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Overview of GREET Model Development at Argonne

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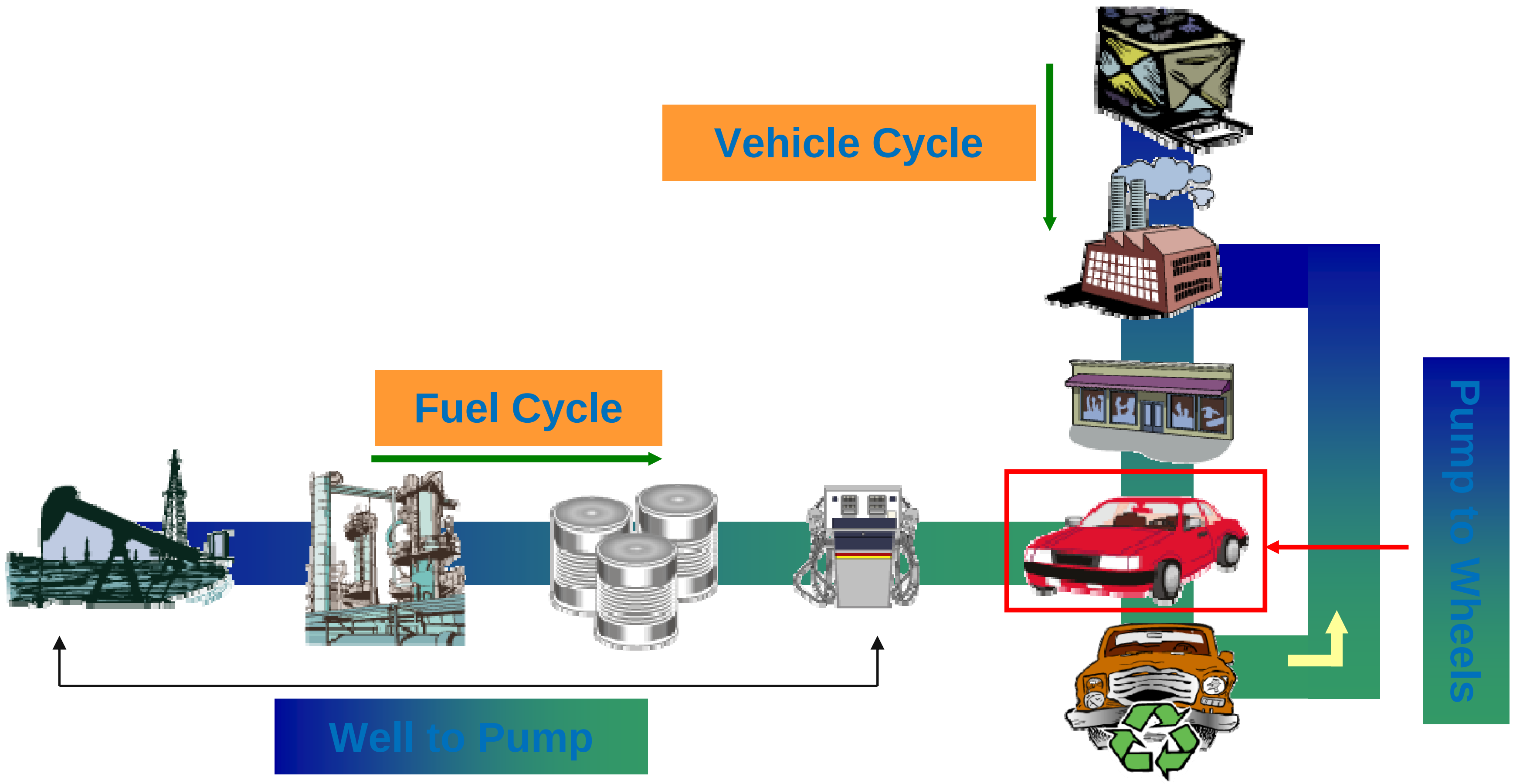
Life-Cycle Analysis for Vehicle/Fuel Systems Has Been Evolved in the Past 20 Years

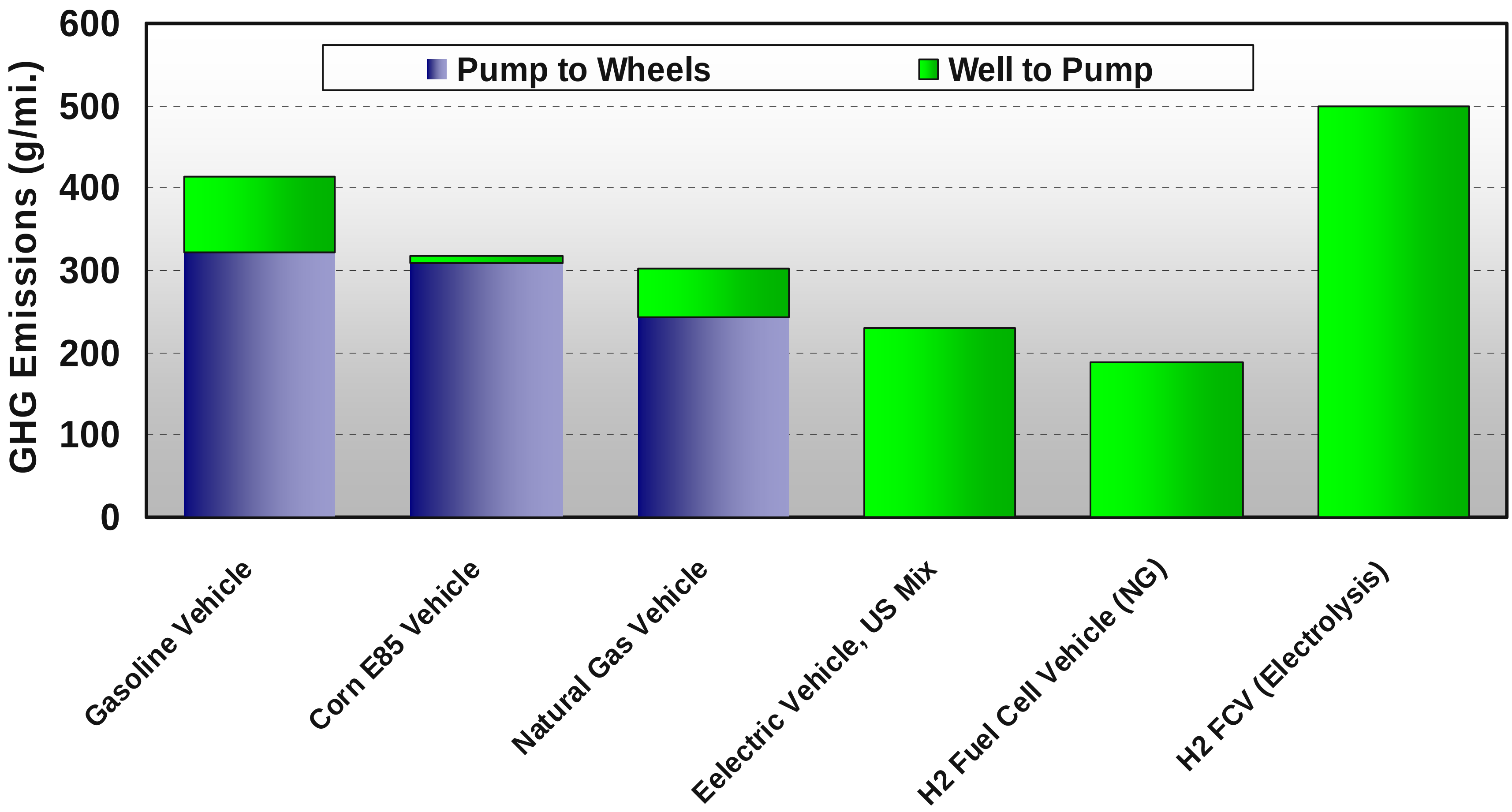
- Historically, evaluation of vehicle/fuel systems from wells to wheels (WTW) was called fuel-cycle analysis
- Pioneer transportation WTW analyses began in 1980s
  - Early studies were motivated primarily by battery-powered EVs
  - Recent studies are motivated primarily by introduction of new fuels such as hydrogen and biofuels
  - Pursuing reductions in transportation GHG emissions will demand for WTW analyses
- For transportation technologies, especially internal combustion engine technologies, the significant energy and emissions effects occur in
  - The fuel usage stage
  - The fuel production stage

Well-to-Wheels Analysis of Vehicle/Fuel Systems Covers Activities for Fuel Production and Vehicle Use



WTW Analysis Is a Complete Energy/Emissions Comparison

As an example, greenhouse gases are illustrated here



LCA Models have Been Developed to Examine Transportation Fuels and Vehicle Technologies

- The GREET model at Argonne National Laboratory
- The lifecycle emission model (LEM) by Dr. Mark Delucchi of University of California at Davis
- Canadian GHGenius model (a derivative of the LEM)
- LBST's E3 model in Europe
- The Ecobalance model by PriceWaterhouseCooper in Europe
- Other models?

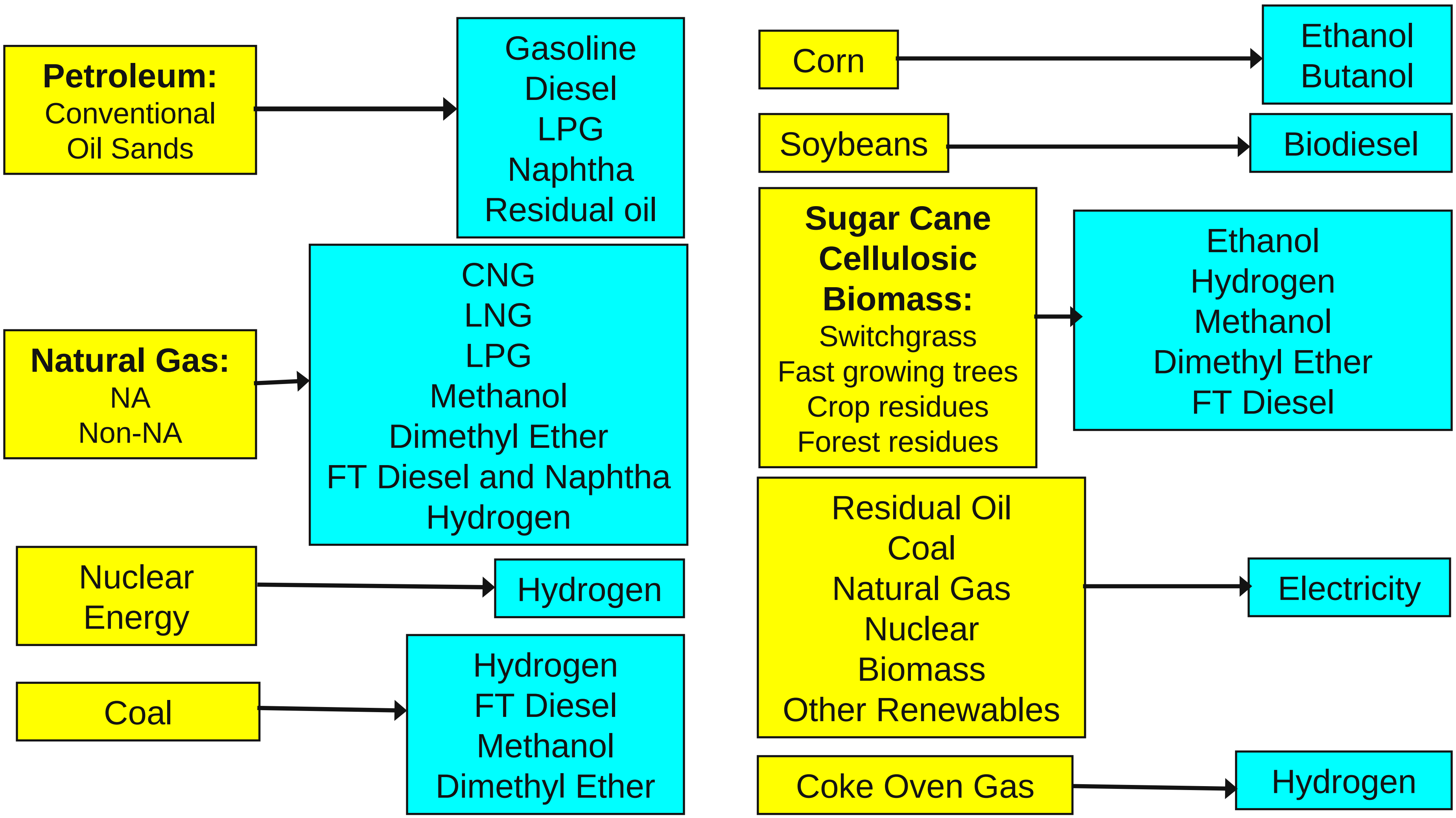
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model

- **Includes emissions of greenhouse gases**
  - CO_2, CH_4, and N_2O
- **Estimates emissions of six criteria pollutants**
  - Total and urban separately
  - VOC, CO, NO_x, SO_x, PM_{10}, and $PM_{2.5}$
- **Separates energy use into**
  - All energy sources (fossil and non-fossil)
  - Fossil fuels (petroleum, natural gas, and coal combined)
  - Petroleum
  - Coal
  - Natural gas
- **The GREET model and its documents are available at Argonne's website at *http://www.transportation.anl.gov/software/GREET/***
- **The most recent GREET versions (GREET 1.7 and GREET 2.7 versions) was released in June 2007**

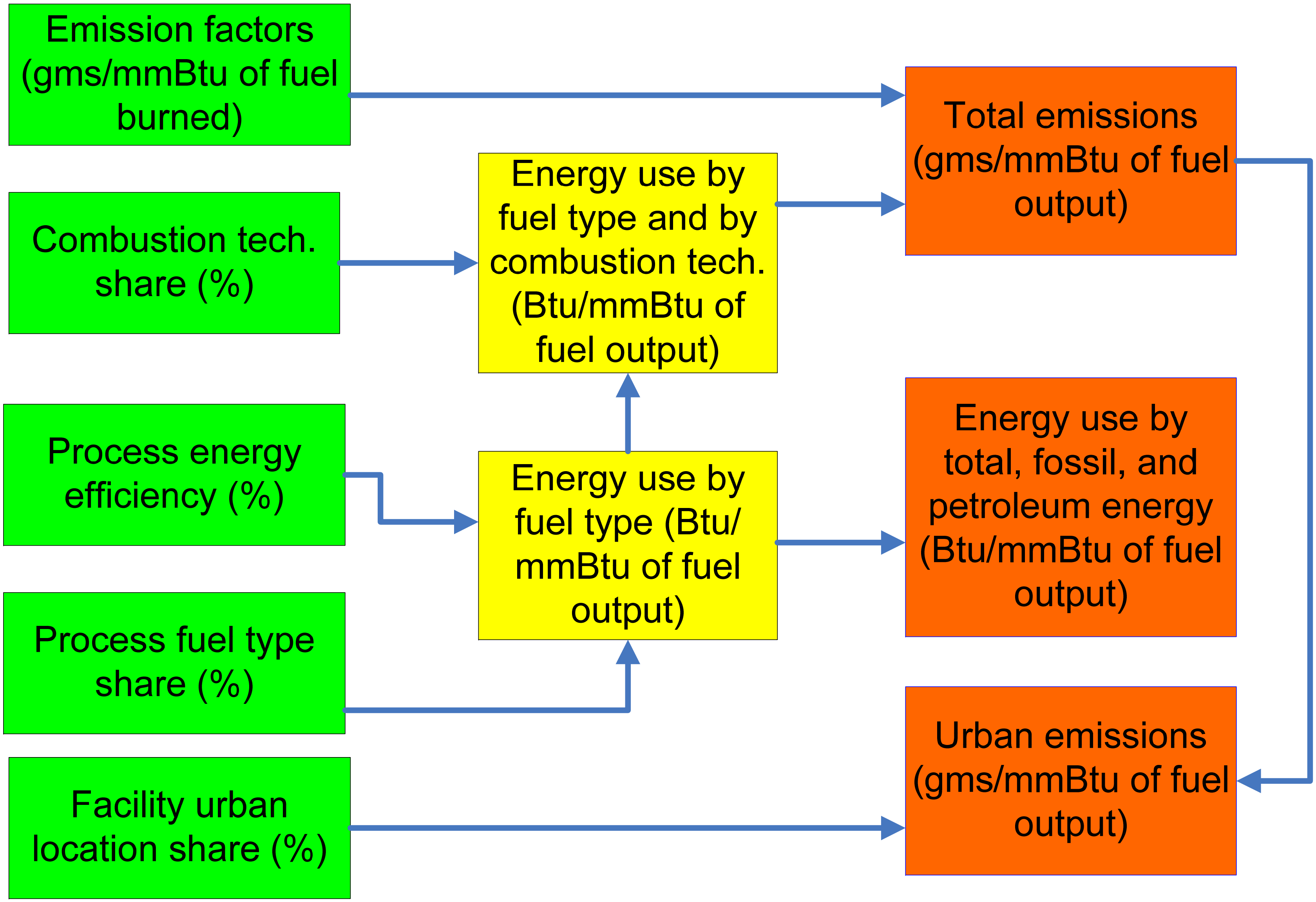
Besides DOE, Other Organizations Have Supported GREET Development and Applications at Argonne

- DOE: began to support GREET development and applications at Argonne in 1995
- General Motors Corporation (2000-05): produced two reports that are standard citation by auto and oil industry
- Illinois Department of Commerce and Economic Opportunities (1997-98, 2002-03): closely worked with the ethanol industry and governmental agencies to examine ethanol's energy and environmental benefits; Argonne's results have changed the debate on ethanol
- U.S. Environmental Protection Agency (2003-04, 06): incorporated GREET into EPA's MOVES model and assisting EPA in its rulemaking of renewable fuel standards
- In-kind support
  - BP (2000-01)
  - Chevron (2002-04)
  - ExxonMobil (2000-01)
  - Shell (2000-04)
  - U.S. Department of Agriculture (since 1997)

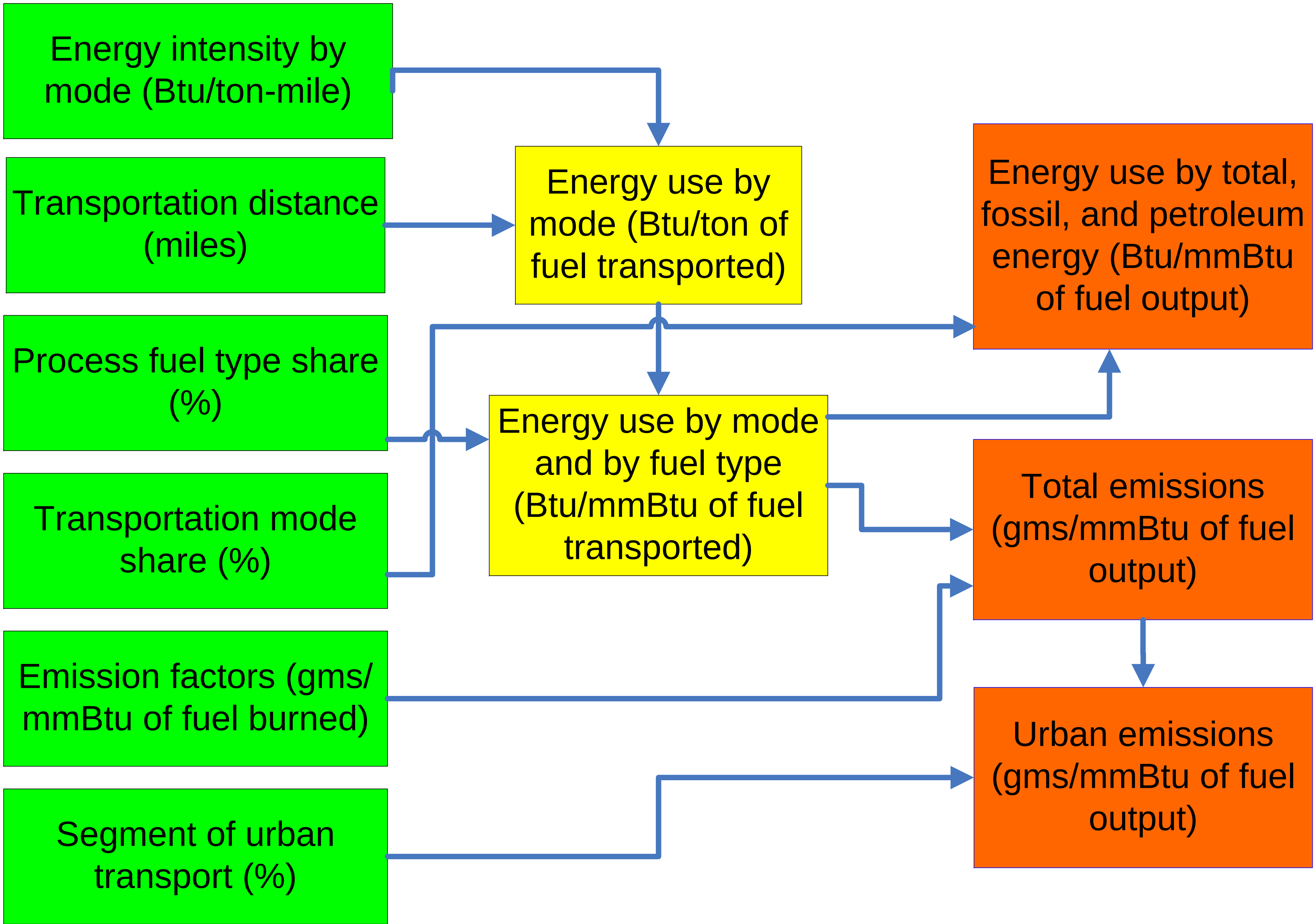
GREET Includes More Than 100 Fuel Production Pathways from Various Energy Feedstocks



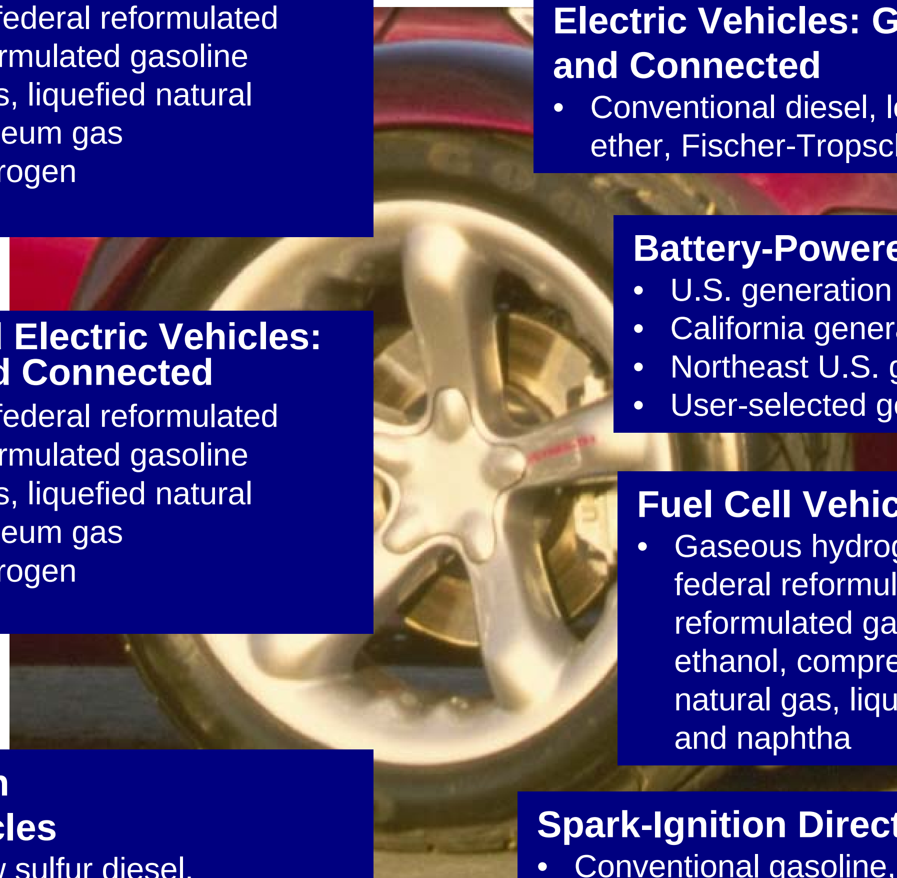
Calculation Logic for a Given WTP Production Activity in GREET



Calculation Logic for a Given WTP Transportation Activity in GREET



GREET Includes More Than 75 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
- Gaseous and liquid hydrogen
- Methanol and ethanol

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

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

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

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

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

WTW Results Are Affected by These Key Assumptions

- WTP assumptions
  - Energy efficiencies of fuel production activities
  - GHG emissions of fuel production activities
  - Emission factors of fuel combustion technologies
- PTW assumptions
  - Fuel economy of vehicle technologies
  - Tailpipe emissions of vehicle technologies
- Large uncertainties exist in key assumptions
  - GREET is designed to conduct stochastic simulations
  - Distribution functions are developed for key assumptions in GREET

GREET Relies on a Variety of Data Sources

Well-to-Pump Data Sources

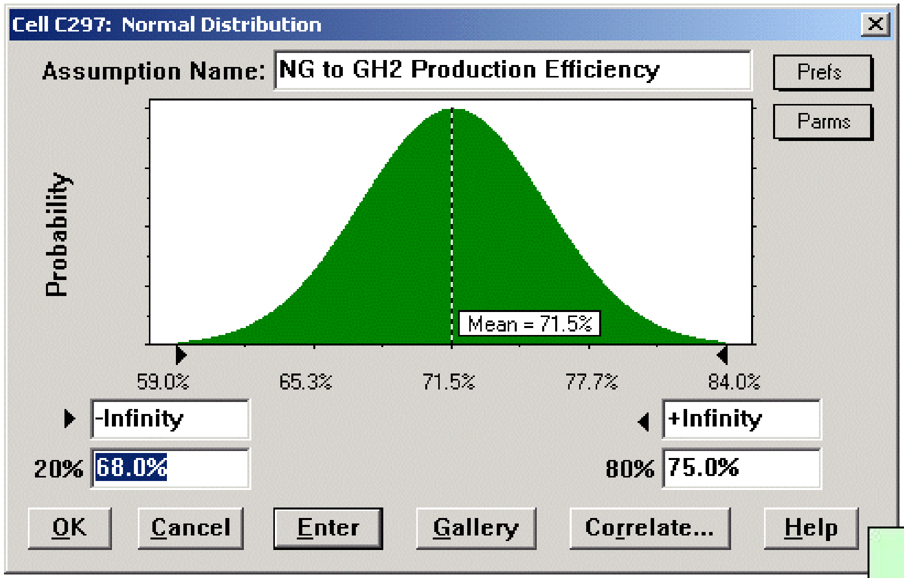
- Open literature
- Engineering analysis (such as ASPEN simulations for mass and energy balance)
- Stakeholder inputs (e.g., collaboration with the energy industry)

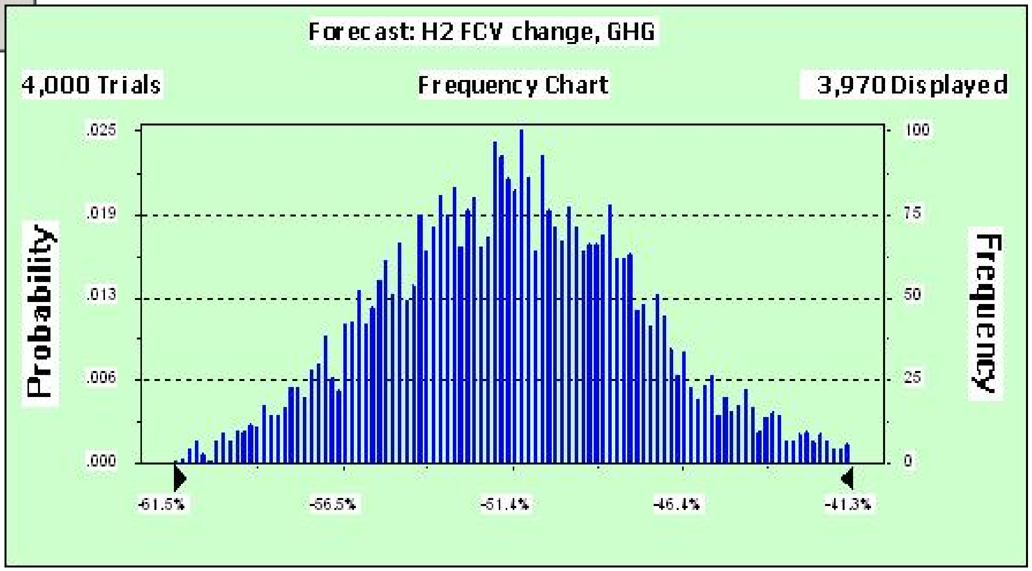
Pump-to-Wheels Data Sources

- Fuel economy
  - Open literature
  - Vehicle simulations with models such as Argonne's PSAT model
- Vehicle operation emissions
  - Open literature
  - Emission testing results
  - EPA MOBILE model
  - CARB EMFAC model

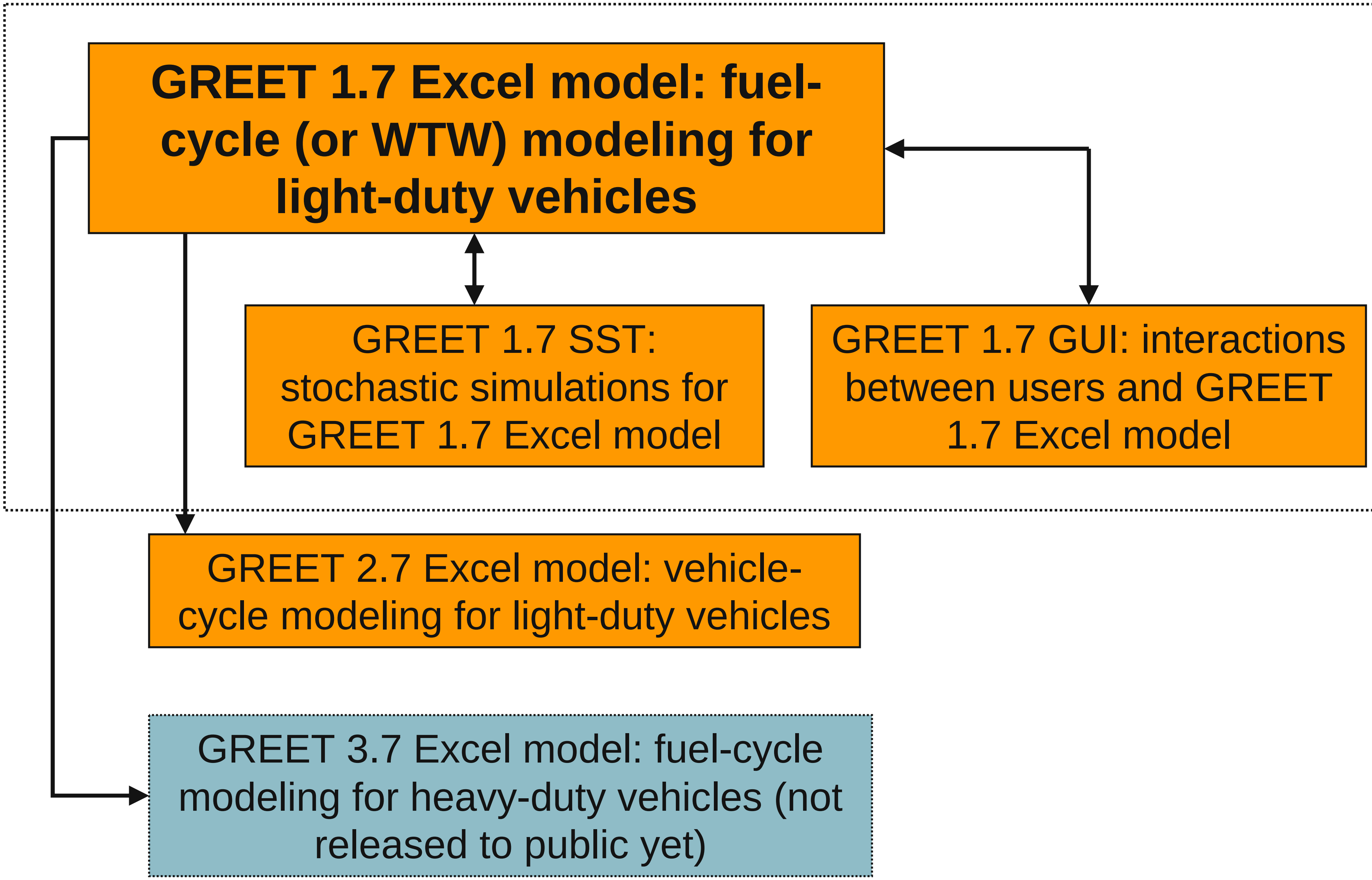
GREET Is Designed With Stochastic Simulations to Address Uncertainties

Distribution-Based Inputs Generate Distribution-Based Outputs





The Suite of GREET Models



GREET 1.7 Graphical User Interface (GUI)

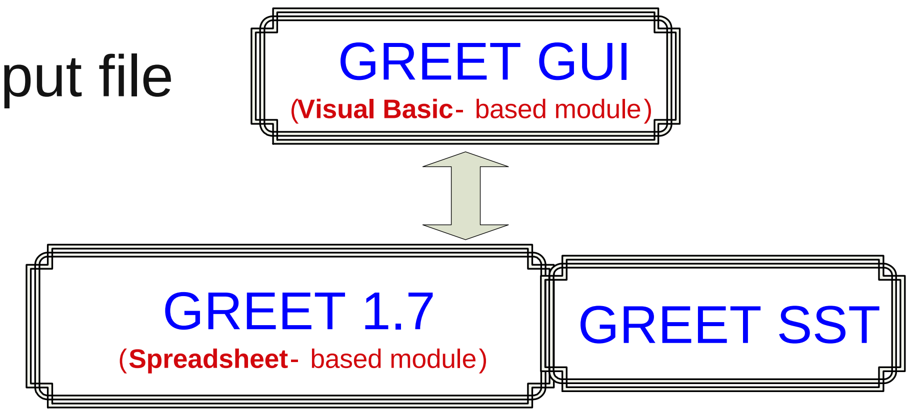
GREETGUI, developed using Microsoft® Visual Basic 6.0, works as follows:

1. Receives inputs from the user through option buttons, check boxes, and input text boxes

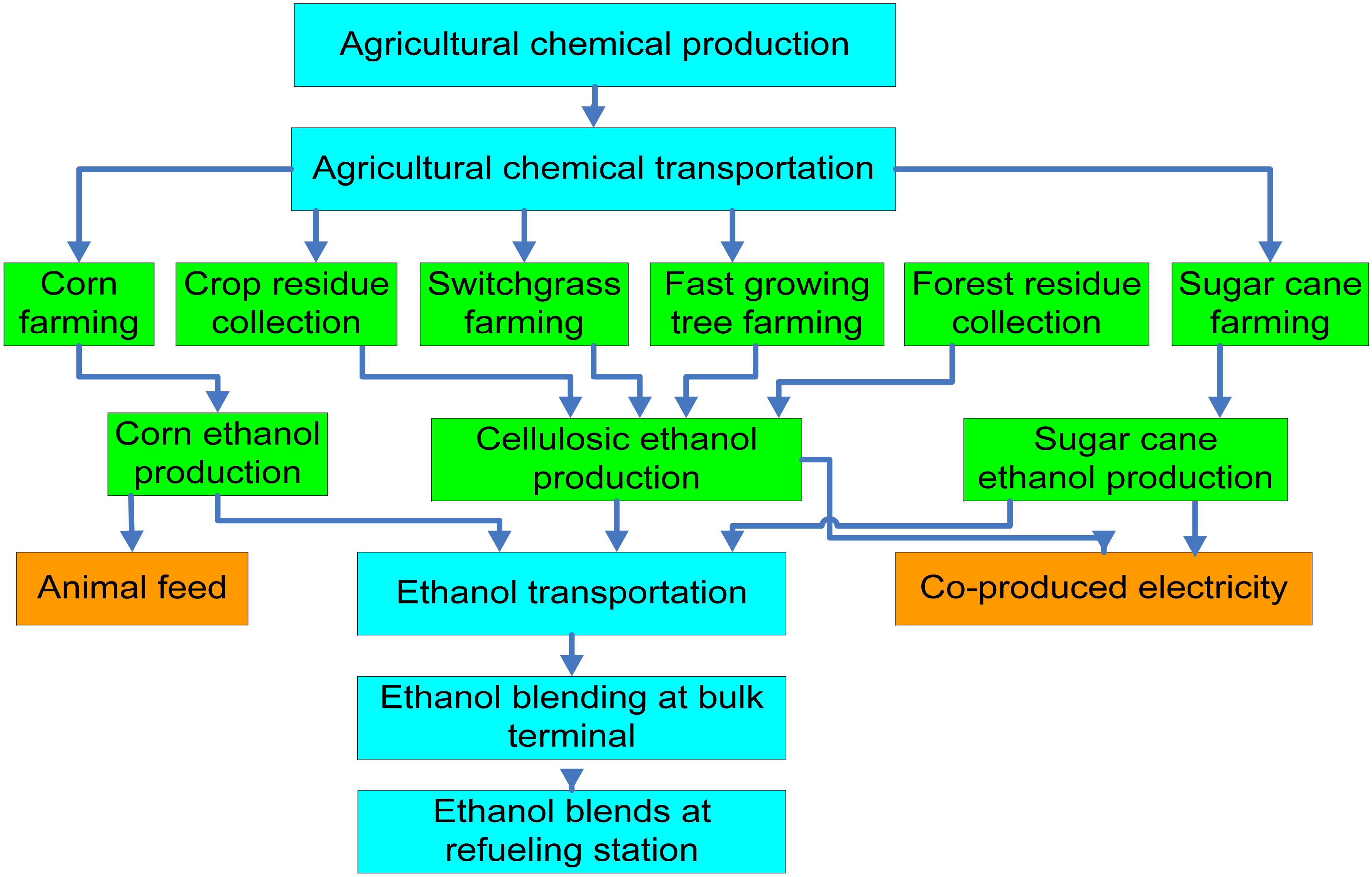
2. Communicates the inputs to an underlying Excel spreadsheet model (GREET)

3. Runs the GREET model in the background

4. Displays results in a separate output file



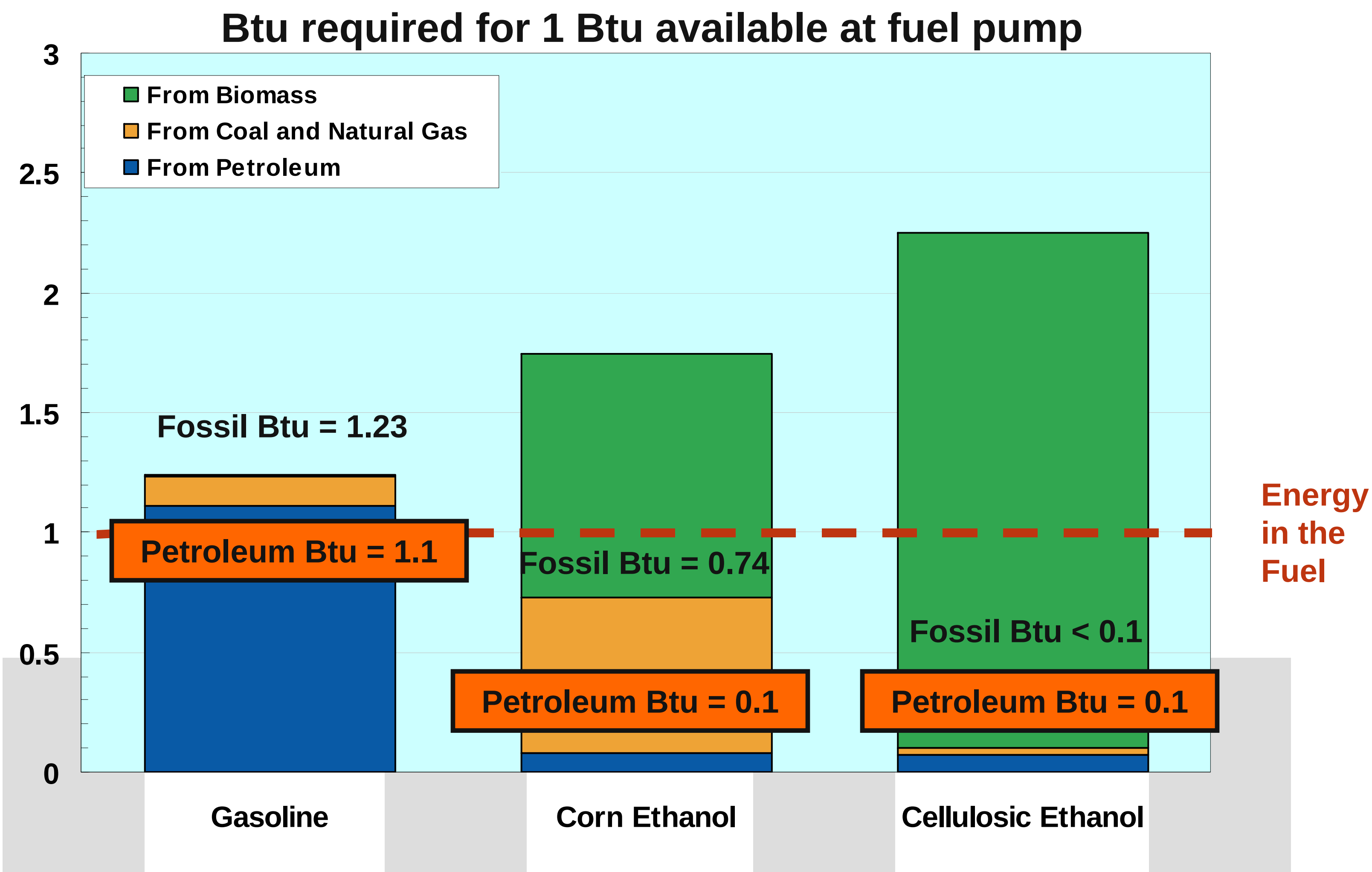
GREET Ethanol Life-Cycle Analysis Includes Activities from Fertilizer to Ethanol at Stations



U.S., Brazil and China Are Major Ethanol Consuming Countries

- U.S.
  - Corn ethanol
  - No.1 consuming country with 4.2 billion gallons in 2005
- Brazil
  - Sugarcane ethanol
  - No.2 consuming country with ~4 billion gallons in 2005
- China
  - Corn ethanol
  - No.3 consuming country with ~340 million gallons in 2005

The Type of Energy, As Well As the Amount of Energy, Is Important in Addressing Energy Effects of Ethanol

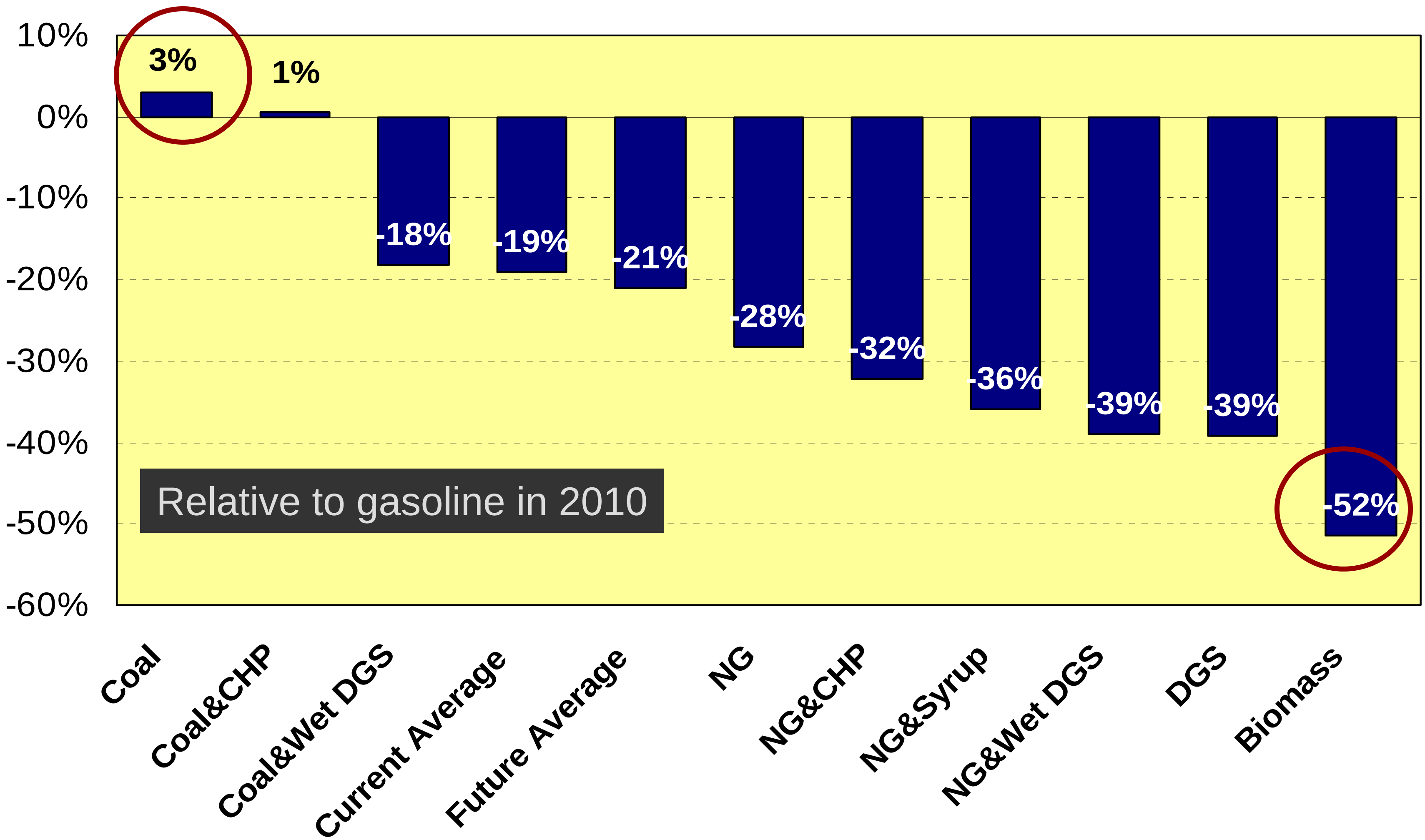


Accounting for Animal Feed Is a Critical Factor in Ethanol's Lifecycle Analysis

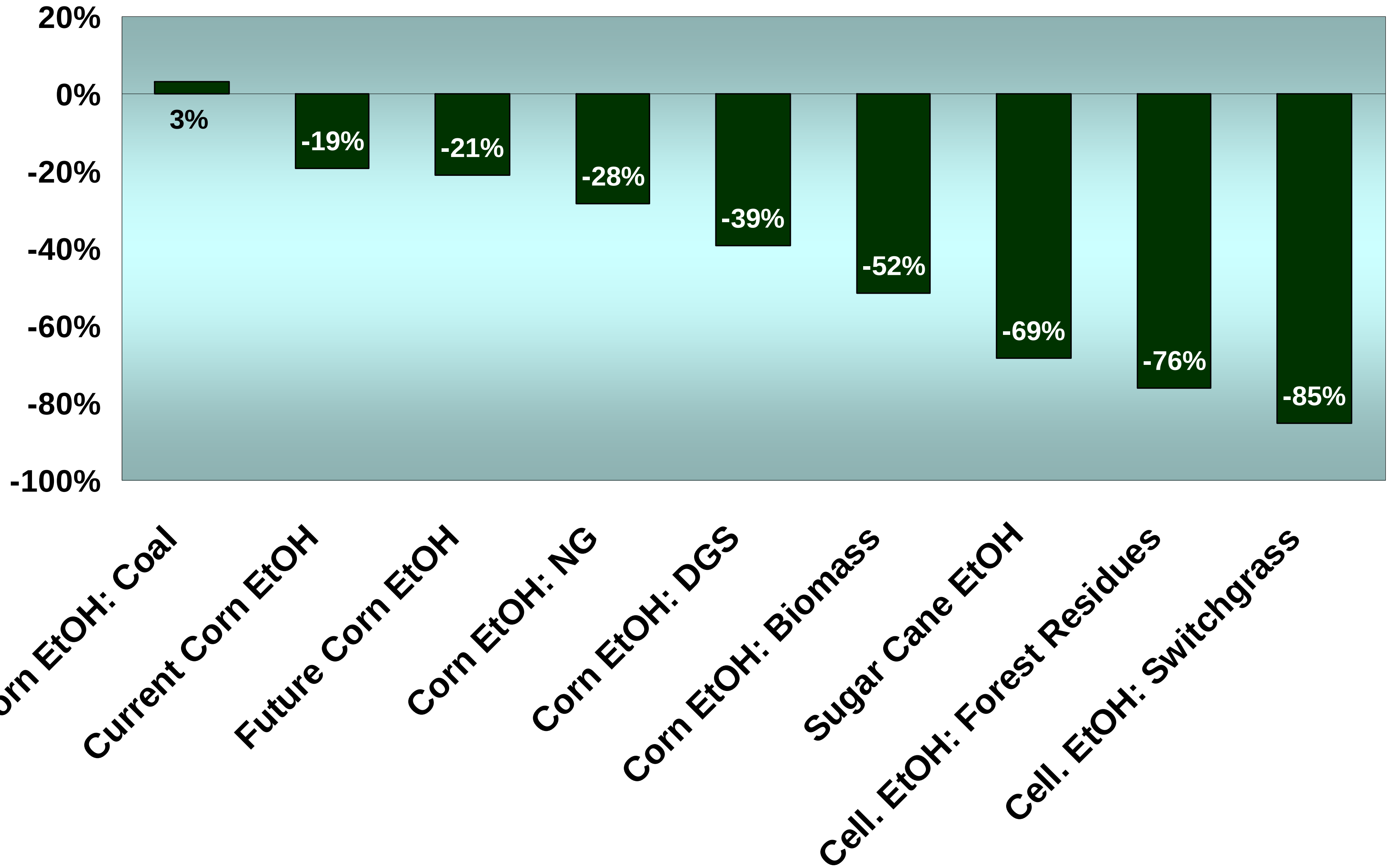
Allocation Method	Wet milling	Dry milling
Weight	52%	51%
Energy content	43%	39%
Process energy	36%	41%
Market value	30%	24%
Displacement	~16%	~20%

Argonne uses the displacement method, the most conservative approach.

Large Avoidance of GHG Emissions by Corn Ethanol With Use of Renewable Process Fuels



GHG Emissions Avoided by Various Feedstocks and with Different Process Fuels



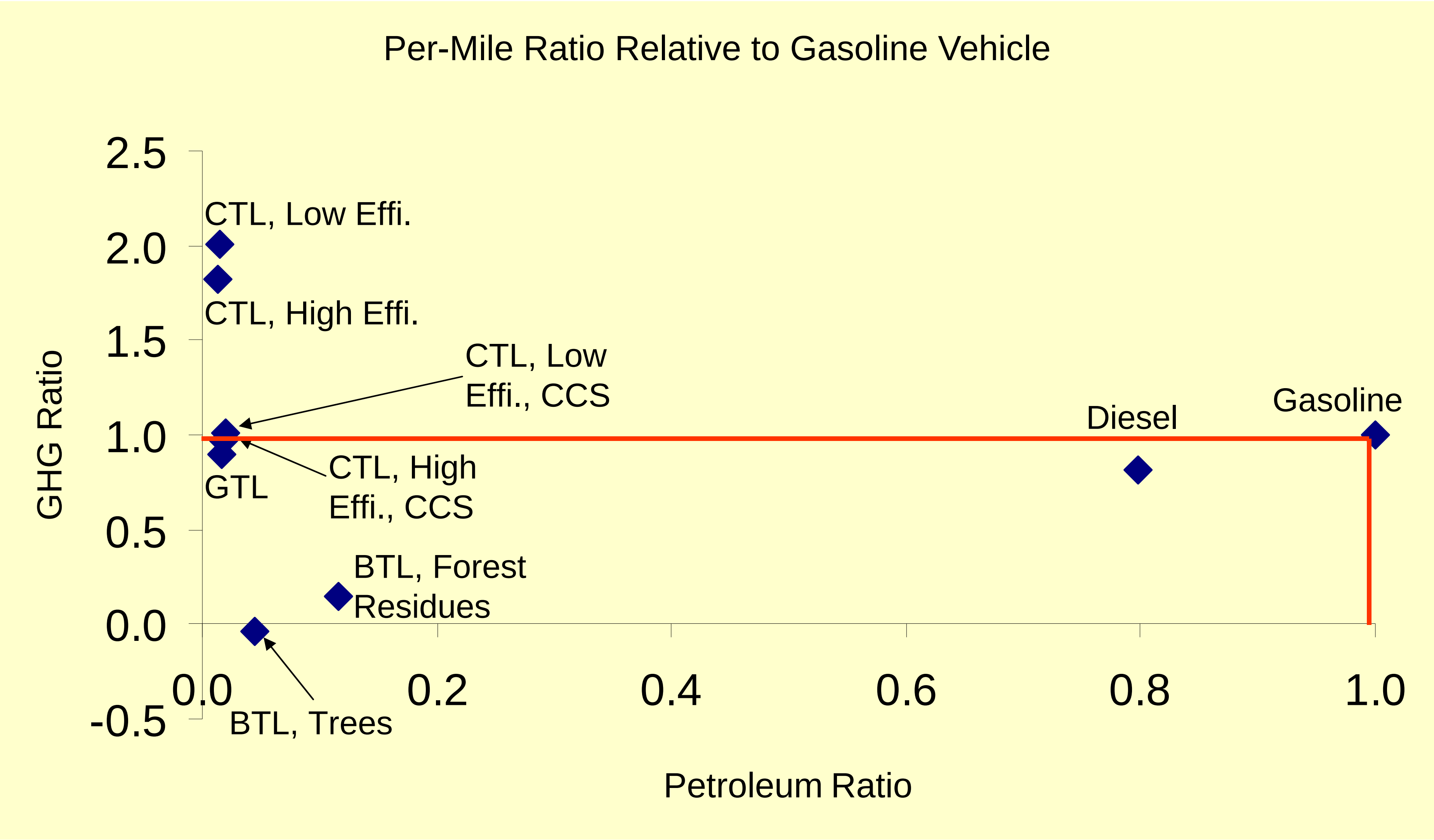
FT Diesel Can Be Produced from A Variety of Feedstocks

- Fischer-Tropsch process is a synthesis process to convert synthetic gas (syngas) to diesel fuels
- Brief history
  - Developed by Germany during World War II to produce liquid fuels from coal
  - Coal-based FT diesel production was modernized by South Africa's Sasol
  - Many companies involve in FT diesel technology development and commercialization
- Syngas (thus FT diesel) can be produced from a variety of feedstocks
  - Natural gas
  - Coal via gasification
  - Biomass via gasification
  - Heavy refinery products such as pet coke via gasification

Key Issues and Assumptions for FT Diesel Plants

- FT diesel plant designs
  - Standalone to produce diesel, naphtha, and other products
  - Co-generation of steam and/or electricity for export
- Post-synthesis refining/upgrading
  - Affect product slate and product quality
  - Ultimately affect WTW energy efficiencies and GHG emissions
- GTL plant assumptions in this study
  - Energy conversion efficiency of 63%
  - Carbon conversion efficiency of 80%
- CTL plant assumptions in this study
  - Based on studies by National Energy Technology Laboratory (2003) and by Southern State Energy Board (2006)
  - Low efficiency scenario with 47.4% efficiency
  - High efficiency scenario with 52% efficiency
  - A carbon capture and storage (CCS) case with a carbon capture rate of 85% at FT plants
- BTL plant assumptions in this study
  - Based on a summary report on Choren Industries' technology
  - An energy efficiency of 47% for wood chip feedstock

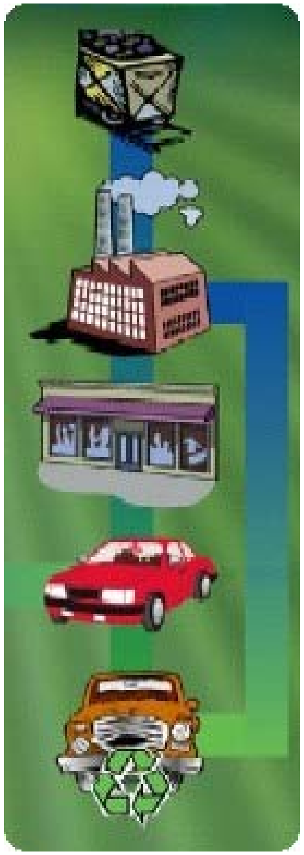
Trade-Offs Between Petroleum Reductions and GHG Reductions



Argonne Has Been Working on Vehicle-Cycle Analyses for More Than a Decade

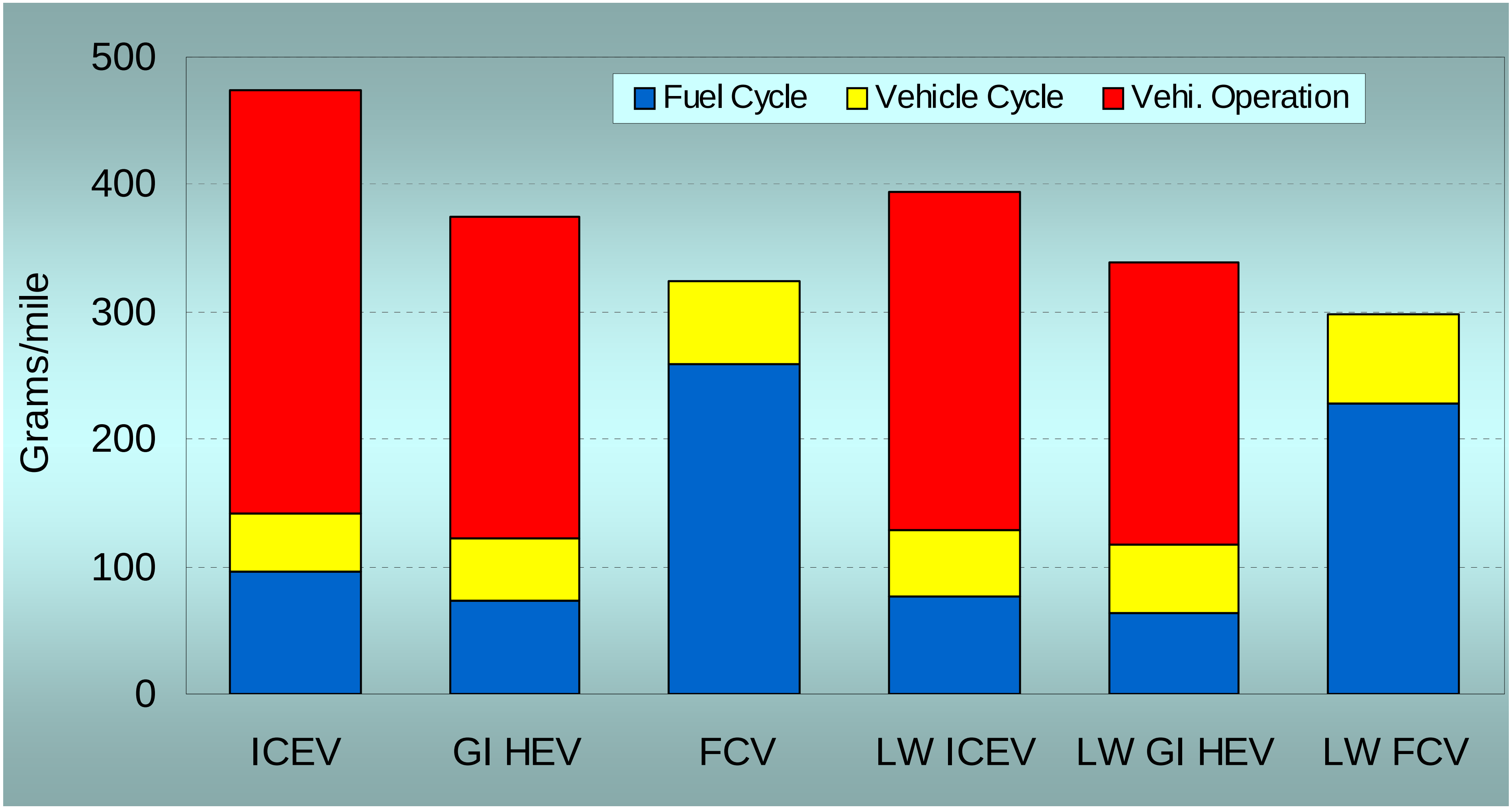
- In 1995, Stodolsky et al. investigated the life-cycle energy savings from aluminum-intensive vehicles
- In 1997, Wang et al. examined the vehicle-cycle impacts of HEVs
- In 1998, Gaines et al. analyzed the life-cycle impacts heavy duty vehicles
- Also in 1998, Argonne in a joint effort performed a total-energy cycle assessment of electric and conventional vehicles
- Argonne resumed its efforts with the release of a report documenting the development and applications of the GREET 2.7 vehicle-cycle model

GREET 2.7 Simulates Vehicle Cycle Energy Use and Emissions from Material Recovery to Vehicle Disposal



- Raw material recovery
- Material processing and fabrication
- Vehicle component production
- Vehicle assembly
- Vehicle disposal and recycling

Vehicle Cycle Contribution Could Be Non-Trivial to Total Energy-Cycle GHG Emissions



Outstanding Life-Cycle Analysis Issues

- Models are helpful for LCAs, but input assumptions determine LCA results
- Technology advancement over time need to be considered
  - Vehicle technologies for fuel economy and emissions
  - Fuel requirements and production technologies
- Transparency should be emphasized in LCAs and their results
- System boundary issues will continue to be debated
  - LCA includes operation-related activities, but usually does not include infrastructure-related activities such as building of petroleum refineries
  - Definition of the boundary for a fuel is a moving target
  - It is critical to maintain a consistent boundary for all fuels
- Absolute values vs. relative changes among vehicle/fuel systems: relative changes are more reliable, especially when comparing different studies

References and Resources for GREET 1.7 and 2.7 Applications

- Wang, M., 1999, GREET 1.5 – Transportation Fuel-Cycle Model, Volume 1: Methodology, Development, Use, and Results: **GREET model methodologies**
- Brinkman, N., M. Wang, T. Weber, T. Darlington, 2005, Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems — A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions: **updated key assumptions in GREET 1.7**.
- Wang, M., Y. Wu, and A. Elgowainy, 2005, Operation Manual: GREET Version 1.7 (revised in Jan. 2007): **user manual for GREET 1.7**
- Subramanyan, K. and U. Diwekar, 2005, User Manual for Stochastic Simulation Capability in GREET: **user manual for GREET 1.7 stochastic simulations**
- Burnham, A., M. Wang, and Y. Wu, 2006, Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model: **GREET 2.7 model methodologies and results**
- Other materials (presentations, reports, and papers) are posted at the GREET website (please google GREET on the web to get to the GREET site)

A Few Tips of Using GREET Database Resources and Additional Simulations

- The *Fuel-Specs* Sheet: containing fuel specifications of each fuel (Btu/gal, density, carbon content, and sulfur content)
- The *EF* Sheet: containing emission factors of fuel combustion by fuel type and combustion technology
- Simulation of any vehicle types in GREET 1.7: changing fuel economy and emissions of vehicle operation stage in the *Vehicles* sheet
- WTW results per unit of fuel (instead of per mile): adding additional cells in the *Results* sheet
- GHG reduction per gallon of ethanol vs. the same amount of gasoline displacement
  - Setting ethanol blend to E100 in the *Inputs* sheet
  - Zeroing out natural gasoline as denaturant in ethanol in the *Inputs* sheet
  - Calculating WTW results per mmBtu for ethanol and gasoline in the *Results* sheet
  - Calculating the difference between ethanol and gasoline