ARGONNE NATIONAL LABORATORY

TRANSPORTATION TECHNOLOGY R&D CENTER

Well-to-Wheels Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions -- Hybrid Electric and Fuel-Cell Vehicles --

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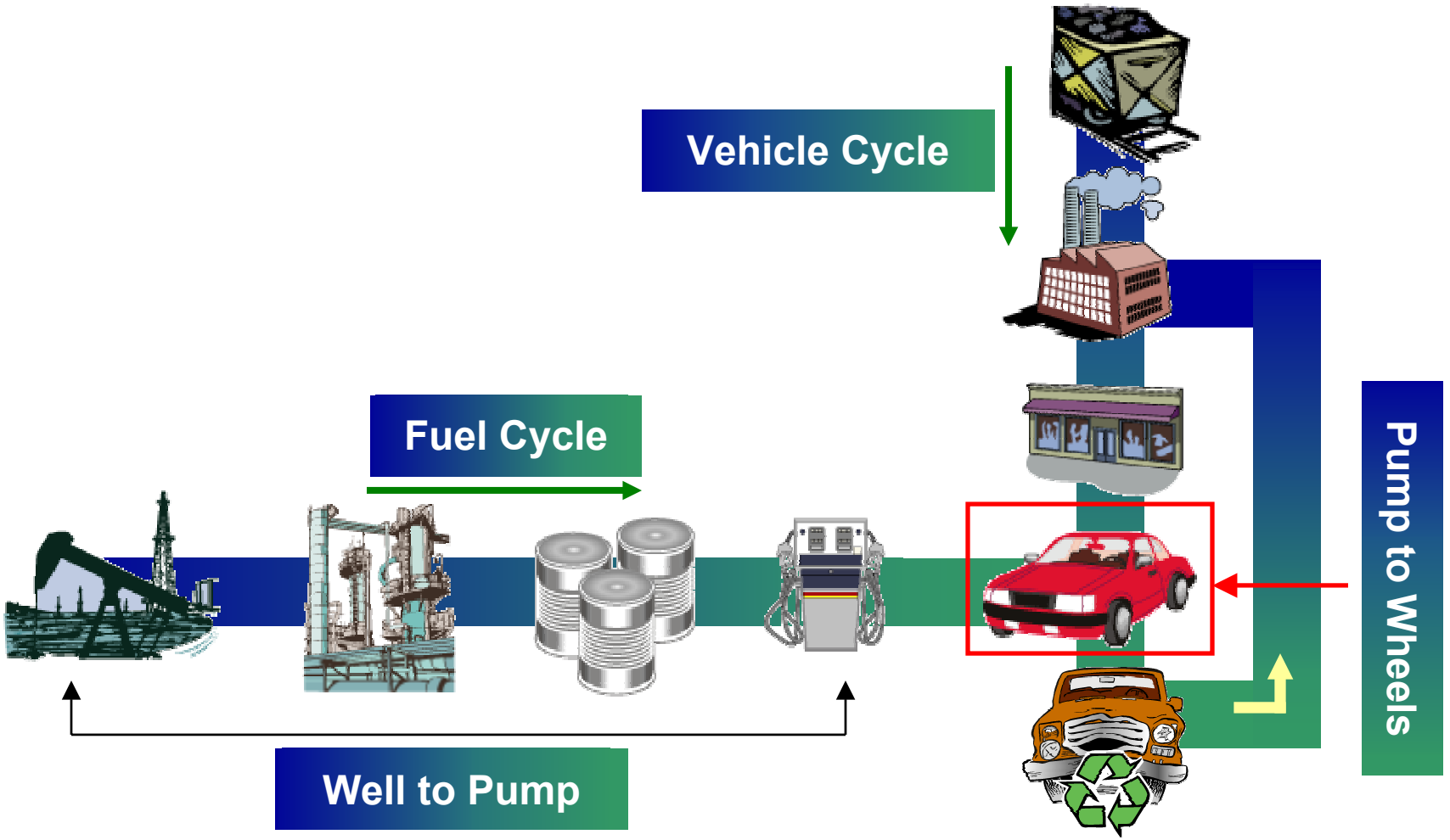
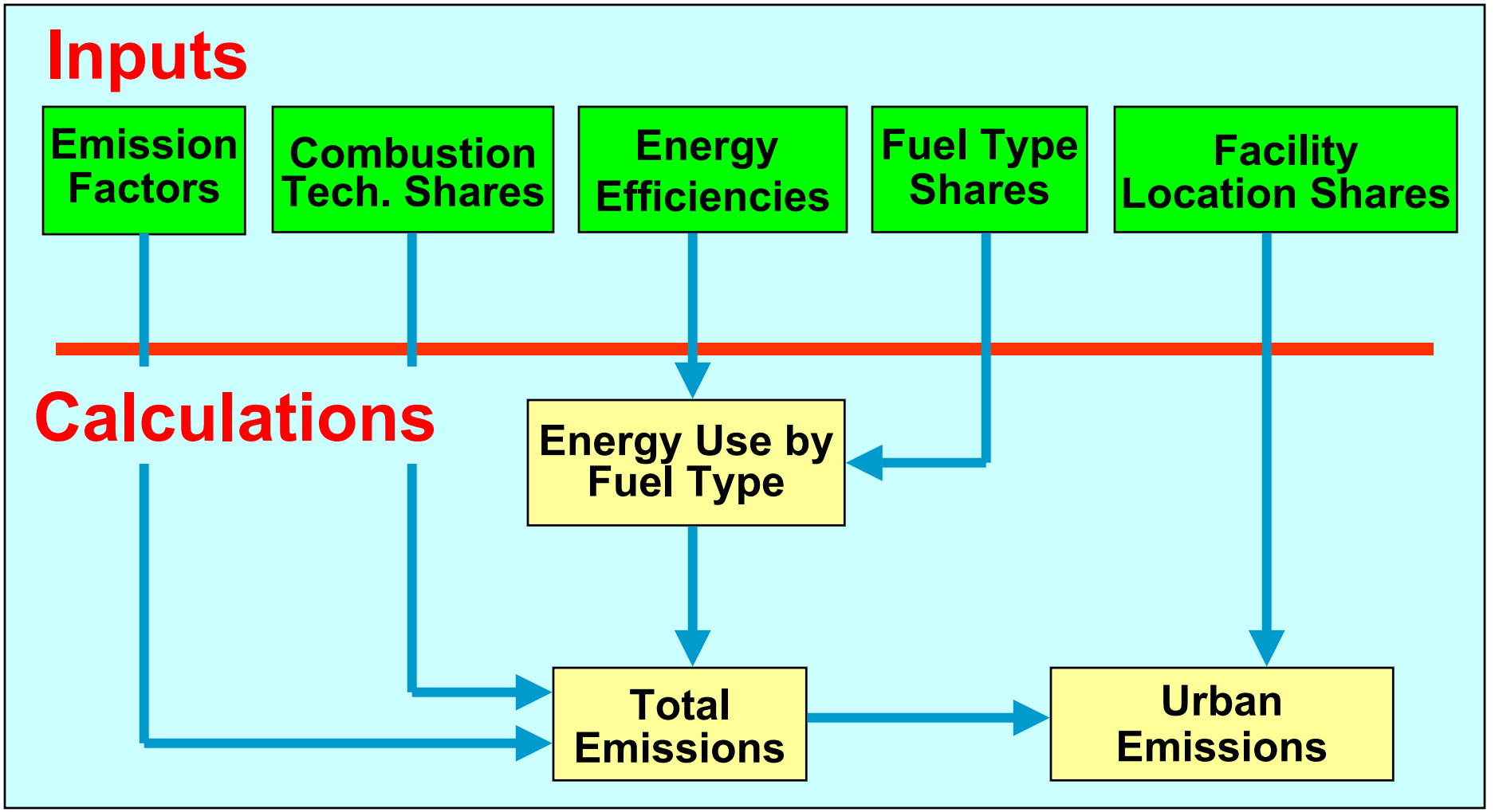
Vehicle and Fuel Cycles: Petroleum-Based Fuels



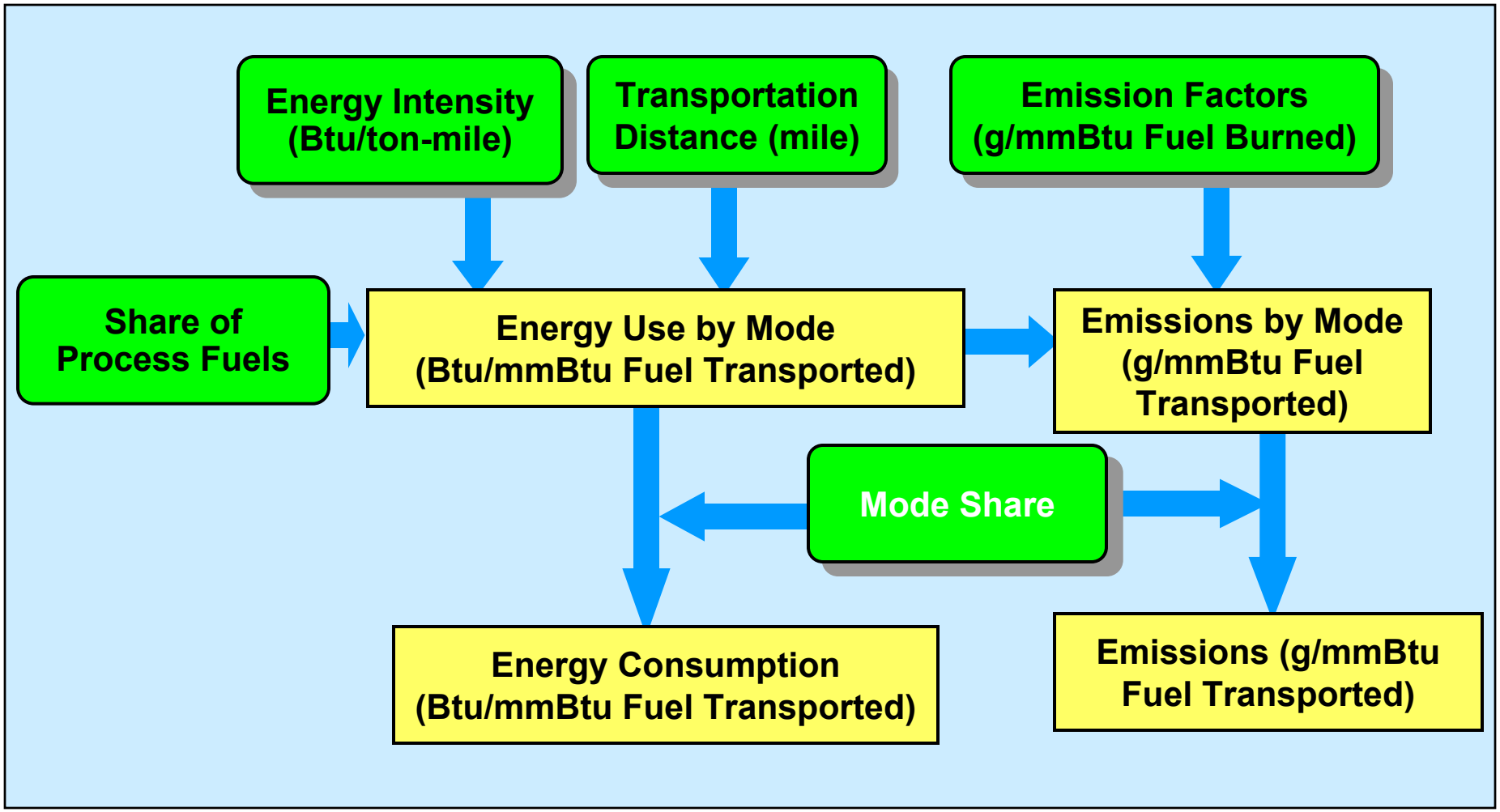
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

- **Includes emissions of greenhouse gases**
  - CO_2, CH_4, and N_2O
  - VOC, CO, and NO_x as optional GHGs
- **Estimates emissions of five criteria pollutants**
  - Total and urban separately
  - VOC, CO, NO_x, SO_x, and PM_{10}
- **Separates energy use into**
  - All energy sources
  - Fossil fuels (petroleum, natural gas, and coal)
  - Petroleum
- **The GREET model and its documents are available at Argonne's GREET website at *http://greet.anl.gov***

Calculation Logic for a Given WTP Production Activity in GREET



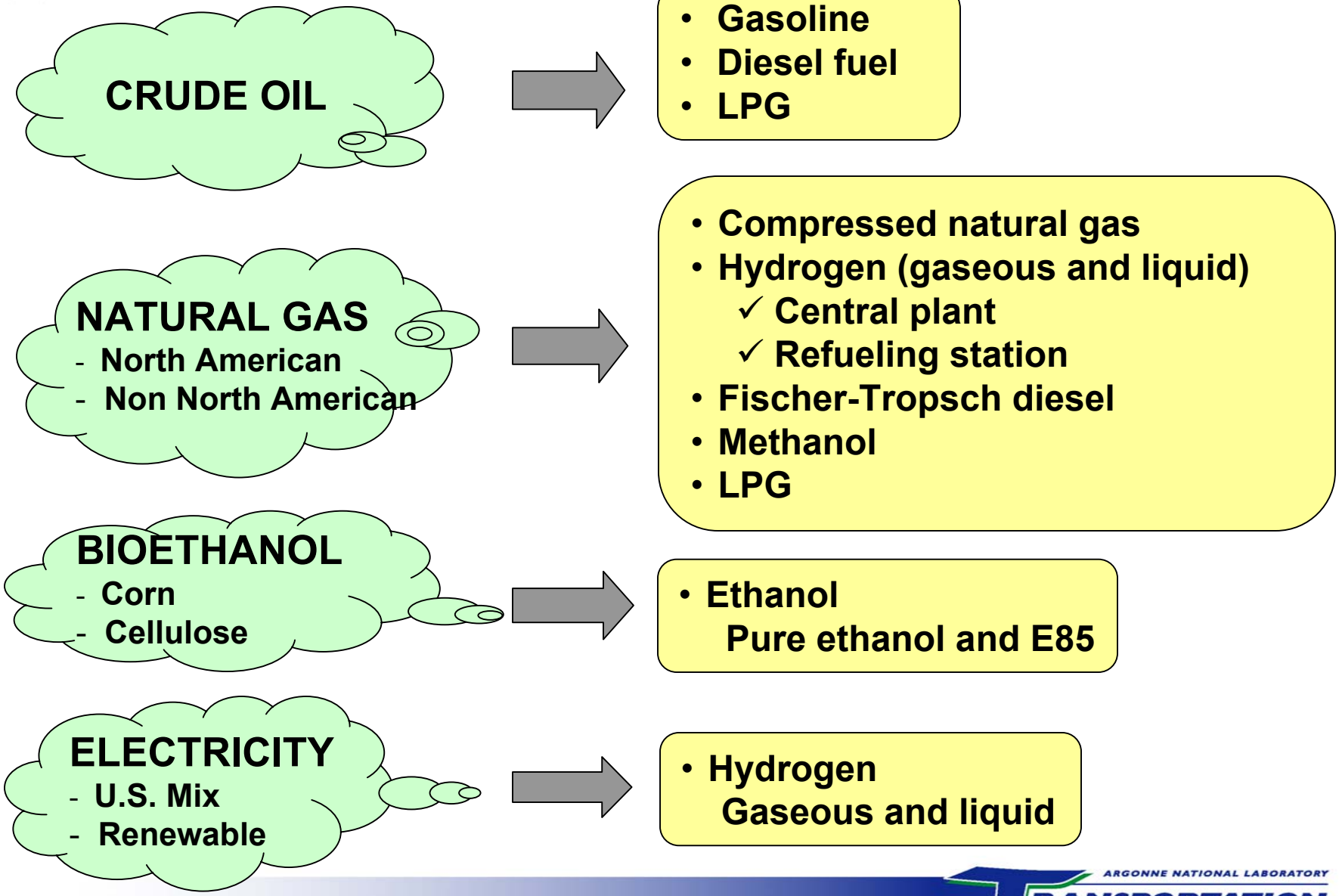
Calculation Logic for a Given WTP Transportation Activity in GREET



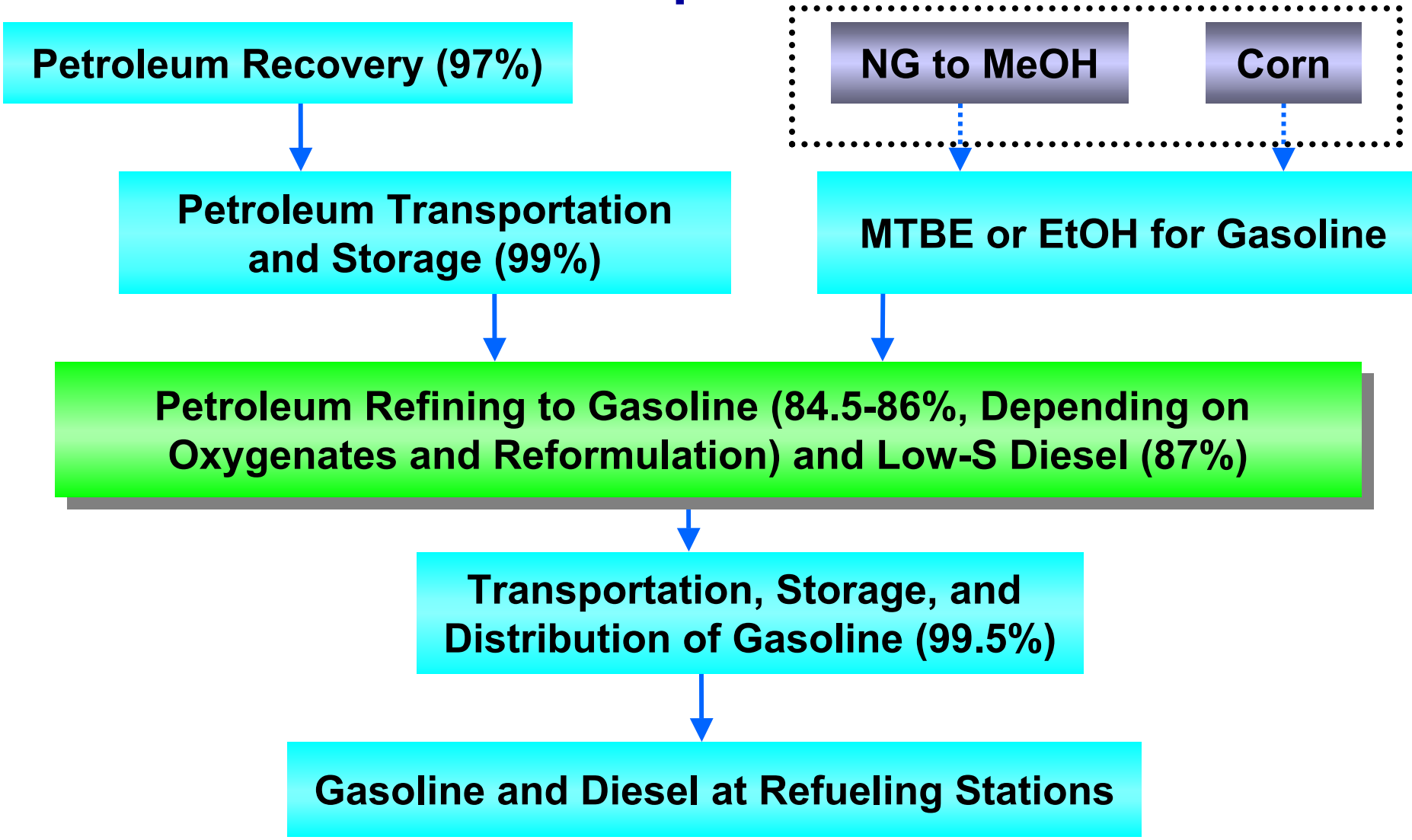
WTP Criteria Pollutant Issues Are Addressed Through an On-Going Project with GM

- Data for relevant facilities were extracted from EPA's 1999 National Emissions Inventory database
- Total emissions for a given facility were divided by its throughput to develop emissions factors
- Distribution curves were developed to fit to the developed emission factors
- The curves were further adjusted to account for improved future technologies and emission controls

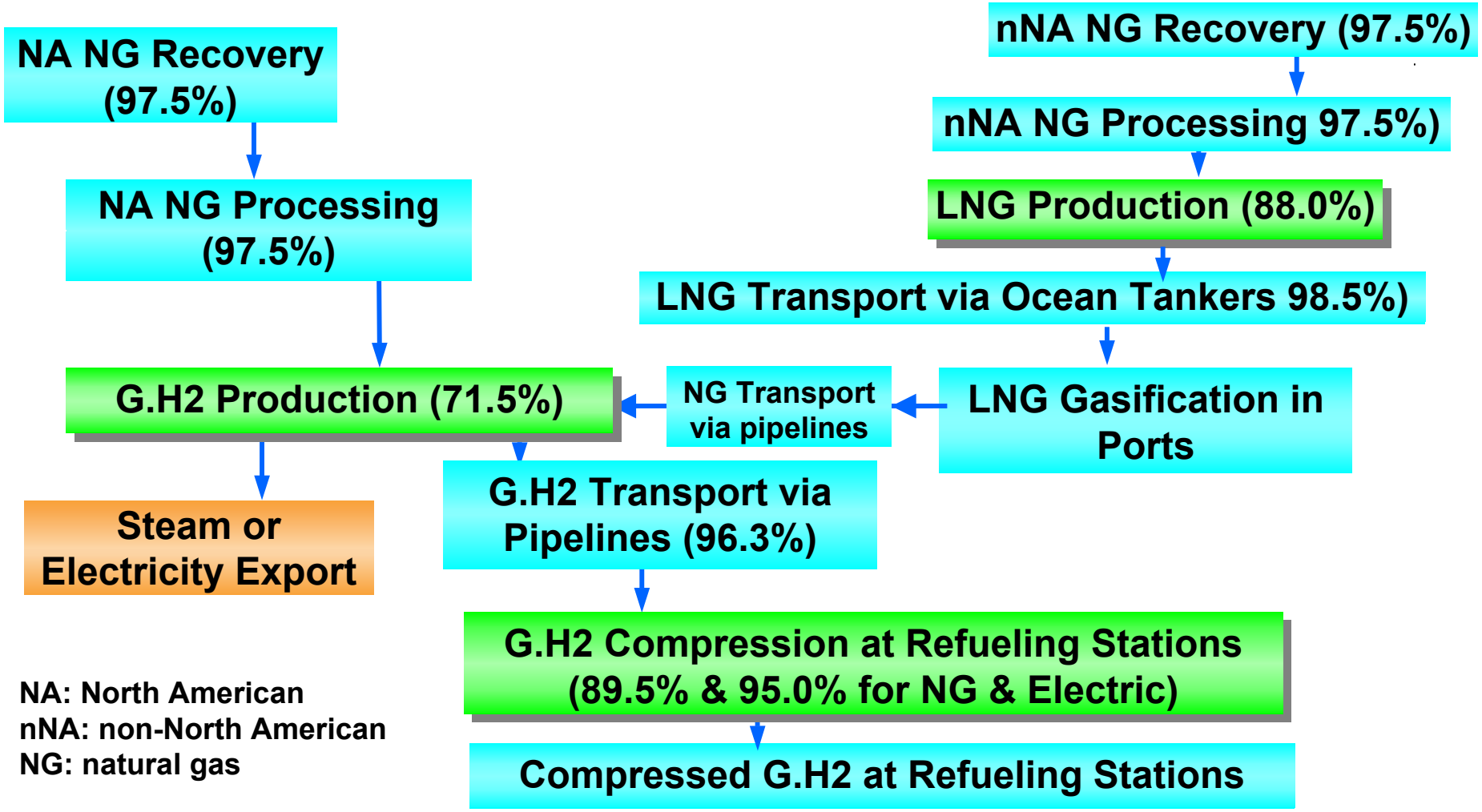
This Study Includes Many Fuel Pathways



Petroleum Refining Is the Key Energy Conversion Step for Gasoline and Diesel

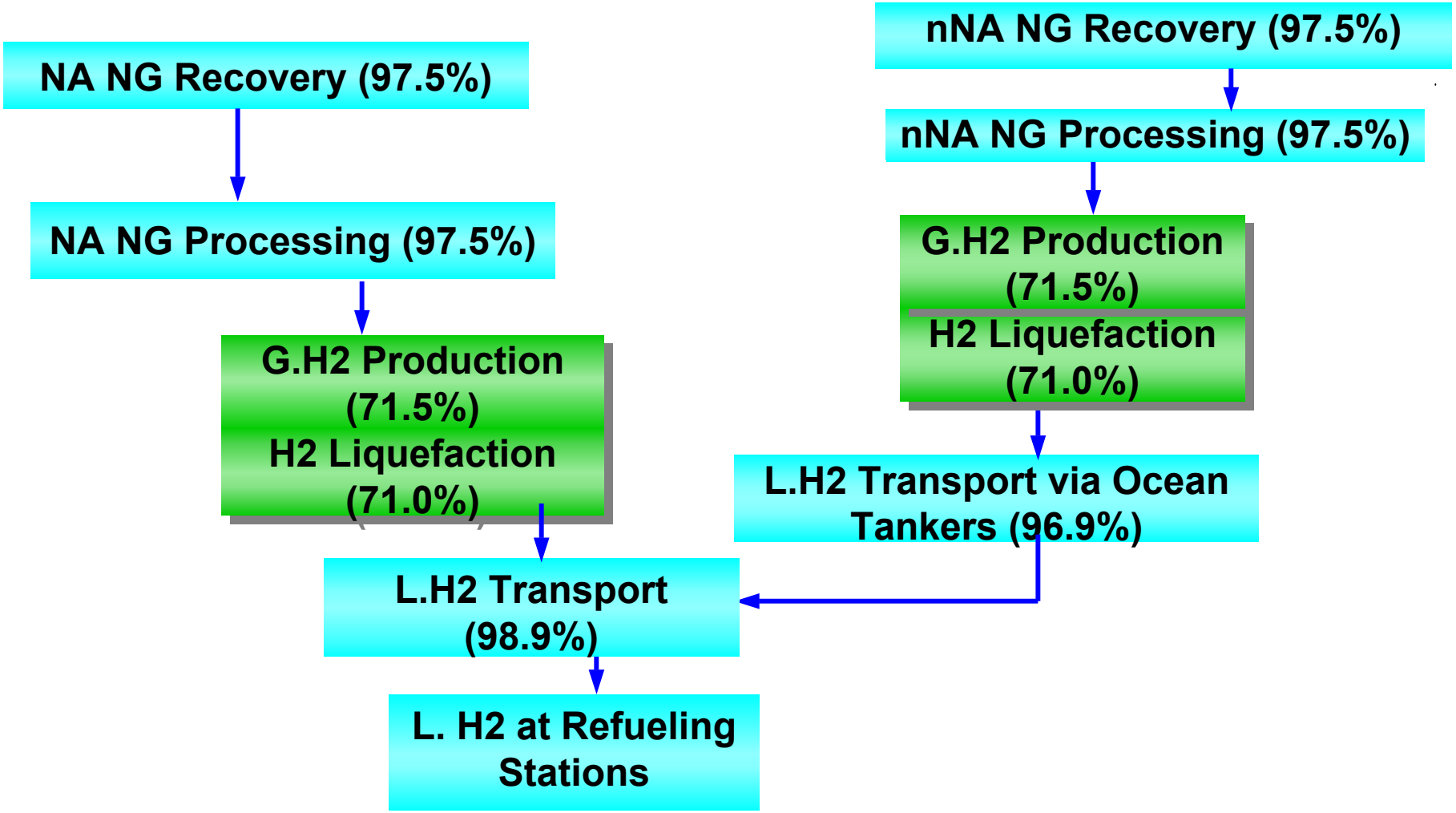


Production and Compression Are Key Steps for G.H_2 Production



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

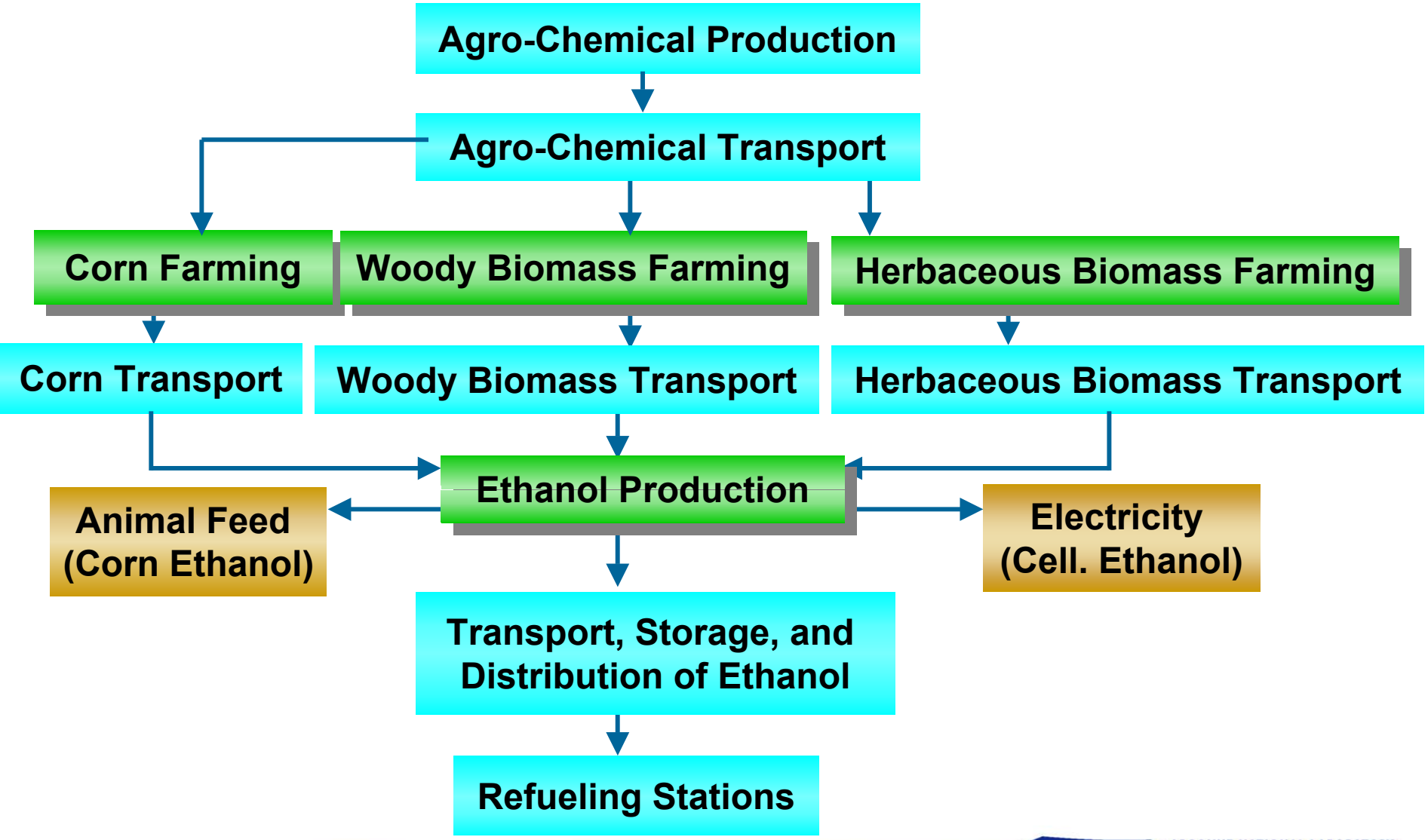
H_2 Liquefaction Has Higher Energy Losses Than H_2 Compression



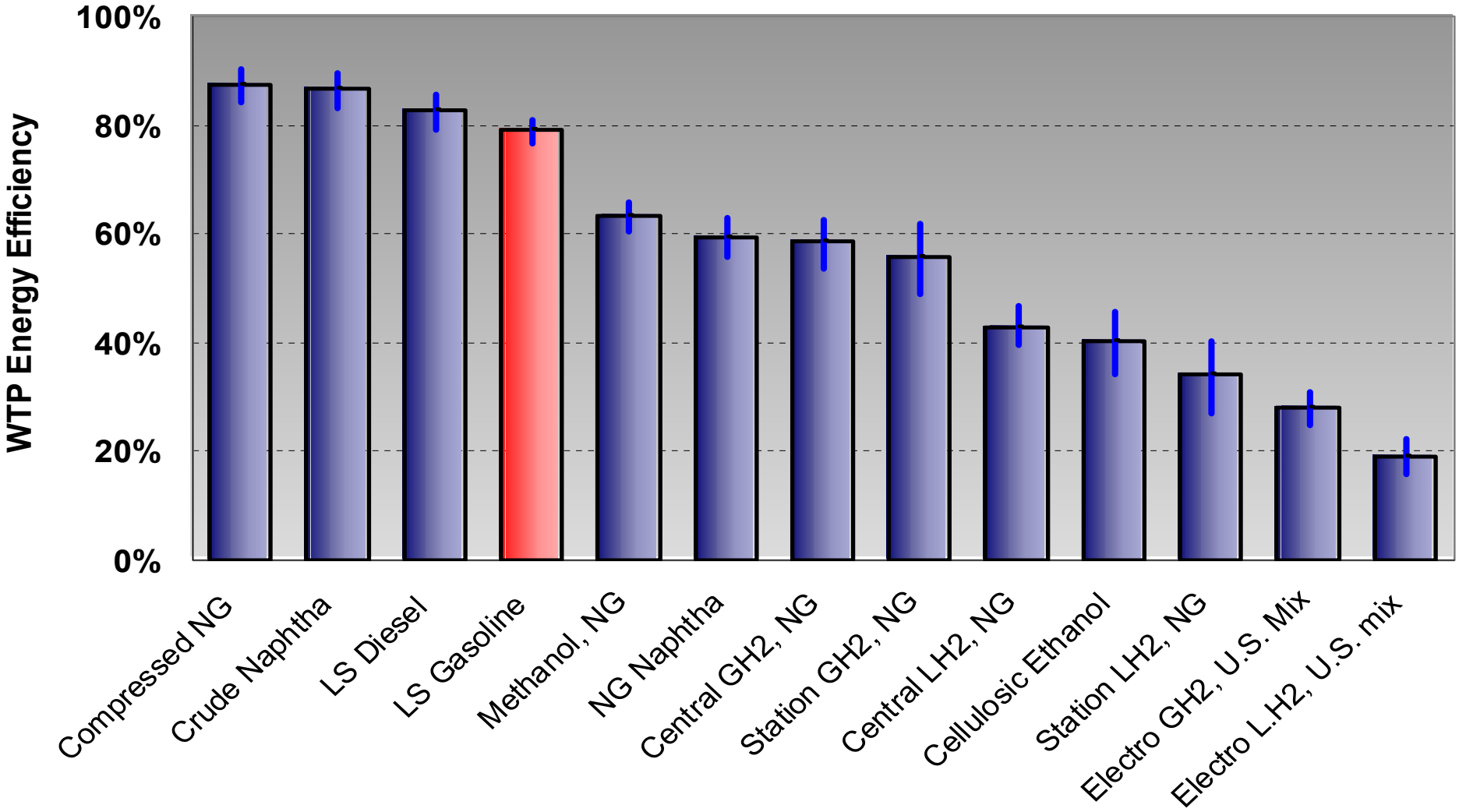
Resource and Infrastructure Options Result in Many Potential H2 Pathways

- H2 is 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 are close to urban areas
- Central SMR CO_2 emissions can be potentially sequestered
- Electrolysis' H2 energy and emissions depend on electricity sources
- Gasification for H_2 production
  - Coal: CO_2 and criteria pollutant emissions; possible CO_2 sequestration
  - Biomass: criteria pollutant emissions
- Nuclear electrolysis or thermal cracking H_2 - virtually no air emissions

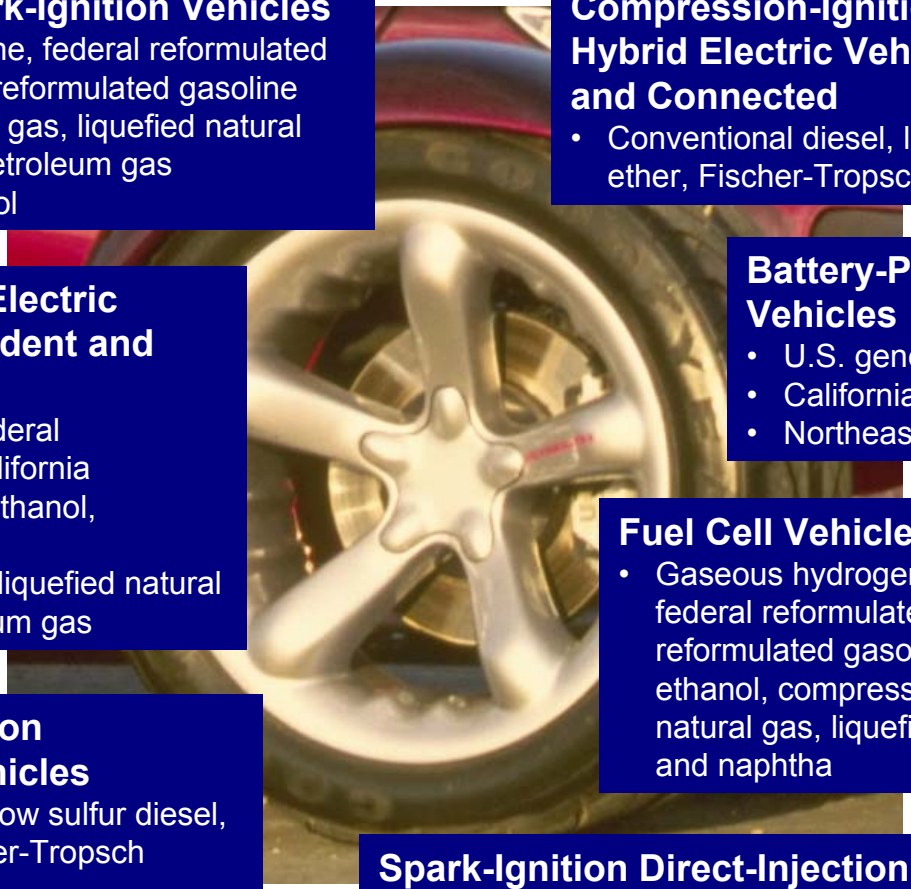
Ethanol WTP Pathways Include Activities from Fertilizer to Ethanol at Stations



WTP Energy Use Significantly Affects Ranking of Total WTW Energy and GHGs



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

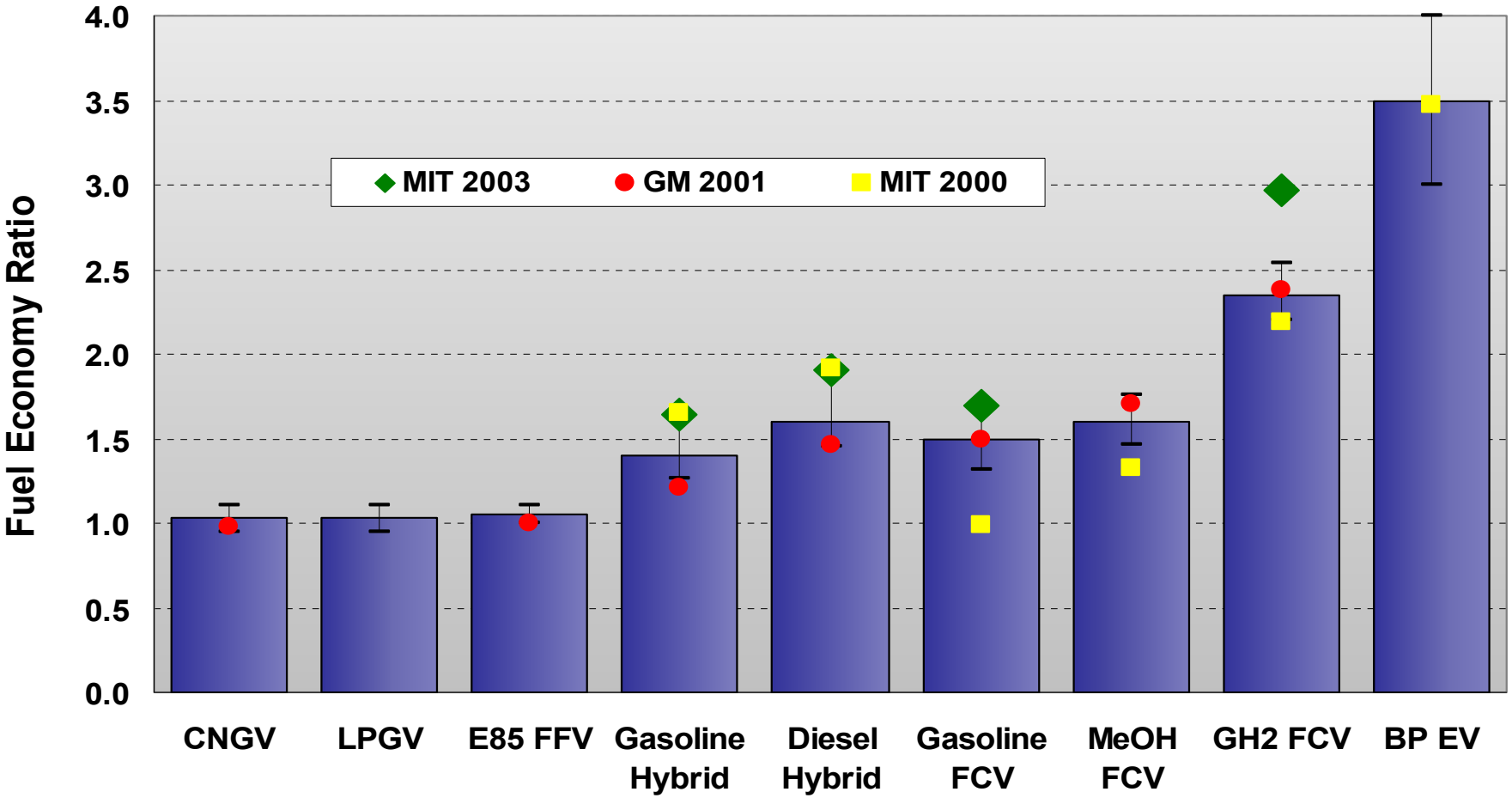
Battery-Powered Electric Vehicles
- U.S. generation mix
- California generation mix
- Northeast U.S. generation mix

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

Vehicle Fuel Economy Is One of the Most Important Factors for WTW Results

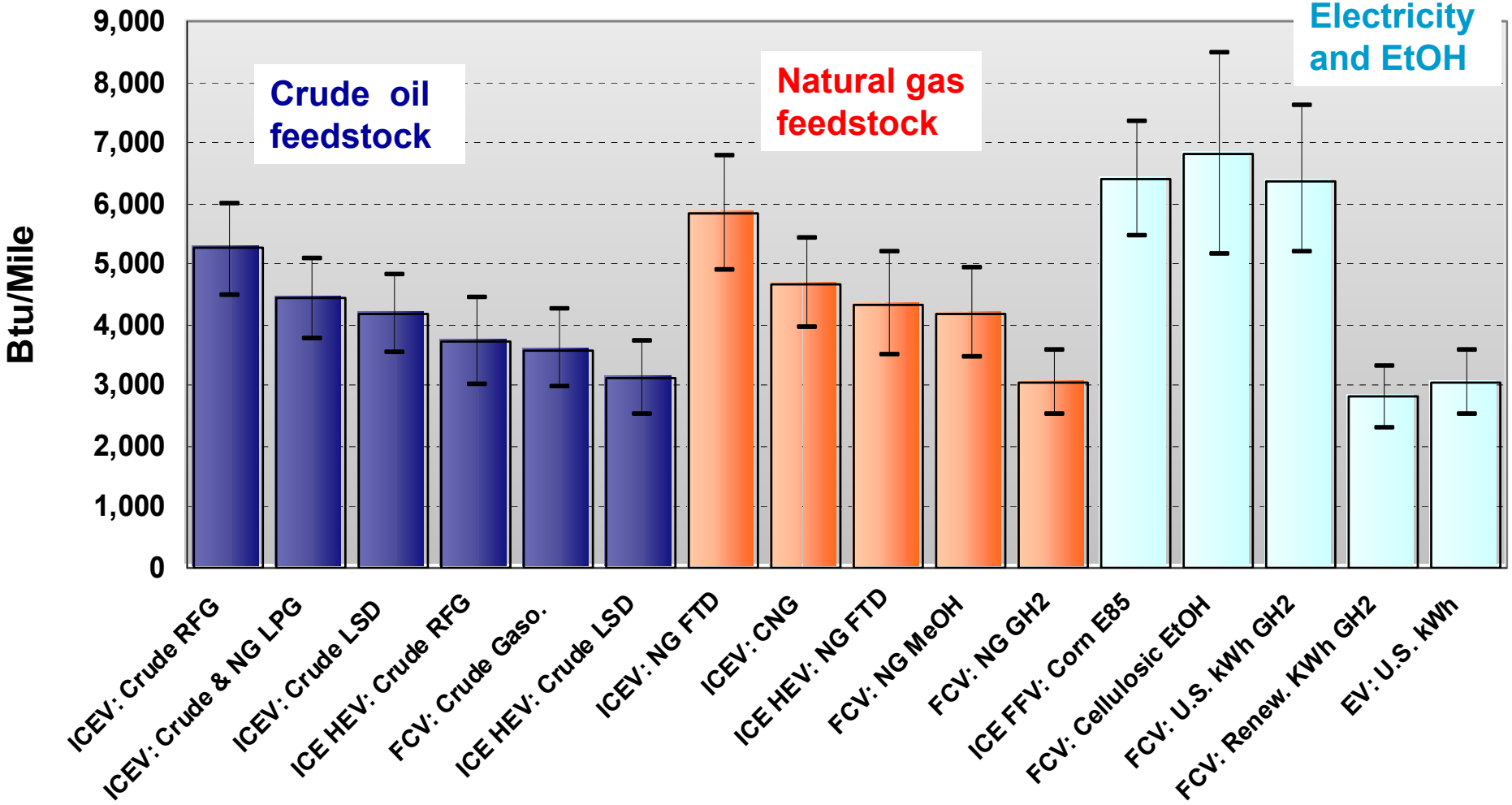


Fuel economy ratios are relative to improved future gasoline ICE technology

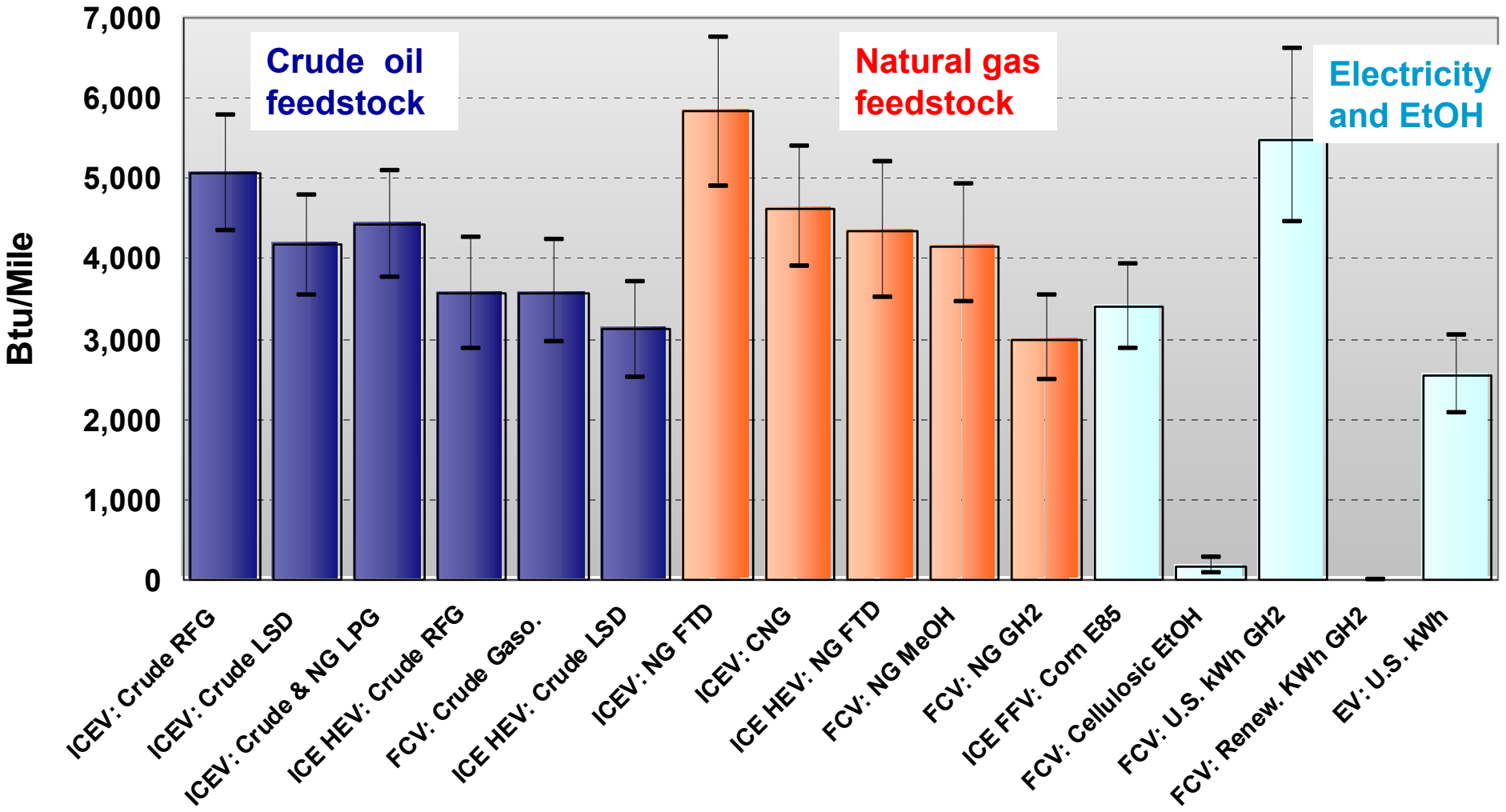
Vehicle/Fuel Technologies for WTW Energy and GHG Emission Results

- Crude oil-based technologies
  - RFG ICE
  - LS Diesel ICE
  - Gasoline FCV
  - LPG ICE
  - RFG ICE hybrid
  - LS diesel ICE hybrid
- Natural gas-based technologies
  - FT diesel ICE
  - FT diesel ICE hybrid
  - G.H2 FCV
  - CNG ICE
  - MeOH FCV
- Bioethanol and Electricity
  - Corn E85 ICE FFV
  - U.S. average electri.-to-G.H2 FCV
  - U.S. average electricity battery-powered EV
  - Cellulosic EtOH FCV
  - Renewable electricity-to-G.H2 FCV

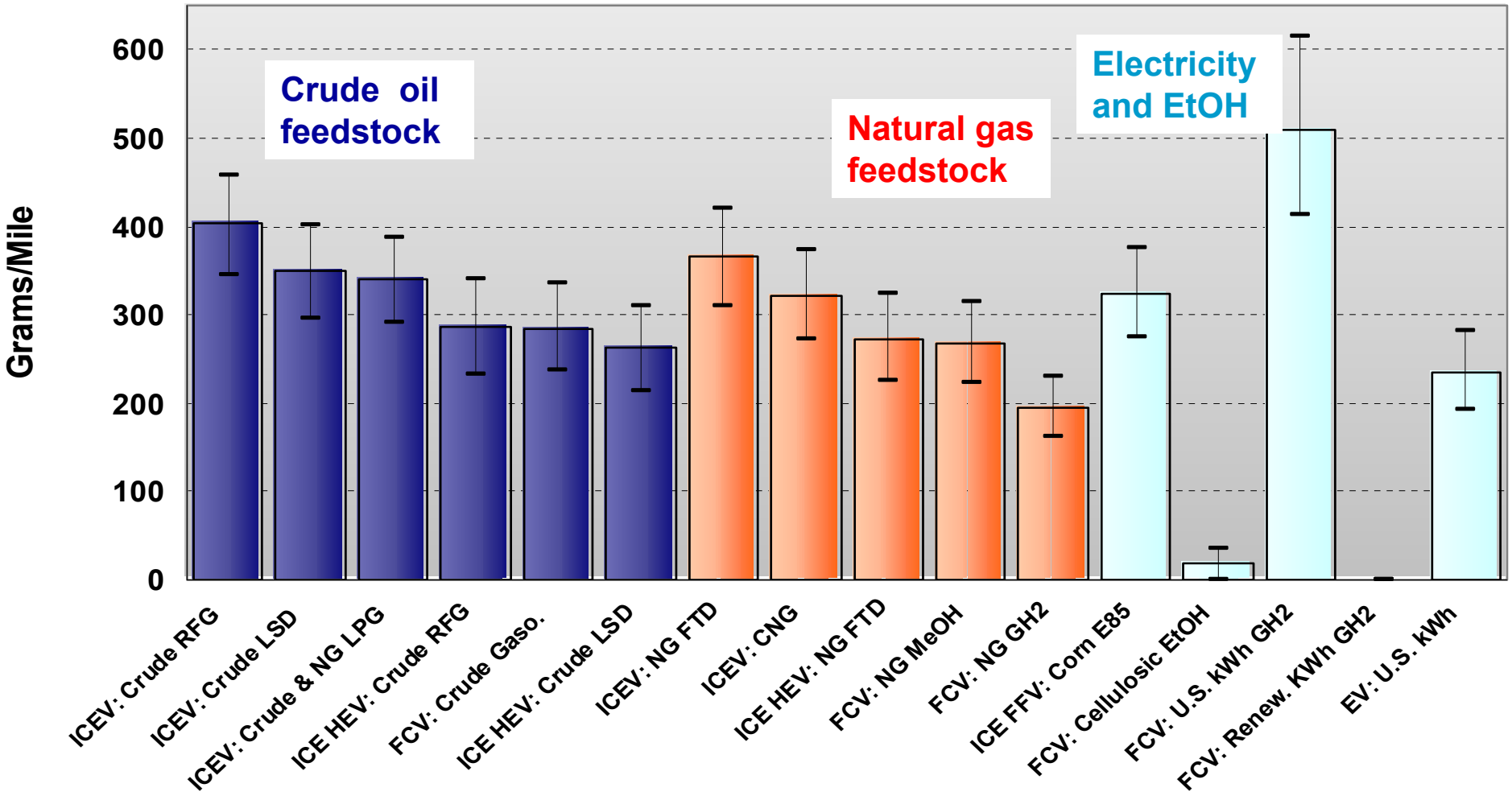
WTW Total Energy Use of Selected Vehicle/Fuel Systems



WTW Fossil Energy Use of Selected Vehicle/Fuel Systems



WTW GHG Emissions of Selected Vehicle/Fuel Systems



ANL/GM Study Takes the Following Key Assumptions for PTW Emissions

2010 MY Vehicle Emissions Targets

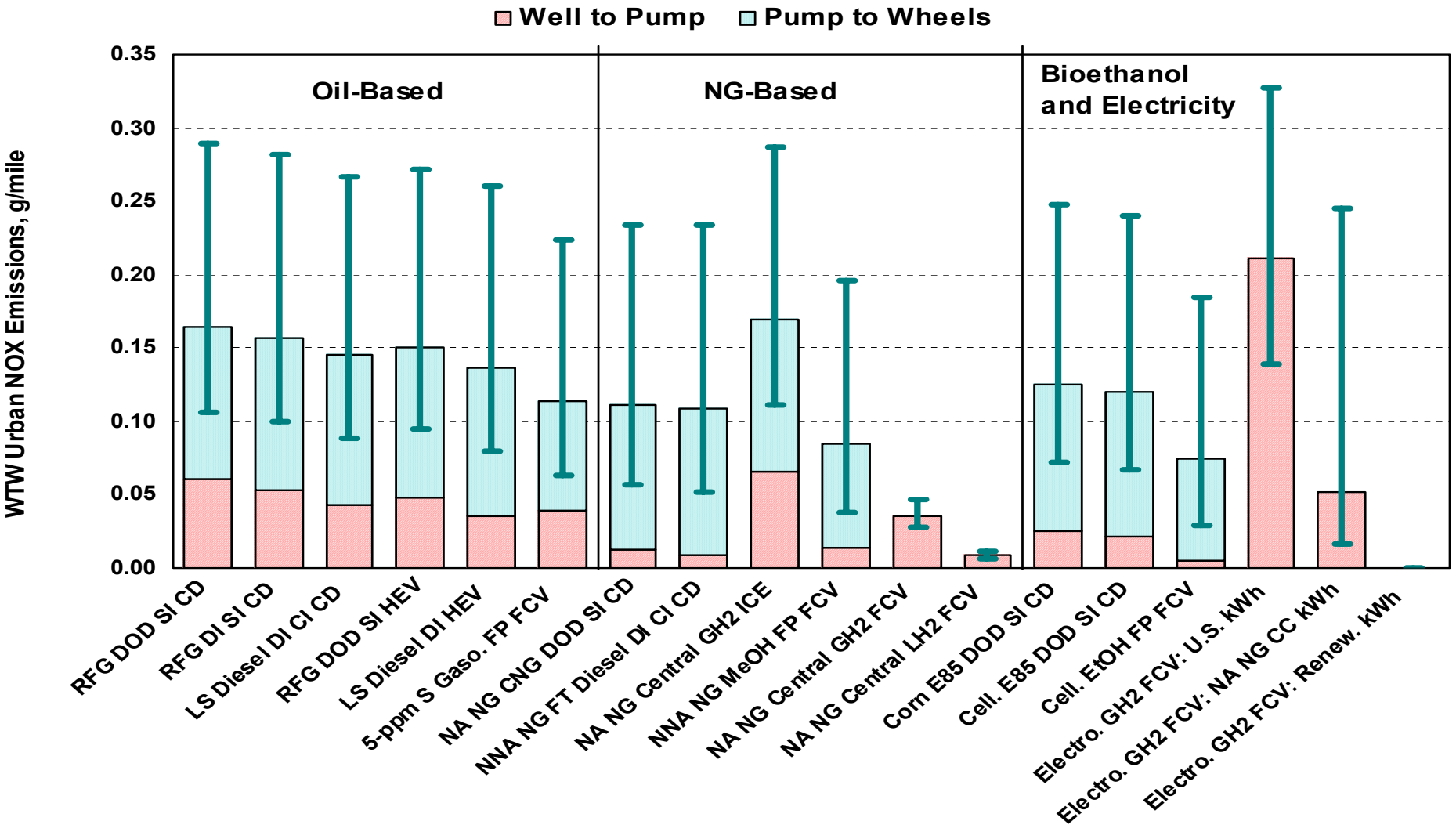
Propulsion System	Assumed Emission Performance
Gasoline ICE	Tier 2 Bin 5
Diesel and CNG ICE	Tier 2 Bin 5, but no evap VOC
Hydrogen ICE	Tier 2 Bin 2, no evap, Bin 5 NOx
Fuel processor fuel cell	Tier 2 Bin 2
Hydrogen fuel cell	Tier 2 Bin 1 (zero emissions)

- **Fuel consumption penalties of aftertreatment systems to meet standards were considered in the study**
- **Bin 5 diesel has not been demonstrated**
- **MY 2010 vehicle in-use emissions in 2016 were modeled using**
  - **EPA MOBILE 6.2**
  - **ARB EMFAC2002 version 3**

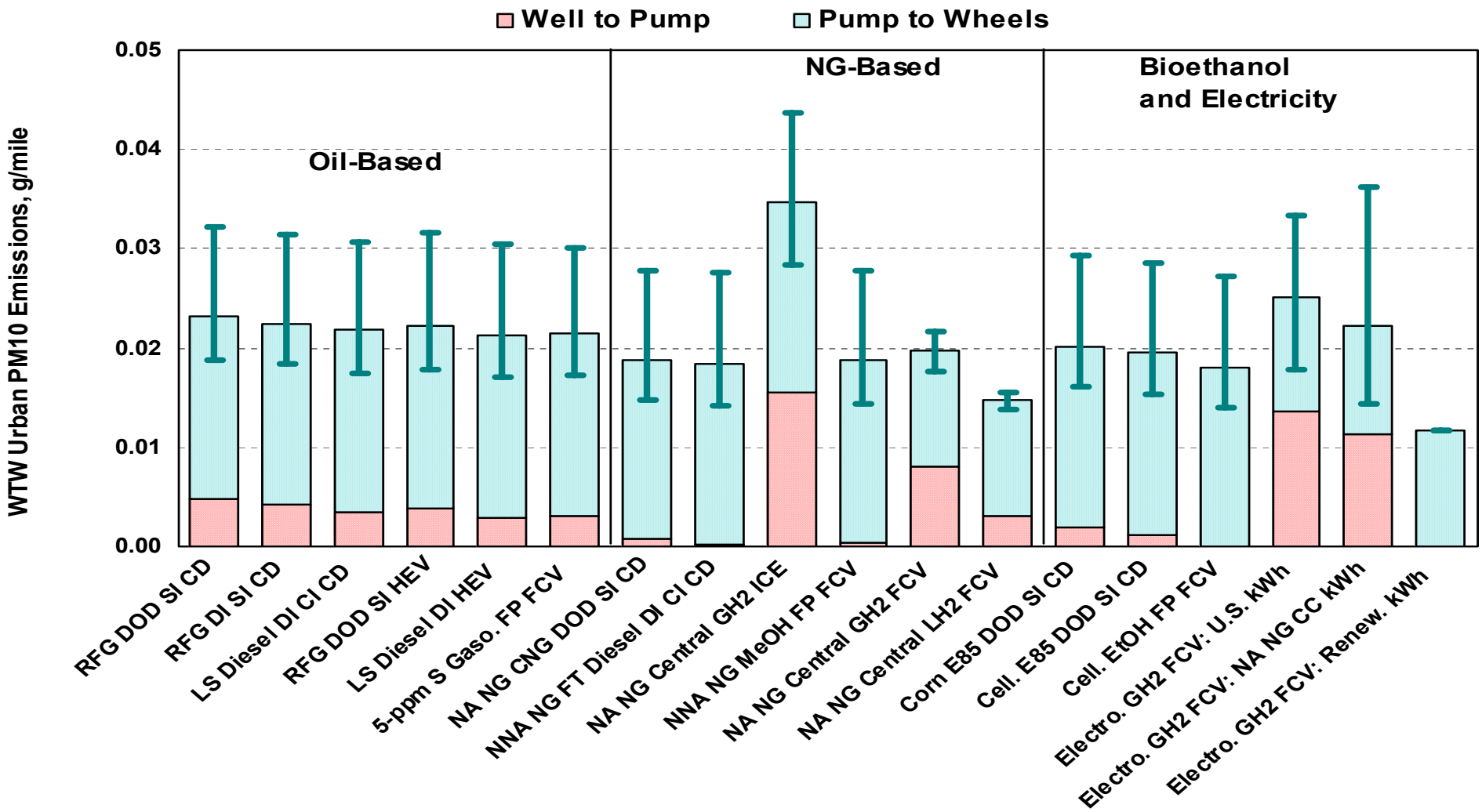
Vehicle/Fuel Technologies for WTW Criteria Pollutant Emission Results

- Crude oil-based technologies
  - RFG displacement on demand (DOD) SI conventional drive (CD)
  - RFG DI SI CD
  - RFG DOD SI hybrid
  - Gasoline fuel-processor (FP) FCV
  - LS Diesel DI CI CD
  - LS diesel DI CI hybrid
- Natural gas-based technologies
  - CNG DOD SI CD
  - G.H2 SI CD
  - G.H2 FCV
  - FT diesel DI CI CD
  - MeOH FP FCV
  - L.H2 FCV
- Bioethanol and Electricity
  - Corn E85 DOD SI CD
  - Cellulosic EtOH FP FCV
  - NG CC electri.-to-G.H2 FCV
  - Cellulosic E85 DOD SI CD
  - U.S. average electri.-to-G.H2 FCV
  - Renewable electricity-to-G.H2 FCV

WTW Urban NOx Emissions of Selected Vehicle/Fuel Systems



WTW Urban PM_{10} Emissions of Selected Vehicle/Fuel Systems



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
- For criteria pollutants, as tailpipe emissions continue to decline, WTP emissions could become a significant share of total WTW emissions
- Fuel pathways need to be carefully examined for achieving intended energy and emission benefits by advanced vehicle/fuel systems