The Promise and Challenge of Hydrogen Energy

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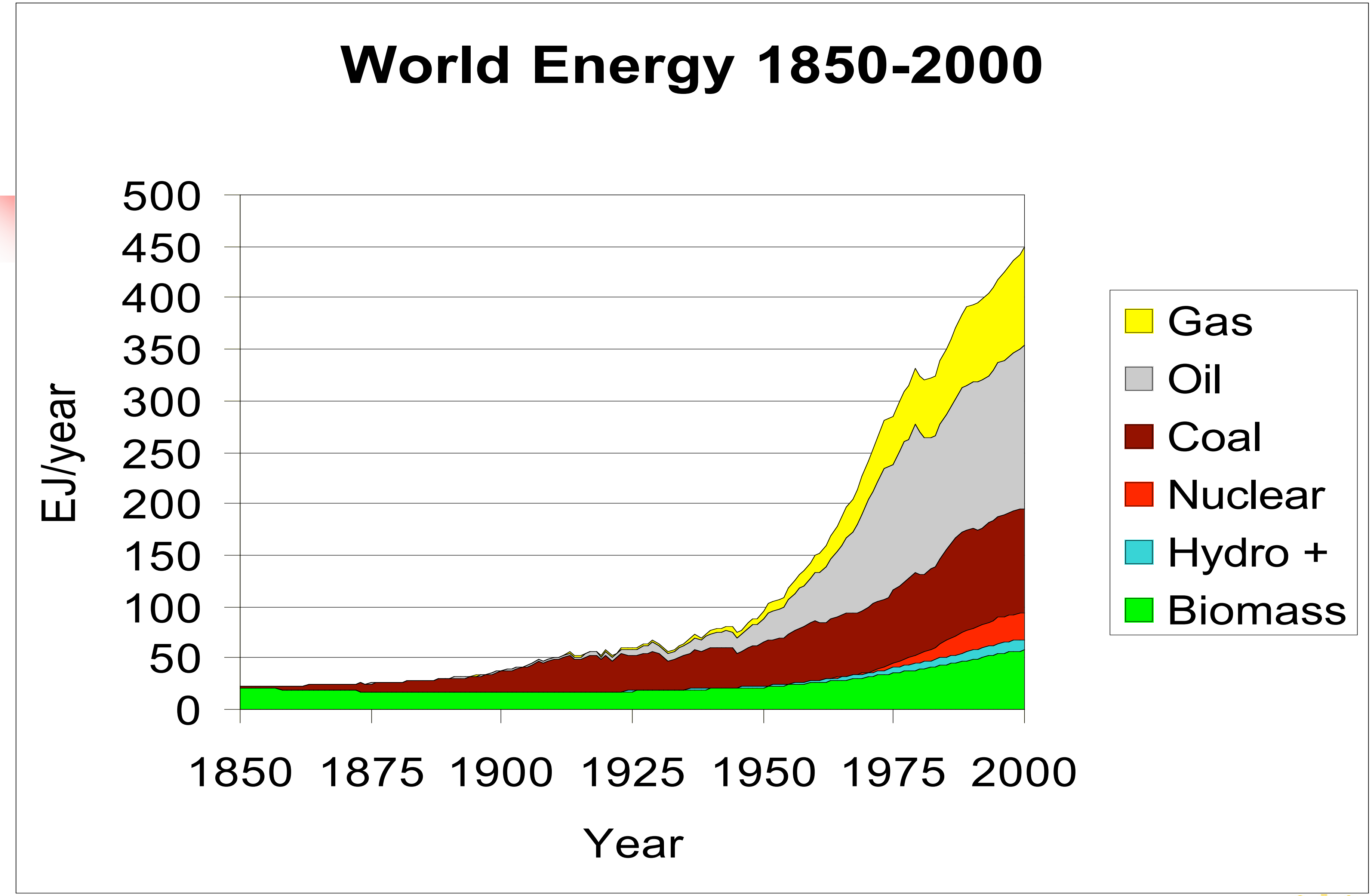
Session Topics

- Why hydrogen energy ?
- Alternative ways of H_2 production today and tomorrow, including those suitable for nuclear energy match.
- What nuclear technologies can play a role in the hydrogen economy?
- What plans does DOE have for nuclear hydrogen?



Fossil fuels are dominant and are almost 80% of supply today

Is there enough fossil fuel for 2100? YES.

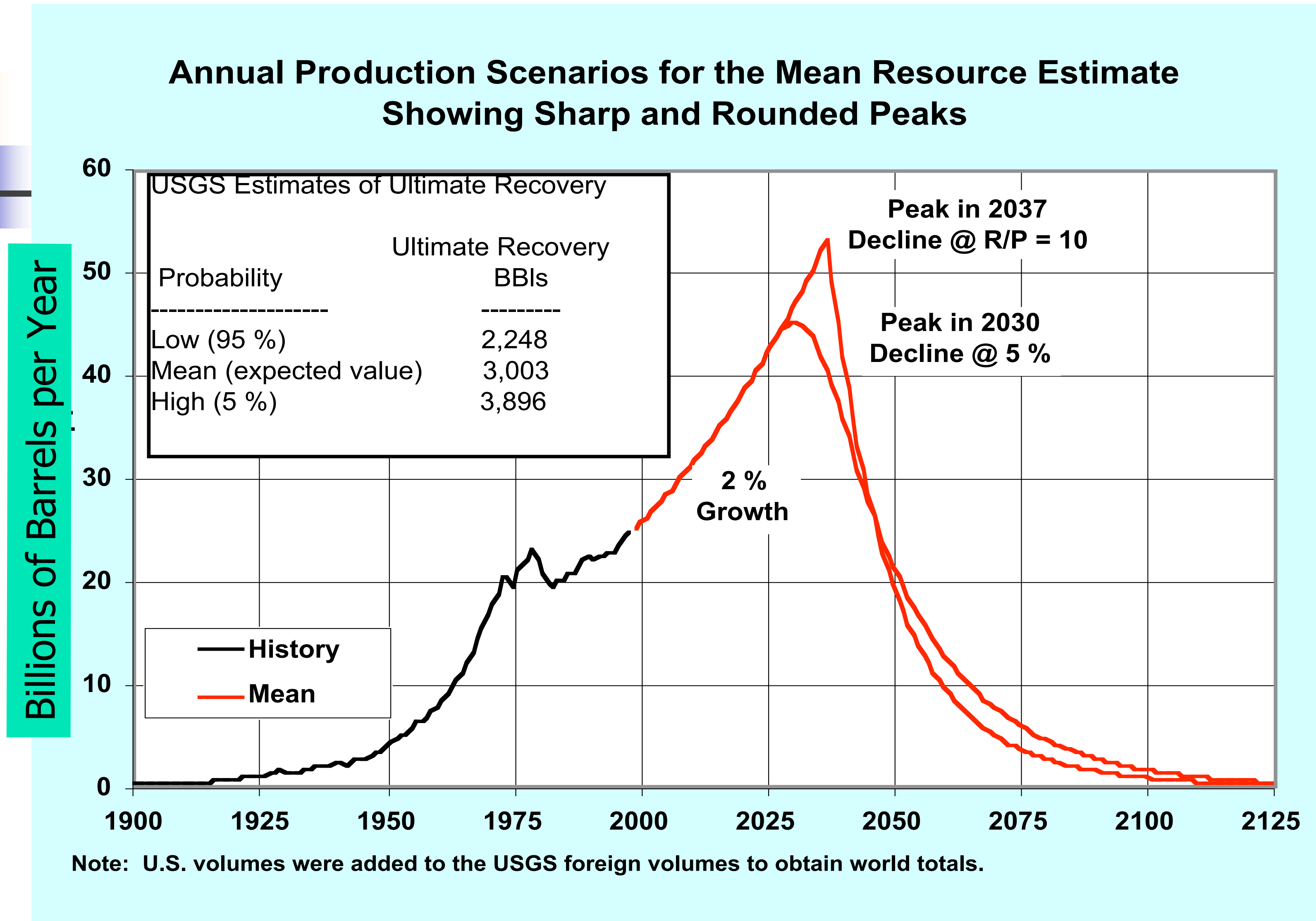
ULTIMATELY RECOVERABLE NONRENEWABLE RESOURCES

Rounded & Approximate in Twy

1 TWy ≈ 30 EJ; today the world uses only ~15 TWy per year in total.

OIL & GAS, CONVENTIONAL	1,000	
UNCONVENTIONAL OIL & GAS (excluding clathrates)		2,000
COAL	5,000	
METHANE CLATHRATES		20,000
OIL SHALE		30,000
URANIUM IN CONVENTIONAL REACTORS	2,000	
...IN BREEDER REACTORS	2,000,000	
THORIUM in BREEDERS	6,000,000	
FUSION, D-T FUEL (limited by lithium availability)		100,000,000
...D-D FUEL		200,000,000,000
GEOTHERMAL STEAM	4,000	
...HOT DRY ROCK	1,000,000	

Sources: John Holdren, talk at the Carnegie Institution in Washington DC, March 2000
--Modified by thorium addition to Nuclear Resources

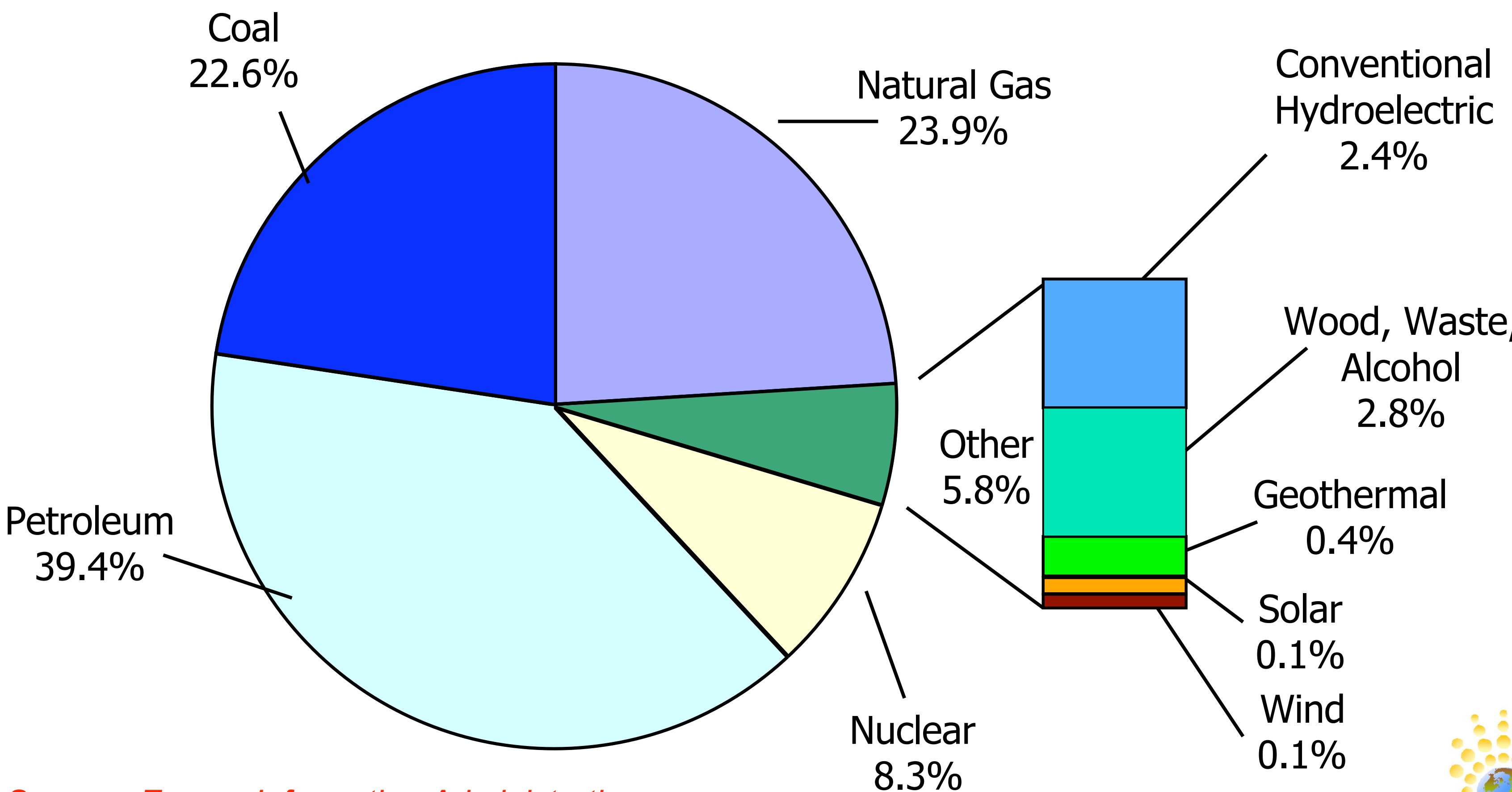


EIA Mean Estimate Forecast of World Oil Production

(EIA. Long Term World Oil Supply. April 2000)

U.S. Sources of Energy: 2001
Total Use: 97 Quadrillion Btu

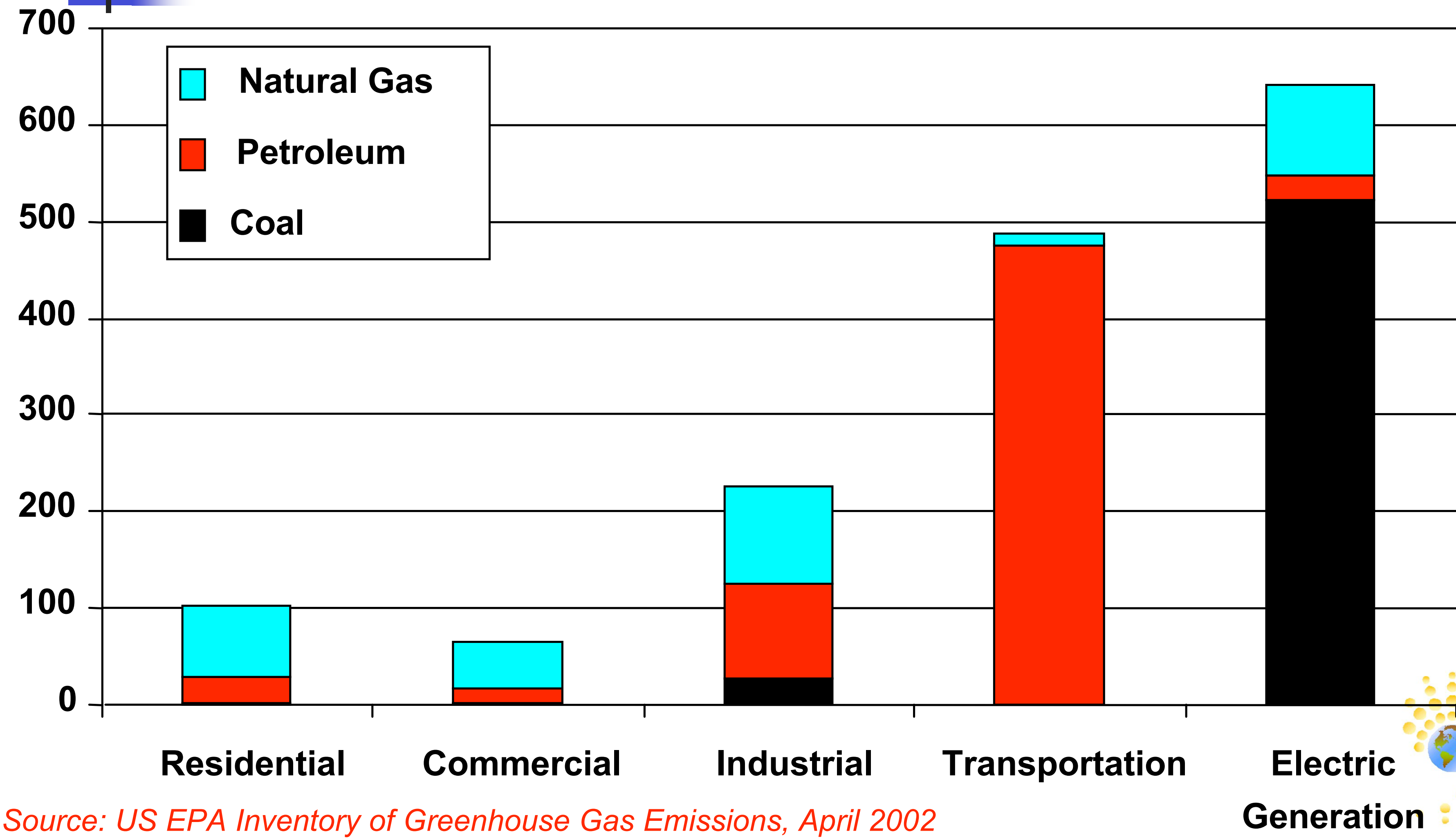
1 Quad = 1.055 EJ



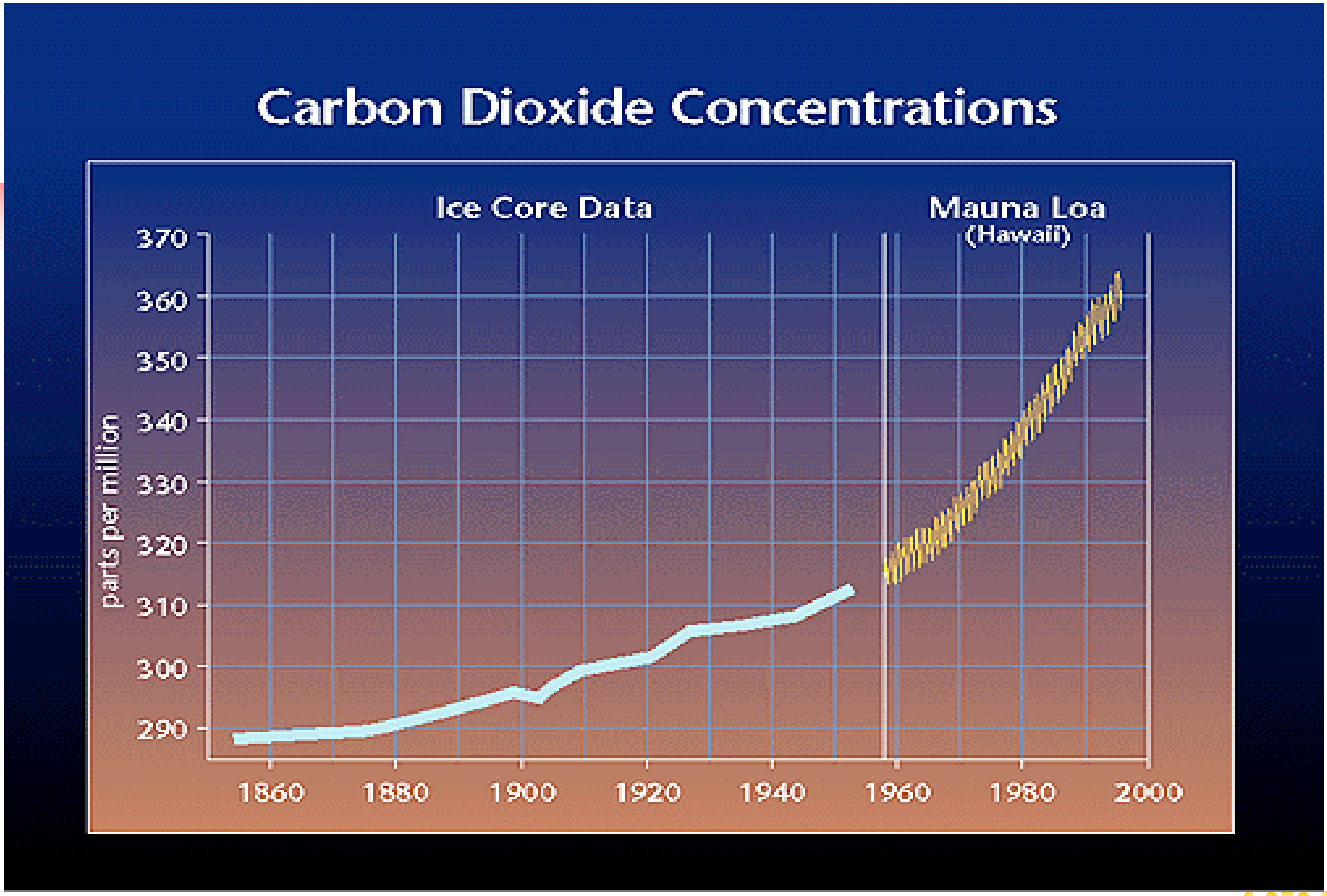
Source: Energy Information Administration
http://www.eia.doe.gov/emeu/aer/txt/ptb0102.html

United States CO_2 Emissions by Sector and Fuels 2000

Millions of metric tons per year carbon equivalent



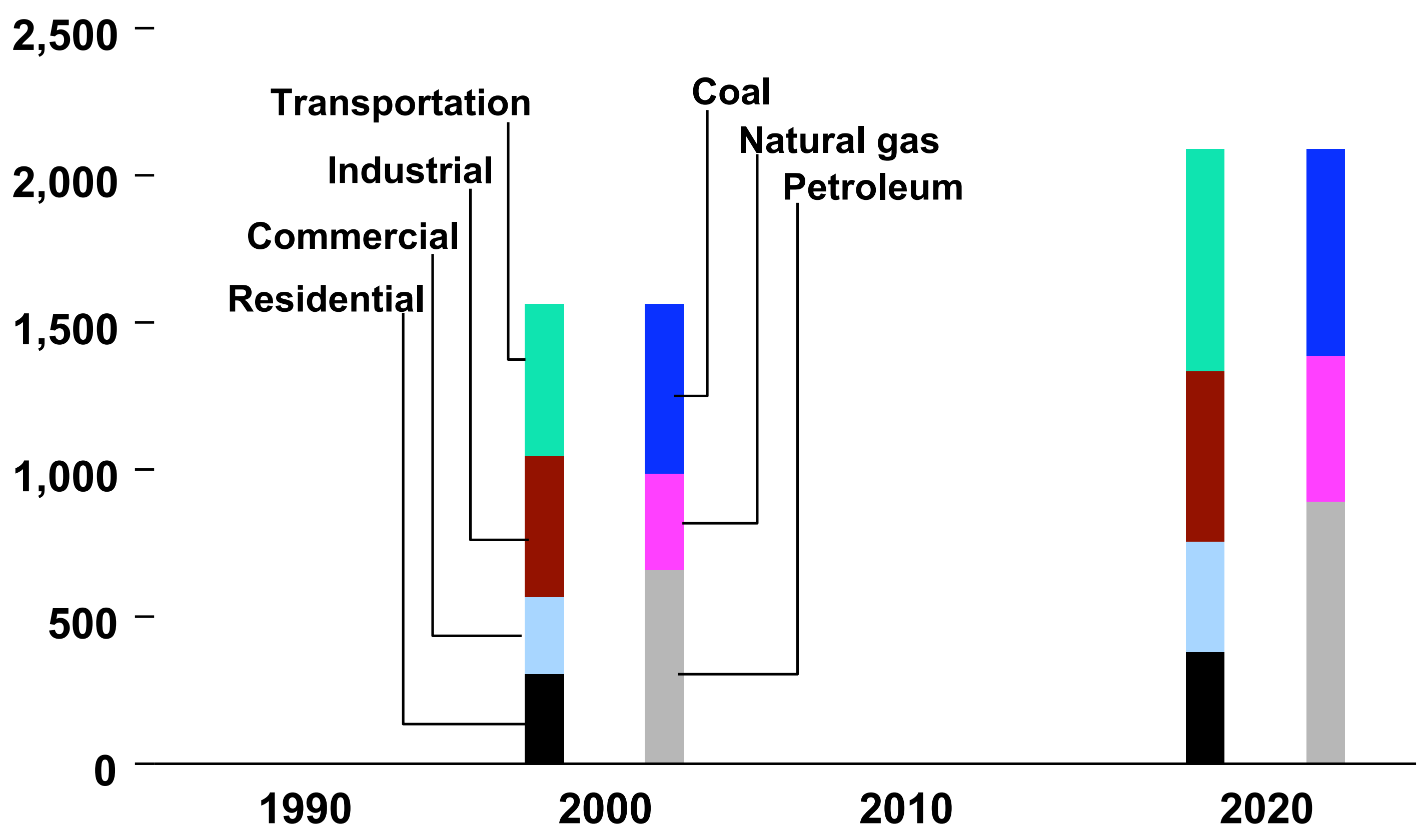
Source: US EPA Inventory of Greenhouse Gas Emissions, April 2002



Atmospheric CO2 grew from 290 to 370 ppmv over the last 150 years

Projected U.S. CO_2 Emissions by Sector and Fuel, 2000-2020

(million metric tons carbon equivalent per year)



Hutzler, M.J. Annual Energy Outlook 2002. Energy Information Administration. 2002

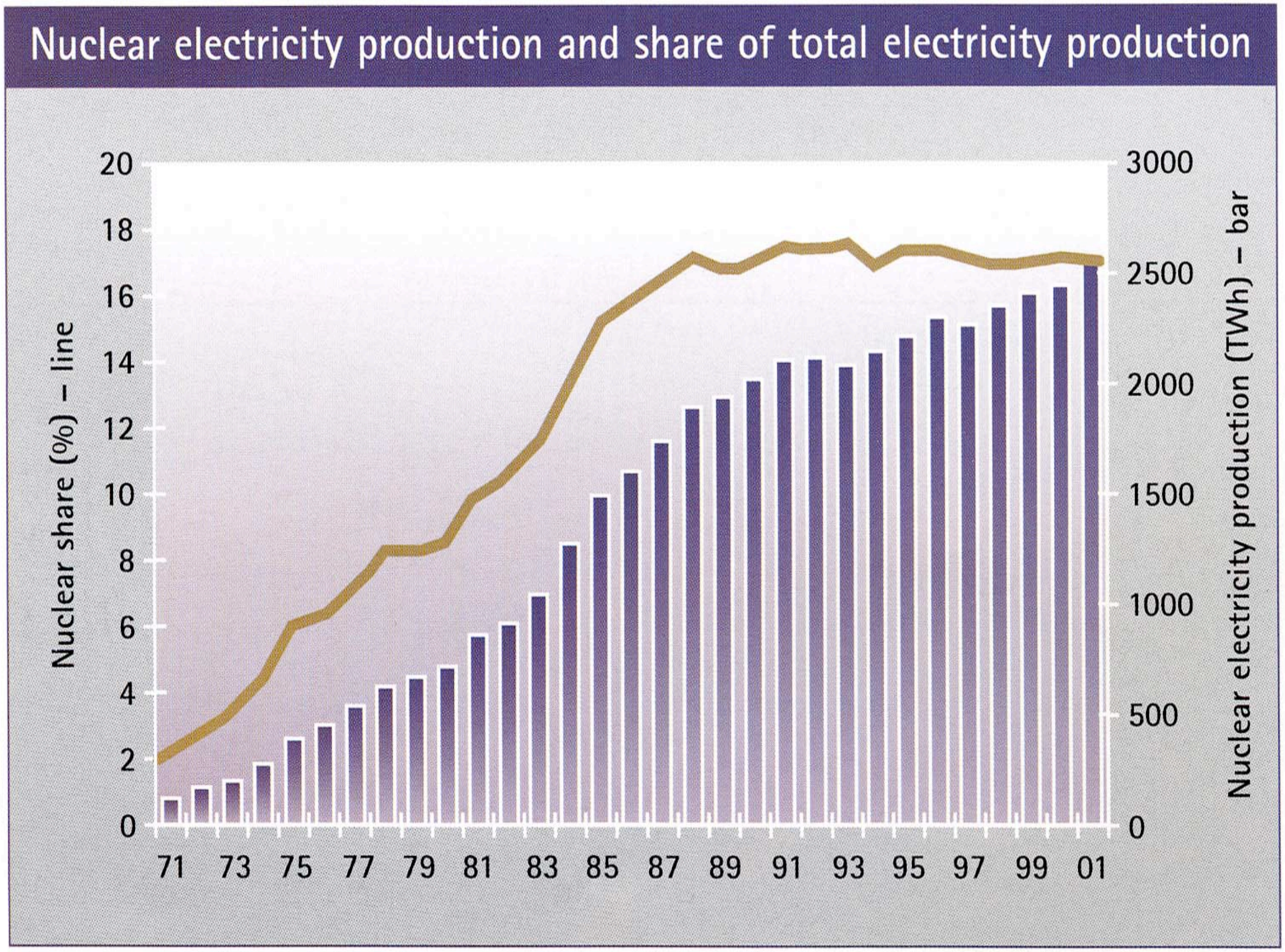
Solutions for World Energy Concerns

- Nuclear, Renewable Energy and Coal with CO_2 Sequestration can provide clean sources for electricity without emissions.

- Hydrogen is an energy carrier not an energy source

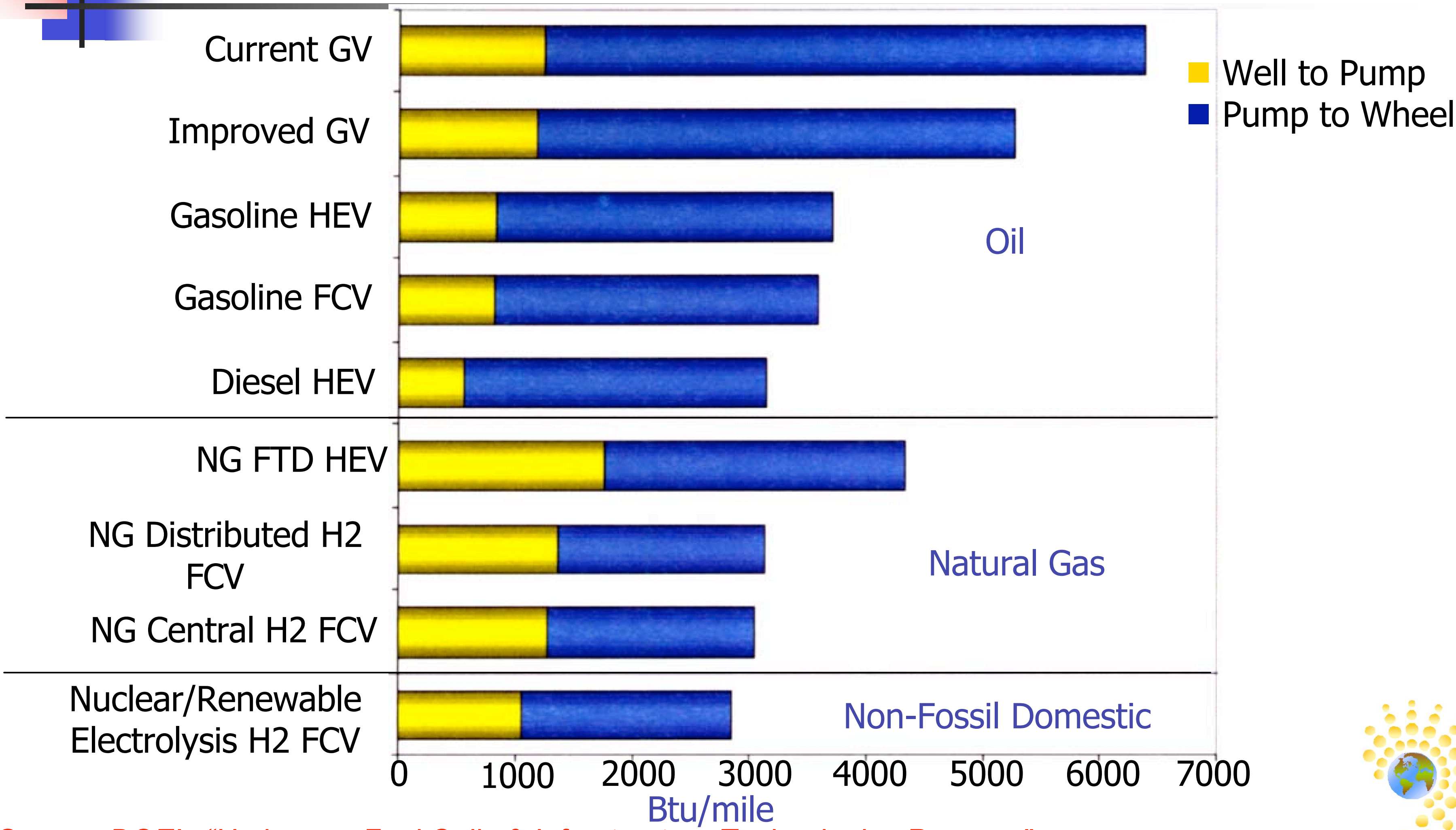
- Efficiency improvements can only help reduce demand but not eliminate it.

- Transportation alternative energy sources are needed:
  Electrical Batteries and hydrogen fuel cells are desirable but have many challenges.



Source: Nuclear Engineering International, 2002

Comparative Vehicle Technologies: Well-to-Wheels Energy Use



Source: DOE's "Hydrogen, Fuel Cells & Infrastructure Technologies Program"

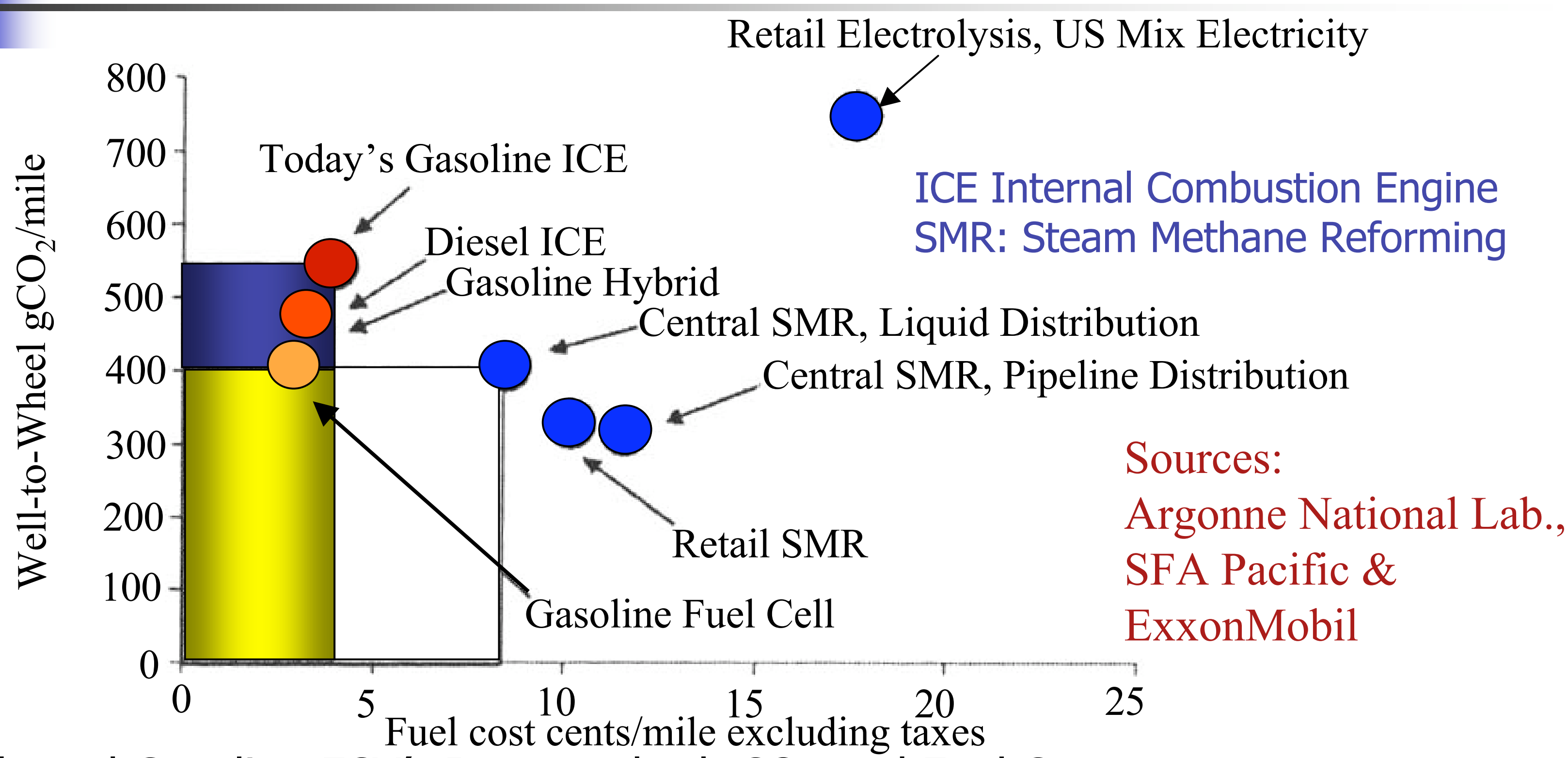
Comparison of Energy Density & Specific Energy of Batteries & Hydrogen Fuel Cell

	Fuel Cell System + 5,000 psi Hydrogen Tanks	Pb-Acid Deep Discharge Battery	NiMh Battery	Lithium-Ion Battery	USABC Long Term Goals
Energy Density (Wh/l)	302	85	135	100	230
Specific Energy (Wh/kg)	1,038	41	75	110	150

Batteries require frequent recharges for a 300 mile range

Source: The Hydrogen Economy, Fuel Cells and Hydrogen Fueled Cars: A technical Evaluation" by C. E. Thomas

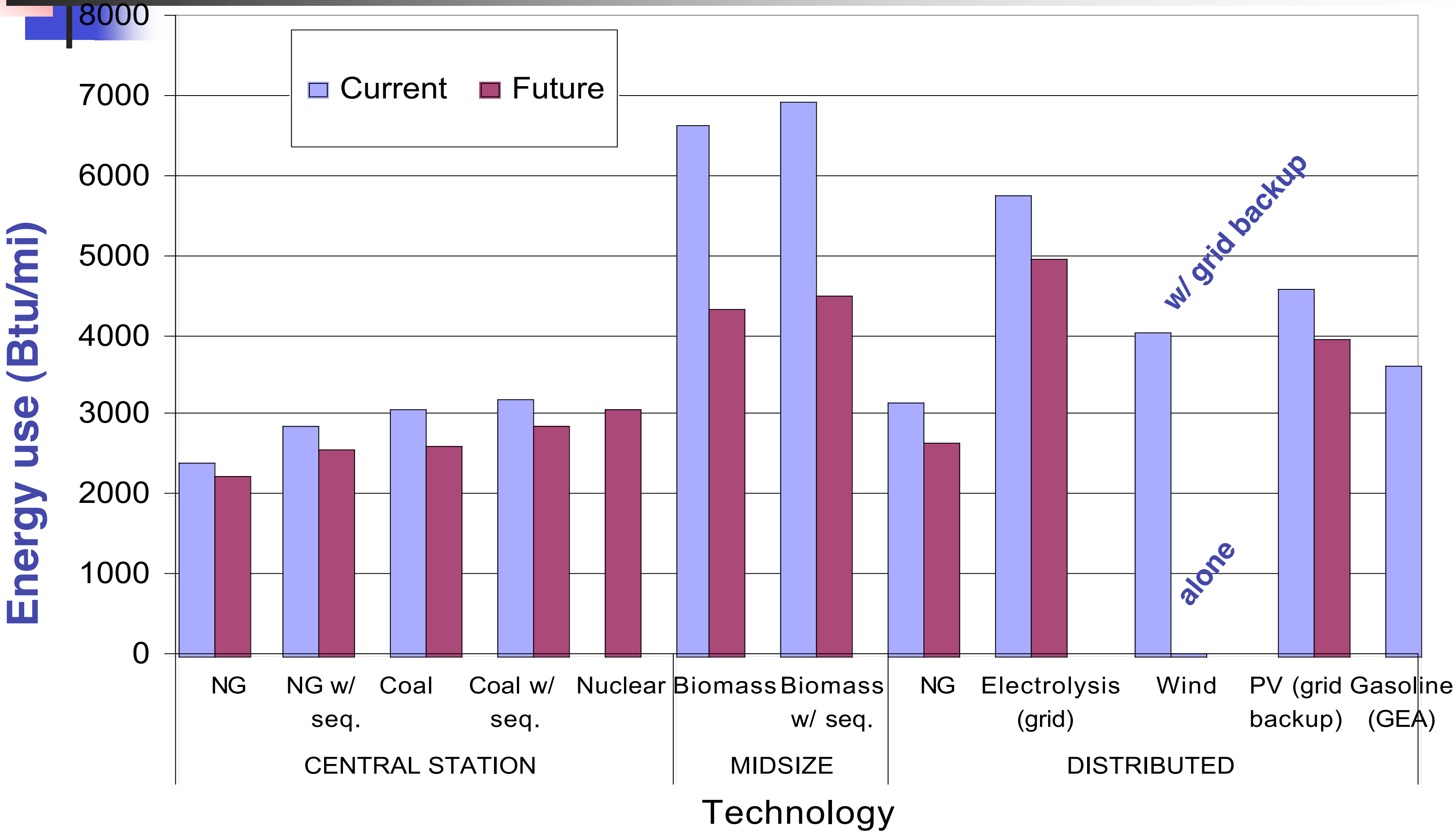
Comparative Vehicle Technologies: WTW Fuel Costs and CO_2 Emissions



- Hybrids and Gasoline FCV's Improve both CO_2 and Fuel Cost
  - Hybrids are commercially available
  - Gasoline FCV has several technical hurdles
- SMR Hydrogen Cases Have Attractive CO_2 Performance but Major Cost Challenges

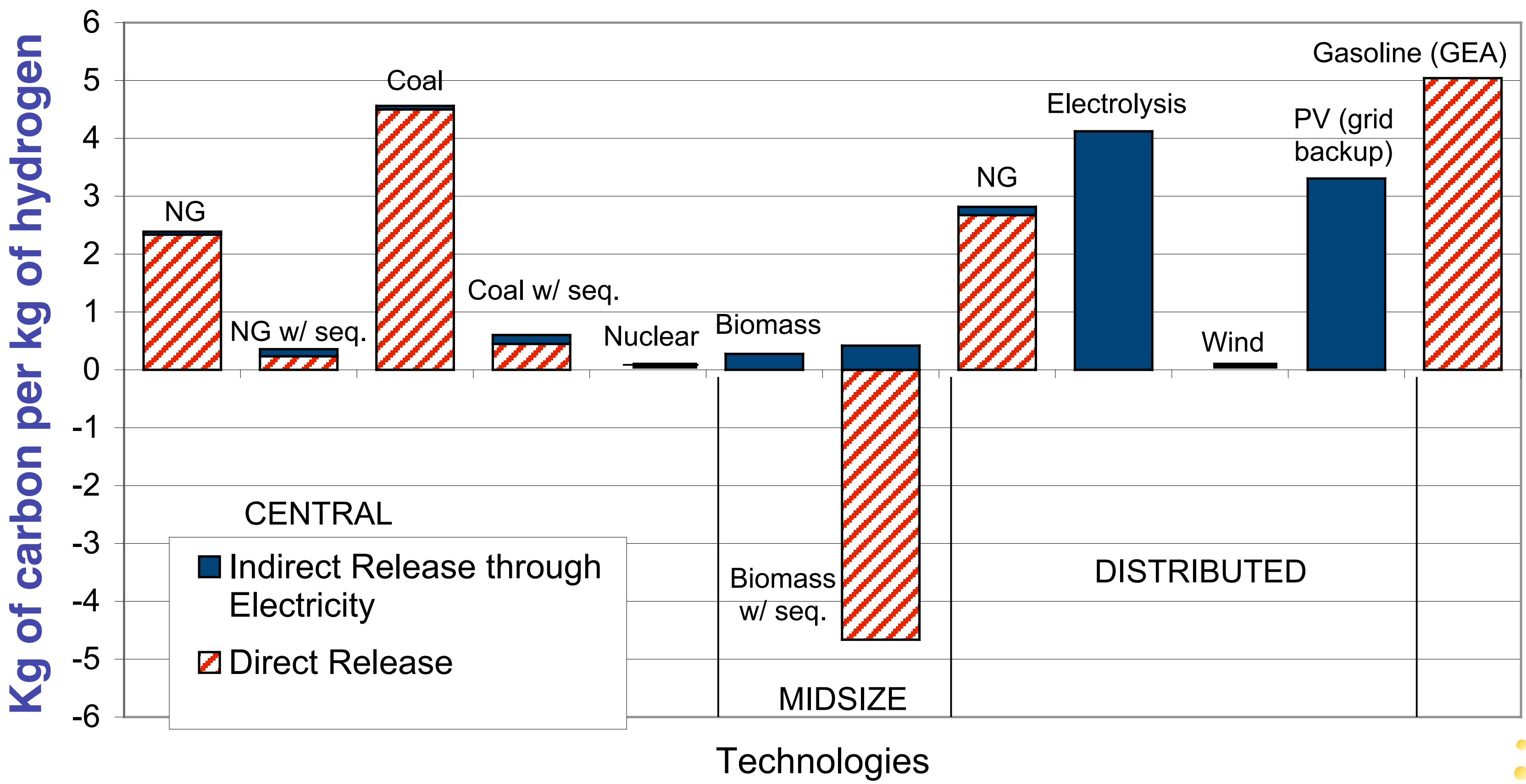
WELL-TO-WHEELS ENERGY USE

Based on NAE Assumptions, Report of January 2004



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

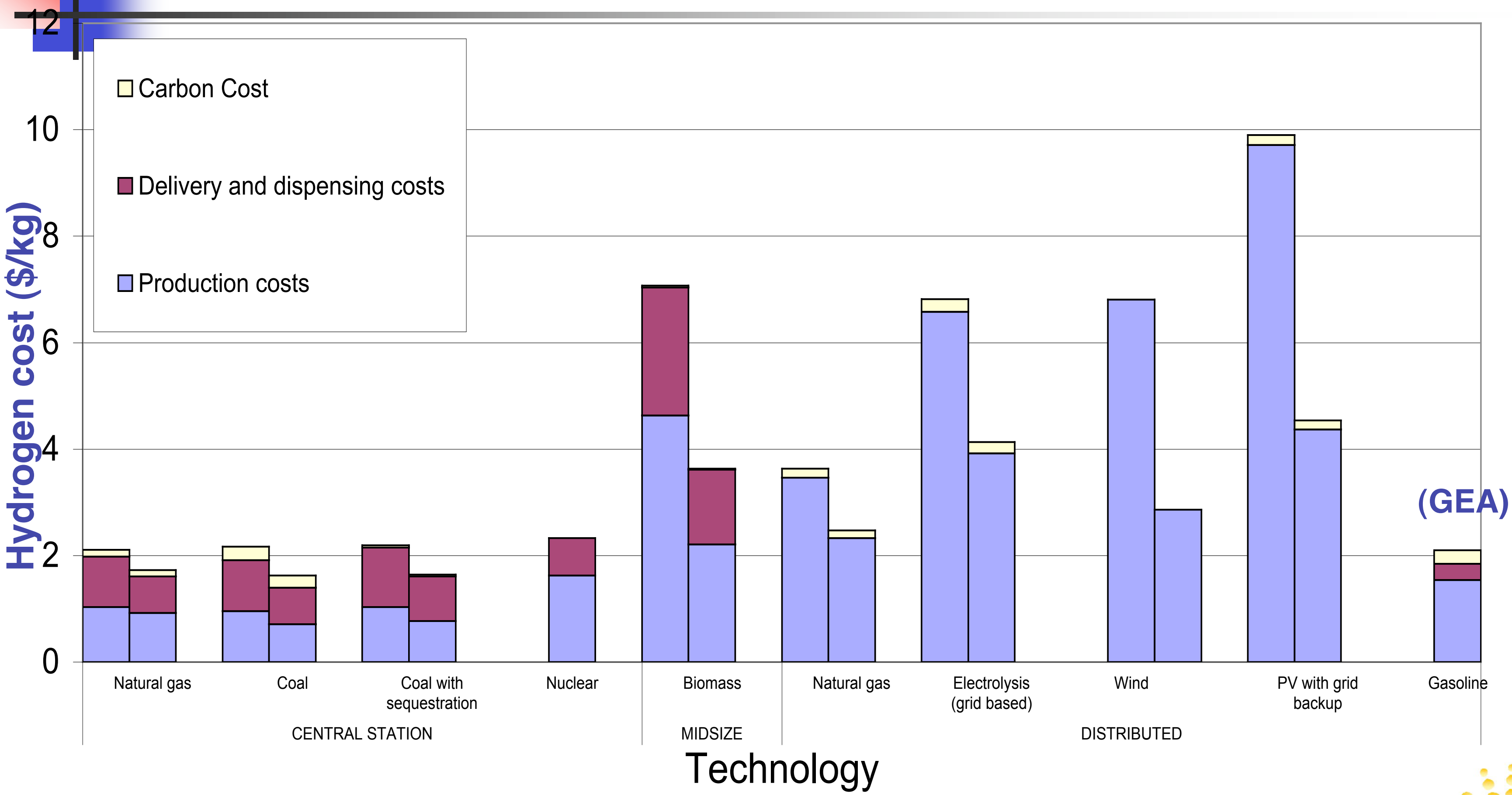
Based on NAE Assumptions



DELIVERED H_2 COSTS OF VARIOUS TECHNOLOGIES

Current (left) and Future(right) Projections

Based on NAE Assumptions



- ***GEA = Gasoline Efficiency Adjusted – scaled to hybrid vehicle efficiency***

The Hydrogen Economy Has Started

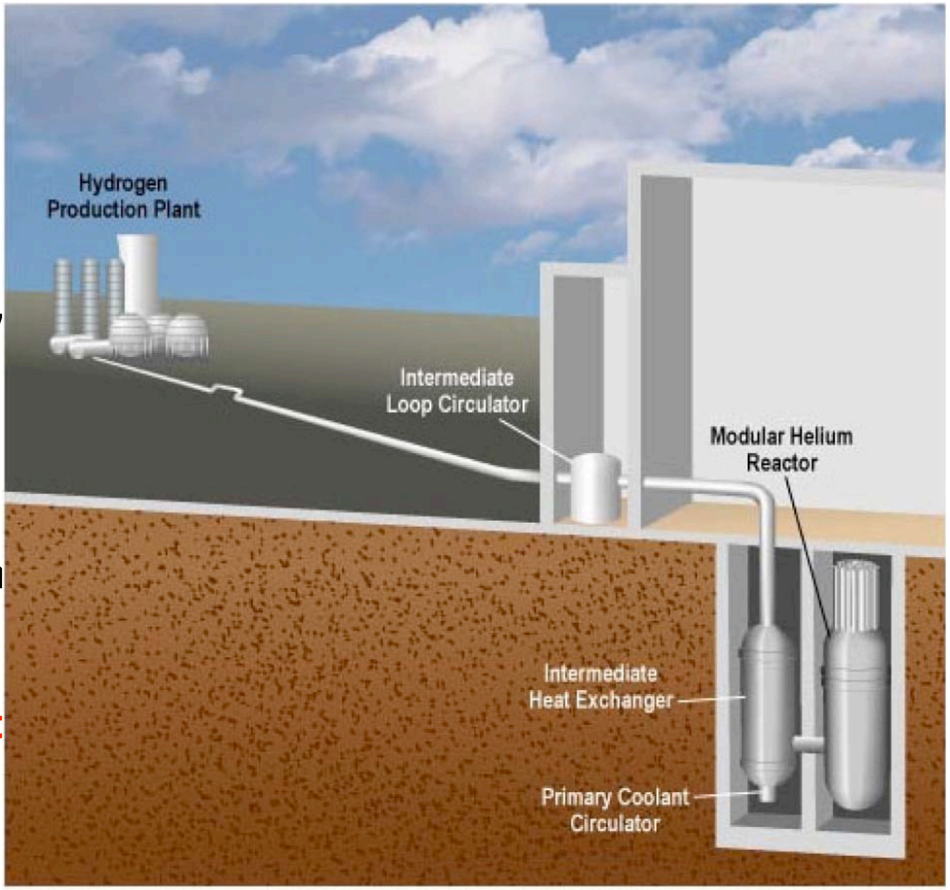
- World wide 150 GWt worth of hydrogen were produced in 2002.
- The US uses 10 million tons/y (45 GWt)
- 95% produced from Methane
  - Consumes 5% of natural gas usage
  - Not CO_2 free: 74 M tons of CO_2/y
- 50% is used in fertilizer industry, and 37% in the oil industry
- 97% produced near use site, no distribution infrastructure
- ~ 10%/y growth
  ➔ X 2 by 2010, X 4 by 2020
- Hydrogen Economy will need
  X 18 current for transportation
  X 40 for all non-electric

How Can We Get Hydrogen from Nuclear Energy?

- Electricity – Electrolysis of Water ES
  - Current technology but not efficient
- Thermal source for SMR
  - Current Technology: Steam Methane Reforming
  - Reduces GHG emissions by 20 to 40%
- Heat for Thermo-chemical water splitting TC
  - R&D scale technology, high temperature catalyzed reactions for water splitting
- Electricity/Heat – high temp. steam electrolysis HTES
  - R&D scale technology
  - Reversed fuel cells

Candidate Nuclear Reactors for Thermochemical Water-Splitting

- SNL/GA NERI evaluated 9 categories
  - PWR, BWR, Organic, Alkali metal, Heavy metal, Gas-cooled, Molten salt Liquid-core and Gas-core
  - Assessed reactor features, development requirements
- Current commercial reactors have too low temperature
- Helium, heavy metal, molten salt rated well; helium gas-cooled most developed
- Selected Modular Helium Reactors as best suited for thermochemical production of hydrogen
- **MIT(Yildiz and Kazimi) examined the He cooled MHR and added the concept of: Supercritical CO2 cooled Advanced Gas Reactor with electrolysis as highly desirable**

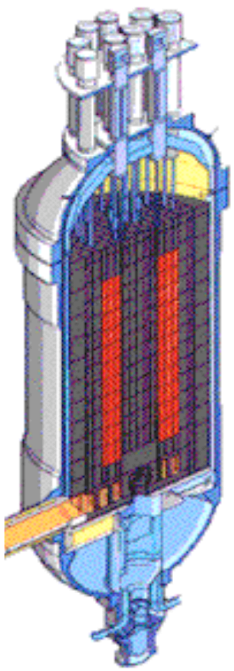


H_2-MHR

Scenario 1: MHR-SI

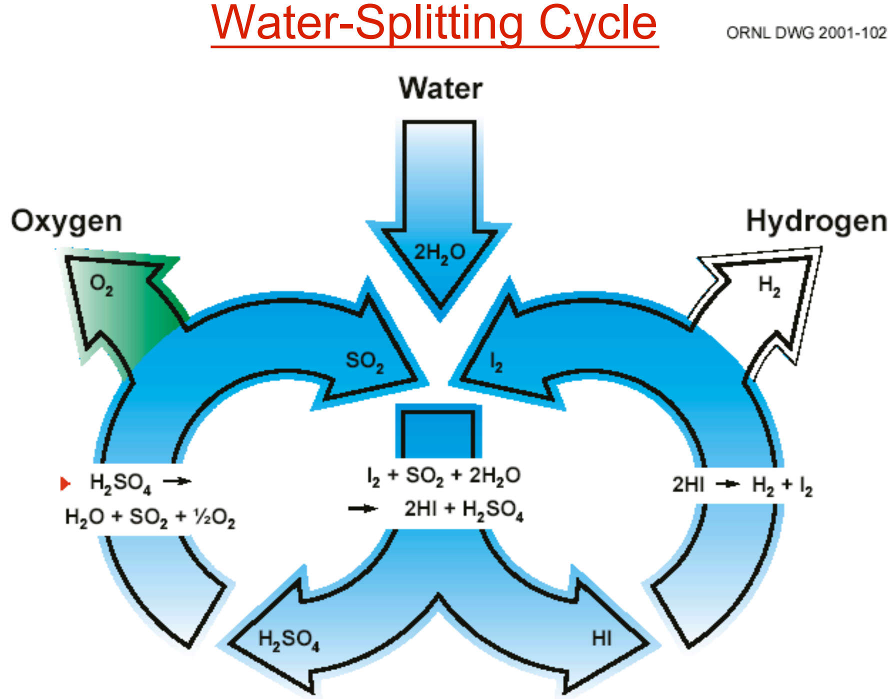
- SI-MHR: SI cycle using the heat from MHR, 4x600MWt=2400MWt.
- SI cycle was developed by GA:

MHR



Heat

Sulfur-Iodine Thermochemical Water-Splitting Cycle



Alternatives within the Sulfur Process

- GA used chemical process design code Aspen Plus
- Designed the three main chemical systems for the S-I process
  - Prime or Bunsen reaction
    $2\ H_20 + SO_2 + I_2 \rightarrow H_2SO_4 + 2HI$
  - Sulfuric acid & HI decomposition
    $H_2SO_4 \rightarrow SO_2 + H_2O + 1/2\ O_2$
    $2HI \rightarrow I_2 + H_2$
- GA estimated high efficiency (52% at 900^0C) and reasonable cost (~$250/kWt)
  - Benefit of high reactor outlet temperature important
- Experimental verification is needed
  - HI, H_20, I_2 Vapor-Liquid Equilibrium data needed
  - Confirmation of HI reactive Distillation analysis important, may allow further cost savings
- The Westinghouse hybrid Chemical-Electrolysis Process simplifies the system and boosts the energy efficiency above the S-I process

600 MWt H_2 MHR Process Parameters		
Material	**Flow rate tons/day**	**Inventory tons**
H_2	200	2
H_2O	1,800	40
H_2SO_4	9,800	100
I_2	203,200	2,120

Candidate Nuclear Reactors for H_2 Production

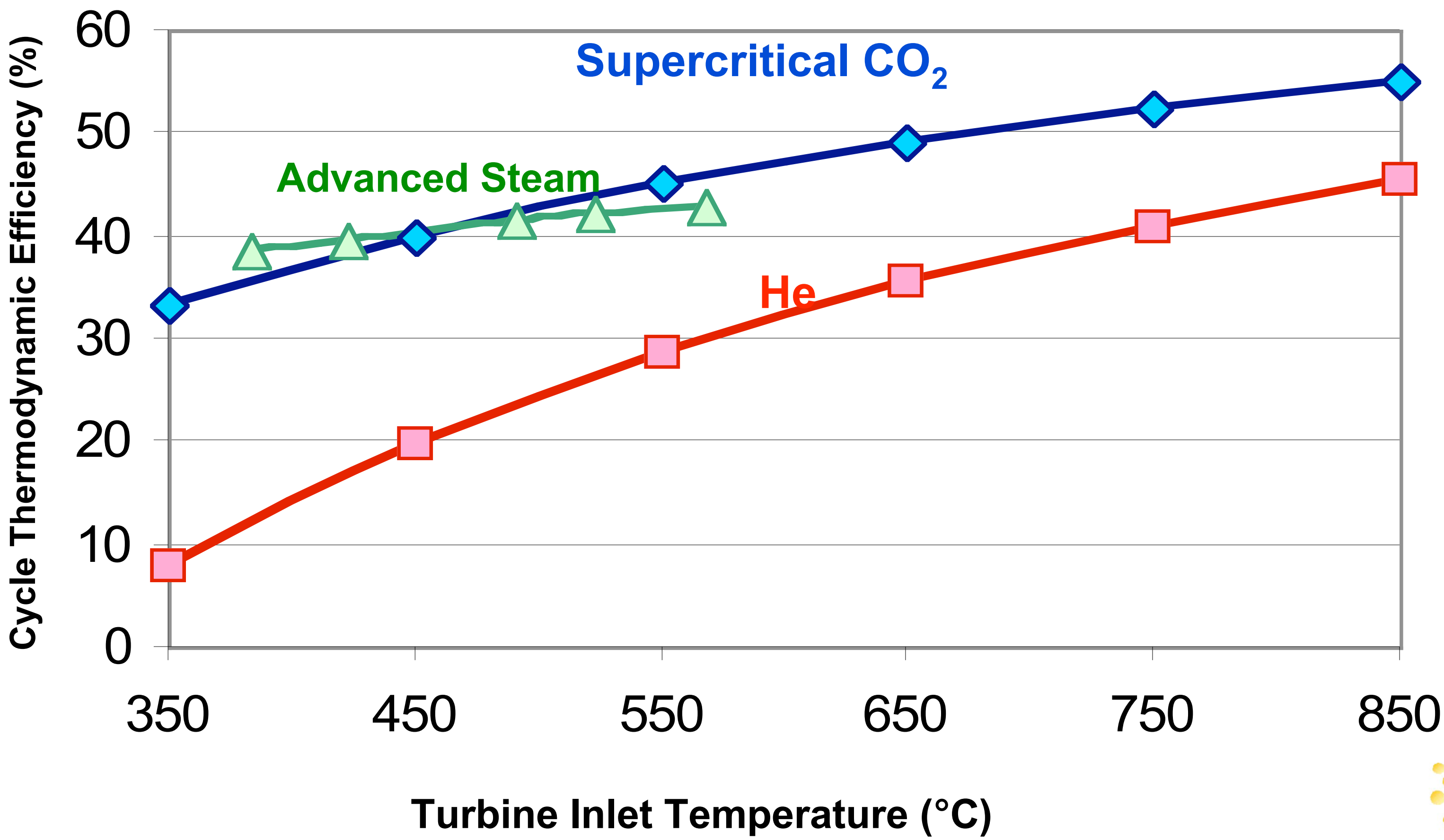
Current Technology (base case)	T_{outlet} (°C)	η_h (%)
Light Water Reactor, LWR (PWR)	320	33

Advanced Reactor Technology	T_{outlet} (°C)	η_h (%)
Helium Gas Cooled Reactor, GT-MHR	850-950	42-48
Supercritical CO2 Cycle, e.g.: S-AGR	550-650	40-45
Advanced Light Water Reactors, ALWR	285-320	32-34
Super Critical Water Reactor, SCWR	400-600	38-45
Advanced High Temperature Reactors, AHTR	900 -1100	NE
Lead Bismusth Cooled Reactor	550 - 850	NE

Uncertainties exist in the future technology efficiency estimates.

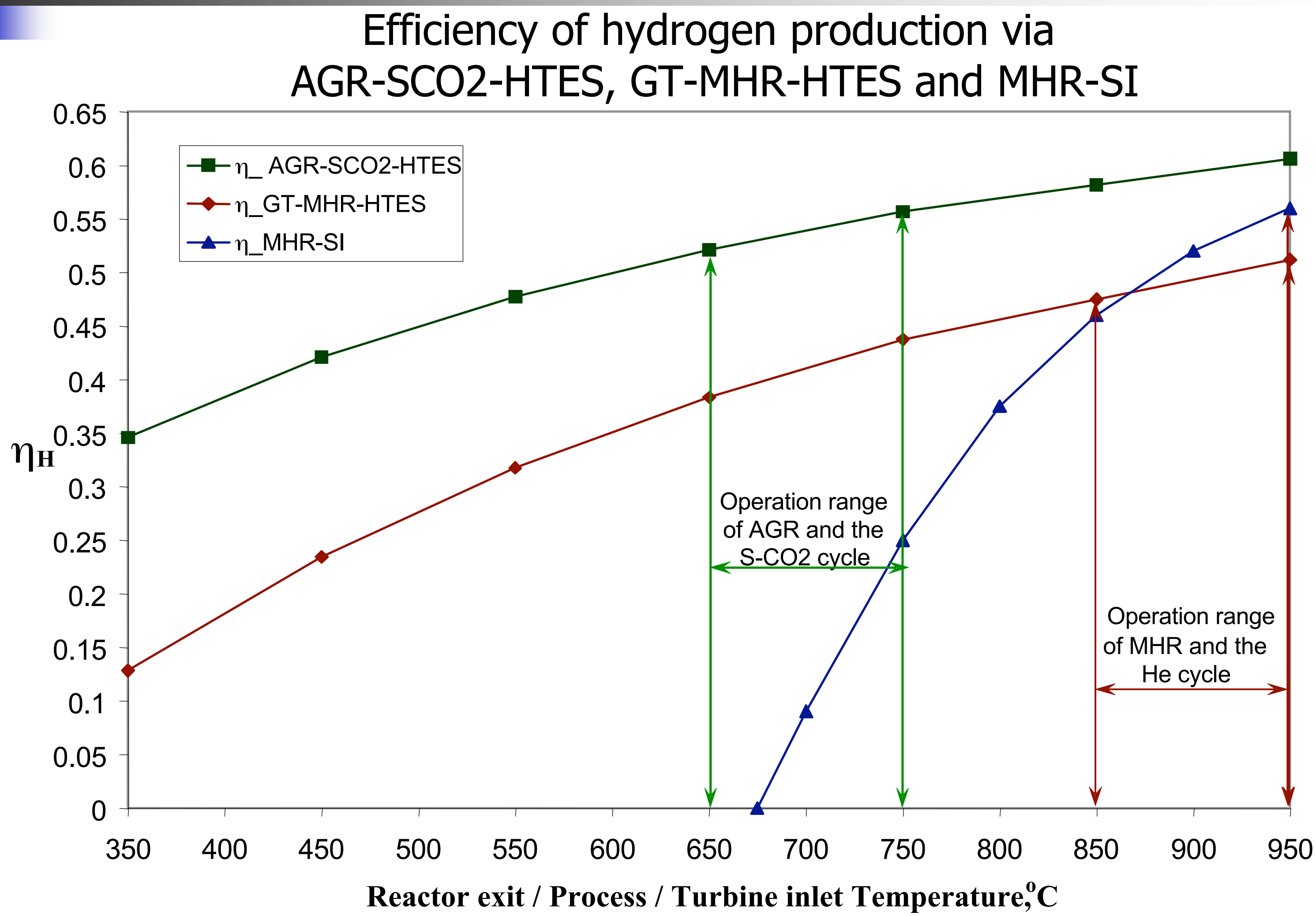
NE: Not evaluated by Yildiz and Kazimi

Power Cycle Thermodynamic Efficiency



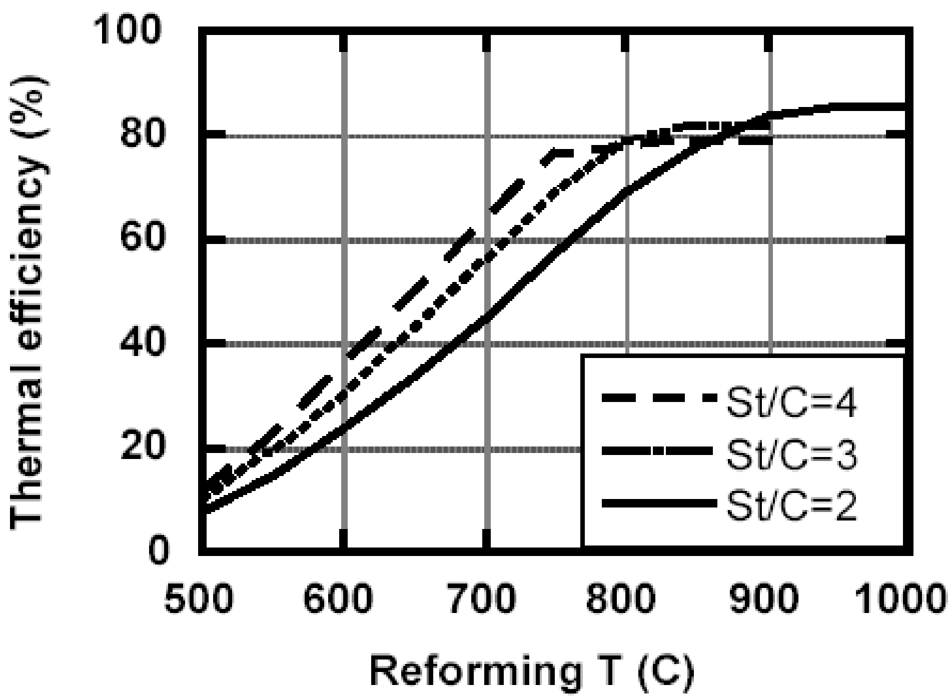
Dostal et al, MIT 2002

Overall efficiency for three scenarios



The Near Term Scenario: SMR-MHR

- Steam Methane Reforming theoretical process efficiency at the MHR operating temperature of 850°C is 80%



** Source: Sandia National Laboratory*

Concluding Remarks

- Hydrogen Fuel Cells can improve energy security and reduce CO_2 emissions but R and D efforts are needed to overcome infrastructure and cost issues.
- Obstacles are more difficult for mobile FC than stationary FC.
- Hydrogen production favors high temperature reactors.
- Thermochemical and Thermoelectrical methods of water splitting can be powered by nuclear and/or solar sources of heat.
- Electrolysis of high temperature steam could be preferred because of its lower temperatures than chemical water splitting. However, its units are small and total cost may be an issue.
- Supercritical CO_2 power cycle is very promising and worthy of development either for S-AGR or as an indirect cycle.
- Sequestration of CO_2 is the wild card in affecting future solutions.