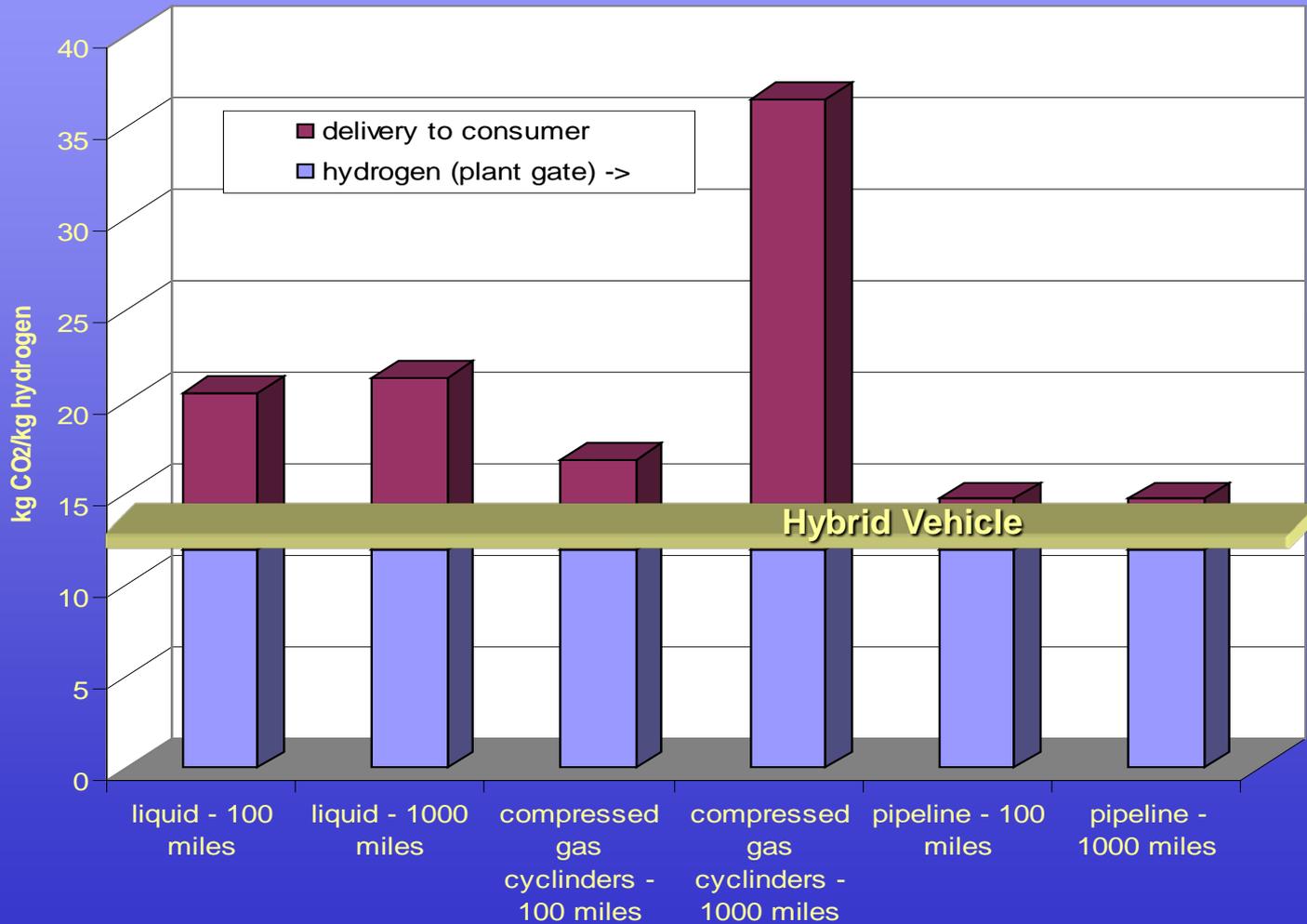


Environmental Implications

- Gasoline hybrid – the real competition?
 - Well-to-Wheels:
 - Toyota Prius (2010 fuel economy and emission numbers from www.fueleconomy.gov)
 - 0.22 kg CO_{2-equivalent}/mile driven, for fuel economy of 50 mpg (combined driving), full fuel cycle basis
 - For 15,000 miles driven per year: 3,364 kg CO_{2-equivalent}/year
- Hydrogen FCV: zero tailpipe CO₂ emissions
 - Well-to-Wheels:
 - At 60 mpgge (~60 mpkg): 250 kg hydrogen needed yearly
 - No CO₂ from the tailpipe
 - but need to do better than 13.5 kg CO_{2-equivalent}/kg hydrogen for production *and delivery* (if we compare to hybrid technology)

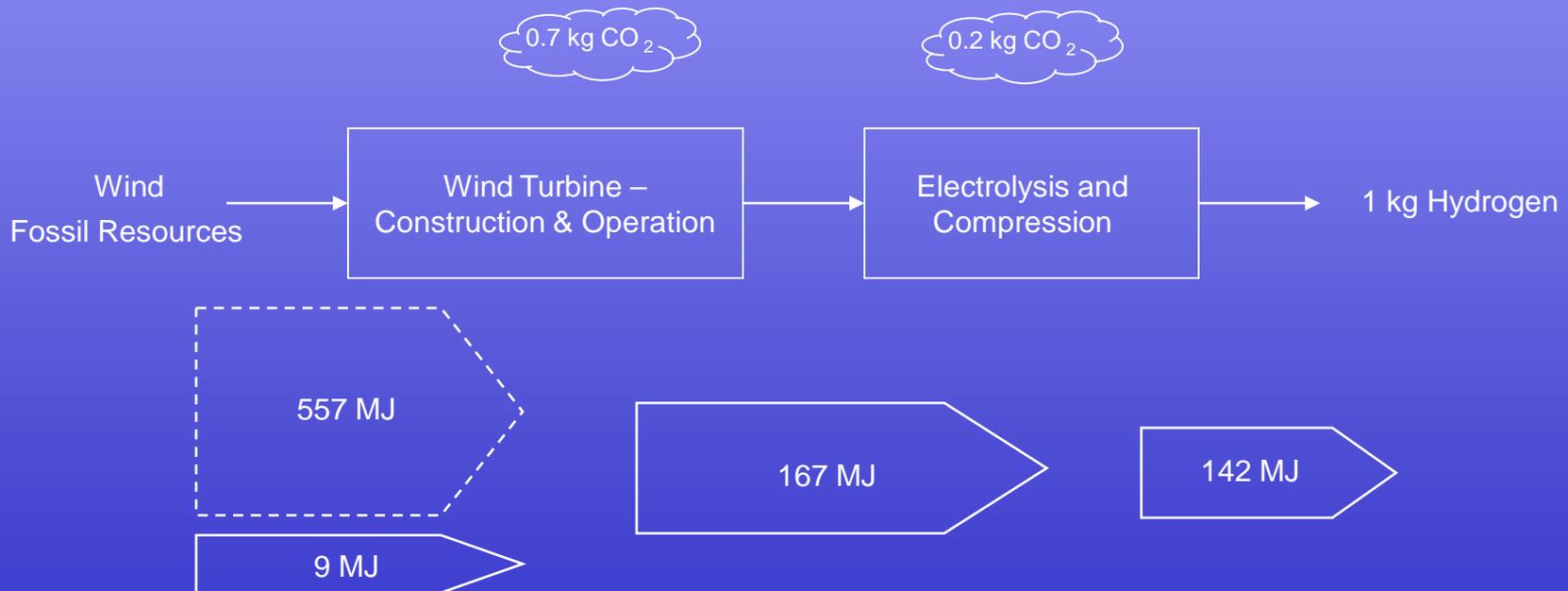
Environmental Implications

Hybrid Gasoline Vehicle and Hydrogen Fuel Cell Vehicle



Environmental Implications

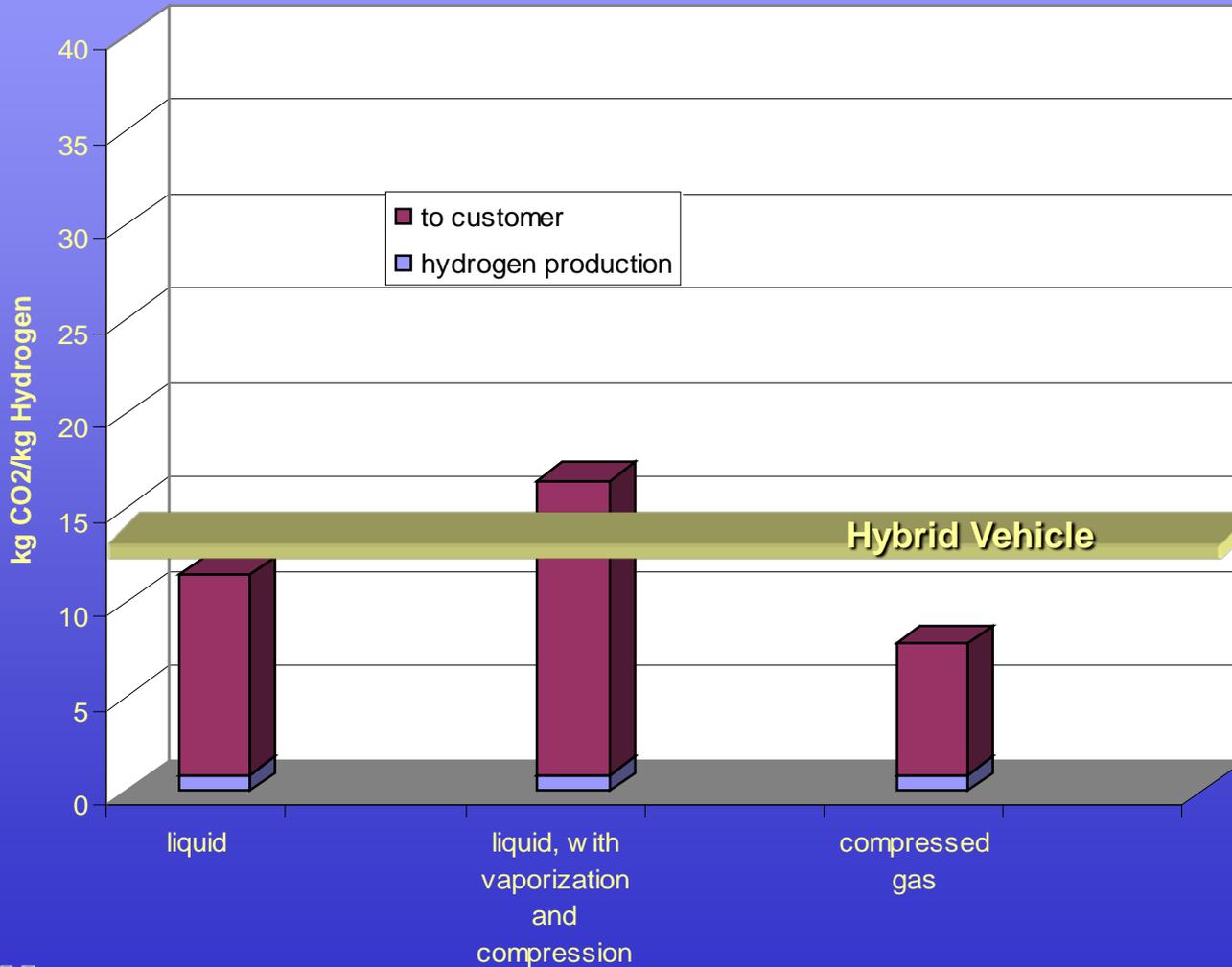
Near-Term Renewable Technology: Distributed Hydrogen from Wind Electrolysis



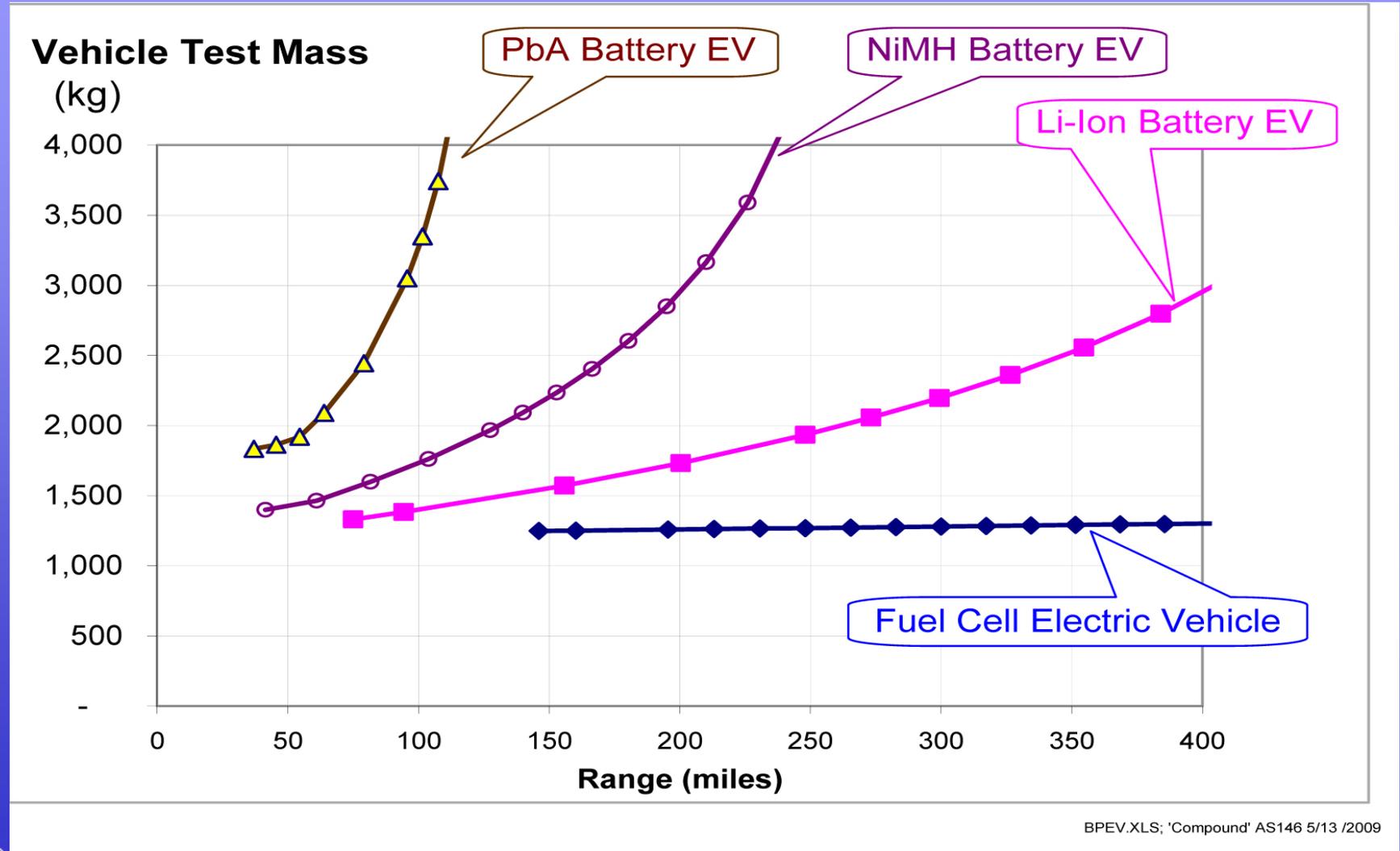
1 kg hydrogen produces 0.9 kg CO₂-equivalent emissions (stoichiometry says 0 kg CO₂)

Environmental Implications

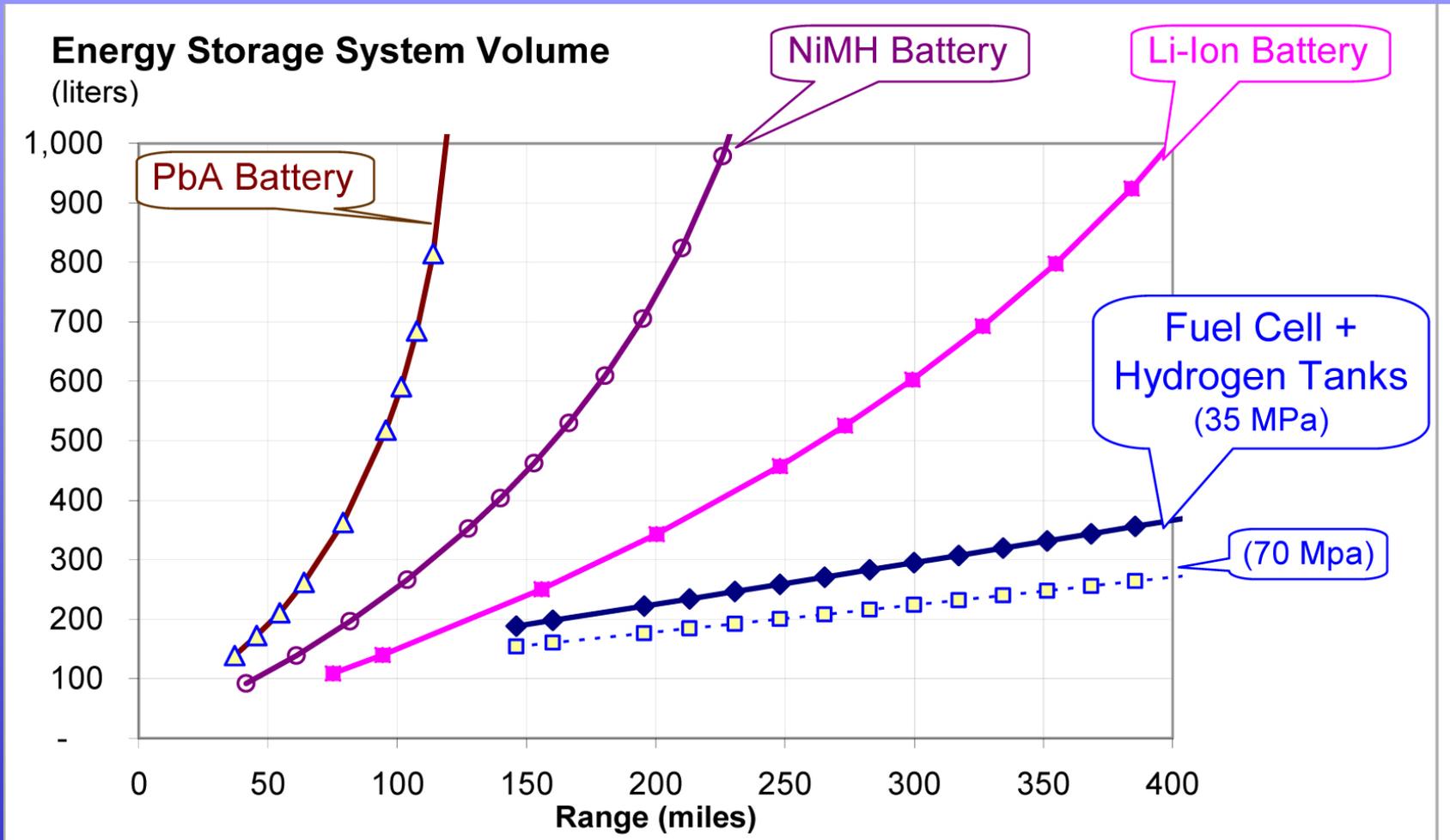
Hybrid Gasoline Vehicle and Hydrogen Fuel Cell Vehicle



What about BEVs?



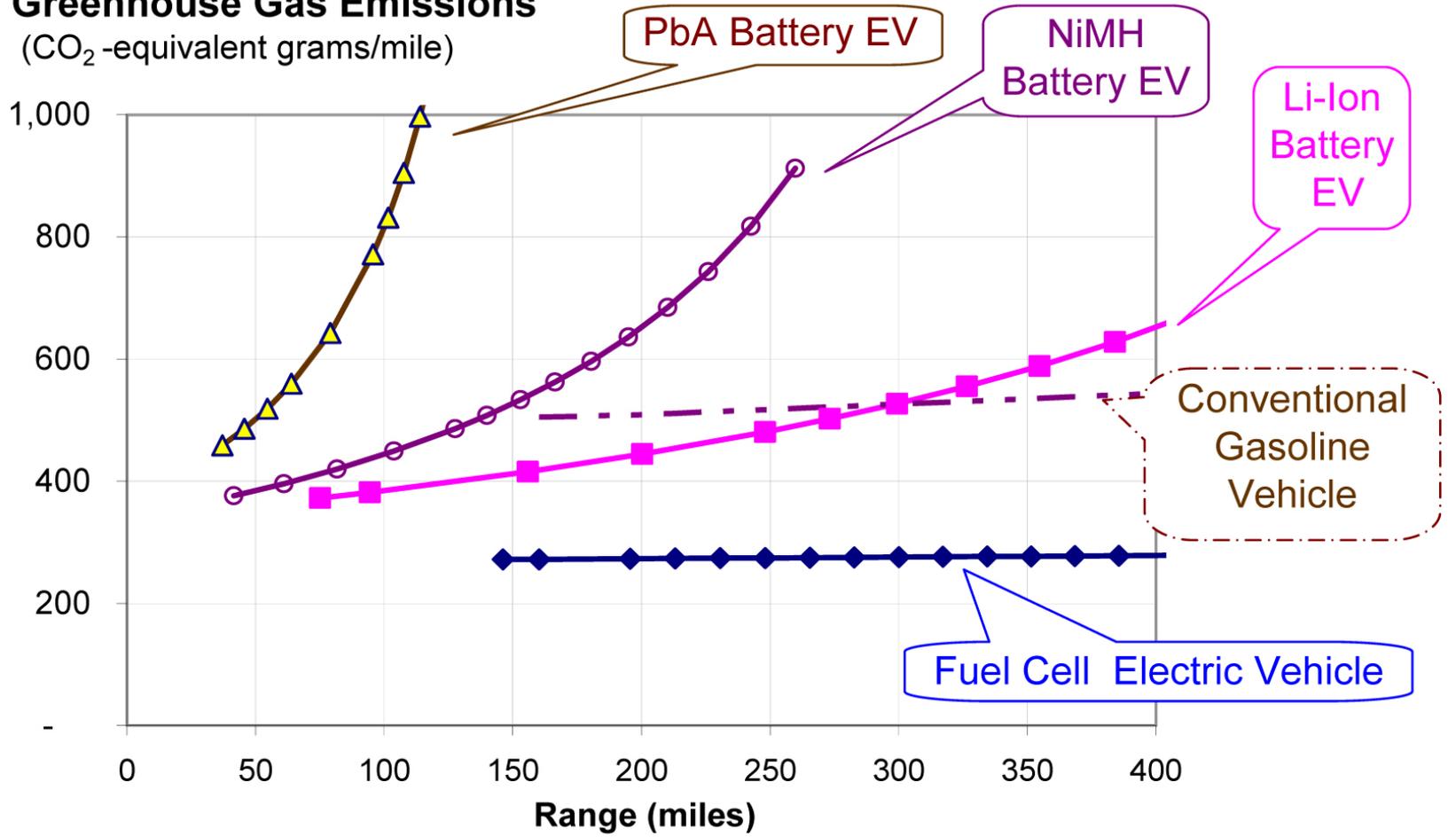
What about BEVs?



BPEV.XLS; 'Compound' AS113 5/13 /2009

What about BEVs?

Greenhouse Gas Emissions
(CO₂-equivalent grams/mile)

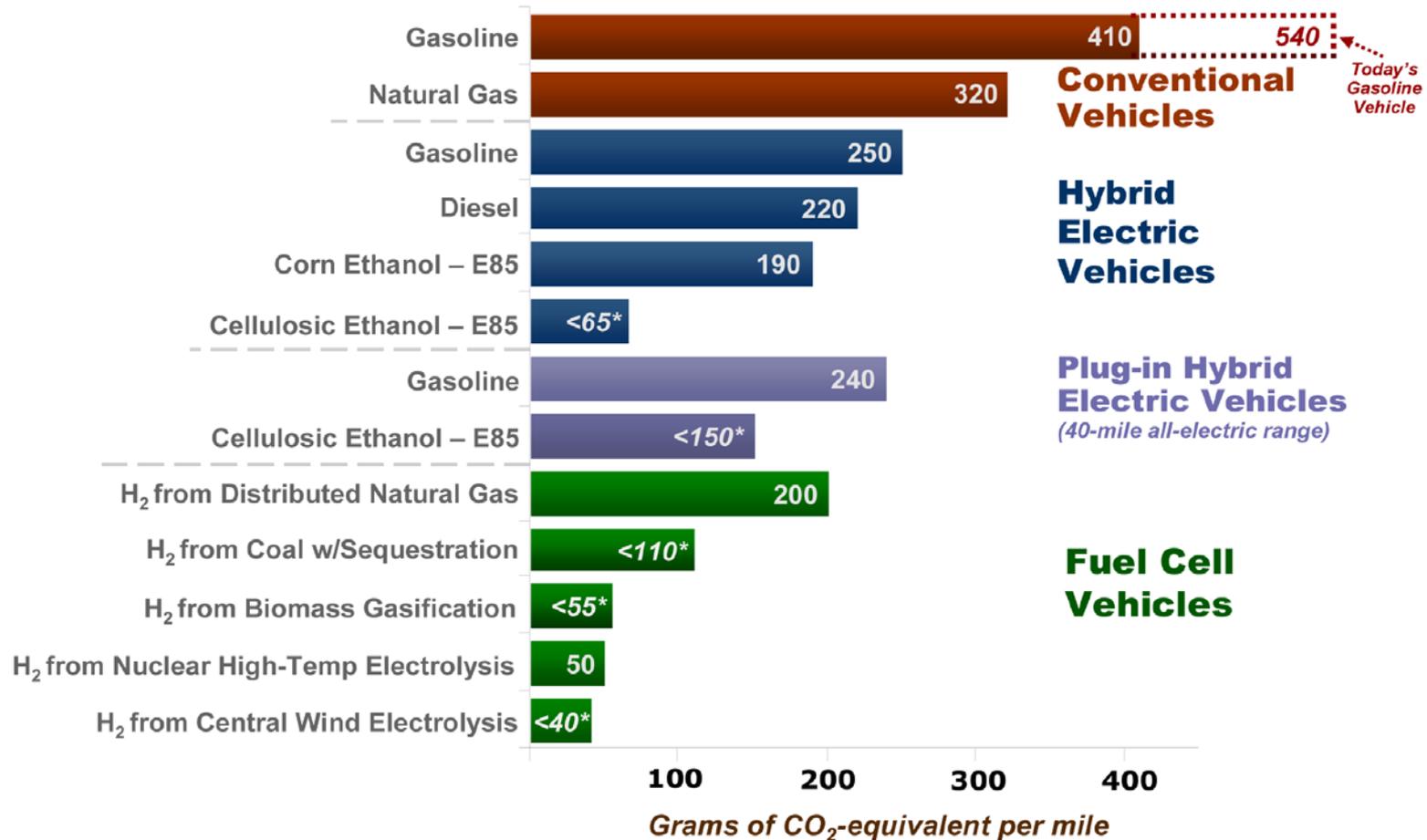


Grid Mix: US

BPEV.XLS; 'Compound' AQ200 5/13 /2009

Well-to-Wheels Greenhouse Gas Emissions

(life cycle emissions, based on a projected state of the technologies in 2020)

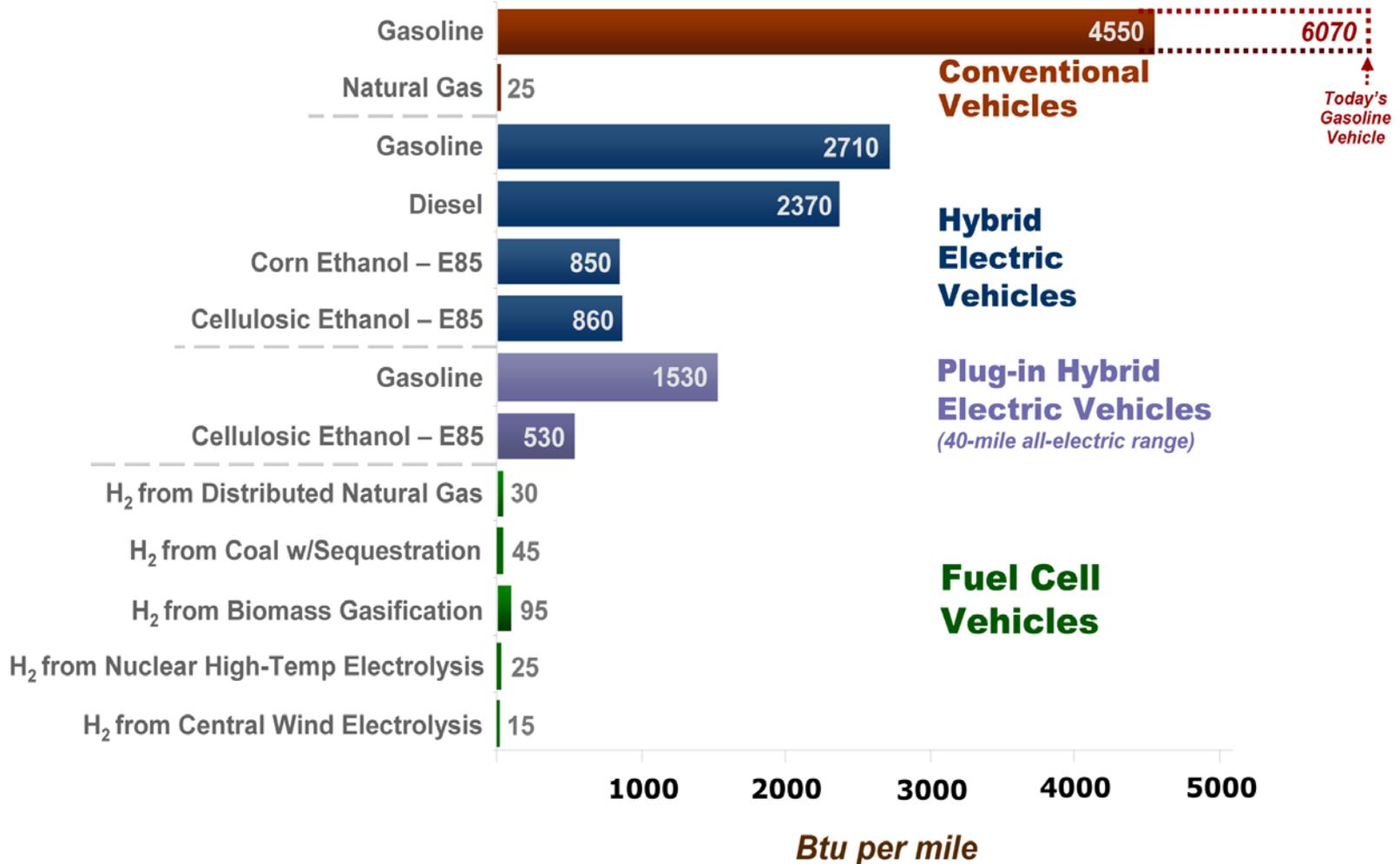


*Net emissions from these pathways will be lower if these figures are adjusted to include:

- The displacement of emissions from grid power-generation that *will* occur when surplus electricity is co-produced with cellulosic ethanol
- The displacement of emissions from grid power-generation that *may* occur if electricity is co-produced with hydrogen in the biomass and coal pathways, and if surplus wind power is generated in the wind-to-hydrogen pathway
- Carbon dioxide sequestration in the biomass-to-hydrogen process

Well-to-Wheels Petroleum Energy Use

(based on a projected state of the technologies in 2020)



Part IV:
Hydrogen Safety
Real and Perceived

Fuel Properties

Property	Hydrogen H ₂	Methane CH ₄	Methanol CH ₃ OH	Gasoline
Boiling point (C)	-253	-162	65	wide range
Physical state at 25 C	Gas	Gas	Liquid	Liquid
Heating Value - weight basis				
LHV (MJ/kg)	120	48	20	42-44
HHV (MJ/kg)	142	53	23	44-46
Heating Value - volume basis				
LHV (MJ/Nm ³)	11	35	15,700	~32,000
HHV (MJ/Nm ³)	13	39	18,100	~33,000
Flammability limits (vol% in air)	4.1-74	5.3-15	6-36.5	1.4-7.6
Explosive limits (vol% in air)	18.2-58.9	5.7-14	6.7-36	1.4-3
Molecular diffusion coeff (cm ² /sec) in air	0.61	0.16	0.13	0.05
Autoignition temperature in air (C)	571	632	470	220
Liquid density (g/liter)	77	425	792	720-780
Specific gravity at 25 C (water=1)	-	-	.79	.72-.78
Specific gravity at 25 C (air=1)	.07	.55	1.1	3.5-4.5

From the Congressional Record 1875

“A new source of power... **called gasoline** has been produced by a Boston engineer. Instead of burning the fuel under a boiler, it is **exploded** inside the cylinder of an engine...

The **dangers** are obvious. Stores of gasoline in the hands of people interested primarily in profit would **constitute a fire and explosive hazard of the first rank**. Horseless carriages propelled by gasoline might attain speeds of 14, or even 20 miles per hour. The **menace to our people** of this type **hurtling through our streets** and along our roads and **poisoning the atmosphere** would call for prompt legislative action even if the military and economic implications were not so overwhelming... the **cost** of producing (gasoline) is far beyond the financial capacity of private industry... In addition the development of this new power may **displace the use of horses**, which would wreck our agriculture.”

Public Acceptance

- We can succeed technically, but still fail if we don't:
 - Involve the public early and often in the demonstration of new technologies
 - Inform the public about hydrogen and fuel cells in ways they can understand
 - Address safety concerns, real and imagined

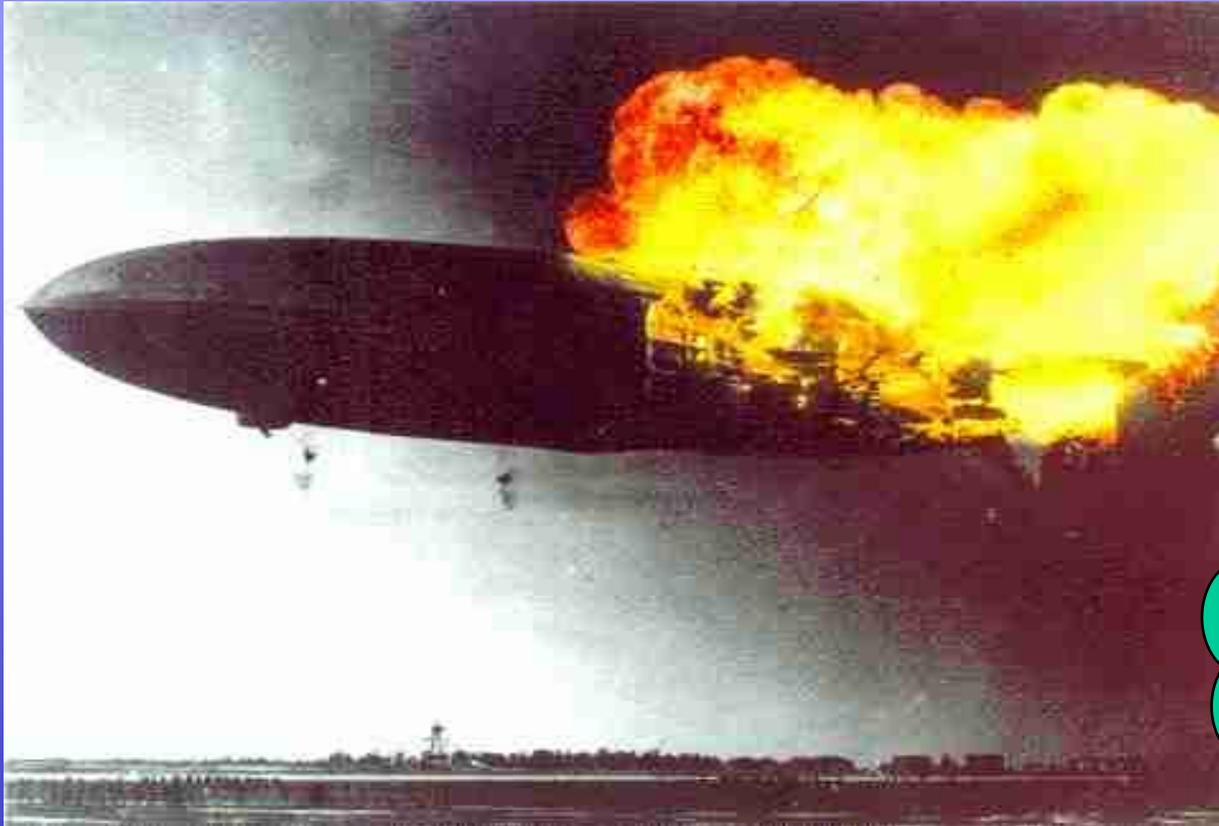
Project Considerations: Community Buy-In

- Community support activities should begin very early in project development to allow ample time for education, feedback, and modifications, if needed. Community members may be unfamiliar with fuel cells, hydrogen fuels, and hydrogen safety and may have concerns about the project. If such concerns are not addressed, project development may be severely delayed or even cancelled.
- Community buy-in activities may include educational presentations, open forums, and other events hosted by the developer or zoning officials. Such activities may be performed simultaneously with zoning and site selection.



The Benning Road hydrogen fueling station in Washington, DC, was delayed one year because of community concerns.

Hydrogen Safety?



Moral of the Story ?

Don't paint your dirigible with rocket fuel !

Hindenberg, 1937

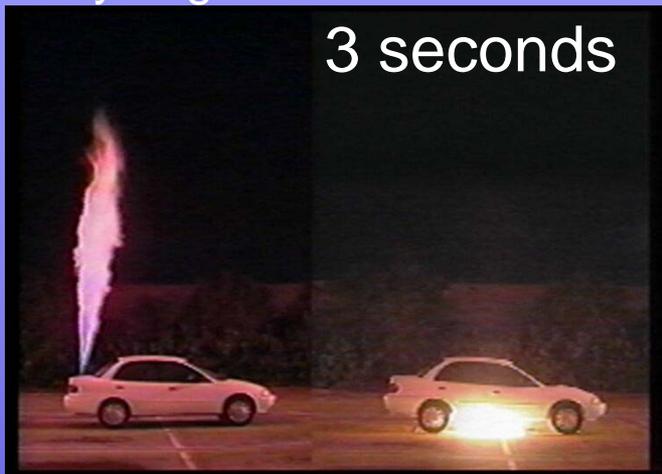
Colorized photo shows burning of outer fabric of dirigible

Hydrogen Safety

Hydrogen

Gasoline

3 seconds



1 minute

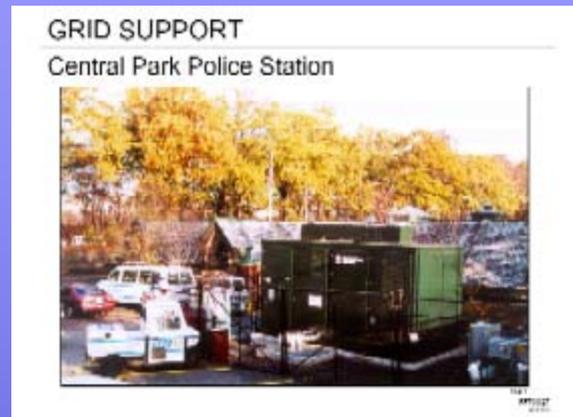


- Fuel leak simulation
 - Hydrogen on left
 - Gasoline on right
 - Equivalent energy release
- Single-mode failure assessment

Which car would you rather be in?

So – why hydrogen?

- It really is all about security
 - Energy security
 - Diverse domestic sources
 - Flexibility of system
 - Economic security
 - International leadership in technology development and deployment
 - Balance of payments
 - Price stability
 - Environmental security
 - Potential to meet GHG targets: with renewables or fossil with sequestration
 - Urban air quality improvements
 - Reduction in air pollutants



Post-Quiz

Quiz Answers – True or False

- Hydrogen pipelines exist nationwide False
- In a hydrogen economy, hydrogen replaces fossil fuels as the dominant form of energy True
- Hydrogen gas is toxic False
- Fuel cells produce electricity through hydrogen combustion False
- Hydrogen is too dangerous for everyday use by the general public False
- Hydrogen is lighter than air True
- Hydrogen has a distinct odor False

Quiz Answers – Multiple Choice

- In which state or condition can hydrogen be stored?
 - a. chemical compound
 - b. liquid
 - c. both of these
 - d. neither of these
- When using pure hydrogen, fuel cell vehicles generate electricity, water, and what else?
 - a. carbon dioxide
 - b. nitrous oxides
 - c. heat
 - d. all of these
- Hydrogen can be produced using which of the following sources of energy?
 - a. natural gas
 - b. sunlight
 - c. organic matter
 - d. all of these
- Which of the following represents a type of fuel cell?
 - a. PDO
 - b. PEM
 - c. CFC
 - d. none of these

STEP ON THE
HYDROGEN

