Well-to-Wheels Analysis of Hydrogen Fuel Cell Vehicles

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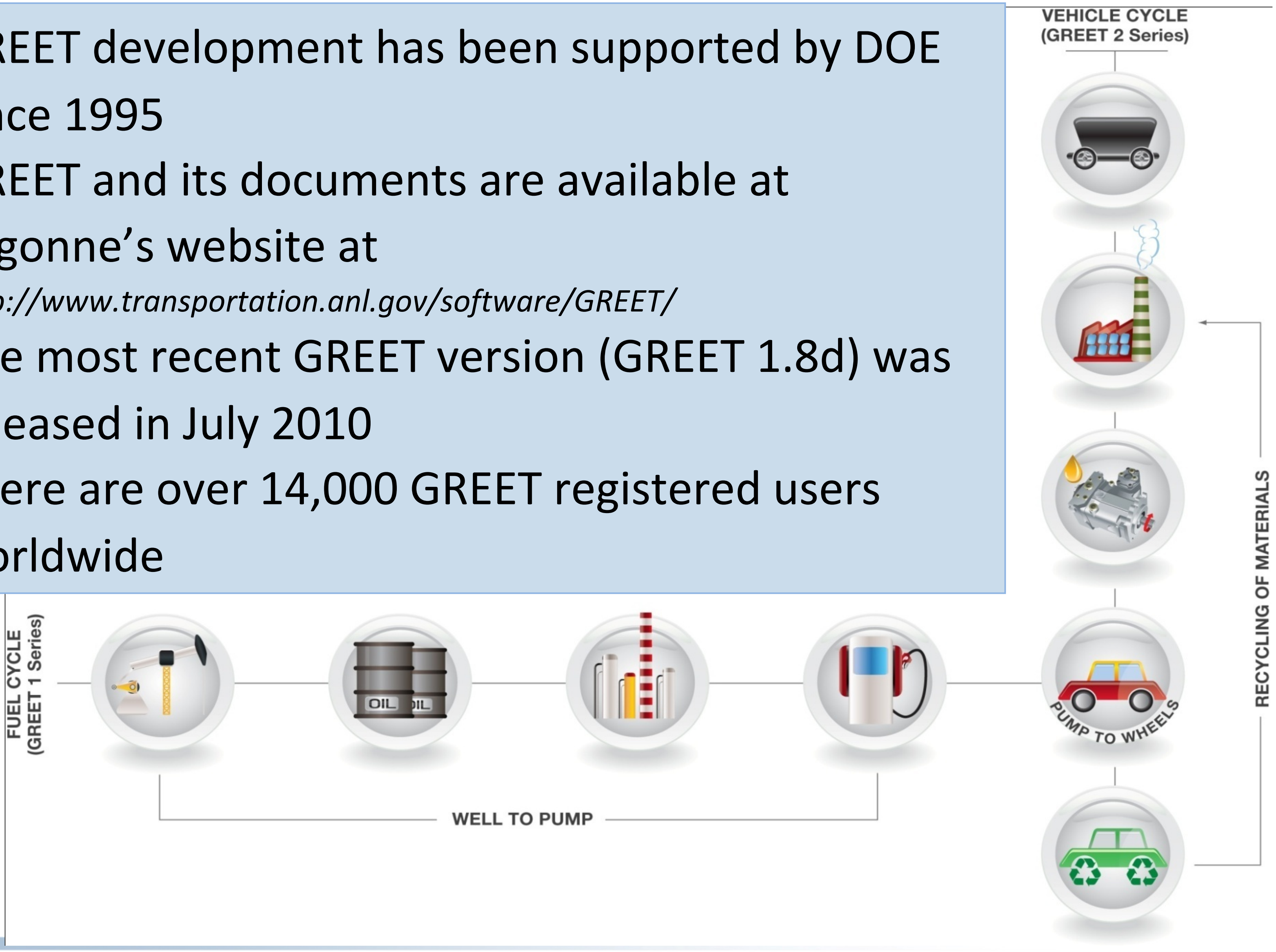
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

- GREET development has been supported by DOE since 1995
- GREET and its documents are available at Argonne's website at *http://www.transportation.anl.gov/software/GREET/*
- The most recent GREET version (GREET 1.8d) was released in July 2010
- There are over 14,000 GREET registered users worldwide

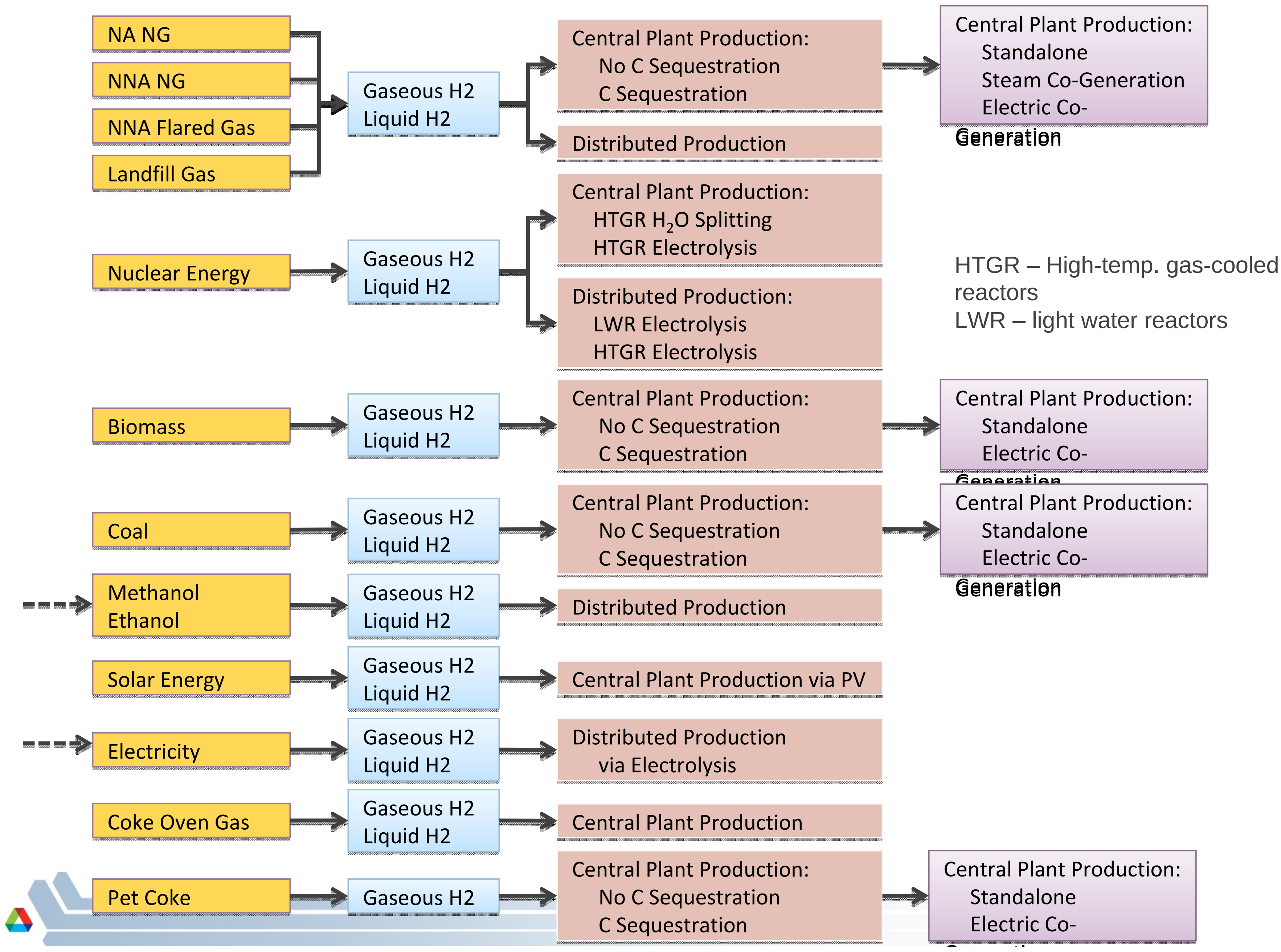


GREET Includes More Than 100 Fuel Production Pathways from Various Energy Feedstocks

Petroleum Conventional Oil Sands	Gasoline Diesel Liquefied Petroleum Gas Naphtha Residual Oil Jet Fuel
Natural Gas North American Non-North American	Compressed Natural Gas Liquefied Natural Gas Liquefied Petroleum Gas Hydrogen Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Naphtha Fischer-Tropsch Jet Fuel
Corn	Ethanol Butanol
Sugarcane	Ethanol
Soybeans	Biodiesel Renewable Diesel Renewable Jet Fuel
Coke Oven Gas Petroleum Coke Nuclear Energy	Hydrogen
Coal	Hydrogen Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Jet Fuel
Renewable Natural Gas Landfill Gas	Compressed Natural Gas Liquefied Natural Gas Hydrogen Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Naphtha Fischer-Tropsch Jet Fuel
Cellulosic Biomass Switchgrass Fast Growing Trees Crop Residues Forest Residues	Ethanol Hydrogen Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Jet Fuel
Residual Oil Coal Natural Gas Biomass Other Renewables	Electricity

The yellow boxes contain the names of the feedstocks and the red boxes contain the names of the fuels that can be produced from each of those feedstocks.

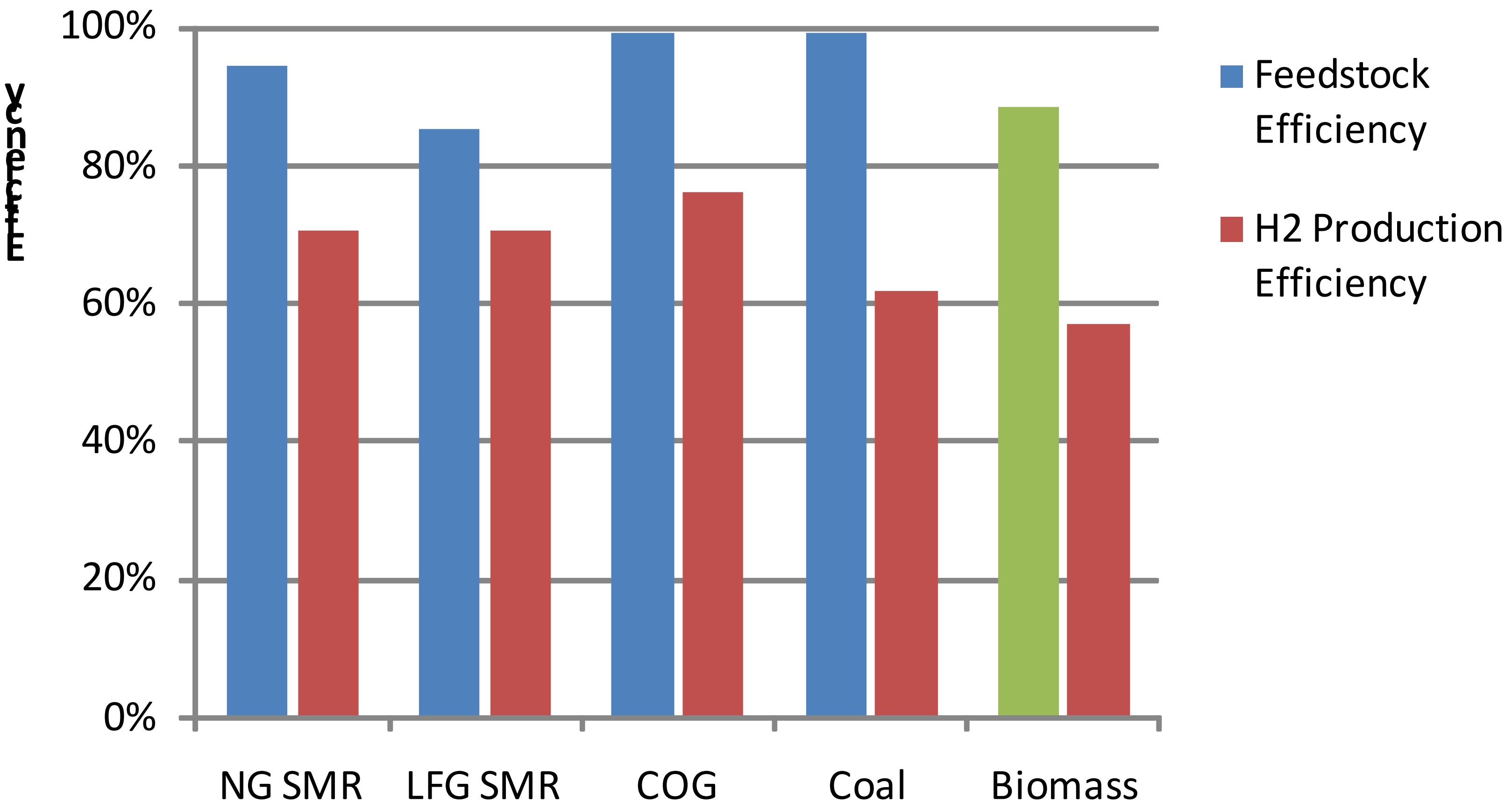
DOE's FCT Program Has Been Supporting Hydrogen Pathway Development in GREET



Hydrogen Production Pathways Examined in This Presentation

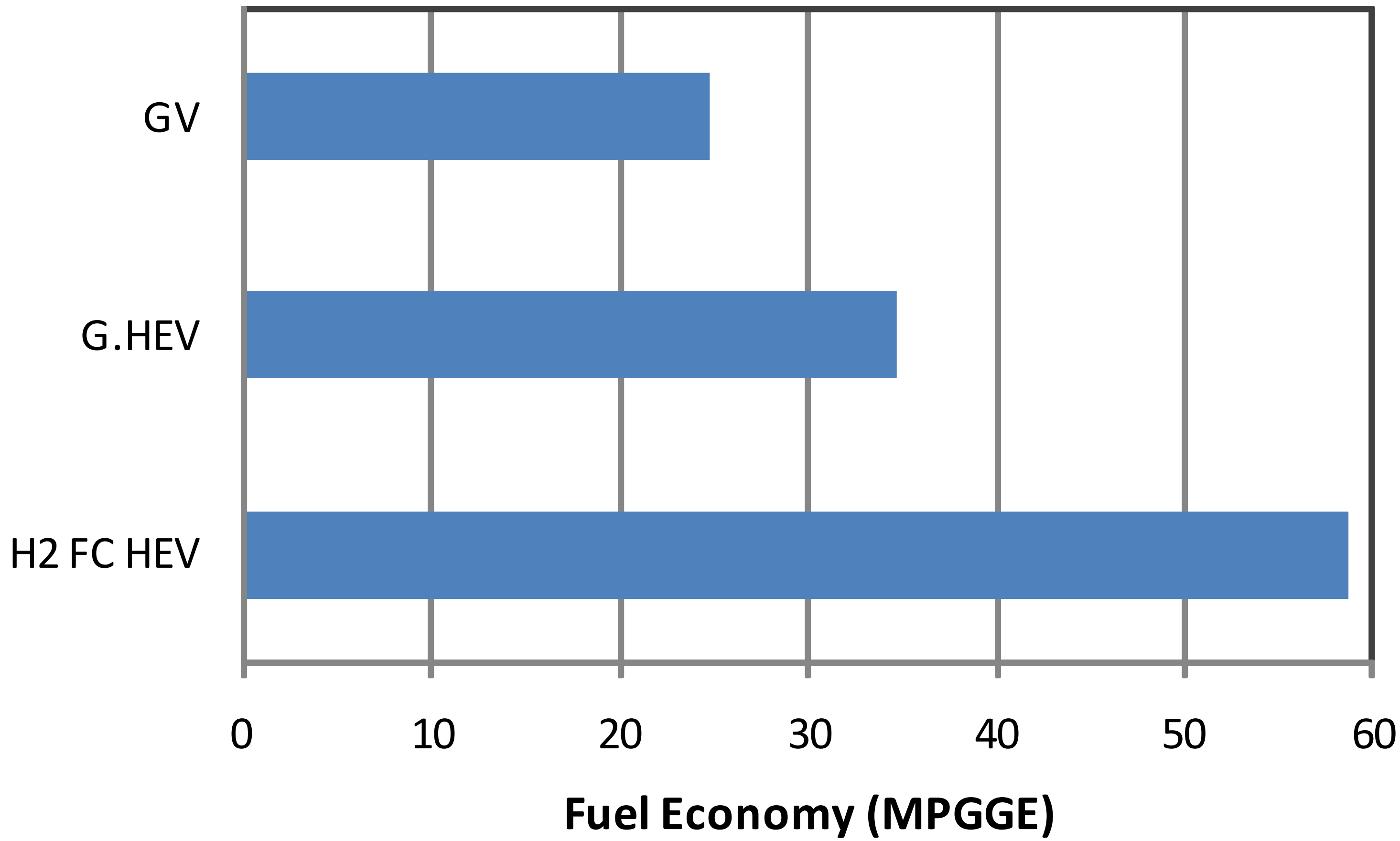
- Hydrogen production pathways included
  - Natural gas-based steam methane reforming (SMR)
  - Land-fill gas-based SMR
  - Coal gasification to hydrogen
  - Coal gasification with carbon capture and storage (CCS) to hydrogen
  - Biomass gasification to hydrogen
  - Biomass gasification with CCS to hydrogen
- Hydrogen is used in a midsize fuel-cell car
- Baseline gasoline is used in conventional vehicles (CVs) and hybrid electric vehicles (HEVs)

Energy Efficiencies for Feedstock Recovery and Hydrogen Production for Key Hydrogen Pathways



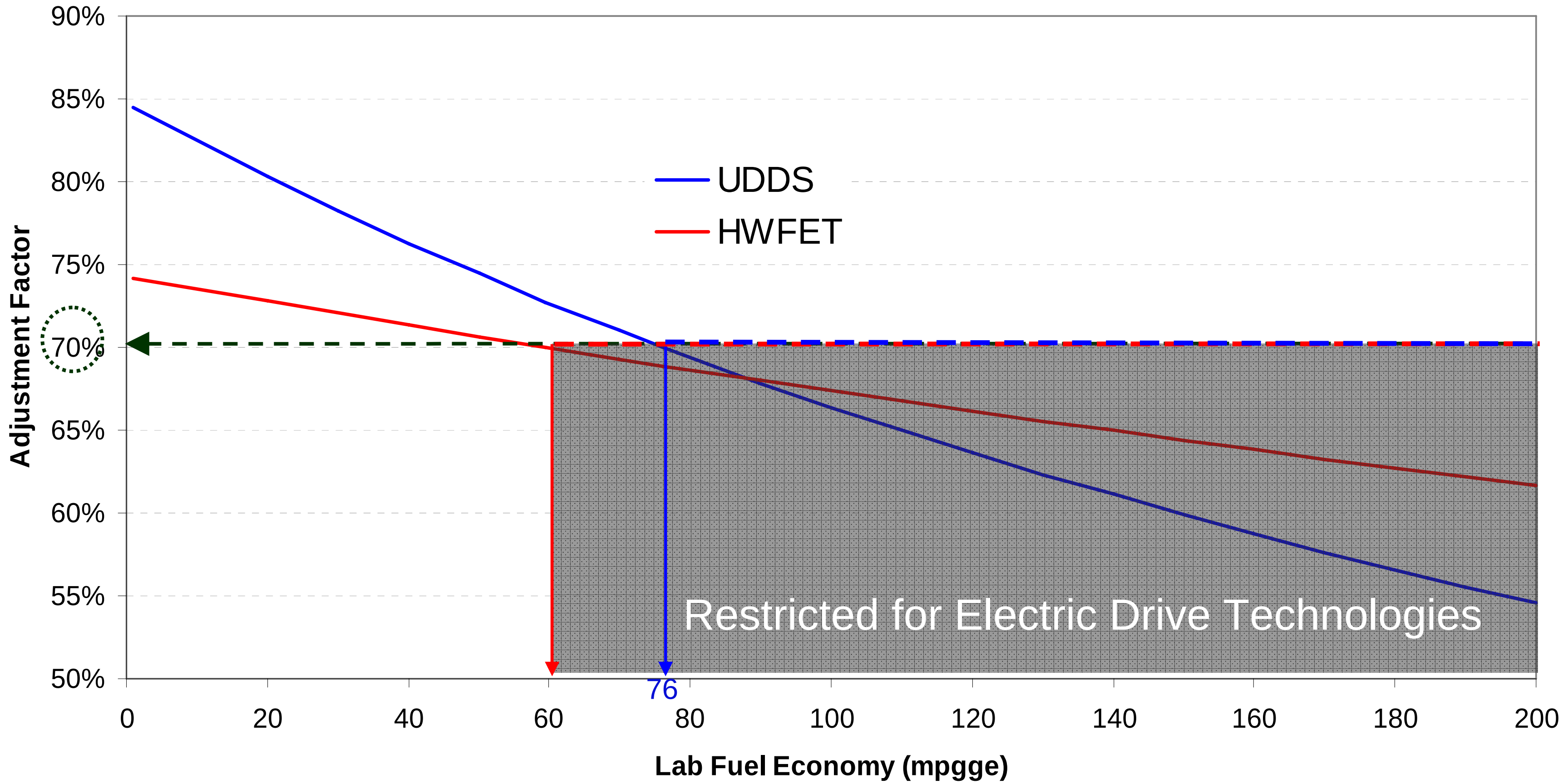
Biomass recovery efficiency includes farming energy, fertilizer/chemical production energy and transportation.

Fuel Economy of Selected Vehicle Technologies



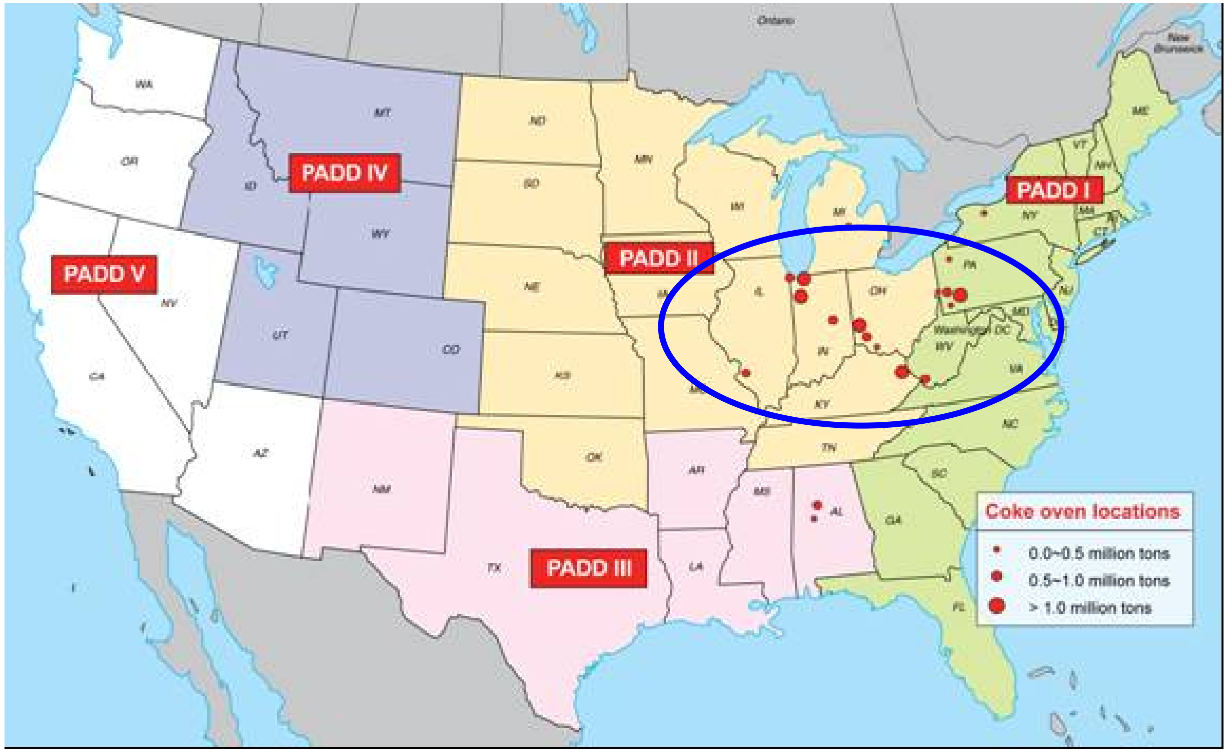
- Argonne has been examining fuel economy of advanced vehicle technologies with its PSAT model for DOE
- Results here are for a midsize car
- Fuel economy results were adjusted to reflect on-road degradation

On-Road Adjustment Factor for Lab Fuel Economy: EPA's MPG-Based Formulae for ICE Technologies vs. Electric Drive Technologies



Potential Hydrogen Production from Coke Oven Gas in the U.S.

Coke Oven Operations in the United States

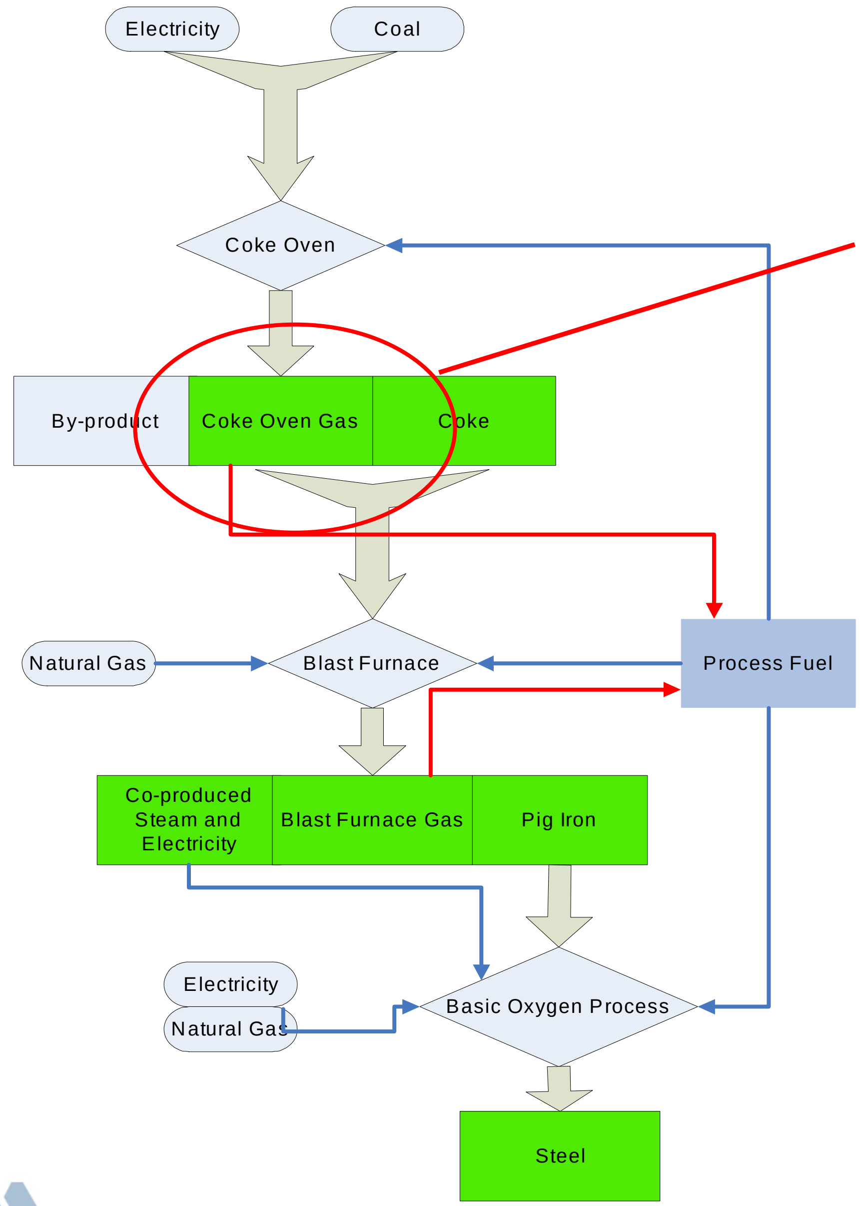


Estimated Annual COG-Based H2 Production by U.S. Regions, metric tons/Year

	2004	2005	Share (Based on 2005 Data)
PADD I	122,259	120,812	33%
PADD II	211,175	208,675	57%
PADD III	37,048	36,610	10%
Total	370,482	366,097	100%

Hydrogen from COG could fuel ~1 million FCVs/yr

Coal-to-Coke Process Flow Diagram



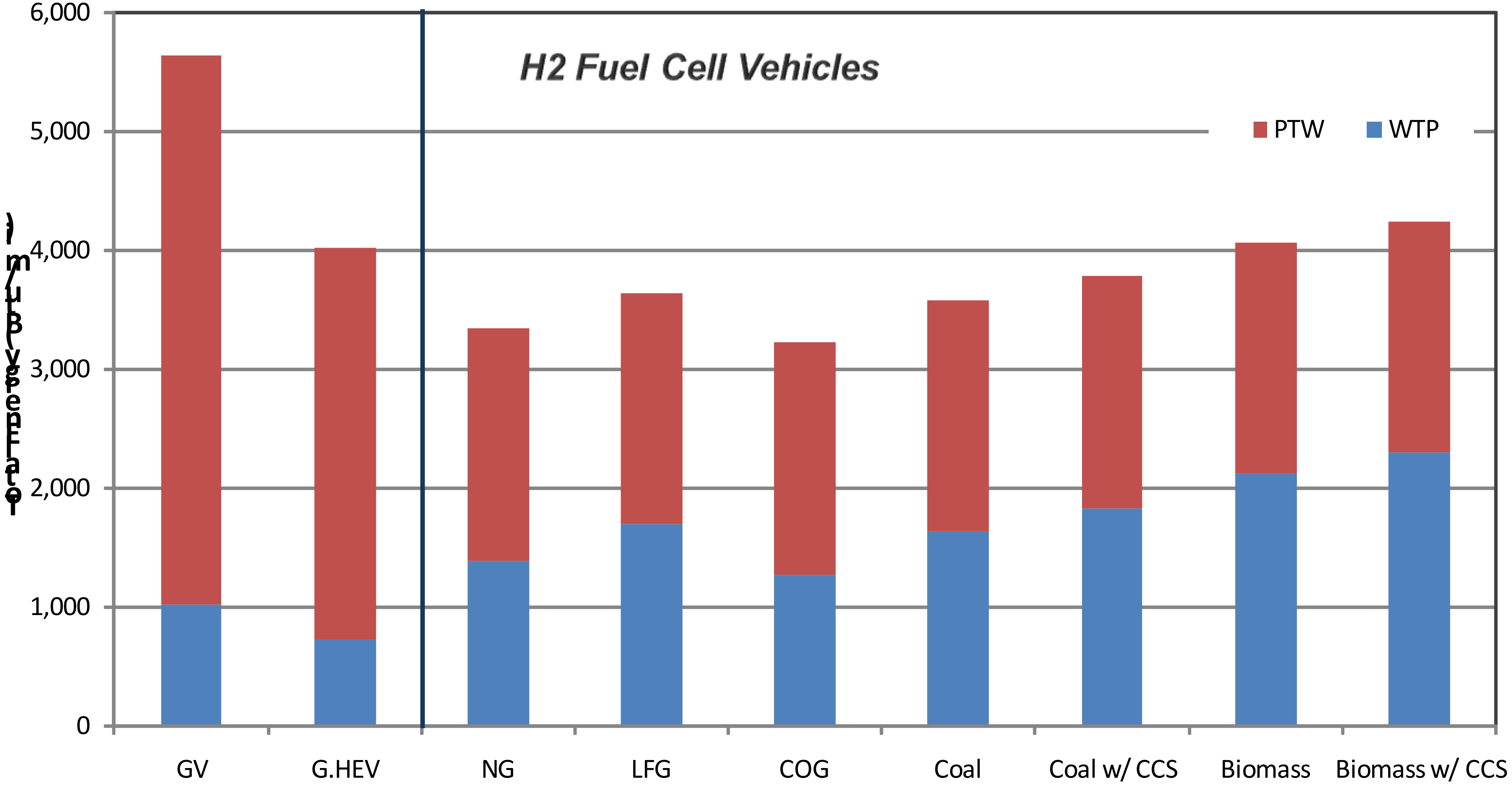
Typical Analysis of Coke Oven Gas

	% by volume
H_2	55
CH_4	25
N_2	10
CO	6
CO_2	3
HC (ethane, propane, etc.)	1
Lower Heating Value (LHV), Btu/standard cubic feet (scf)	443

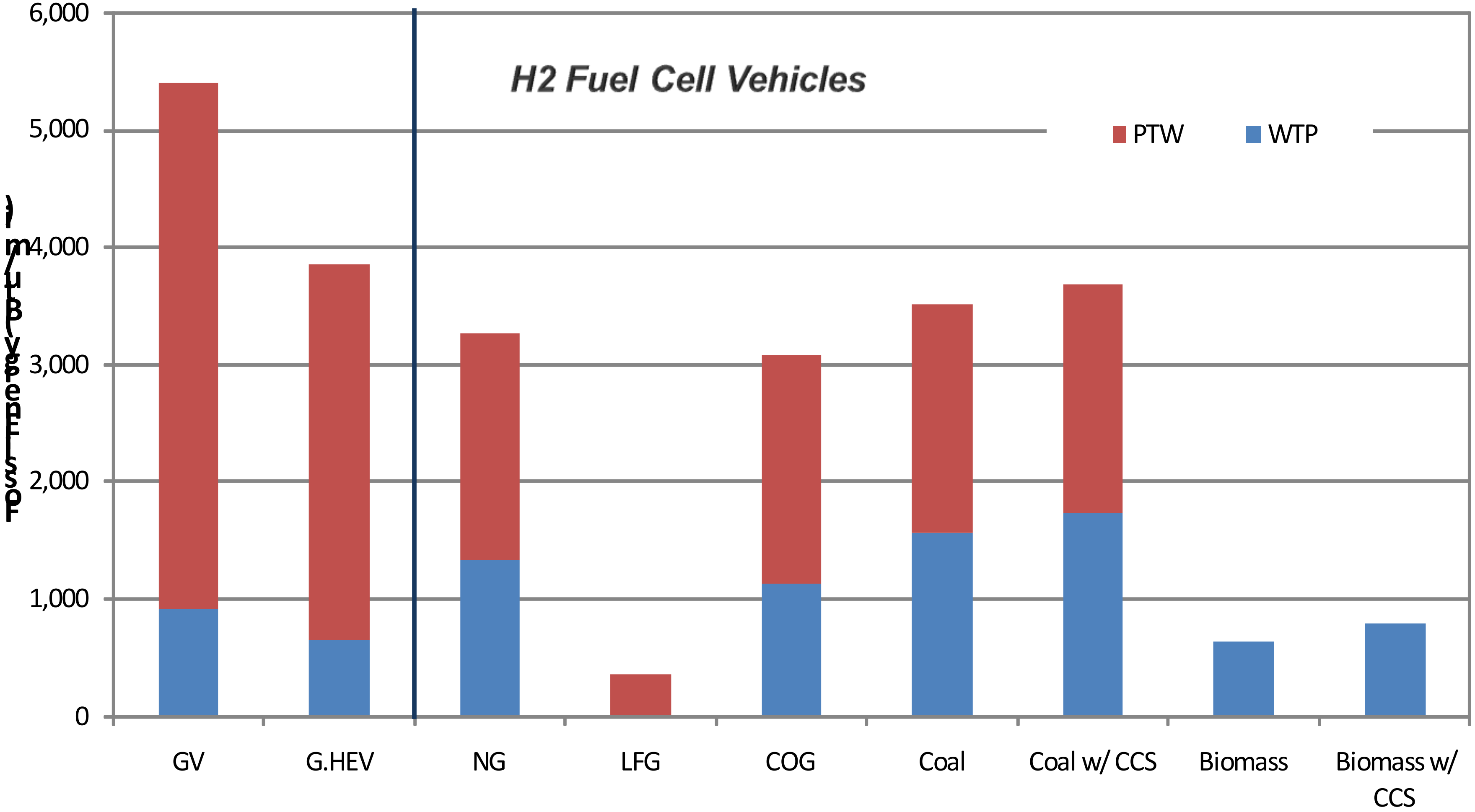
Source:
http://www.energymanagertraining.com/iron_steel/coke_oven_steel.htm

- Producing coke from coal is a traditional process in the steel industry.
- Coke oven gas is a byproduct of the coking process and used as a fuel in other ancillary operations.
- In some cases, excess gas is flared.
- The flow diagram illustrates an integrated steel production facility.

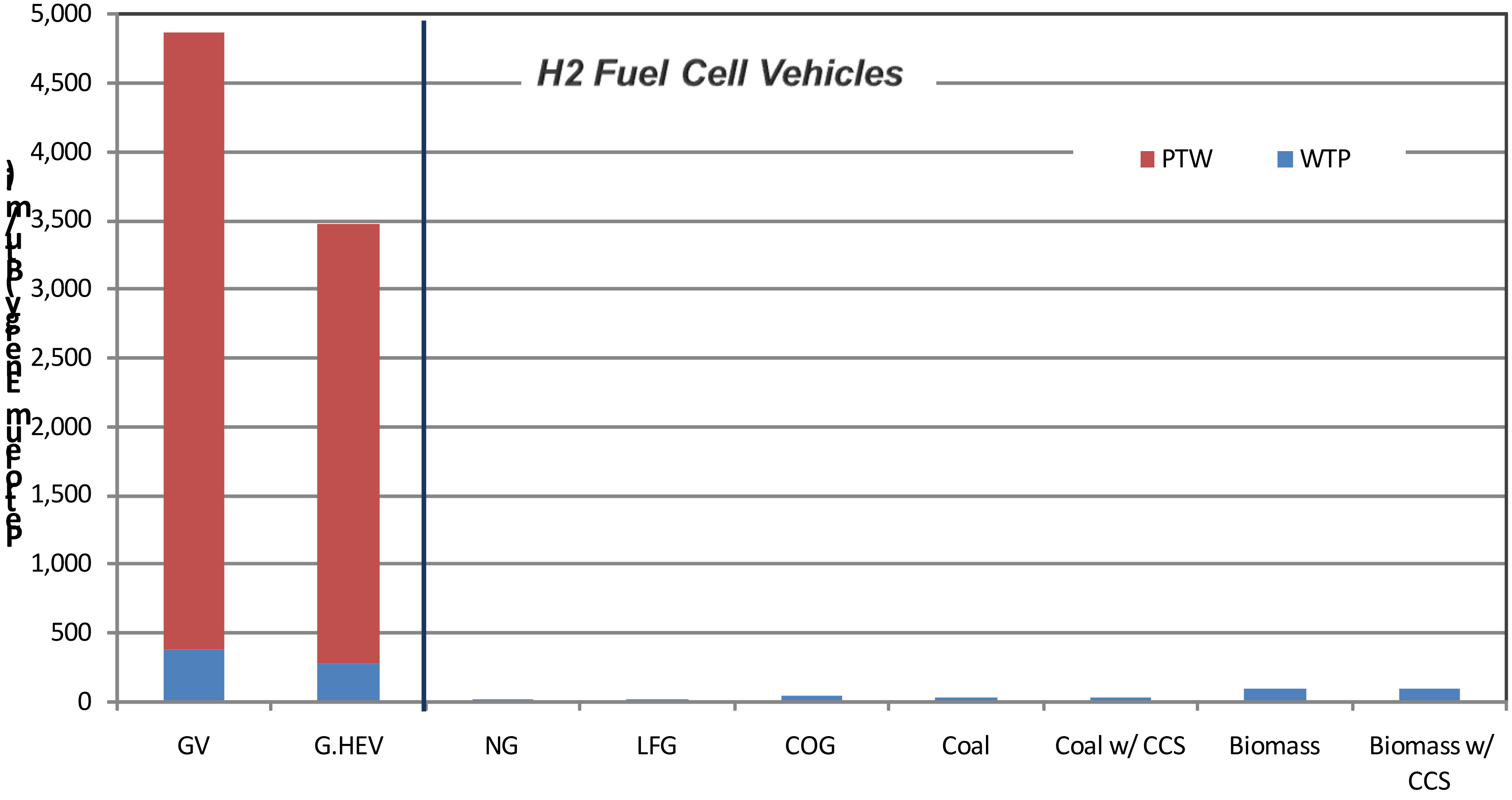
WTW Total Energy Use of H2 FCVs



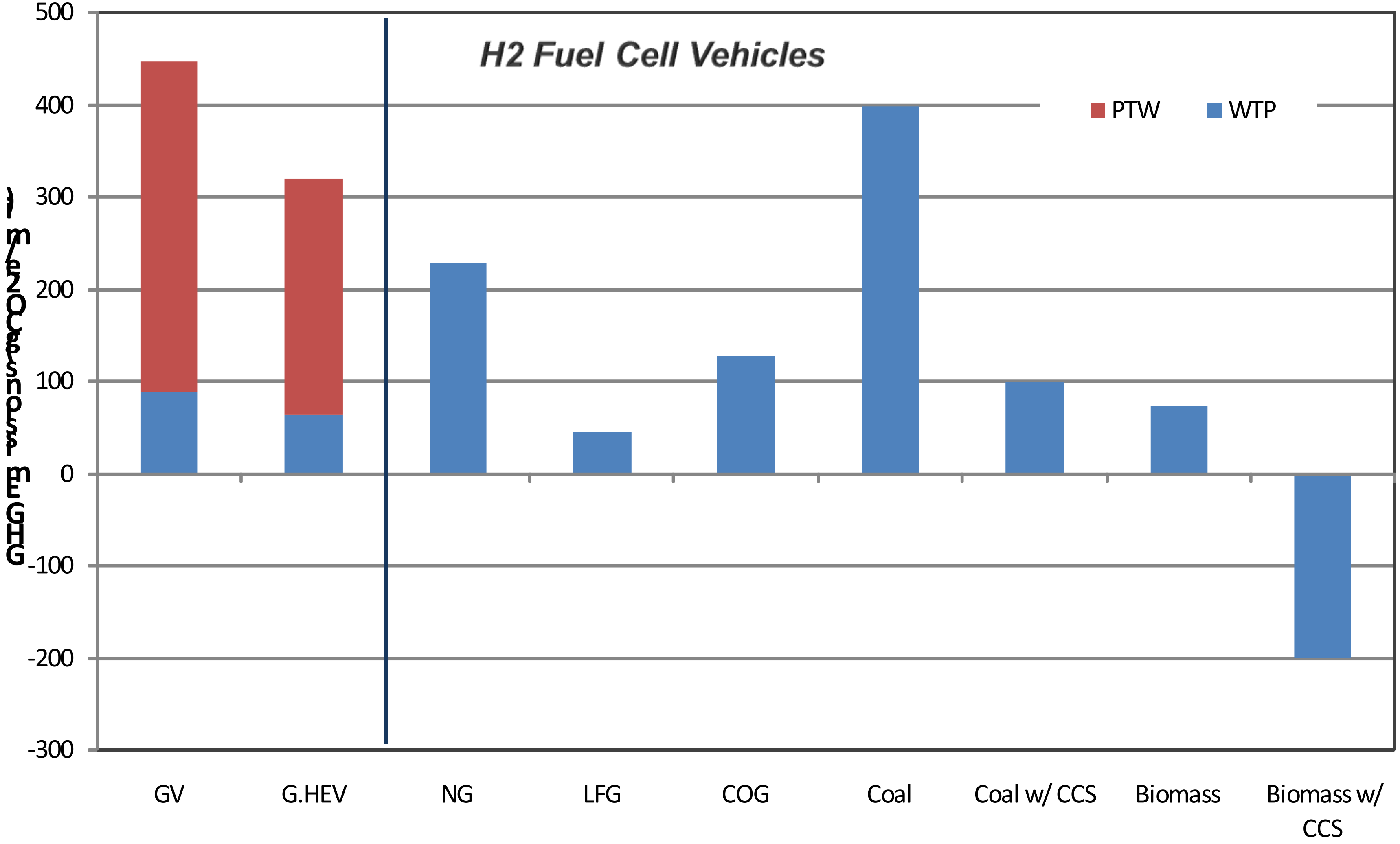
WTW Fossil Energy Use of H2 FCVs



WTW Petroleum Energy Use of H2 FCVs

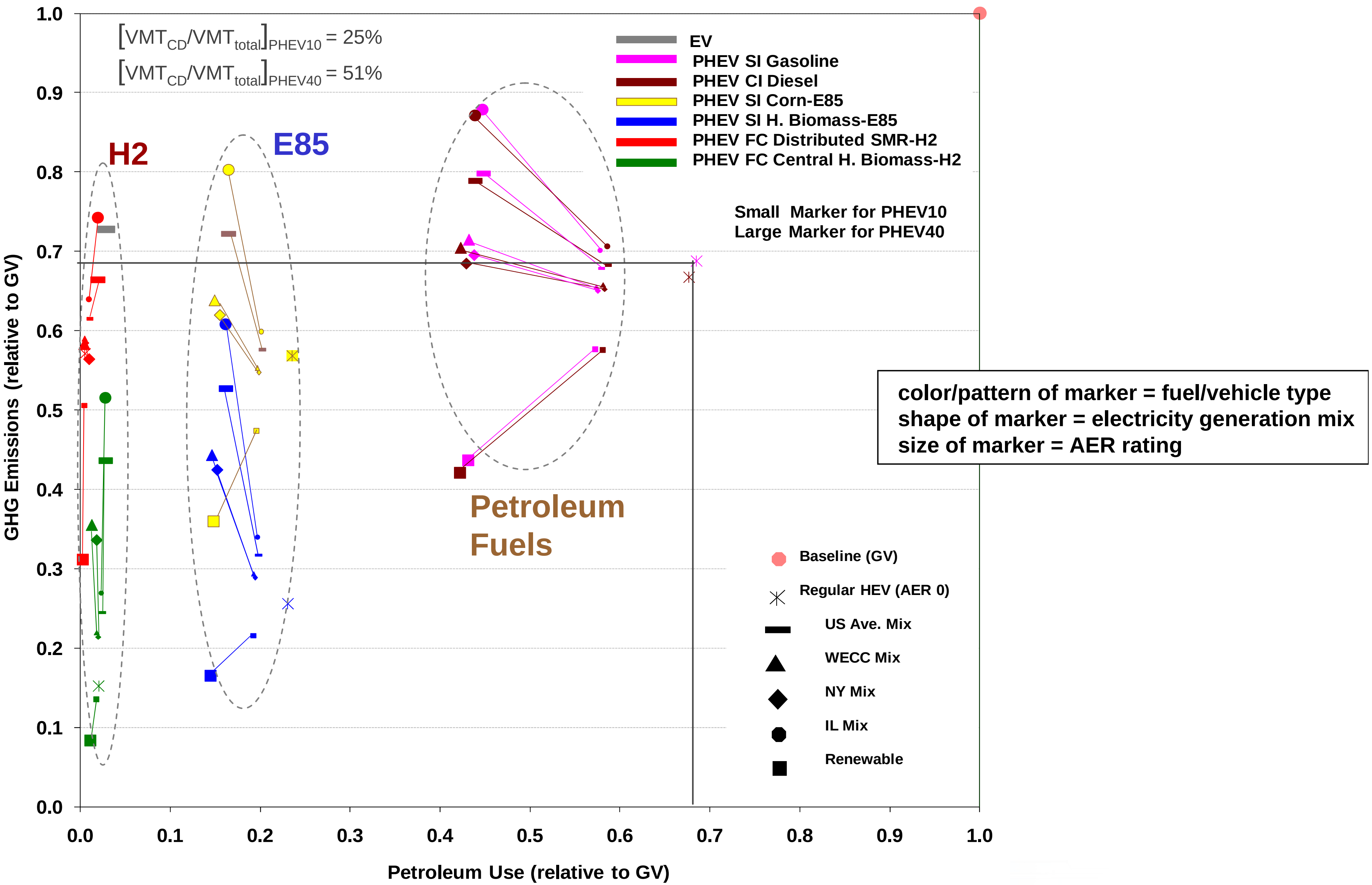


WTW GHG Emissions of H2 FCVs



For CCS, 90% carbon capture rate was assumed; electricity use for capture and transmission of CO2 was considered.

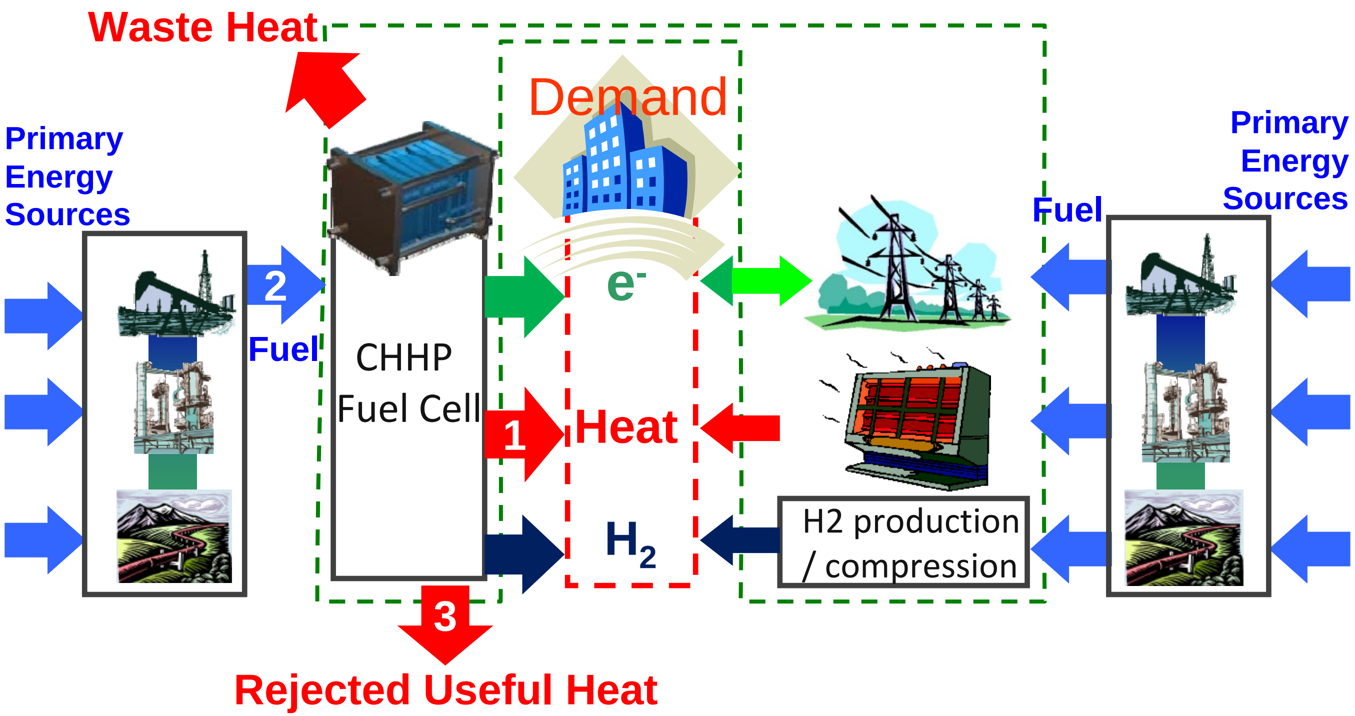
H2 FCVs in Comparison with other Fuels and Vehicle Options: GHG and Petroleum Effects



Argonne Has Examined Energy and Emission Effects of Combined Hydrogen, Heat, and Power (CHHP) Generation

- DOE identified early markets for fuel cells
  - Fuel cell–based distributed energy systems (electricity, heat, and optional hydrogen generation)
- ANL is examining energy and environmental implications for different CHHP system configurations
  - Expansion and use of the GREET model
  - Full fuel-cycle analysis starts with energy feedstock in the ground
  - Benefits depend on system efficiency and percentage of total demand satisfied by the fuel cell system

System Boundary for CHHP Life-Cycle Analysis



- Baseline case is exclusive of CHHP system
- If the useful heat from distributed generators exceeds the heat demand, the excess heat is rejected (wasted)
  - Thermal Efficiency ($\eta_{thermal}$) = **(1)**/**(2)**
    = [Heat delivered]/[Fuel to generator]
  - Heat Utilization (HU) = **(1)**/[**(1)**+**(3)**]
    = [Heat delivered]/[Useful heat from generator]
- Excess electricity is sold to the grid

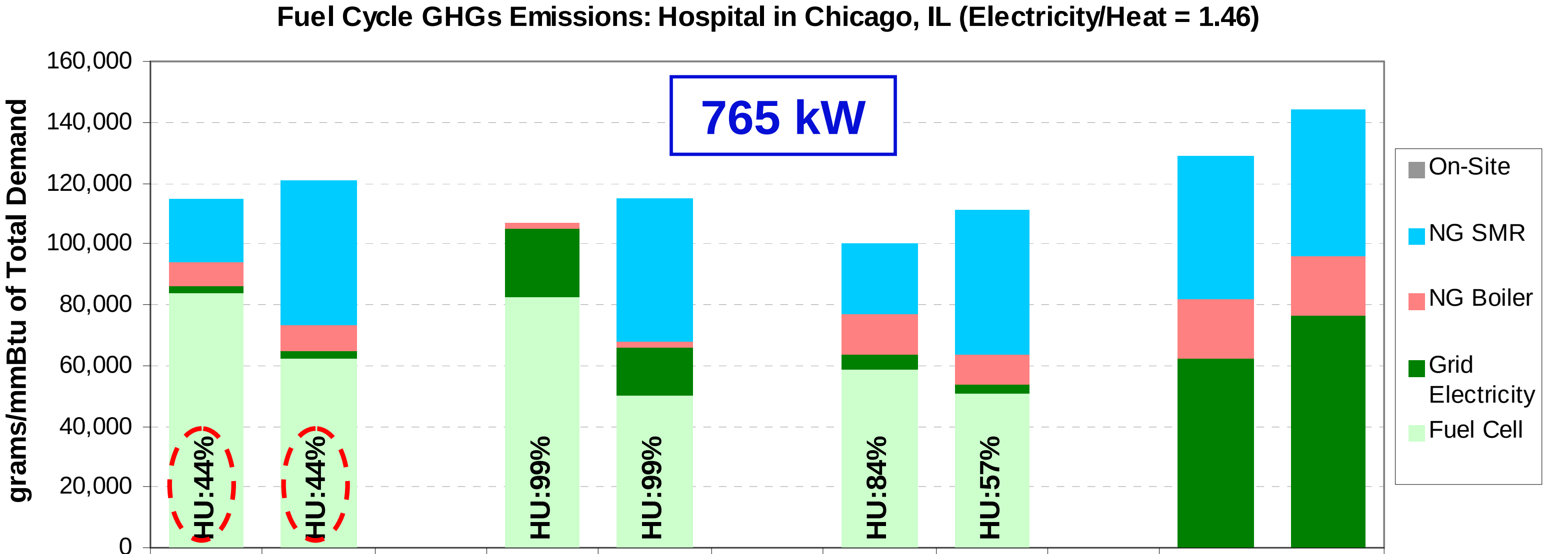
Factors Affecting the Fuel-Cycle Analysis

- ❑ Comparison by technology
  - ➢ PAFC with the electric or heat load following strategy
  - ➢ MCFC with the electric load following strategy
- ❑ Comparison by facility type
  - ➢ A large office and a warehouse in Chicago, IL
  - ➢ Hospitals in Chicago, IL and Los Angeles, CA

Facility Type	**Large Office**	**Warehouse**	**Hospital**	
Location		**Chicago**		**Los Angeles**
Electricity Demand (kWh/day)	16,000 (26%)	580 (8%)	13,000 (35%)	13,000 (35%)
Heat Demand (kWh/day)	3,300 (6%)	1,200 (15%)	9,400 (24%)	2,800 (7%)
Hydrogen Demand (kg/day)	1200 (68%)	170 (77%)	470 (41%)	680 (58%)

- ❑ Fuel cell is sized based on electric demand (for hospitals) or heat demand (warehouse): Avg + Std

GHG Emissions of CHP and CHHP for a Hospital in Chicago (Electric/Heat = 1.46)

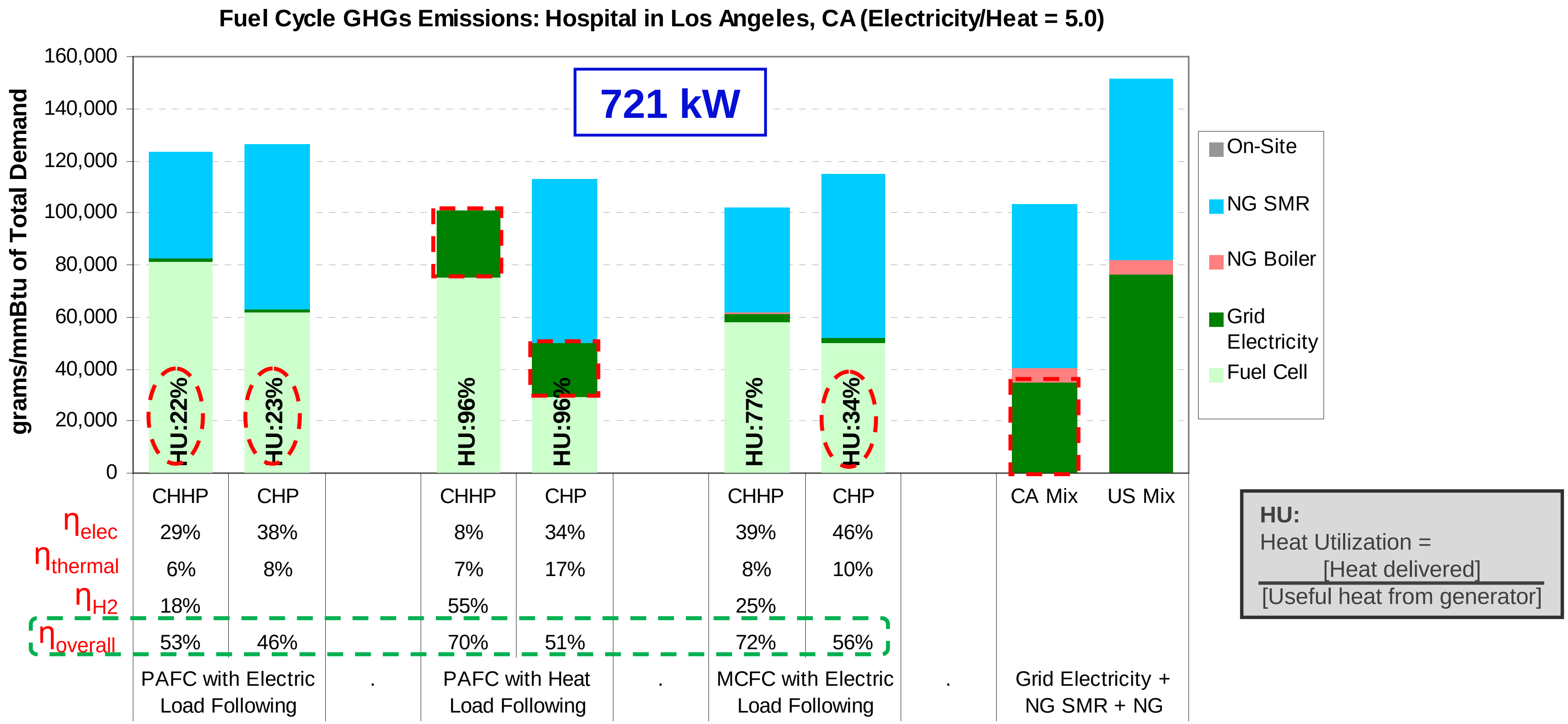


	PAFC with Electric Load Following		.	PAFC with Heat Load Following		.	MCFC with Electric Load Following		.	Grid Electricity + NG SMR + NG	
	CHHP	CHP		CHHP	CHP		CHHP	CHP		IL Mix	US Mix
η_{elec}	28%	38%		19%	37%		39%	46%			
$\eta_{thermal}$	12%	15%		19%	30%		8%	16%			
η_{H2}	19%			35%			25%				
$\eta_{overall}$	59%	53%		73%	67%		72%	62%			

HU:
Heat Utilization = [Heat delivered] / [Useful heat from generator]

- Fuel cells for CHHP provide GHG emissions benefits compared to CHP systems and IL generation mix.
- Benefits depend on the overall efficiency and the utilization of co-produced heat.
- IL electric mix (η=45%): Nuclear 48%, **Coal 48%**, Natural Gas 2%, Rest 2%
- US electric mix (η=39%): **Coal 50%**, Nuclear 20%, Natural Gas 18%, Renewable 10%, Rest 2%.

GHG Emissions of CHP and CHHP for a Hospital in Los Angeles (Electric/Heat = 5.0)



- GHG emissions by CA generation mix are comparable to those by CHHP systems.
  - Low heat demands result in low heat utilization.
  - CA mix (η=48%): Natural Gas 37%, **Renewable 28%**, Nuclear 21%, Coal 13%, Rest 1%.

Concluding Remarks

- H2 FCVs offer energy and GHG benefits
- Renewable H2 pathways offer much larger GHG benefits
- Early FC market applications offer some emission benefits