Well-to-Wheels Energy and Emission Impacts of Vehicle/Fuel Systems

Development and Applications of the GREET Model

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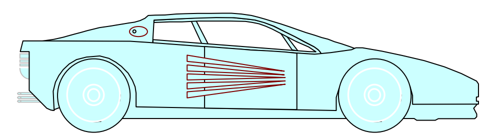
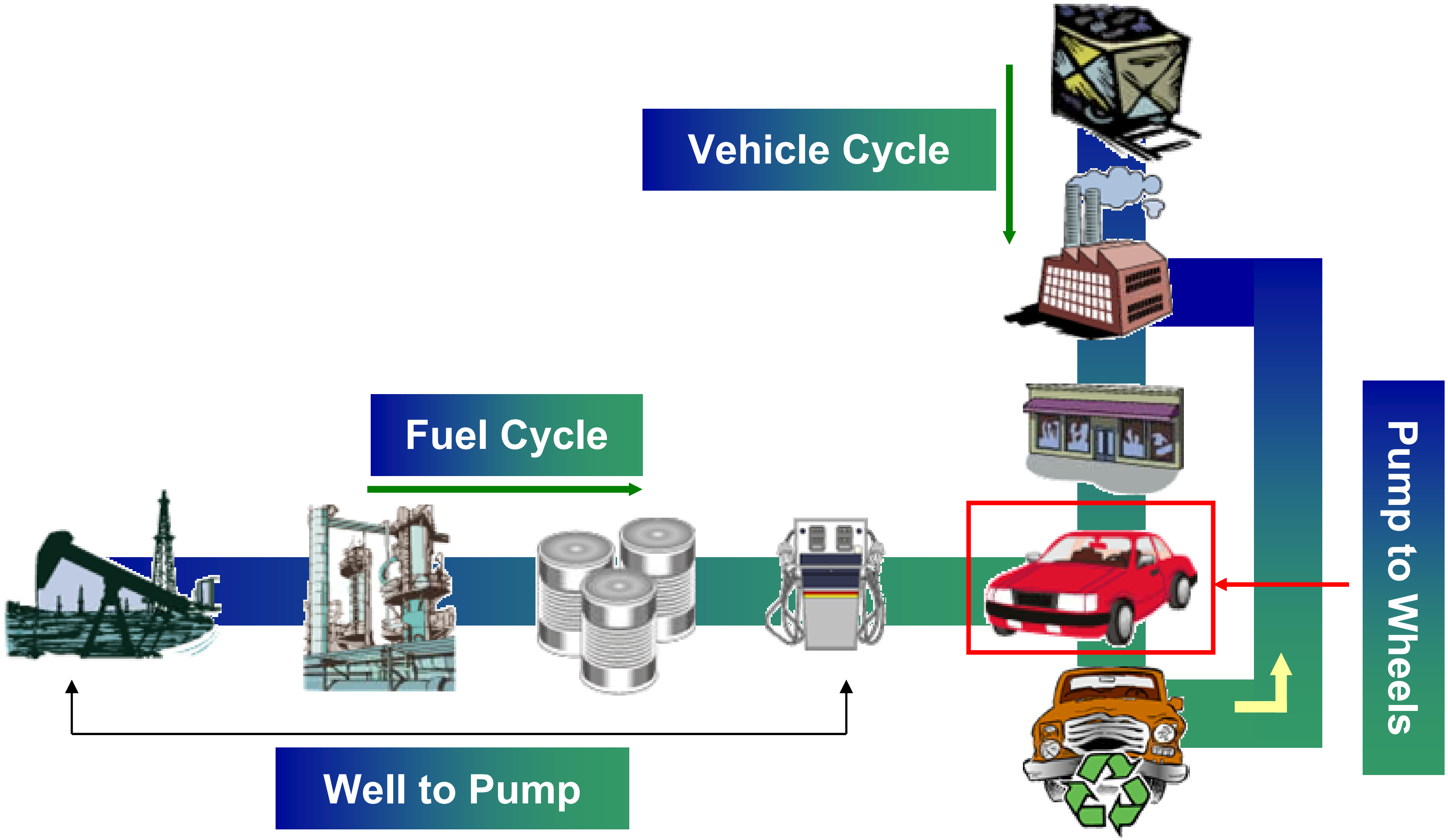


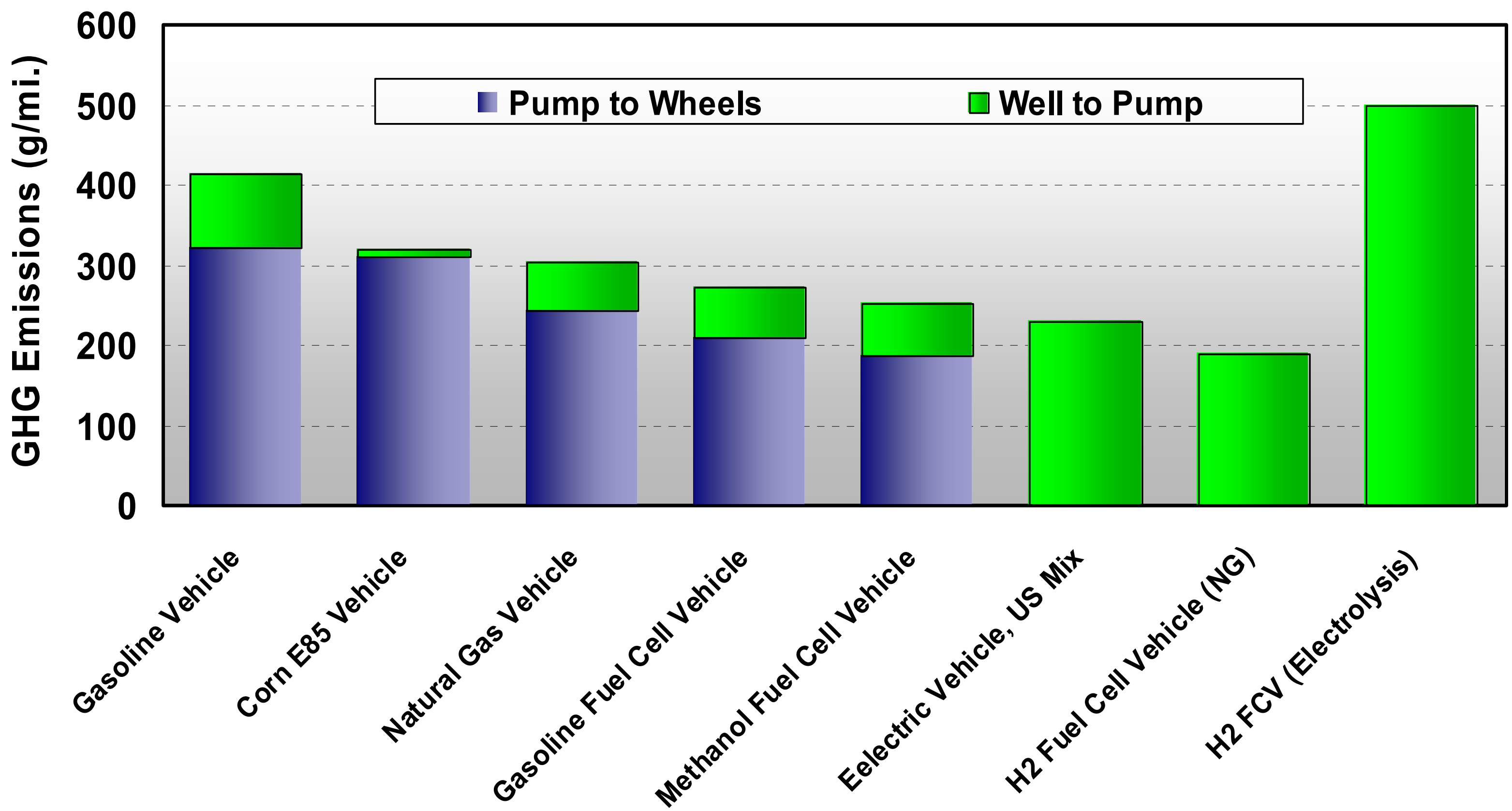
California Air Resources Board
Sacramento, CA, April 14, 2003

Vehicle and Fuel Cycles: Petroleum-Based Fuels



WTW Analysis Is a Complete Energy/Emissions Comparison

As an example, greenhouse gases are illustrated here



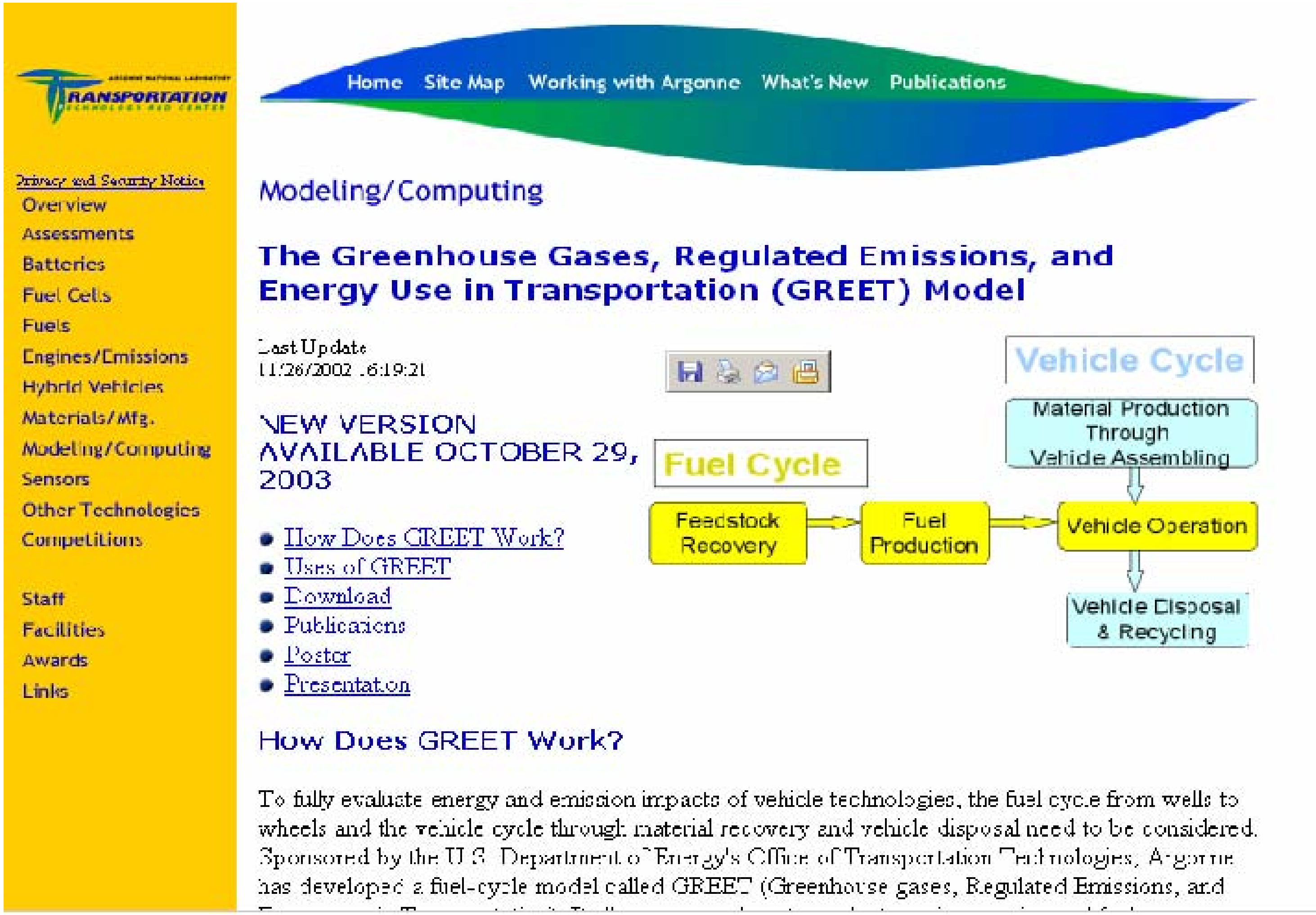
WTW Analysis for Vehicle/Fuel Systems Has Been Evolved in the Past 20 Years

- Historically, evaluation of vehicle/fuel systems from wells to wheels (WTW) was called fuel-cycle analysis
- Pioneer transportation WTW analyses began in 1980s
  - Early studies were motivated primarily by EVs
  - Current studies are motivated primarily by FCVs
- Transportation WTW analyses have taken two general approaches
  - Life-cycle analysis of consumer products
  - Transportation fuel-cycle analysis
  - Most transportation studies have followed the fuel-cycle analysis approach
- For transportation technologies, especially internal combustion engine technologies, the significant energy and emissions effects occur in the fuel usage stage first and fuel production stage second
- Consequently, efforts have been in addressing energy use and emissions of vehicle operations and fuel production
- Since 1995, the U.S. Department of Energy has been supporting the GREET model development at Argonne National Laboratory

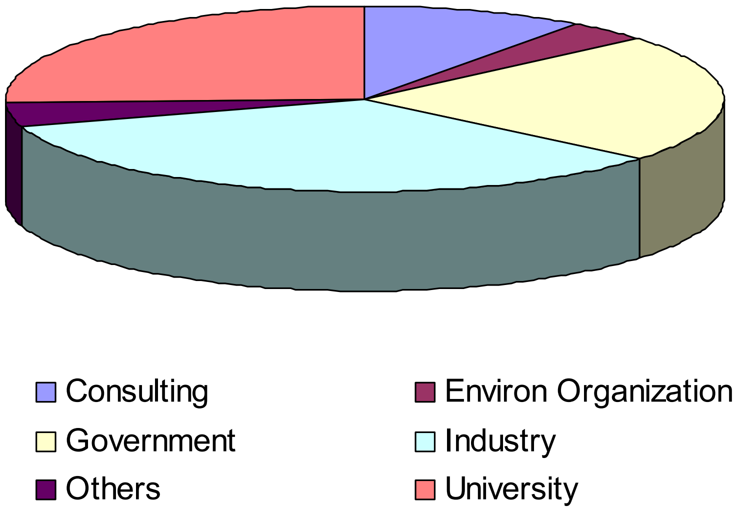
The GREET (*G*reenhouse gases, *R*egulated *E*missions, and *E*nergy use in *T*ransportation) Model

- **GREET includes emissions of greenhouse gases**
  - CO_2, CH_4, and N_2O
  - VOC, CO, and NO_x as optional GHGs
- **GREET estimates emissions of five criteria pollutants**
  - Total and urban separately
  - VOC, CO, NO_x, So_x, and PM_{10} (PM2.5 not included)
- **GREET separates energy use into**
  - All energy sources
  - Fossil fuels (petroleum, natural gas, and coal)
  - Petroleum

The GREET Model and Its Documents Are Available at: *http://greet.anl.gov*

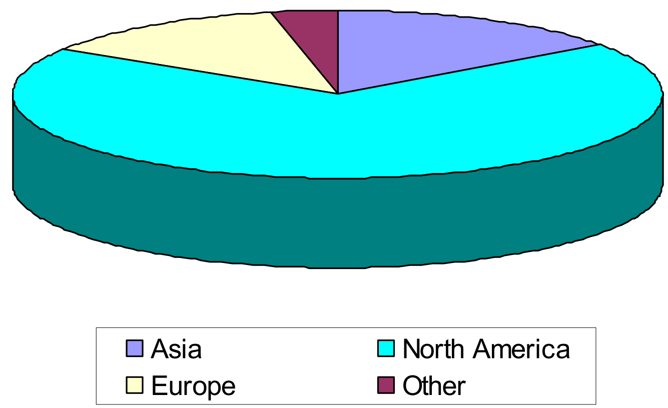


At Present, There Are More Than 790 GREET Registered Users Worldwide

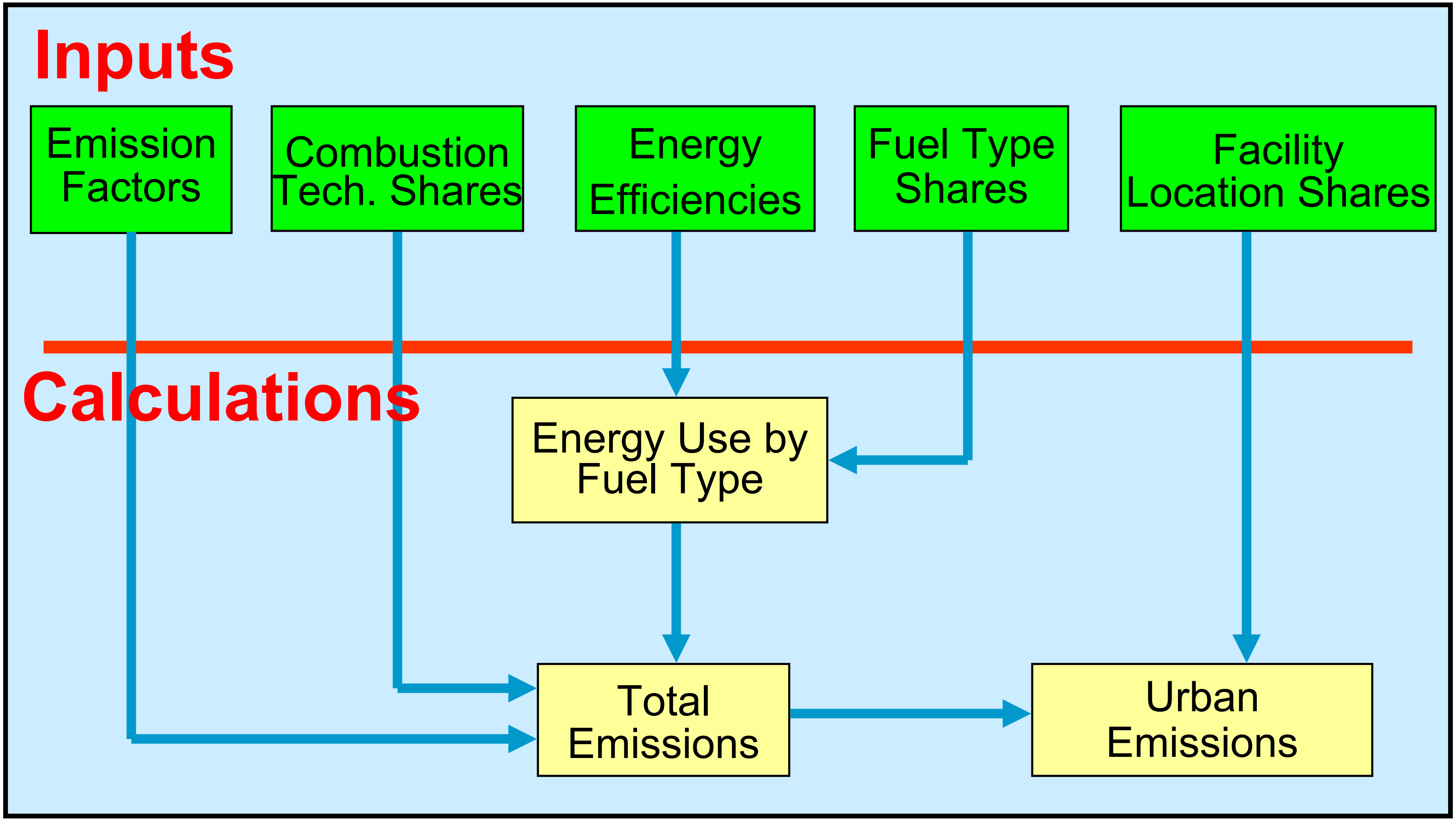


Industries, universities, and governmental agencies are major GREET users

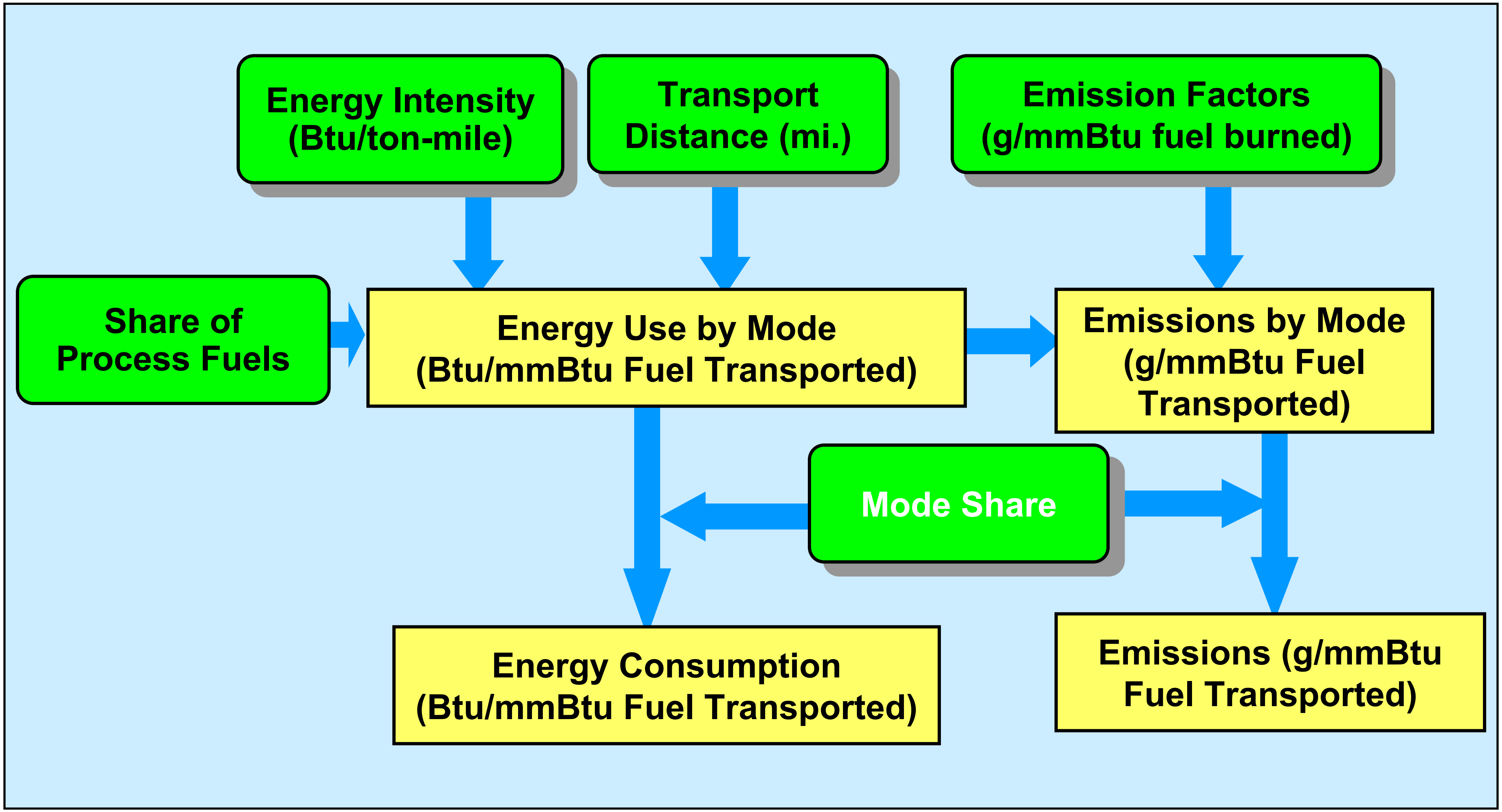
Most GREET users are in North America



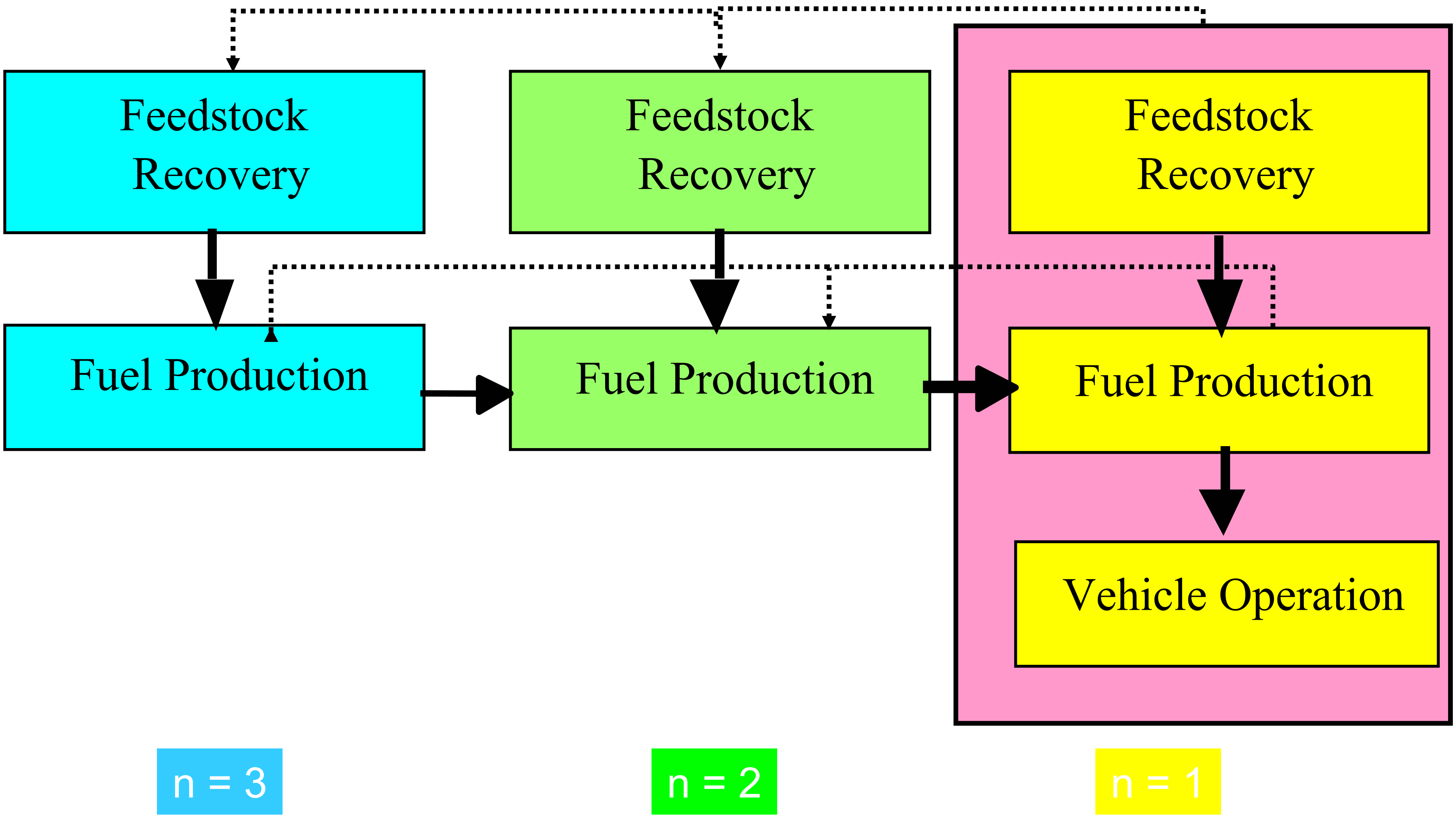
The Simplified Calculation Logic for Individual Production Activities in GREET



The Simplified Calculation Logic for Individual Transportation Activities in GREET

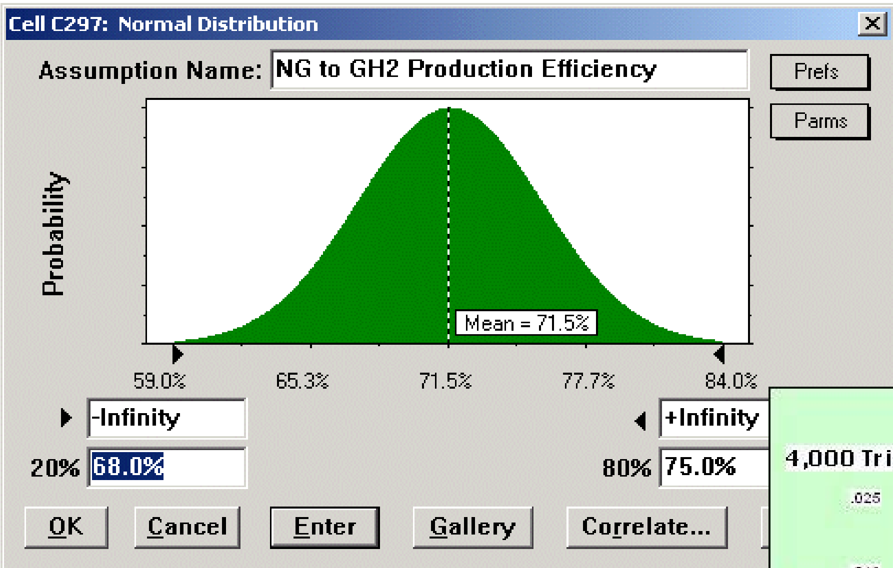


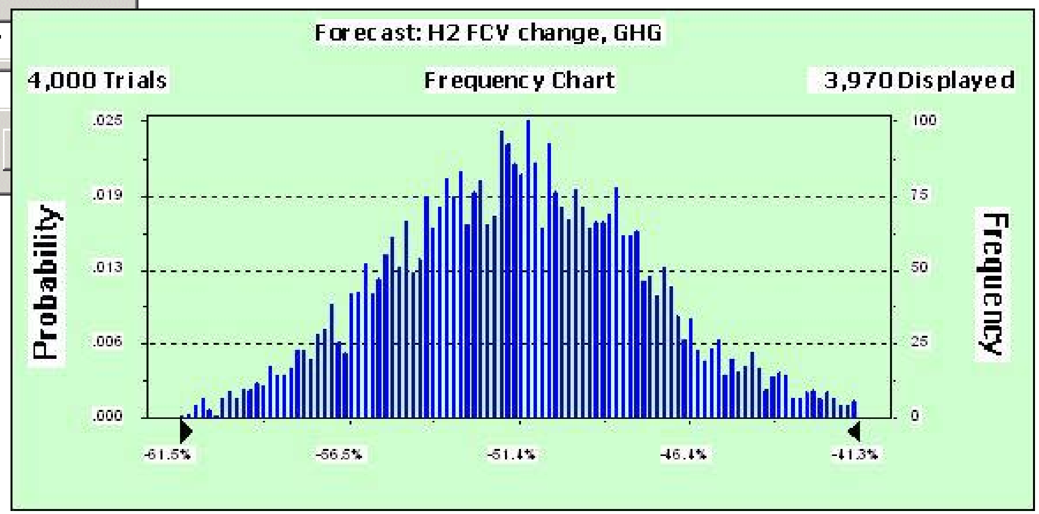
GREET Considers Up^n Well-to-Pump Steps Through Iteration Calculations



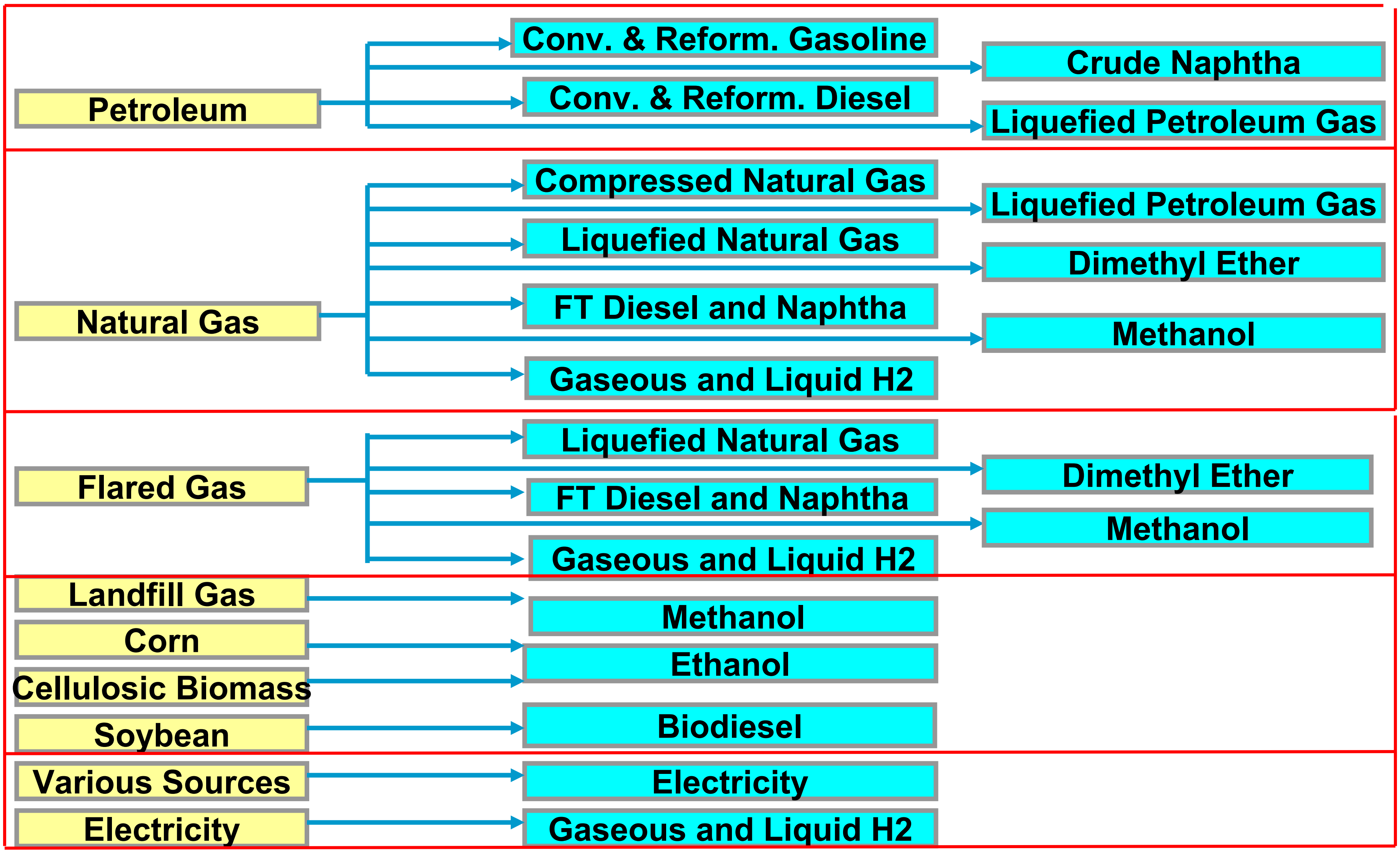
GREET Is Designed to Conduct Stochastic Simulations

Distribution-Based Inputs Generate Distribution-Based Outputs





GREET Has More Than 30 Fuel Pathway Groups



Some Additional Fuel Production Pathways Are to Be Added to GREET

- Biomass gasification to produce
  - Ethanol
  - Methanol
  - Hydrogen
- Coal gasification to produce hydrogen
- Hydrogen production from ethanol and methanol at refueling stations
- Nuclear thermal cracking of water for hydrogen production
- Sodium borohydride ($NaBH_4$) H_2 production and storage
- Metal hydride hydrogen storage

Two ANL WTW Publications Are Cited by Many Organizations

VOLUME I

General Motors Corporation
Argonne National Laboratory
BP
ExxonMobil
and
Shell

Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems
– North American Analysis –

EXECUTIVE
SUMMARY
REPORT

June 2001

Journal of Power Sources 112 (2002) 307–321
www.elsevier.com/locate/jpowsour

Fuel choices for fuel-cell vehicles: well-to-wheels energy and emission impacts

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Petroleum Refining Is the Key Energy Conversion Step for Gasoline

Petroleum Recovery (97%)

Petroleum Transport and Storage (99%)

MTBE or EtOH for Gasoline

Petroleum Refining to Gasoline (84.5-86%, Depending on Oxygenates and Reformulation)

Transport, Storage, and Distribution of Gasoline (99.5%)

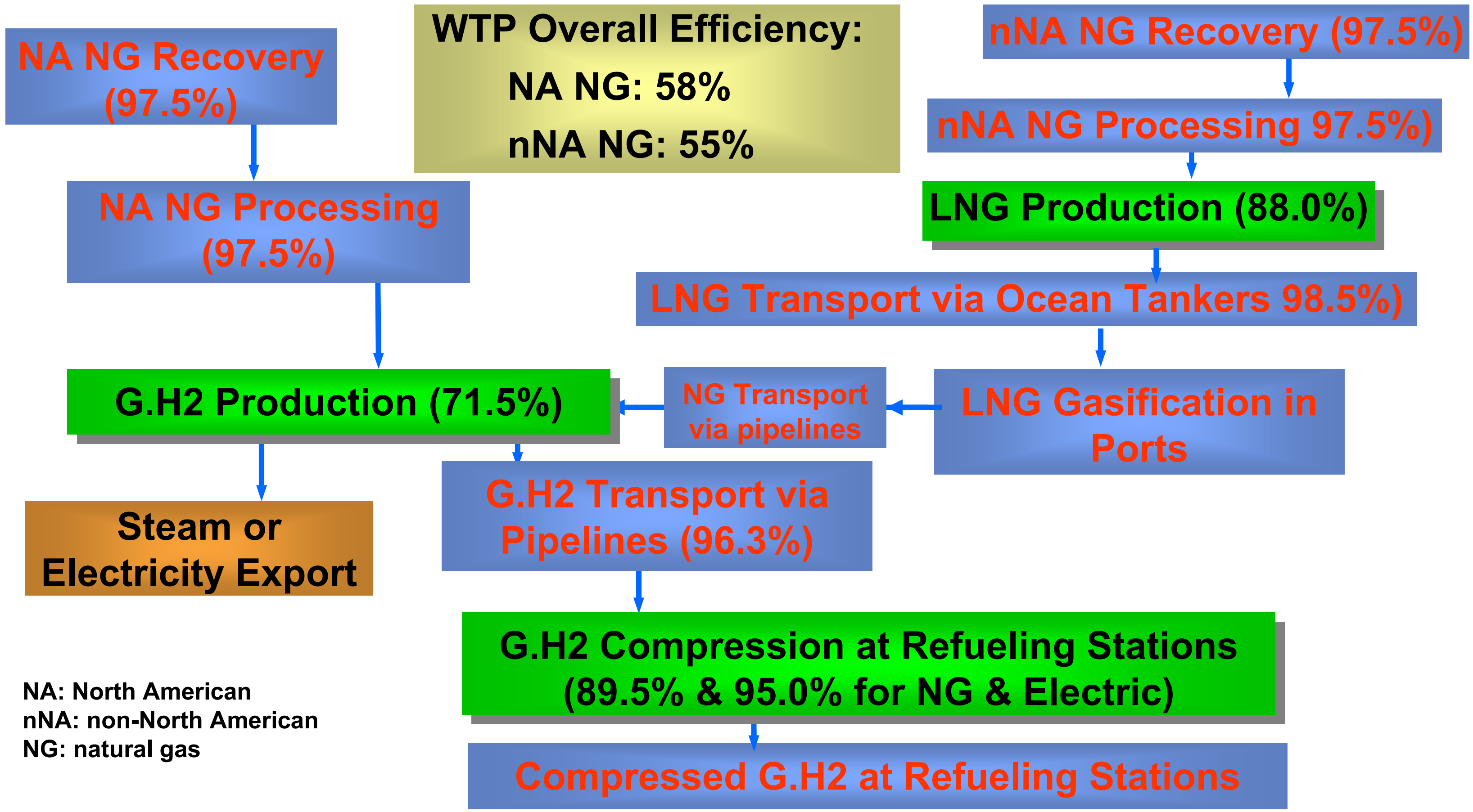
Gasoline at Refueling Stations

WTP Overall Efficiency: 80%

Key Issues for Simulating Petroleum Fuels

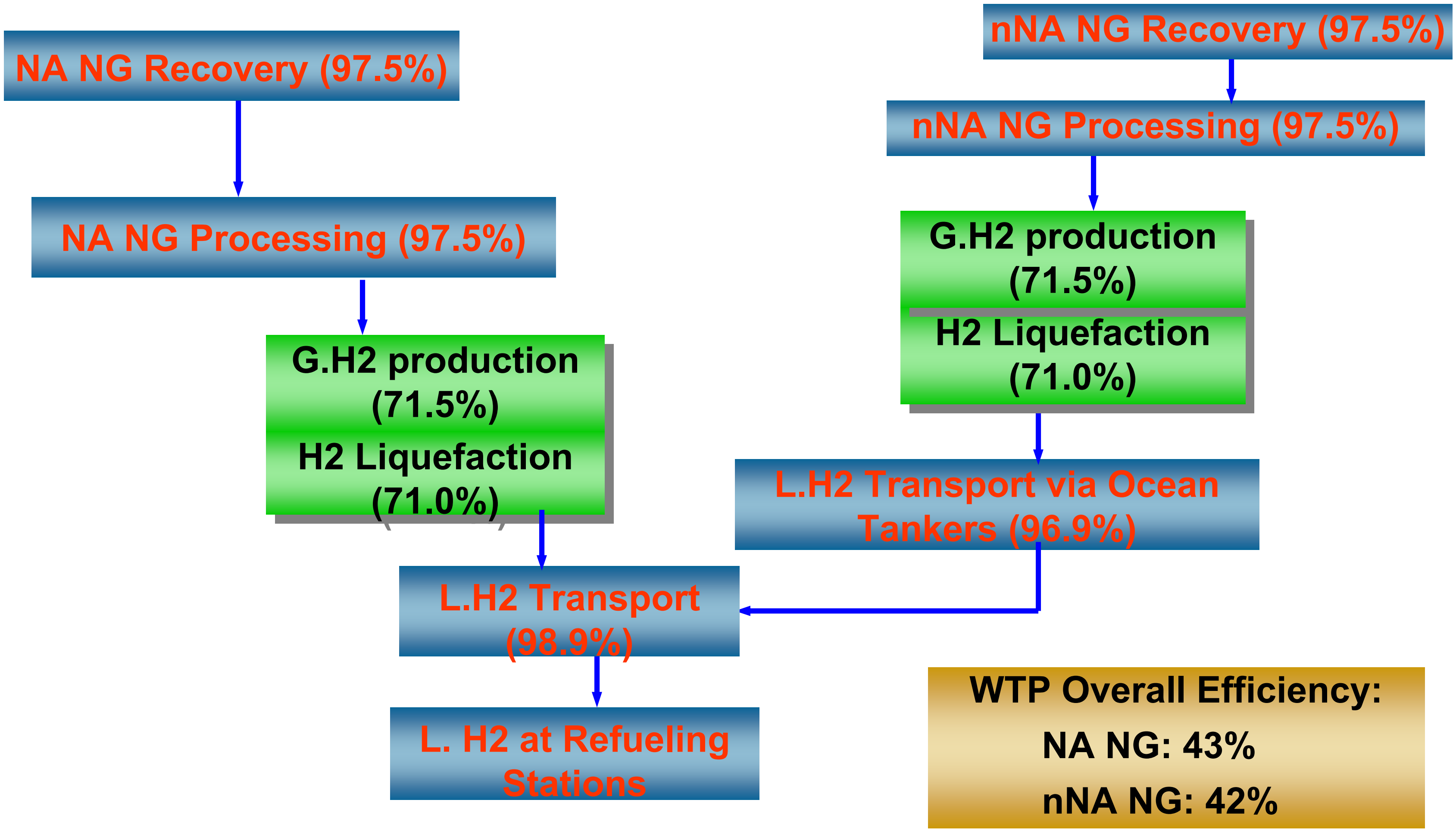
- Gasoline sulfur content will be reduced nationwide to 30 ppm beginning in 2004 vs. 150-300 ppm current level
- Diesel sulfur content will be reduced to 15 ppm in 2006 from the current level of ~300 ppm
- In addition, marginal crude has high sulfur content
- Desulfurization in petroleum refineries adds stress on refinery energy use and emissions
- Ethanol could replace MTBE as gasoline oxygenate
  - Energy and emission differences between ethanol and MTBE
  - Production of gasoline blend stock for ethanol vs. MTBE

Production and Compression Are Key Steps for Centralized G.H_2 Pathways



NA: North American
nNA: non-North American
NG: natural gas

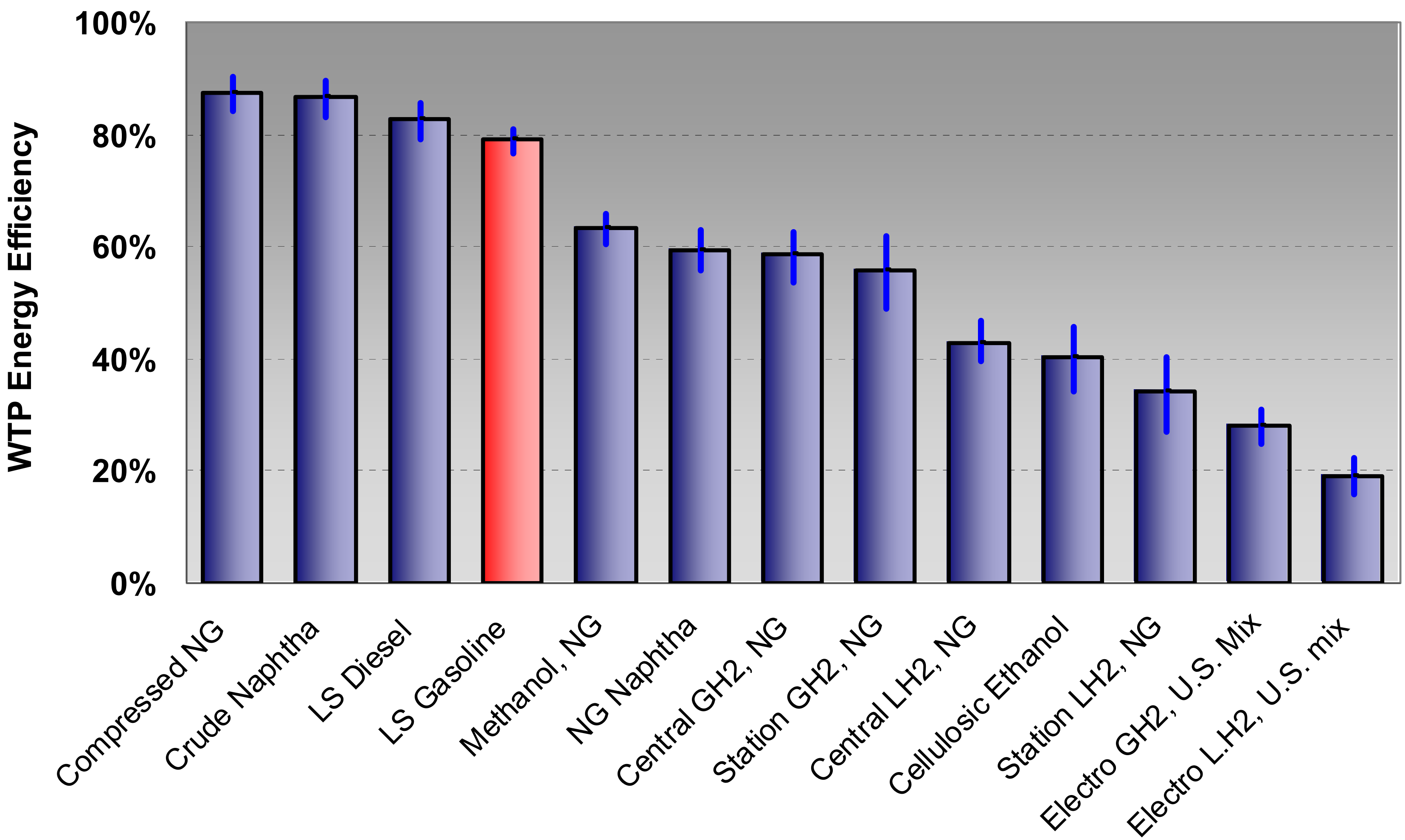
H_2 Liquefaction Has Higher Energy Losses Than H_2 Compression



Resource and Infrastructure Issues Result in Many Potential H2 Pathways

- Produced from natural gas via steam methane reforming (SMR) now, and in the foreseeable future
- SMR plant emissions need to be taken into account
- Regional or station SMR production
  - Could reduce or avoid expensive distribution infrastructure
  - But production emissions move close to urban areas
- Some amount of central SMR CO_2 emissions can be potentially sequestered
- Energy and emission effects of electrolysis H_2 depend on electricity sources
- Gasification for H_2 production
  - Coal: CO_2 and criteria pollutant emissions, but CO2 can be potentially sequestered
  - Biomass: criteria pollutant emissions
- Nuclear H_2 has zero air emissions, but nuclear waste will continue to be an issue

WTP Energy Losses Could Significantly Affect Efficiencies and GHG Emissions



GREET Includes More Than 50 Vehicle/Fuel Systems

Conventional Spark-Ignition Vehicles
- Conventional gasoline, federal reformulated gasoline, California reformulated gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Methanol and ethanol

Compression-Ignition Direct-Injection Hybrid Electric Vehicles: Grid-Independent and Connected
- Conventional diesel, low sulfur diesel, dimethyl ether, Fischer-Tropsch diesel, and biodiesel

Spark-Ignition Hybrid Electric Vehicles: Grid-Independent and Connected
- Conventional gasoline, federal reformulated gasoline, California reformulated gasoline, methanol, and ethanol
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas

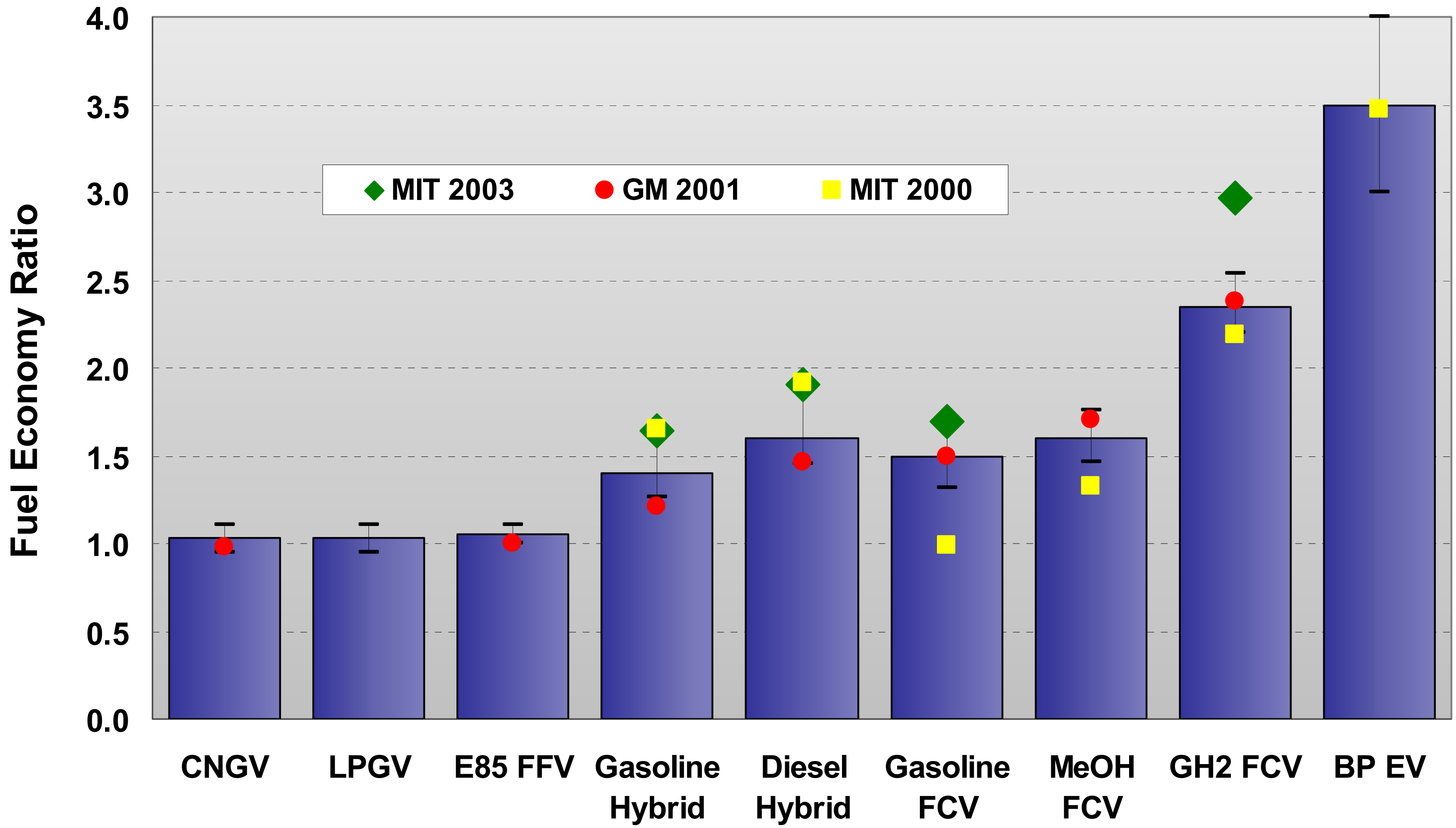
Battery-Powered Electric Vehicles
- U.S. generation mix
- California generation mix
- Northeast U.S. generation mix

Fuel Cell Vehicles
- Gaseous hydrogen, liquid hydrogen, methanol, federal reformulated gasoline, California reformulated gasoline, low sulfur diesel, ethanol, compressed natural gas, liquefied natural gas, liquefied petroleum gas, and naphtha

Compression-Ignition Direct-Injection Vehicles
- Conventional diesel, low sulfur diesel, dimethyl ether, Fischer-Tropsch diesel, and biodiesel

Spark-Ignition Direct-Injection Vehicles
- Conventional gasoline, federal reformulated gasoline, and California reformulated gasoline
- Methanol and ethanol

GREET Fuel Economy Ratios of Vehicle Technologies (Relative to GVs)



Tailpipe Emissions Will Continue to Decline

Tier 2 Standards (Fully in Effect in 2009, g/mi. for 100K miles)

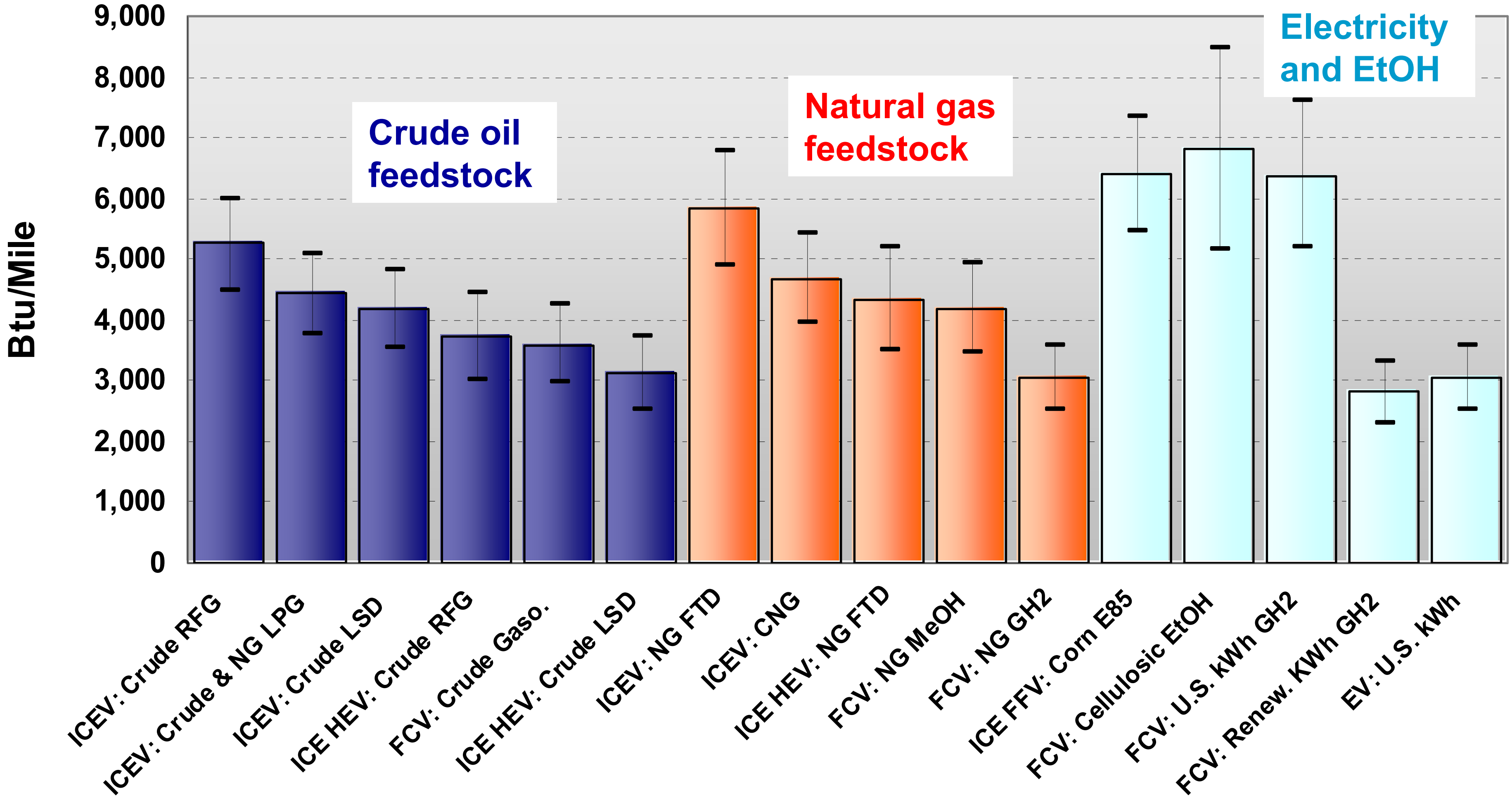
	NMOG	*CO*	*NOx*[c]	*PM*	*HCHO*
Bin 10[a,b]	0.156/0.230	4.2/6.4	0.6	0.08	0.018/0.027
Bin 9[a,b]	0.090/0.180	4.2	0.3	0.06	0.018
Bin 8[a]	0.125/0.156	4.2	0.20	0.02	0.018
Bin 7	0.090	4.2	0.15	0.02	0.018
Bin 6	0.090	4.2	0.10	0.01	0.018
Bin 5	**0.090**	**4.2**	**0.07**	**0.01**	**0.018**
Bin 4	0.070	2.1	0.04	0.01	0.011
Bin 3	0.055	2.1	0.03	0.01	0.011
Bin 2	**0.010**	**2.1**	**0.02**	**0.01**	**0.004**
Bin 1	0.000	0.0	0.00	0.00	0.000

[a] The high values apply to HLDTs. The low values applied to cars and LLDTs.
[b] Bins 10 and 9 will be eliminated at the end of 2006 model year for cars and LLDTs and at the end of 2008 model years for HLDTs.
[c] Corporate average NOx standard will be 0.07 g/mi. and will be fully in place by 2009.

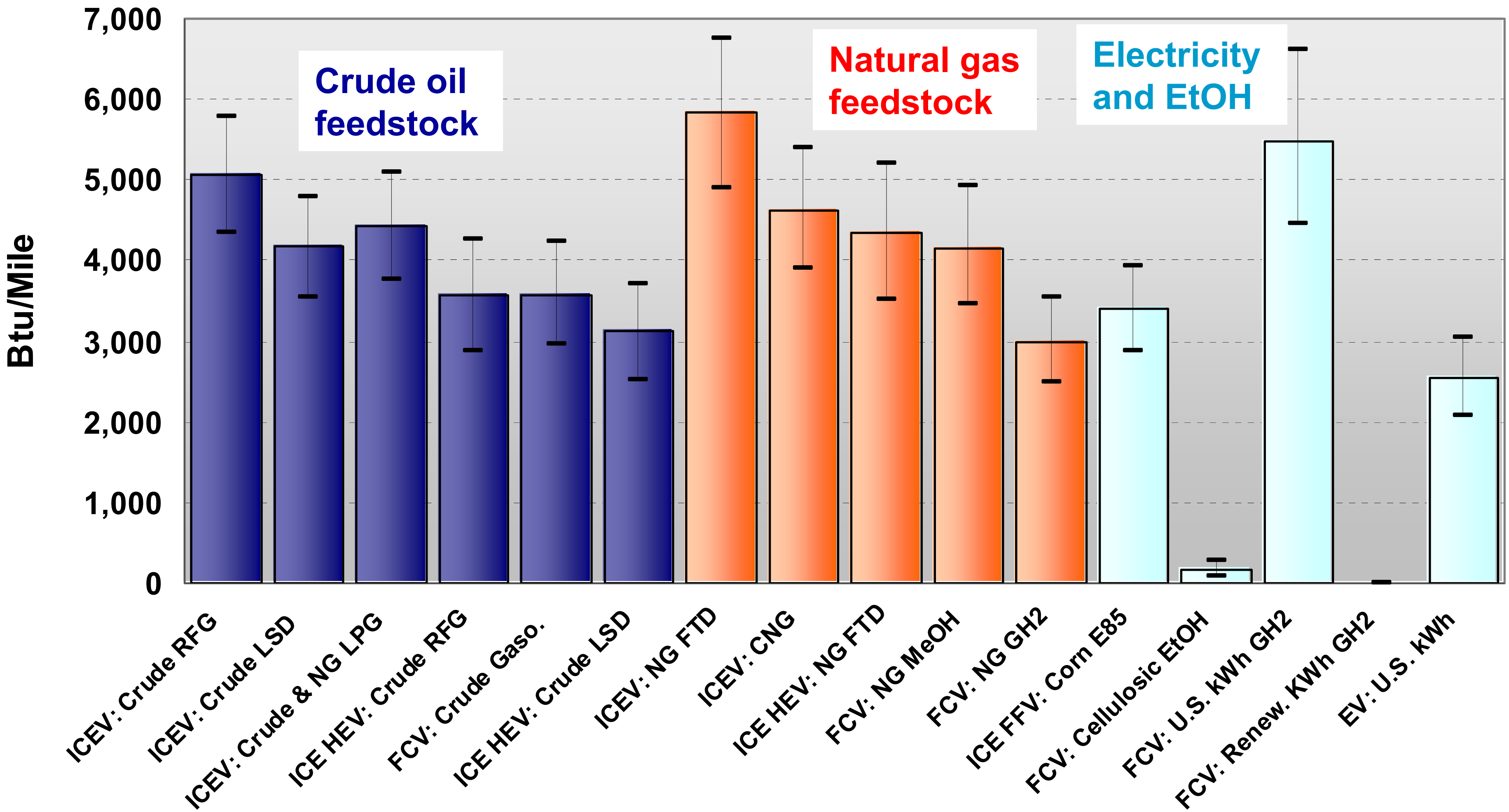
GREET Takes These Steps to Estimate Vehicular Emissions

- Emissions of VOC, CO, NO_x, CH_4, and PM_{10}
  - Baseline gasoline and diesel vehicles:
    - ✓ HC, CO, NO_x and CH_4 are estimated with EPA's Mobile model
    - ✓ PM_{10} is estimated with EPA's Part model
  - Advanced or alternative-fueled vehicles:
    - ✓ Their emission change rates relative to GVs or DVs are estimated with testing results or engineering analysis
    - ✓ Their emission levels are calculated with the estimated emission change rates and baseline GV or DV emissions
- SO_x emissions for each vehicle type are calculated from sulfur contained in fuels
- CO_2 emissions for each vehicle type are estimated from carbon balance
- N_2O emissions are based on limited testing results; CARB and EPA efforts here will greatly reduce tailpipe N_2O uncertainties

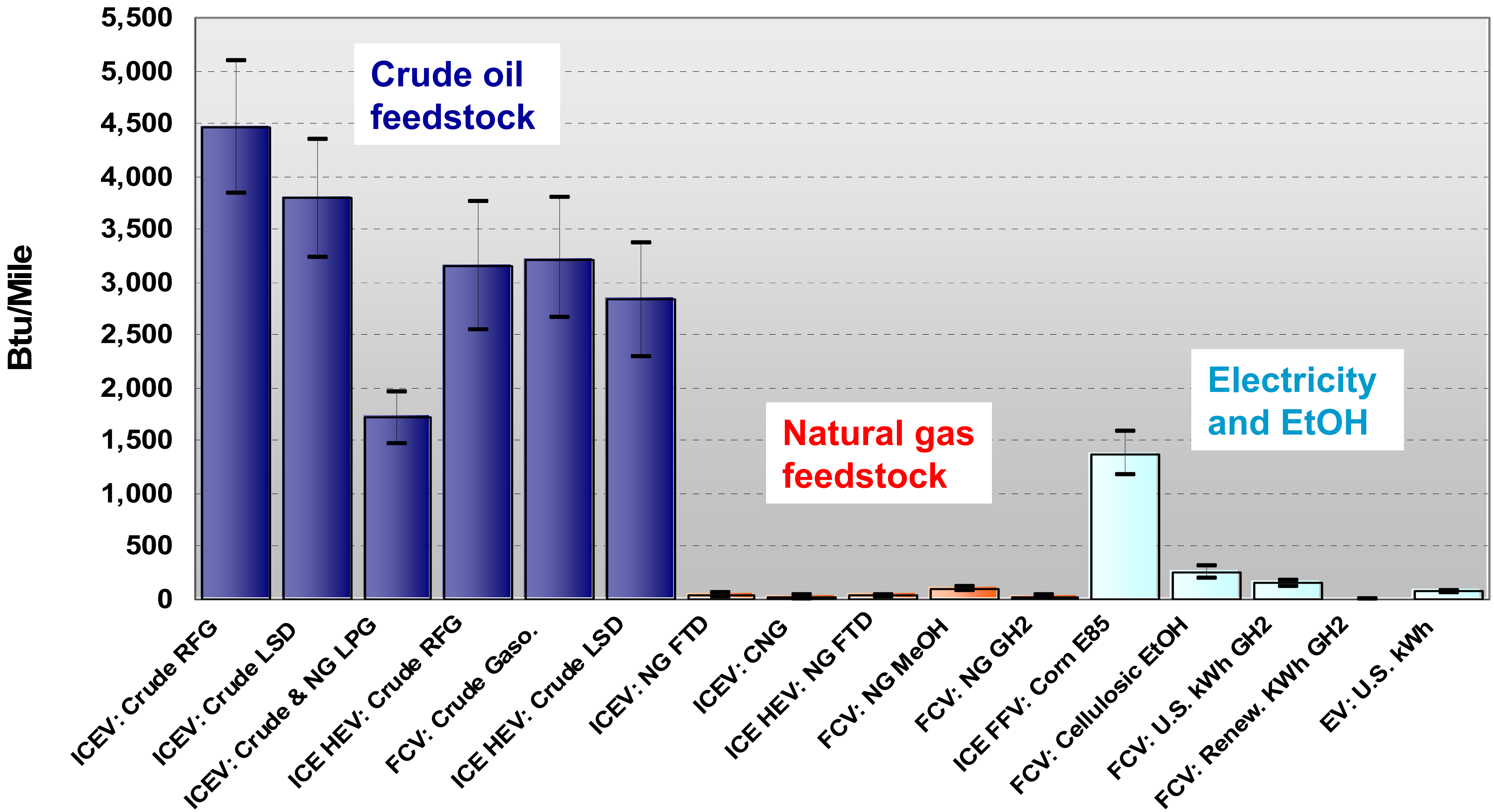
Per-Mile Total Energy Use of Selected Vehicle/Fuel Systems



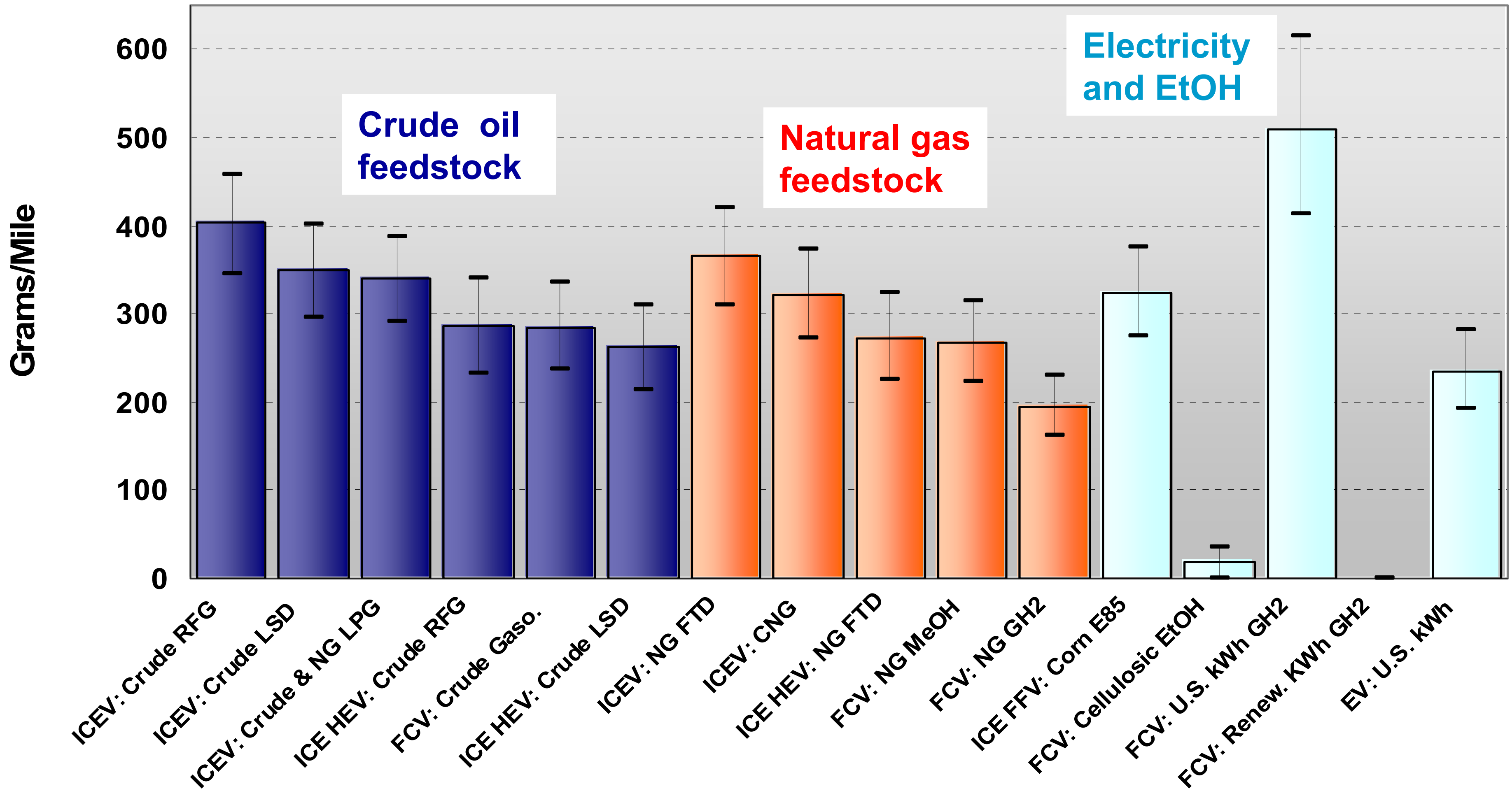
Per-Mile Fossil Energy Use of Selected Vehicle/Fuel Systems



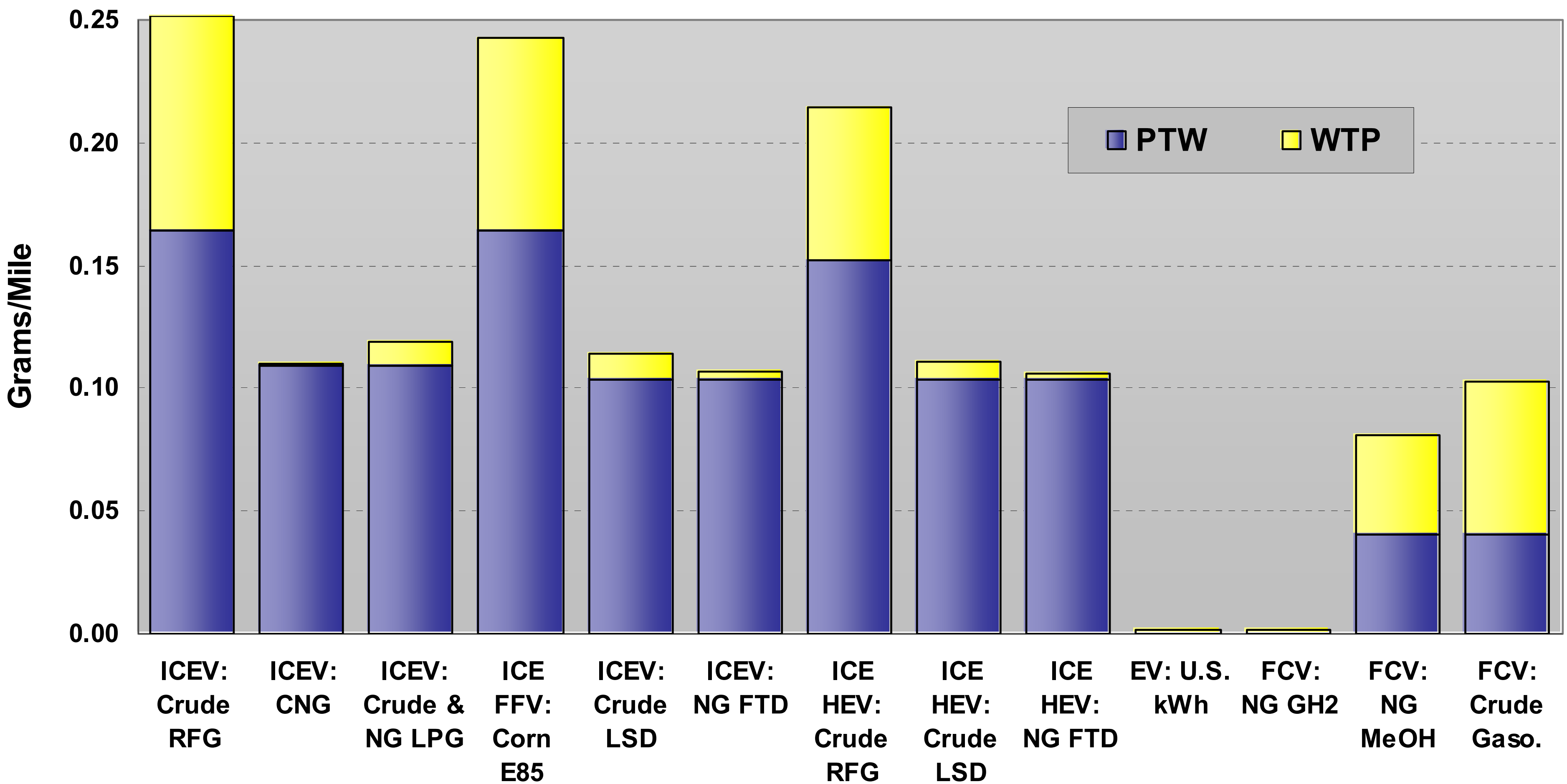
Per-Mile Petroleum Use of Selected Vehicle/Fuel Systems



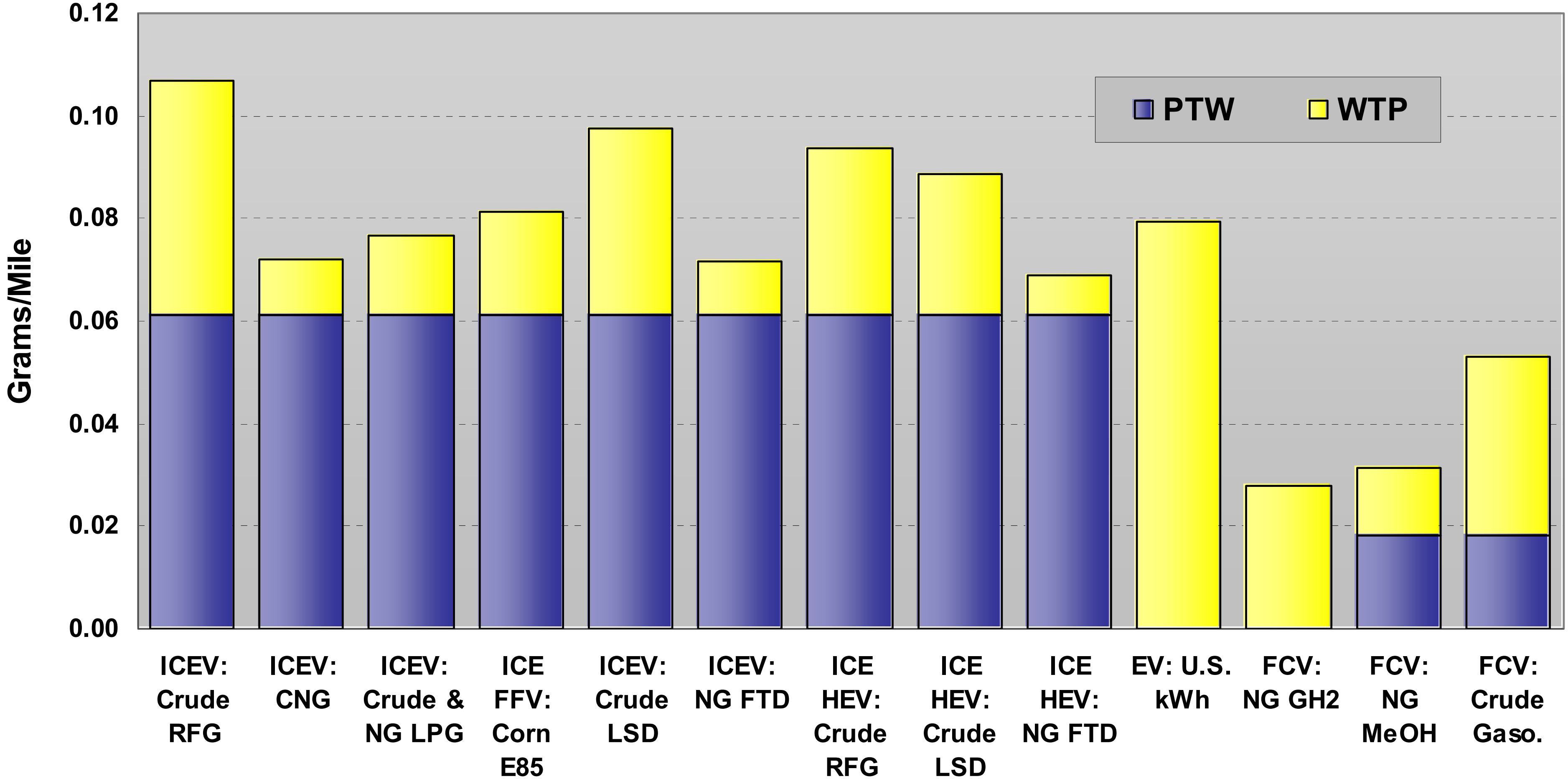
Per-Mile GHG Emissions of Selected Vehicle/Fuel Systems



Per-Mile Urban In-Use VOC Emissions of Selected Vehicle/Fuel Systems



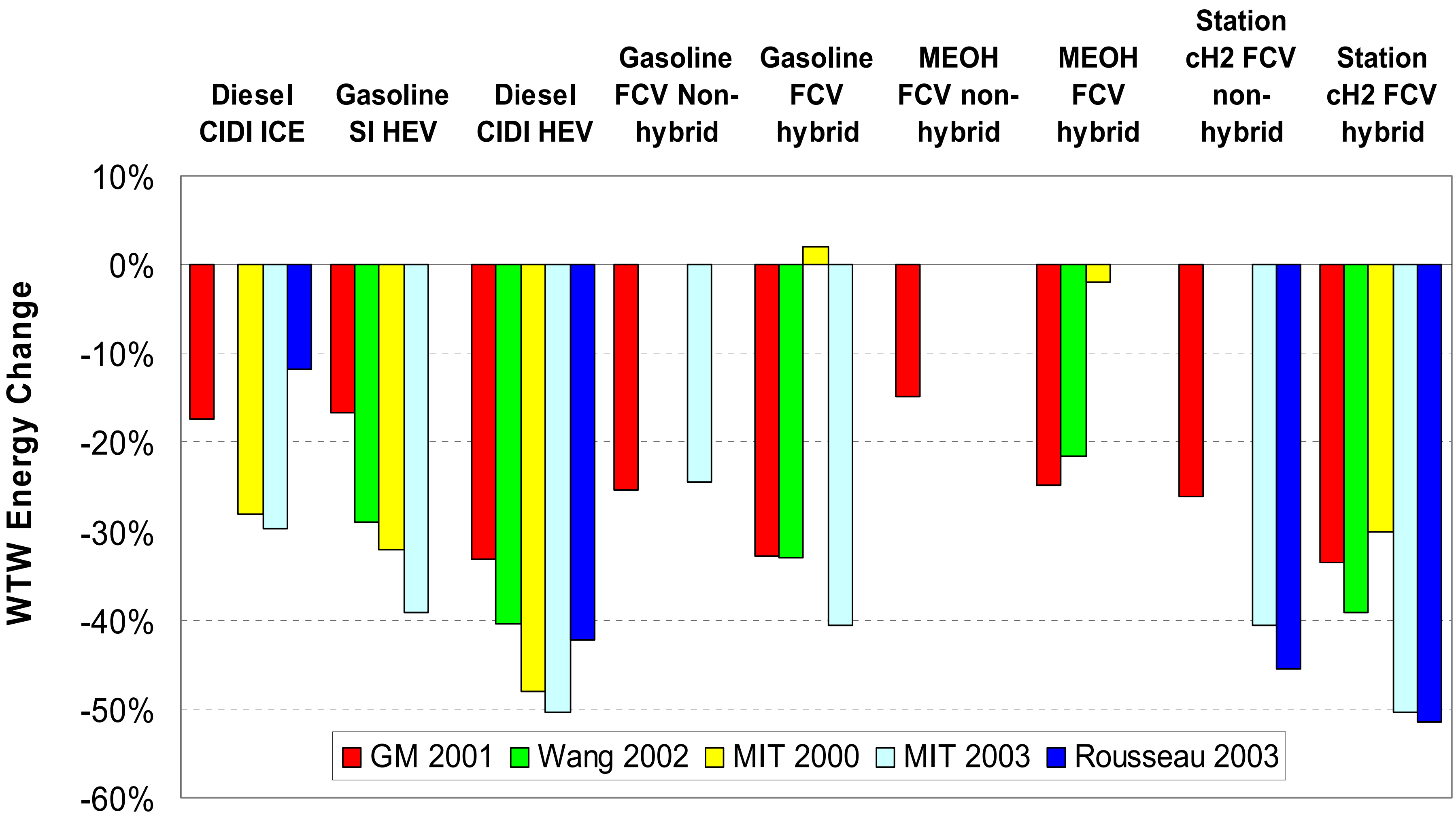
Per-Mile Urban In-Use NOx Emissions of Selected Vehicle/Fuel Systems



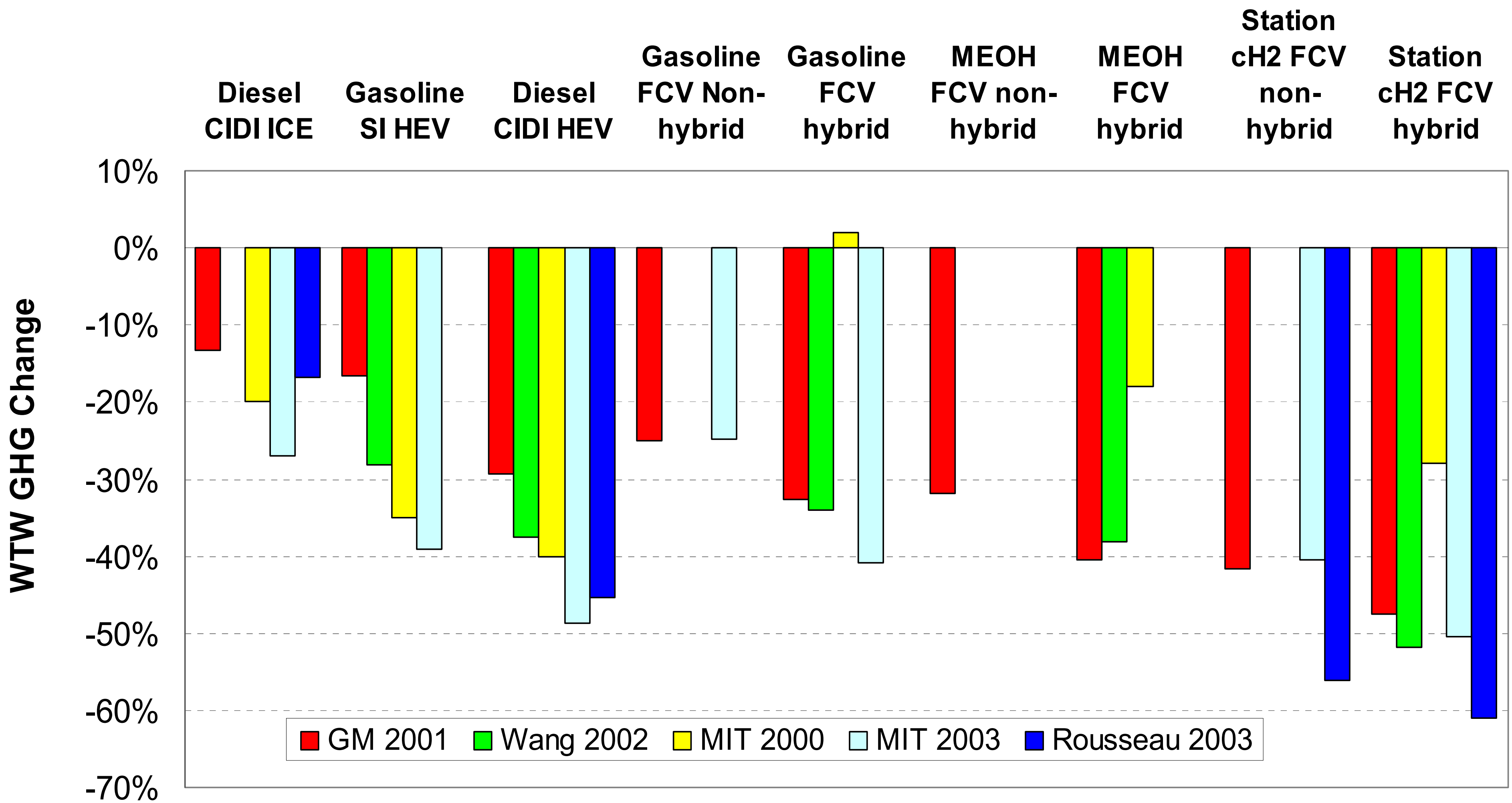
Comparison of Five Publicly Available WTW Studies

- MIT: On the Road in 2020 (2000)
- GM, ANL, BP, ExxonMobil, and Shell (2001)
- Wang of ANL: Journal of Power Sources (2002)
- MIT: Update of the 2000 Study (2003)
- Rousseau of ANL: SAE 2003 Congress paper (2003)
- Studies available but not included in comparison
  - ADL study for DOE (2002)
  - GM European WTW study (2002)
- Studies to be available soon
  - GM, ANL, ChevronTexaco, and Shell (2003)
  - ANL SUV WTW study (2003)

Comparison of Five Recent WTW Studies: Energy Use Changes



Comparison of Five Recent WTW Studies: GHG Emission Changes



Conclusions

- WTW analysis becomes necessary when comparing vehicle technologies powered by different fuels
- Advanced vehicle/fuel technologies could significantly reduce energy use and GHG emissions
- Fuel pathways need to be carefully examined for achieving intended energy and emission benefits by advanced vehicle/fuel systems
- For criteria pollutants
  - As vehicle tailpipe emissions continue to decline, WTP emissions could become a significant share of total WTW emissions
  - To reduce vehicle-induced WTP emissions, fuel producers will need to be actively engaged

Limitations of the Current GREET Version

- So far, PM emissions have been measured and regulated for PM10. PM2.5 and smaller-size PM are more damaging; relative differences between PM10 and PM2.5 could be very different among vehicle technologies
- Black carbon emissions' contribution to GHG emissions could be potentially large
- Secondary formation of PM emissions from NOx and SOx could be important ambient PM emission sources
- Lack of adequate tailpipe N2O emission measurements for vehicles powered by different fuels
- Fuel consumption and GHG emissions of accessory power systems such as AC could be significant sources

Outstanding Issues in WTW Analyses Need to Be Addressed Continuously

- Multiple products
  - System expansion vs. allocation (GREET takes both)
  - System expansion: allocation vs. attribution of effects
- Technology advancement over time
  - Current vs. emerging technologies – leveling comparison field
  - Static snap shot vs. dynamic simulations of evolving technologies and market penetration over time
- Dealing with uncertainties
  - Risk assessment vs. sensitivity analysis
  - Regional differences, e.g, CA vs. the rest of the U.S.
- Trade-offs of impacts
- WTW results are better for identifying problems than for giving the answers

On-Going GREET Efforts

- Adding new fuel pathways
- Integrating GREET into EPA's MOVES model
- Assisting DOE in evaluating its vehicle technology portfolio
- Developing a fully functioning CA version?