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Overview of GREET Model Development at Argonne

Michael Wang
Center for Transportation Research
Argonne National Laboratory

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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 were 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

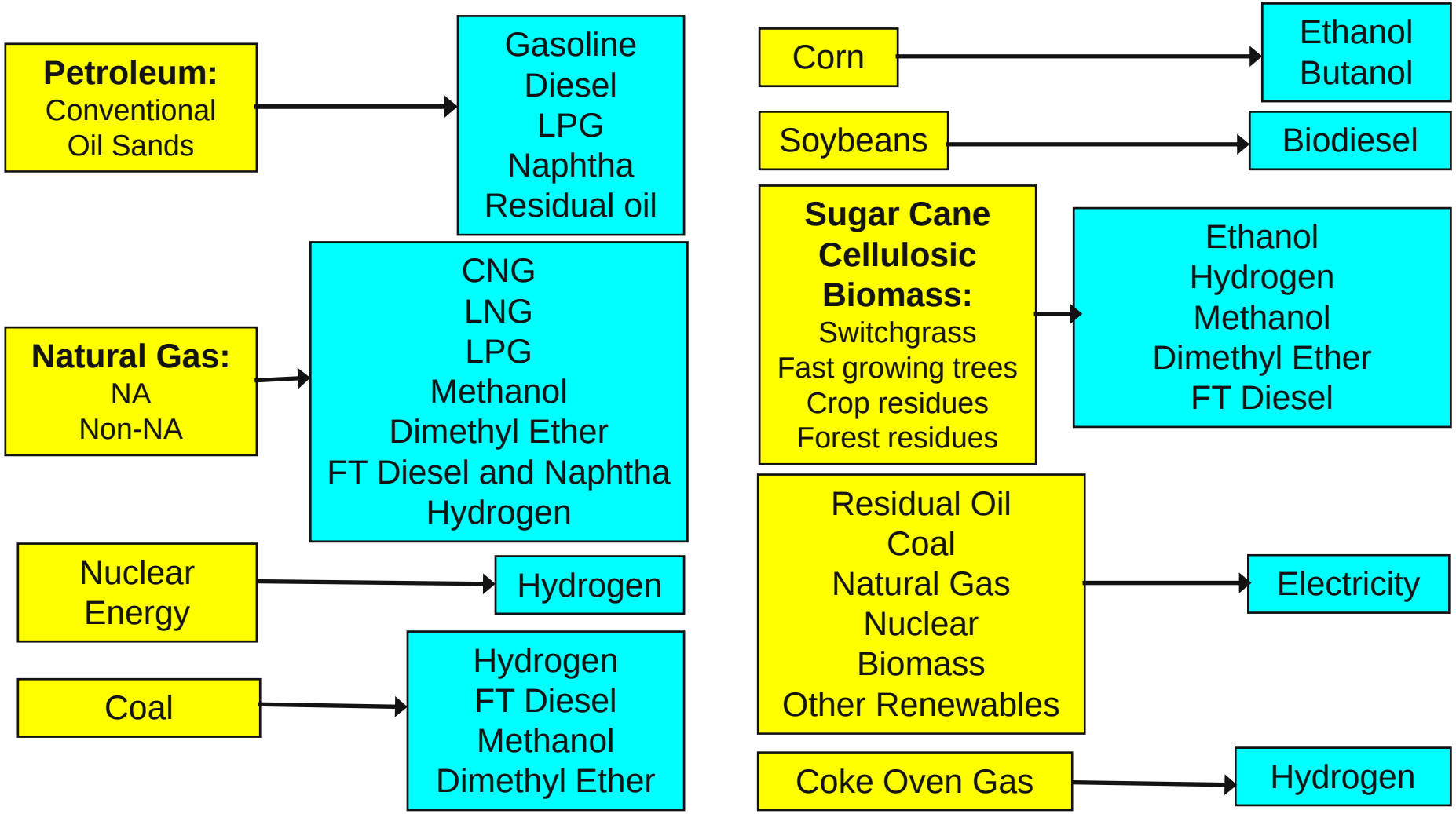
Several Life-Cycle Analysis (LCA) Models Are Available to Examine Vehicle/Fuel Systems

- The lifecycle emission model (LEM) at University of California at Davis
- The GREET model at Argonne National Laboratory
- Canadian GHGenius model (a derivative of the LEM)
- LBST's E3 database in Europe
- The Ecobalance model by PriceWaterhouseCooper in Europe
- Other generic LCA models that can be applied to examine transportation fuels and vehicle technologies

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 version (GREET 1.8b) was released in March 2008**

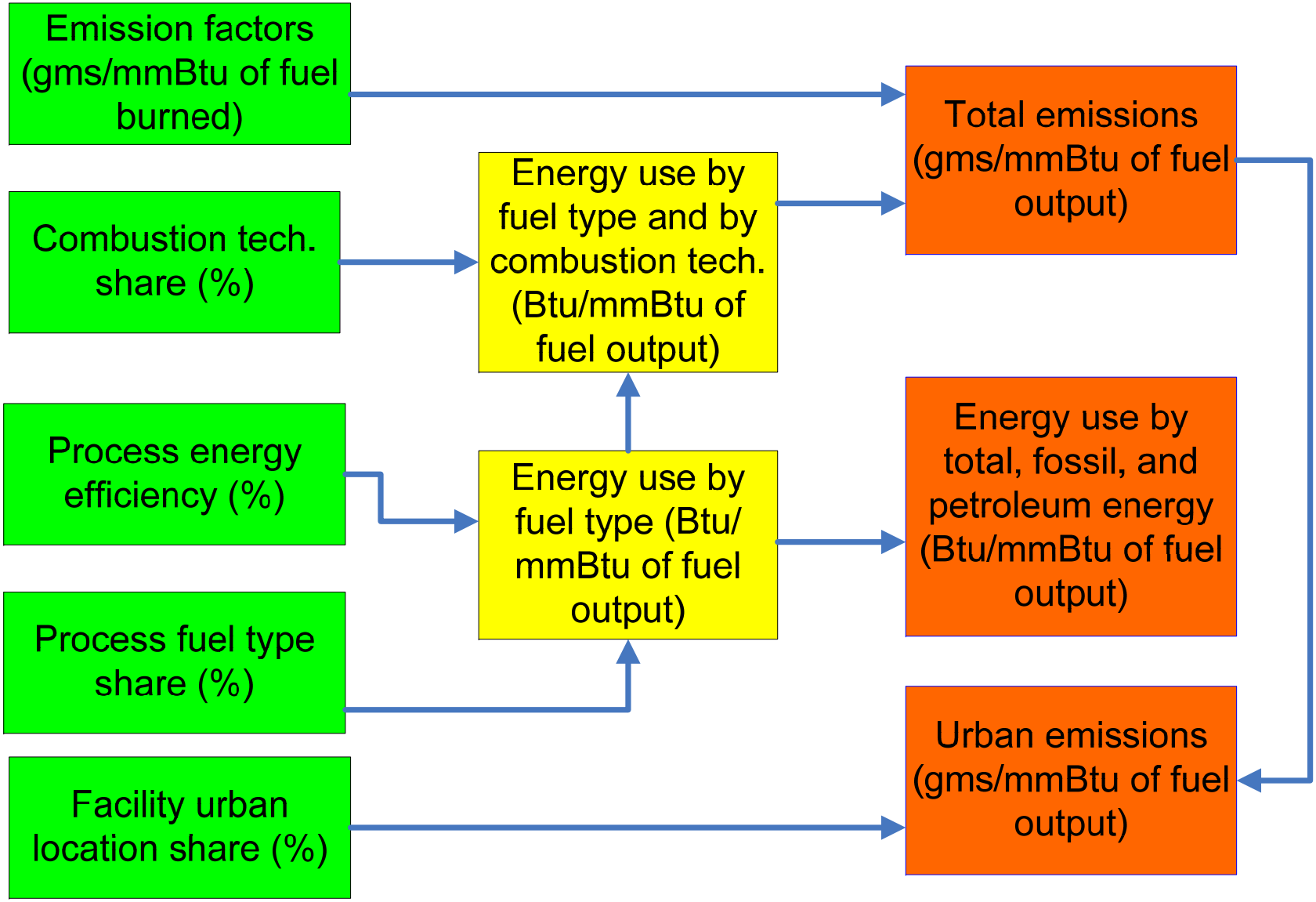
GREET Includes More Than 100 Fuel Production Pathways from Various Energy Feedstocks



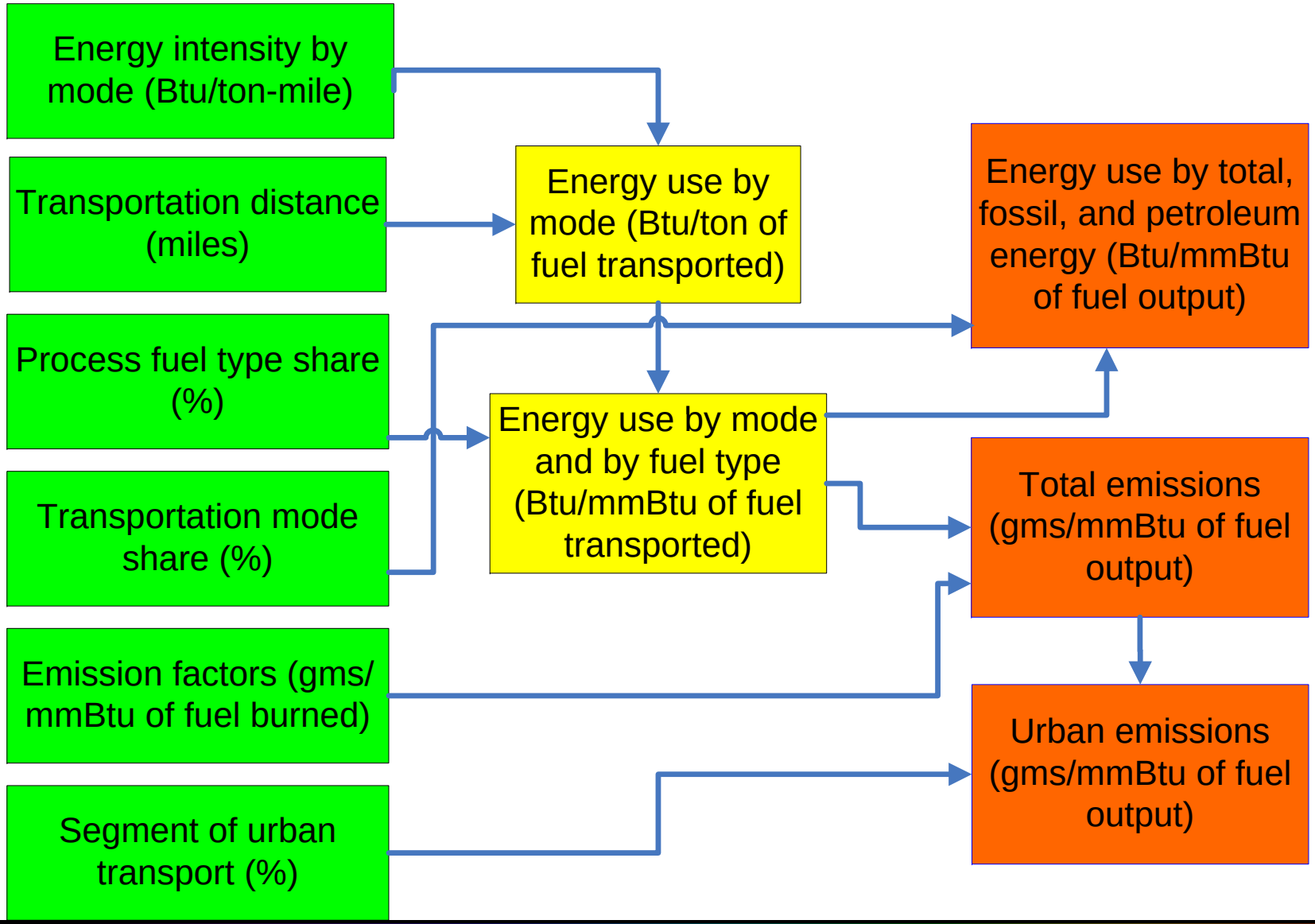
What's New In GREET1.8b?

- New fuel production pathways
  - Brazilian sugarcane ethanol
  - Corn to butanol
  - Soybeans to renewable diesel via hydrogenation
  - Coal/biomass co-feeding for FT diesel production
  - Various corn ethanol plant types with different process fuels
- Enhancements of existing pathways
  - Inclusion of three methods in dealing with co-products for soybean-based biodiesel
  - Compression energy efficiencies for NG and H2 are calculated with the first law of thermodynamics
  - Tube trailer delivery option for gaseous H2 to refueling stations
  - Revision of petroleum refining energy efficiencies

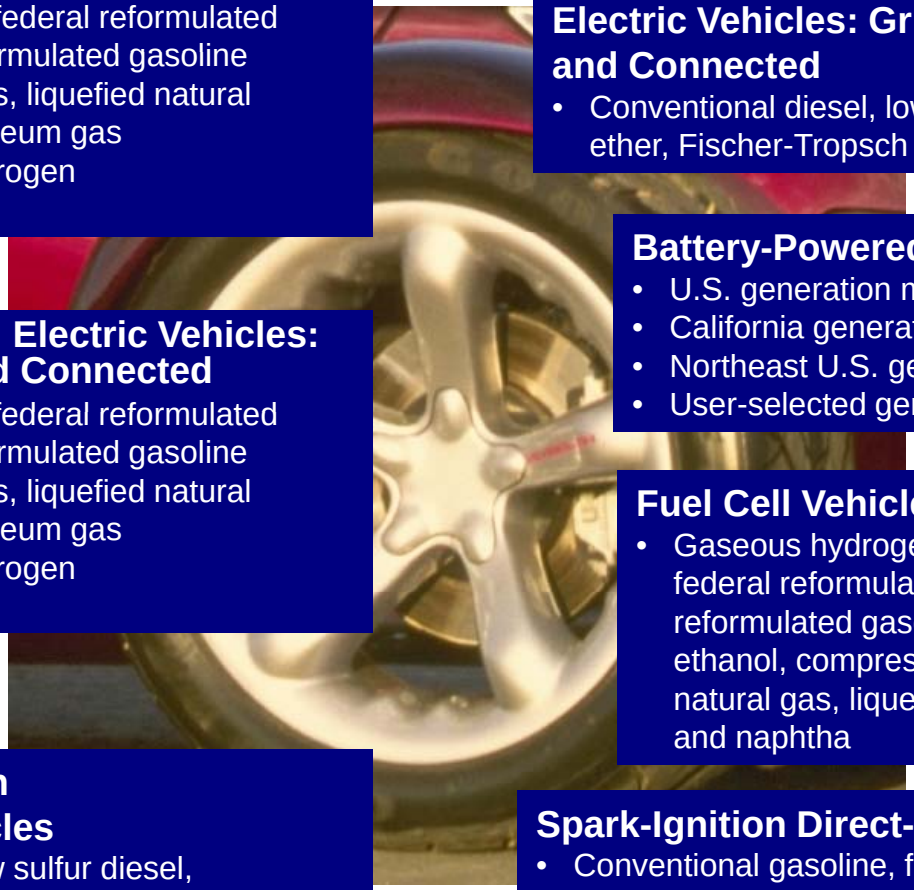
Calculation Logic for a Given WTP Production Activity in GREET



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

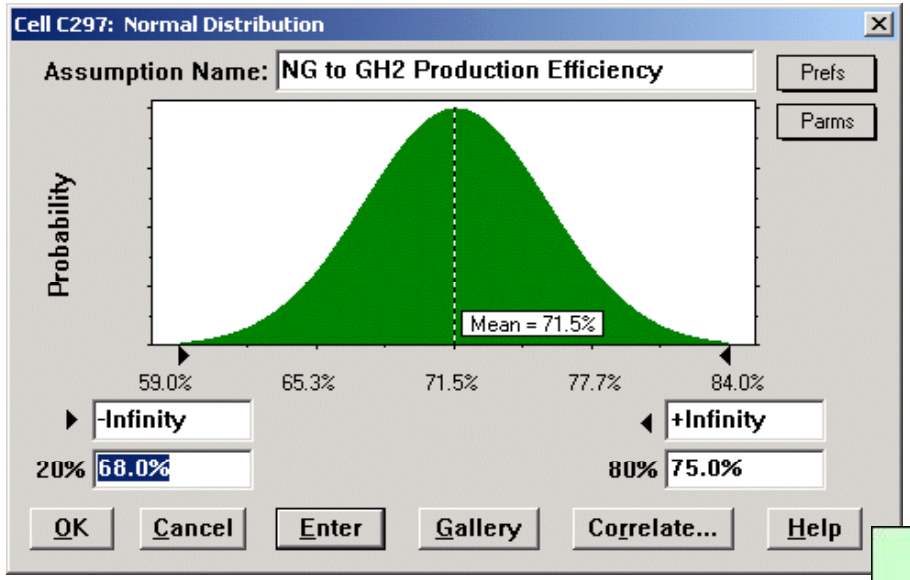
- Open literature
- Engineering analysis (such as ASPEN simulations for mass and energy balance)
- Stakeholder inputs (e.g., collaboration with the energy industry)

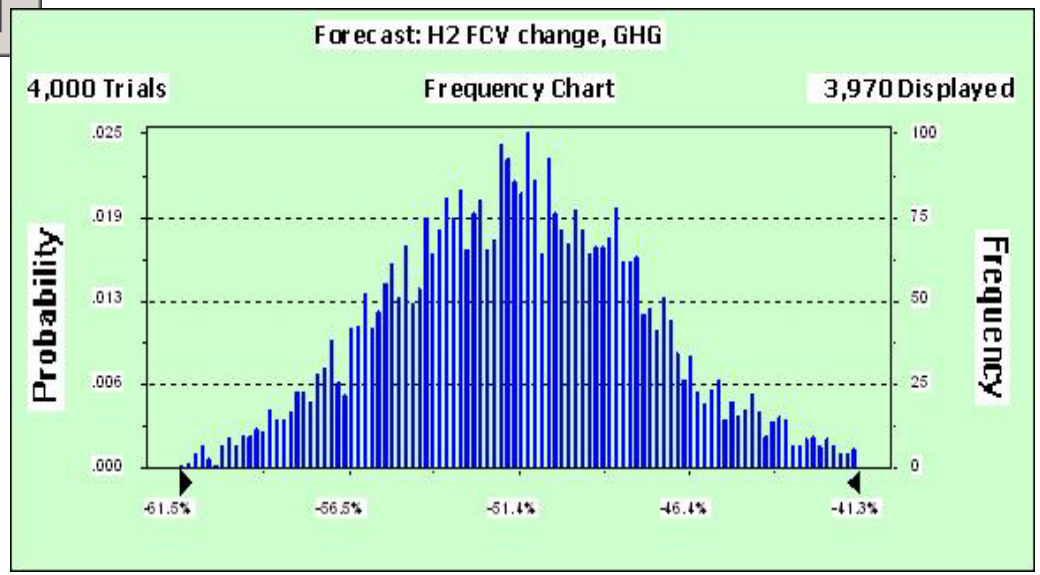
Pump-to-Wheels Data Sources

- 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

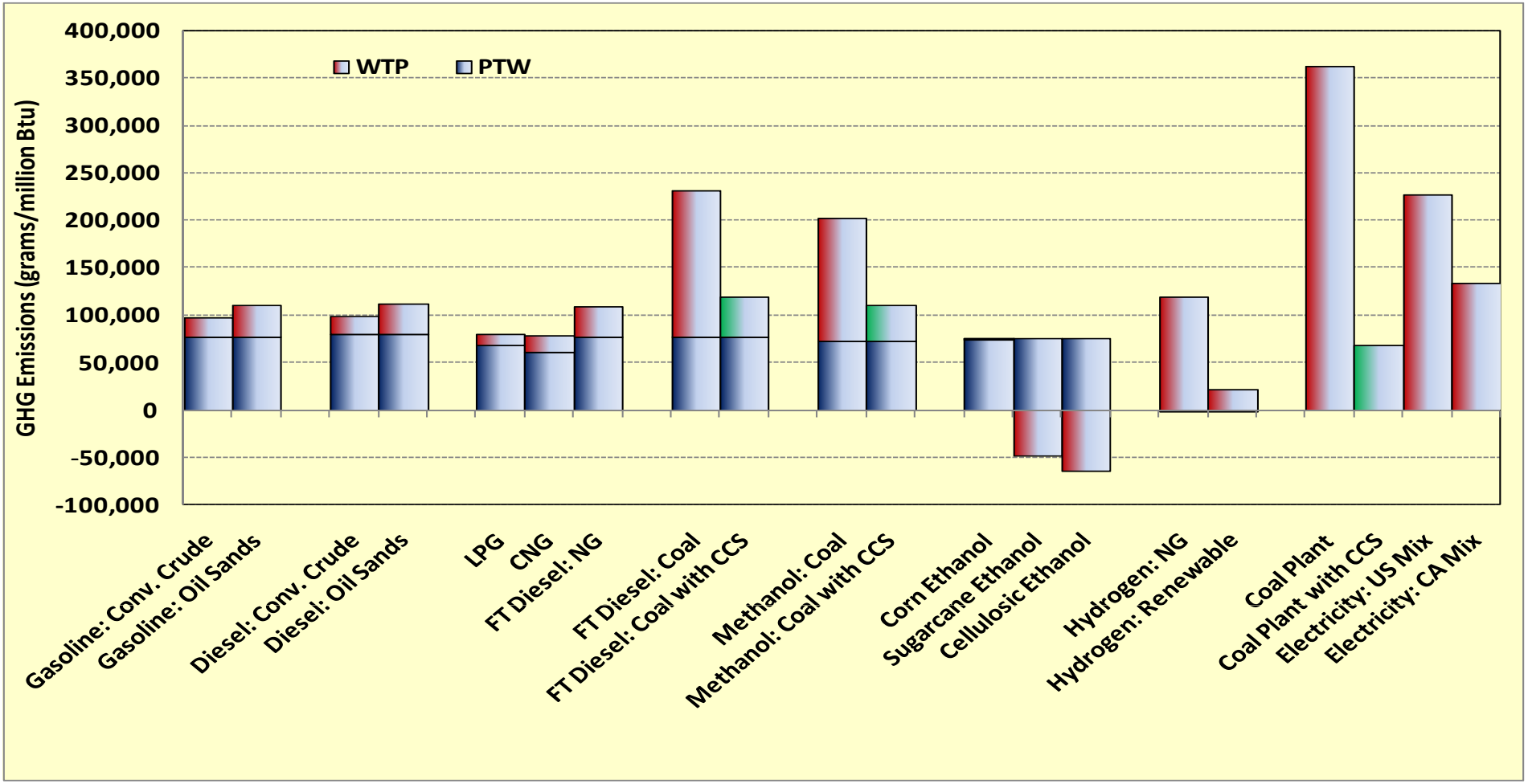
GREET Is Designed With Stochastic Simulations to Address Uncertainties

Distribution-Based Inputs Generate Distribution-Based Outputs





Well-to-Wheels GHG Emissions Vary Considerably Among Transportation Fuel Options



Feedstock recovery → Feedstock Transportation → Fuel Production → Fuel Transportation → Fuel Utilization

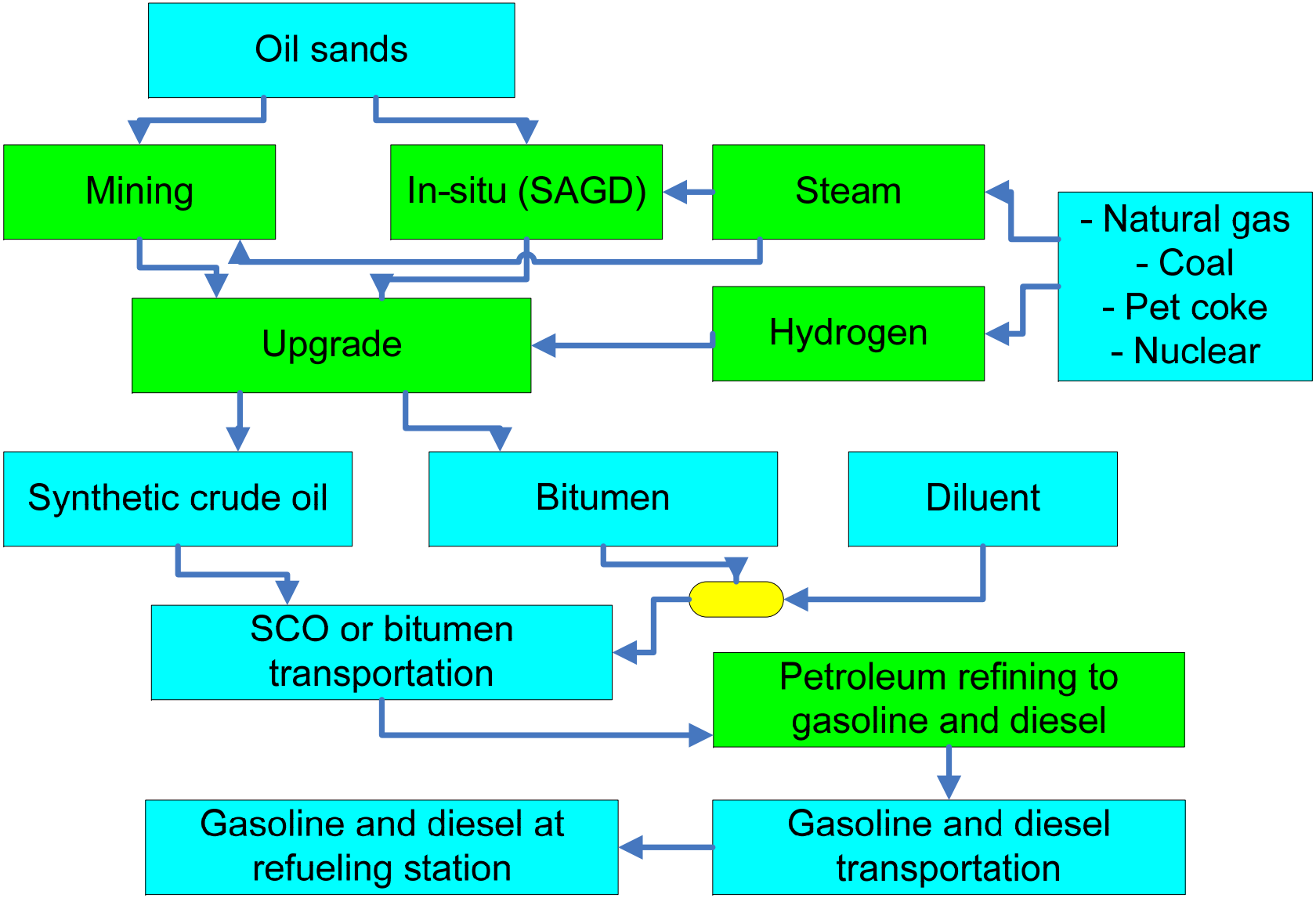
Carbon capture and storage (CCS) is applicable to the fuel production stage; decarbonization of fuels themselves offers additional GHG reduction potentials.

Refining Energy Efficiencies for Individual Petroleum Products

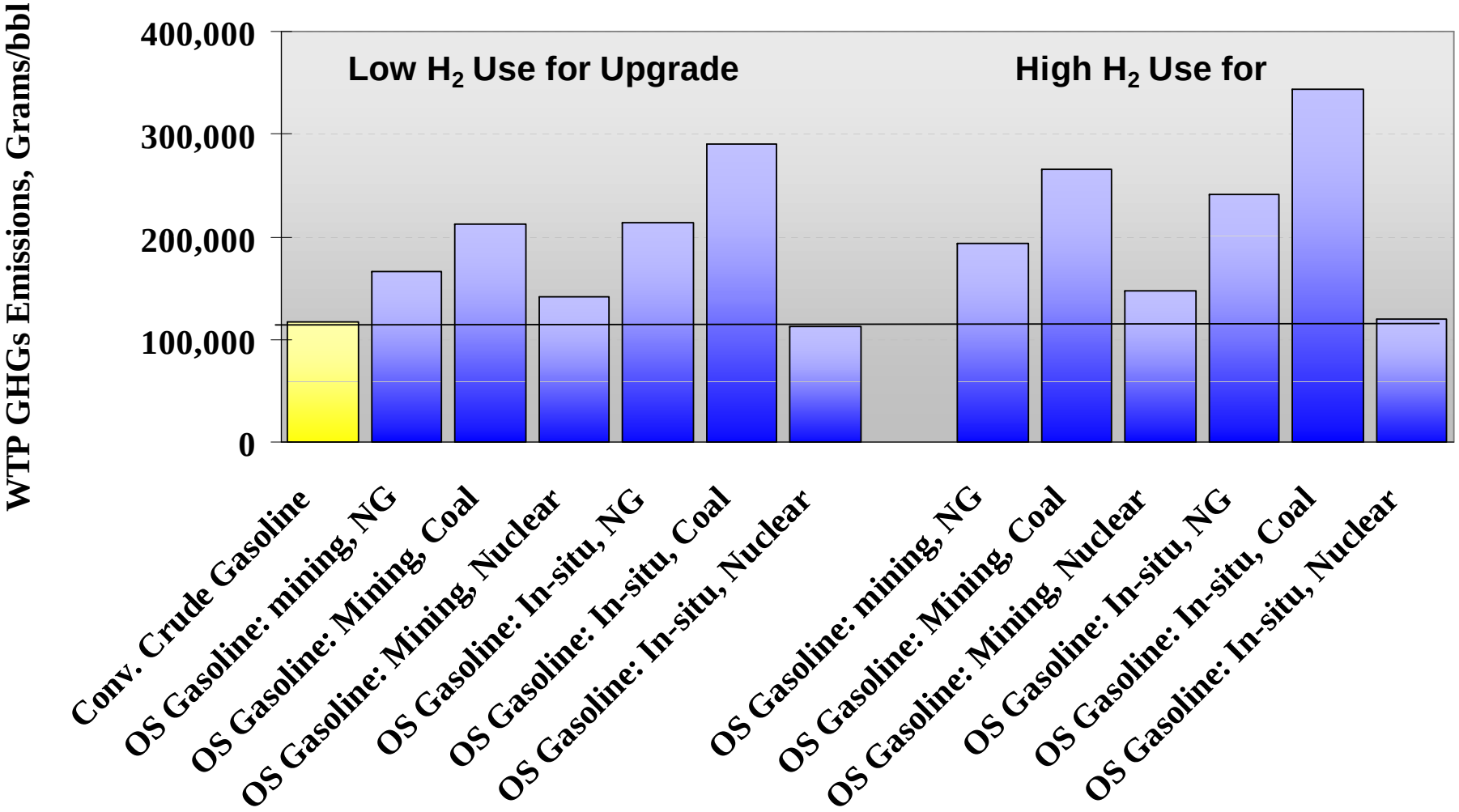
	Petroleum Product Refinery Efficiency		
	GREET1.8a Values	**GREET1.8b Values**	Values If Less Desirable Products Excluded
Gasoline	86.0%	**87.7%**	83.3%
Diesel	88.0%	**90.3%**	86.7%
LPG	93.5%	**94.3%**	92.1%
Residual oil	95.5%	**94.3%**	92.1%
Naphtha	91.0%	**94.3%**	92.1%

M. Wang, 2007, Estimation of Energy Efficiencies of U.S. Petroleum Refineries.

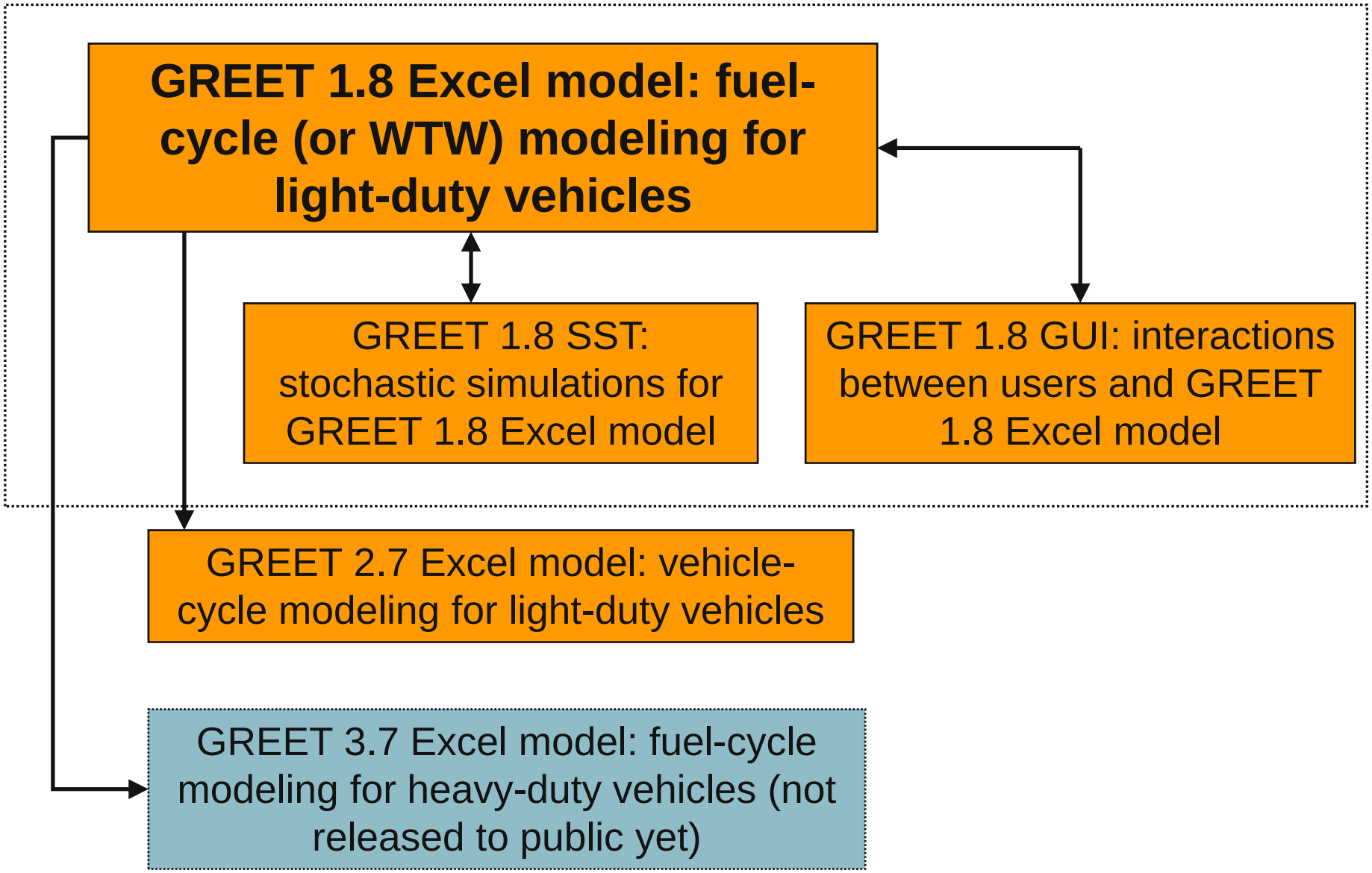
The Pathway of Oil Sands to Gasoline and Diesel Requires a Large Amount of Steam and H_2



WTP GHG Results Show That Oil Sands Operations Are Carbon-Intensive



The Suite of GREET Models

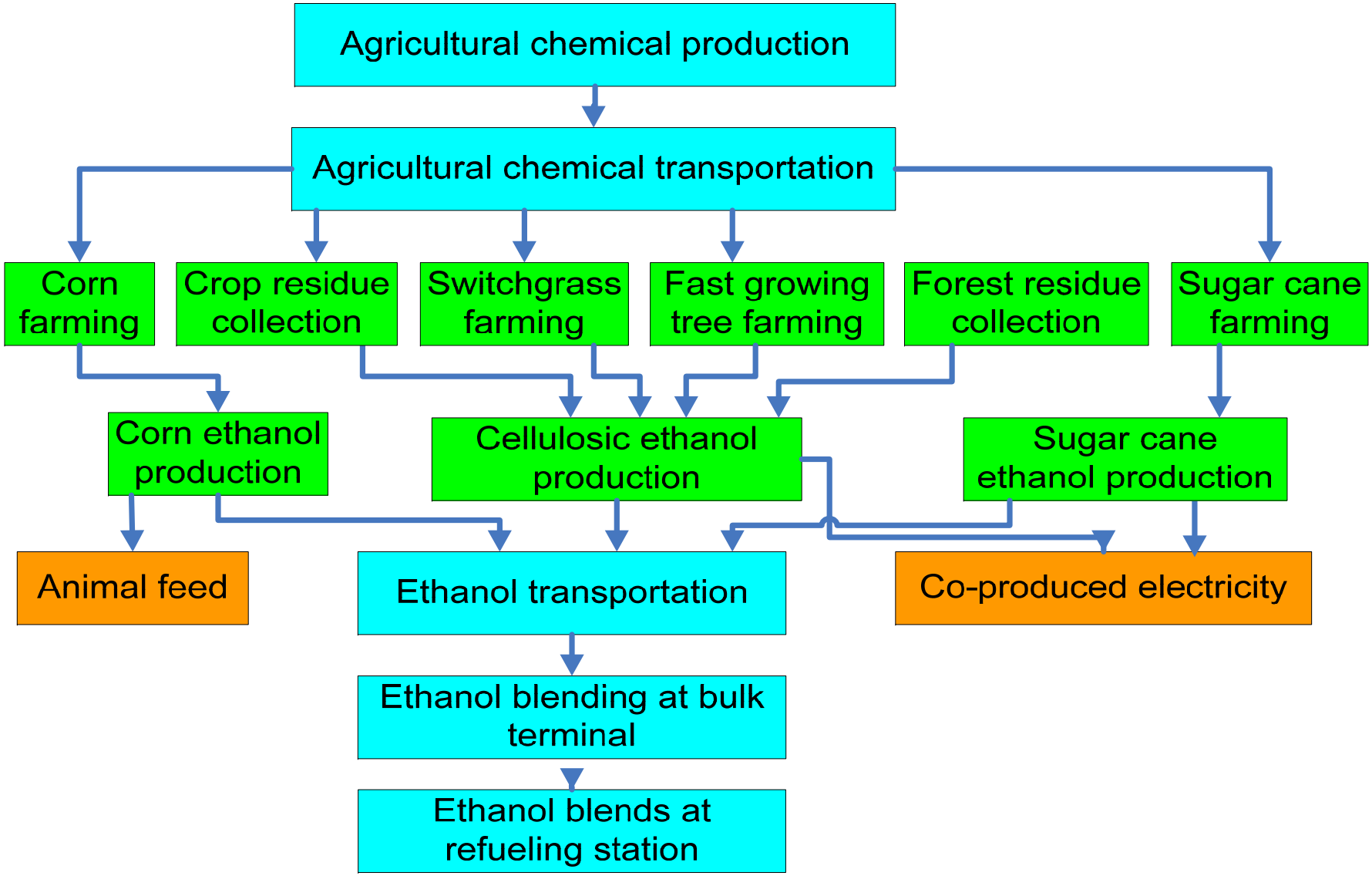


GREET Includes Some of the Potential Biofuel Production Pathways

- Sugar Crops for EtOH
  - **Sugar cane**
  - Sugar beet
  - Sweet sorghum
- Starch Crops for EtOH
  - **Corn**
  - Wheat
  - Cassava
  - Sweet potato
- Butanol Production
  - **Corn**
  - Sugar beet
- Oils for Biodiesel/Renewable Diesel
  - **Soybeans**
  - Rapeseed
  - Palm oil
  - Jatropha
  - Waste cooking oil
  - Animal fat
- Cellulosic Biomass via Gasification
  - **Fitscher-Tropsch diesel**
  - **Hydrogen**
  - Methanol
- Cellulosic Biomass for EtOH
  - **Corn stover**, rice straw, wheat straw
  - **Forest wood residue**
  - Municipal solid waste
  - **Energy crops**
  - Black liquor

The feedstocks that are underlined are already included in the GREET model.

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



Key Issues Affecting Biofuel WTW Results

- Nitrogen fertilizer plants
  - Energy use
  - Natural gas vs. coal as feedstock
- Farming
  - Crop and biomass yields
  - Energy and chemical inputs
- Energy use in ethanol plants
  - The amount of process fuels
  - The type of process fuels
- Credits of co-products of ethanol
  - Distillers grains and solubles for corn ethanol: 0-50%
  - Electricity for cellulosic and sugarcane ethanol
- N2O conversion factors of nitrogen fertilizer
  - IPCC: 1.325% (GREET adopts it; equivalent to 1.77% of Crutzen factor)
  - Crutzen et al.: 3-5% (equivalent to 2.24-3.74% of IPCC factor)
  - Background vs. N fertilizer-induced N2O emissions in fields
- Land use changes and resulted GHG emissions

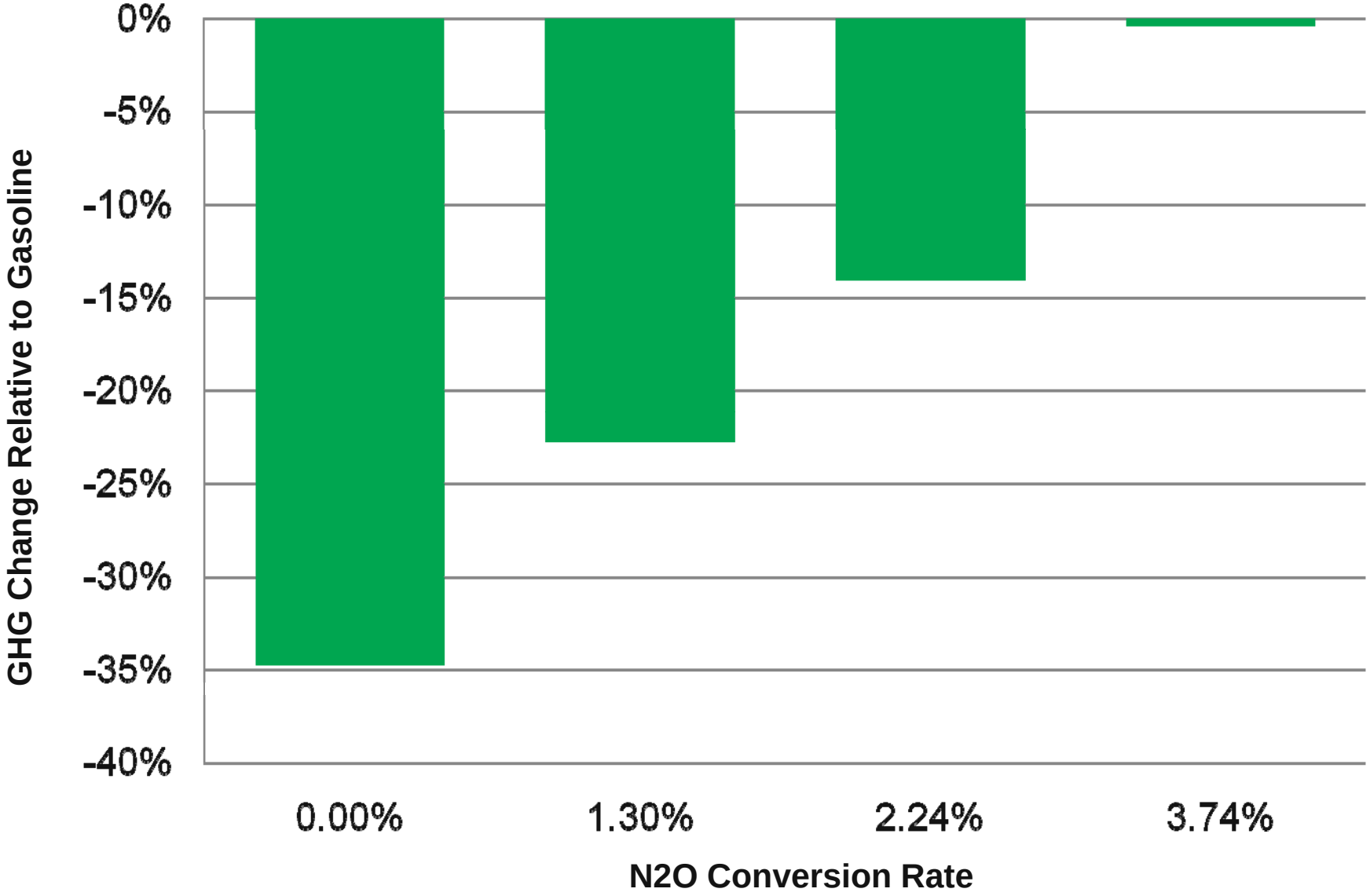
Energy Use in Ethanol Plants Has Reduced by More Than 50% in the Past 20 Years

Corn ethanol plants in early 1980s consumed 70,000 Btu per gallon of ethanol produced.

Current and Near-Future Ethanol Plant Energy Use (per gallon of ethanol)

Ethanol Plant Type	Natural Gas (Btu)	Coal (Btu)	Renewable Process Fuel (Btu)	Electricity (kWh)
1. Plant with natural gas (NG)	33,330	None	None	0.75
2. Plant with NG and wet DGS	21,830	None	None	0.75
3. Plant with coal	None	40,260	None	0.90
4. Plant with coal and wet DGS	None	26,060	None	0.90
5. Plant with wood chips	None	None	40,260	0.90
6. Plant with DGS as fuel	None	None	40,260	0.75

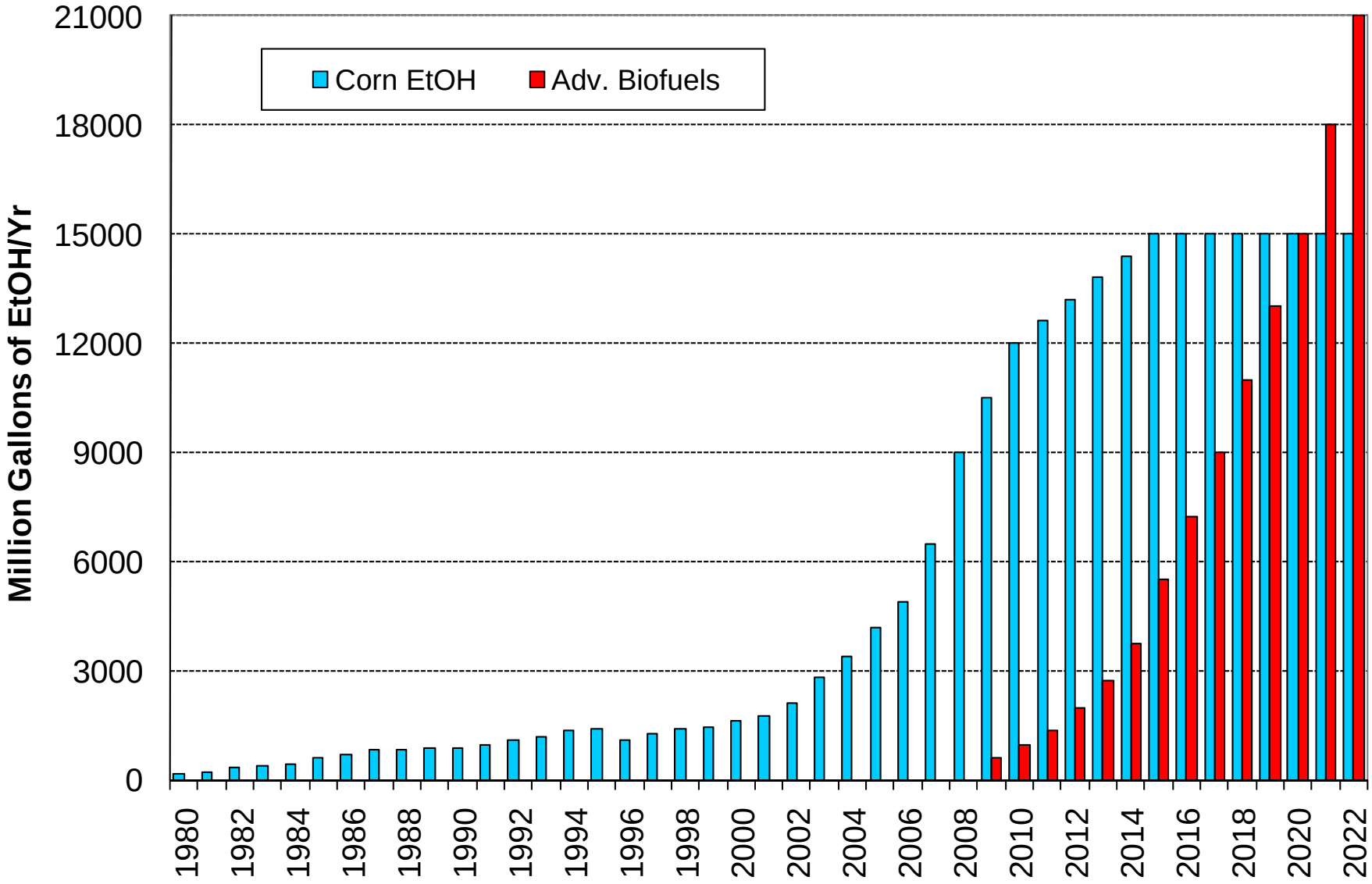
Corn Ethanol GHG Reductions Under Different N2O Conversion Factors



Approach to Address GHG Emissions of Potential Land Use Change by Large-Scale Biofuel Production

- Potential land use changes
  - Direct land use change: regional or national scale
  - Indirect land use change: global scale
  - Both can be simulated with global general equilibrium models
  - The resolution level of global GE models could be a key factor
- Carbon profiles of major land types
  - Models in the U.S. and Europe are available
  - Carbon profiles of land types in other parts of the world (South America, Asia, Africa) may be less understood
- Time horizon of biofuel programs; "for-ever biofuels" can mathematically result in zero GHG emission changes from land use changes
- At present, GREET includes the following soil CO2 sources/sinks for ethanol
  - Corn ethanol: CO2 <u>source</u> of 73 grams/gal. EtOH from soil C reduction
  - Cellulosic ethanol
    - *Fast growing trees: CO2 <u>sink</u> of 1,250 g/gal. EtOH from soil C increase*
    - *Switchgrass: CO2 <u>sink</u> of 540 g/gal. EtOH from soil C increase*

The 2007 Energy Independence and Security Act Established Aggressive Biofuel Production Targets

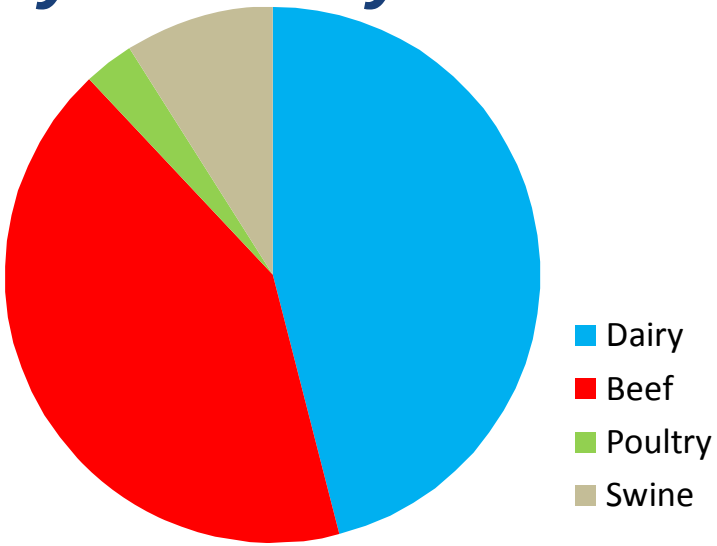


Co-Products with Biofuels

- Types of co-products
  - Corn ethanol: animal feeds (distillers grains and solubles, DGS)
  - Sugarcane ethanol: electricity
  - Cellulosic ethanol: electricity
  - Biodiesel and renewable diesel from soybean and rapeseed: animal feeds, glycerin, and other chemicals
- Ways of dealing with co-products
  - Displacement method (or the system boundary expansion approach)
  - Allocation methods
    - *Mass based*
    - *Energy content based*
    - *Economic revenue based*
  - Production plant process purpose based
- Scale of biofuel production (and resultant scale of co-product production) can affect the choice of methods

Proper Accounting for Animal Feed Is Key to Corn Ethanol's Lifecycle Analysis

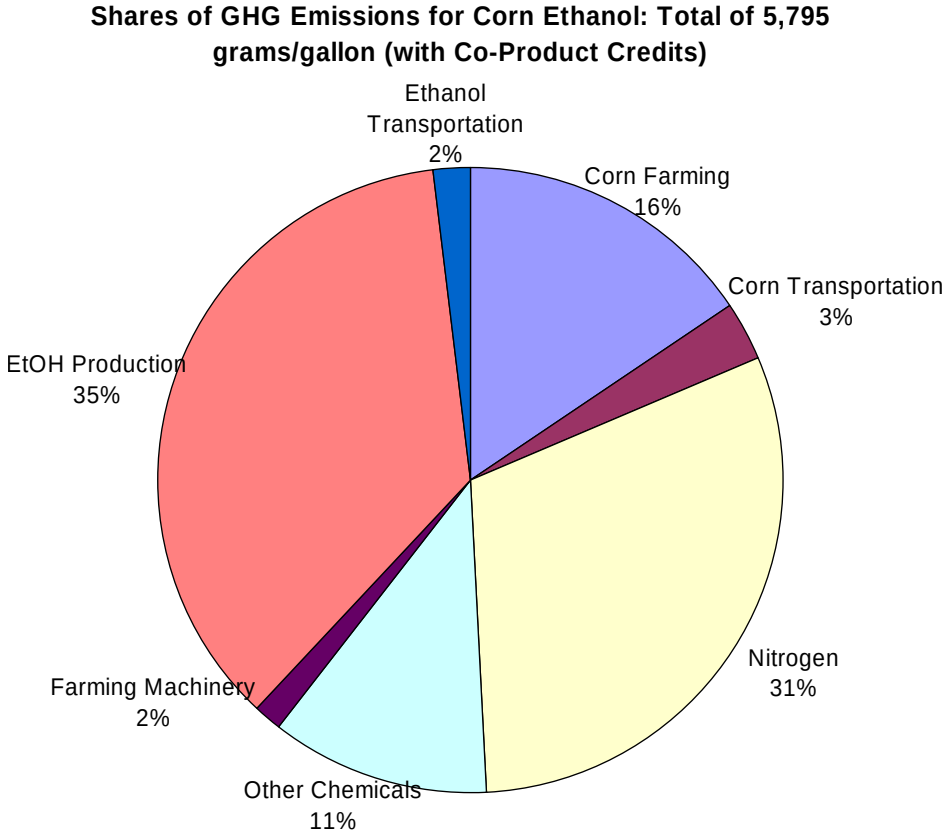
DG S Market Shares In 2006

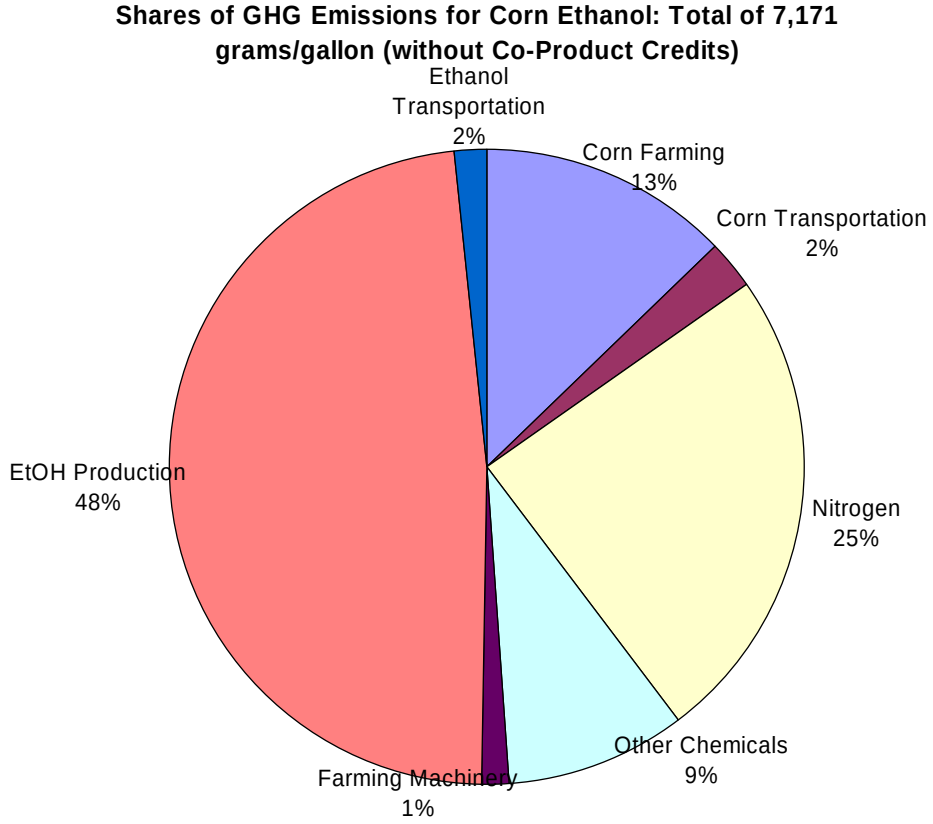


Allocation Method	Wet milling	Dry milling
Weight	52%	51%
Energy content	43%	39%
Process energy	36%	41%
Market value	30%	24%
Displacement	~16%	~20%

Argonne uses the displacement method.

Fuel-Cycle GHG Emission Shares for Corn-Based Ethanol

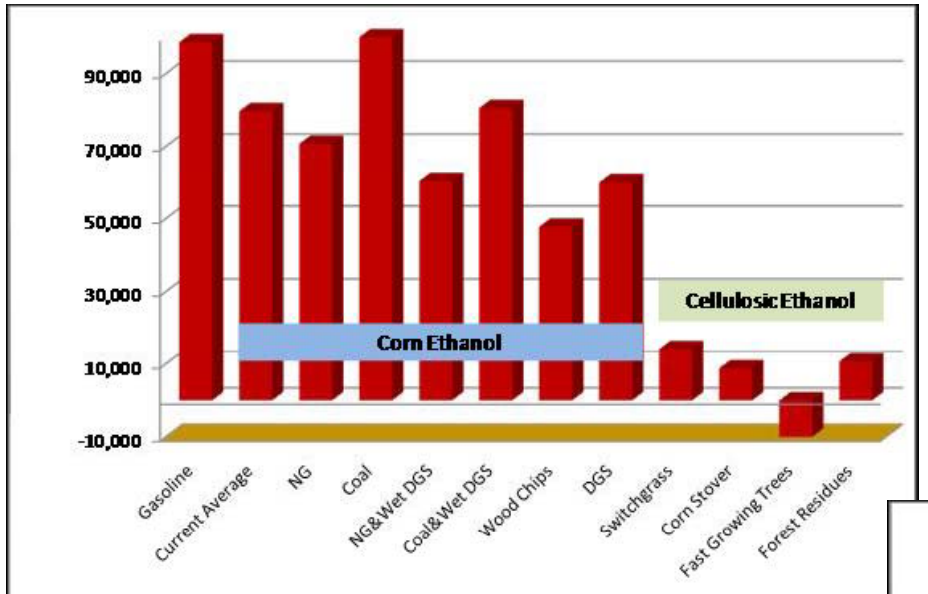




Key Issues Affecting Cellulosic Ethanol Results

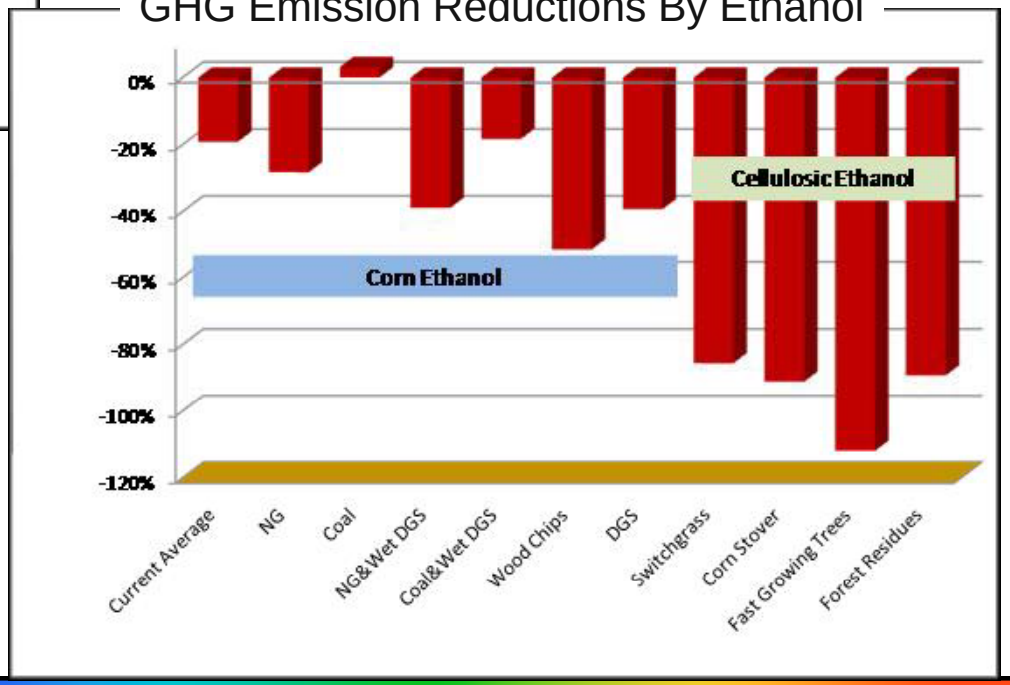
- Cellulosic biomass feedstock types
  - Fast growing trees
    - *Soil carbon could increase*
    - *Fertilizer may be applied*
    - *Irrigation to be needed?*
  - Switchgrass and other native grass
    - *Soil carbon could increase*
    - *Fertilizer will be applied*
    - *Irrigation to be needed?*
  - Crop residues
    - *soil carbon could decrease*
    - *Additional fertilizer will be needed to supplement nutrient removal*
  - Forest wood residues: collection effort could be extensive
- Co-production of ethanol and electricity
  - The amount of electricity produced
  - The types of conventional electric generation to be displaced
- Land use changes could have less effects on cellulosic ethanol's GHG results

GHG Emissions of Corn Ethanol Vary Considerably Among Process Fuels in Plants



WTW GHG Emissions Per Million Btu

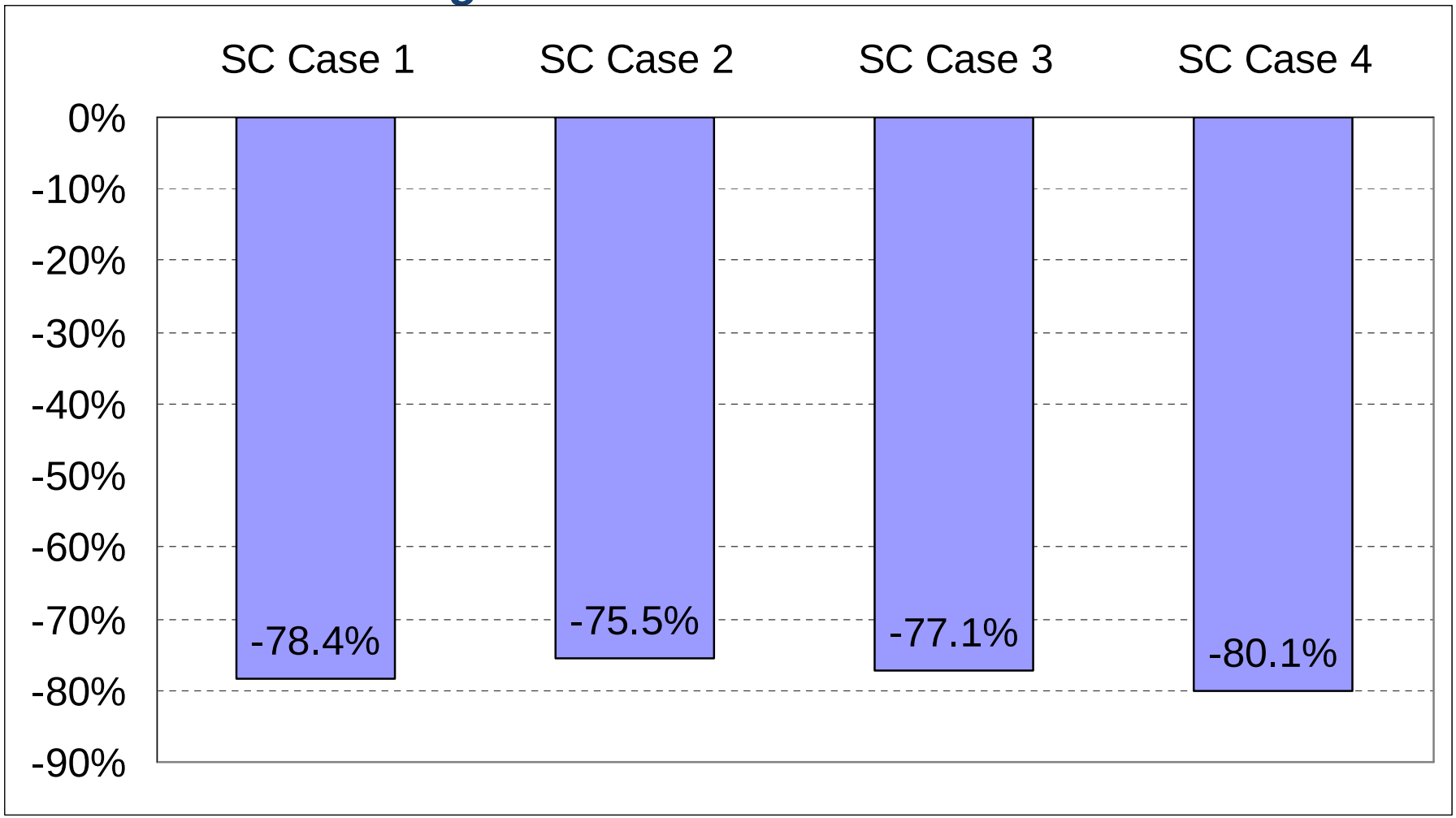
GHG Emission Reductions By Ethanol



Summary and Other Sustainability Issues of Fuel Ethanol

- Corn ethanol can be examined with different process fuels in corn ethanol plants with the new GREET version; it could be examined with different corn farming practices
- So far, corn ethanol has achieved moderate GHG reductions; future GHG effects of corn ethanol are unclear
- The unclear future of corn ethanol's GHG effects is from the potential land changes by the rapid expansion of U.S. corn ethanol production
- Cellulosic ethanol achieves significant GHG reductions
- Water issues of biofuel production
  - Consumptive water requirements: Argonne recently began to address these for biofuels and petroleum fuels
  - Waste water discharge and water quality issues
- Criteria air pollution problems
- Other ecological issues
  - Soil erosion and soil quality impacts
  - Adverse biodiversity effects of monoculture

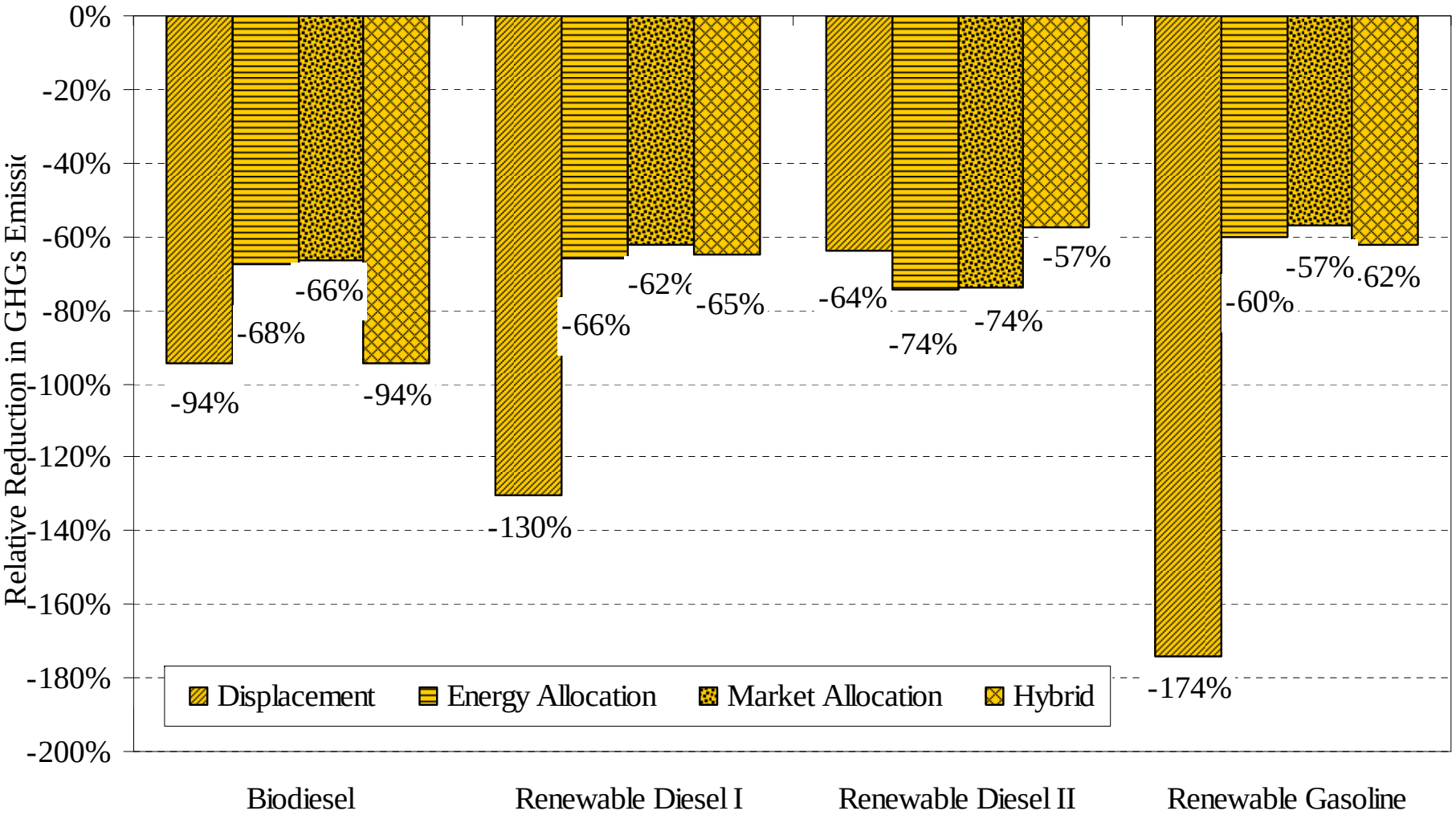
Sugarcane Ethanol Produced in Brazil and Used in the U.S. Results in Large GHG Reductions



Case 1: basecase; Case 2: energy embedded in farming equipment and ethanol plants included; Case 3: energy embedded in farming equipment included; Case 4: production and use in Brazil

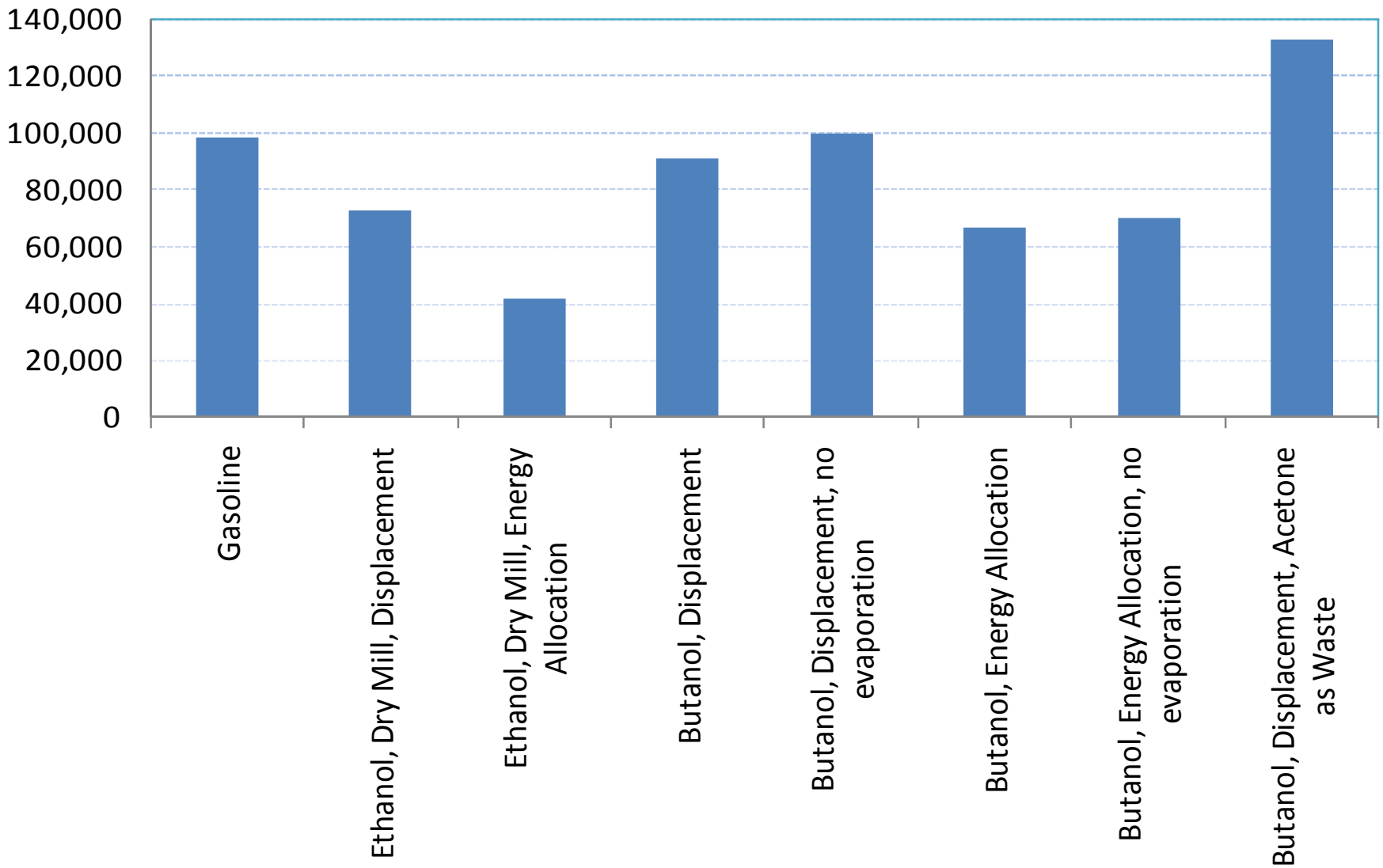
M. Wang, M. Wu, H. Huo, and J. Liu, 2008, Life-Cycle Energy Use and Greenhouse Gas Emission Implications of Brazilian Sugarcane Ethanol Simulated with the GREET Model, forthcoming in International Sugar Journal.

GHG Results of Soybean-Based Biodiesel and Renewable Diesel Are Affected by Methods for Co-Products



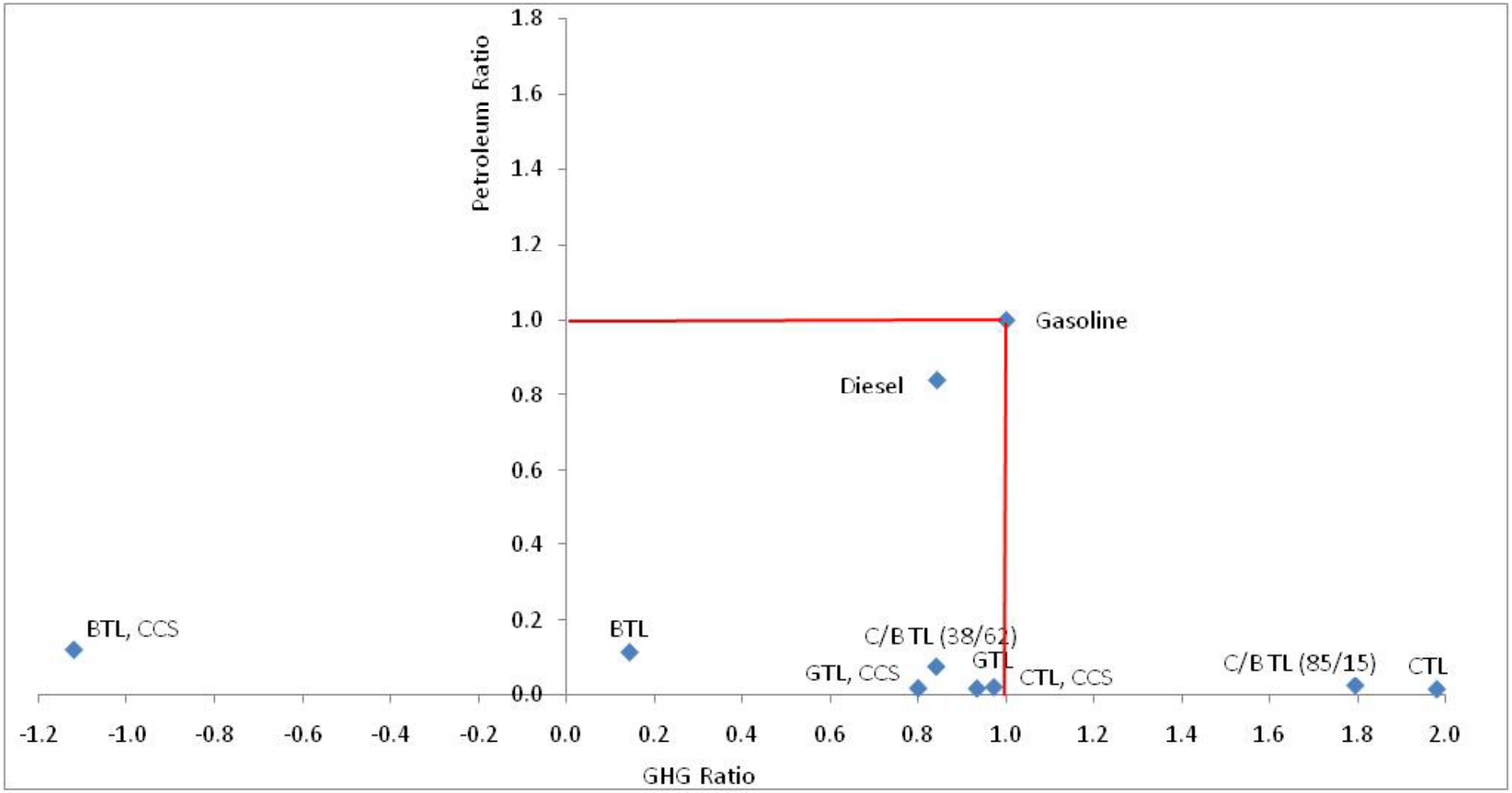
H. Huo, M. Wang, C. Bloyd, V. Putsche, 2008, Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels, Argonne National Laboratory.

Corn-Based Butanol Results Show Importance of Methodologies for Co-Products: GHG Emissions in g/mmBtu



M. Wu, M. Wang, J. Liu and H. Huo, 2007, Life-Cycle Assessment of Corn-Based Butanol as a Potential Transportation Fuel, Argonne National Laboratory

Trade-Offs Between Petroleum Reductions and GHG Reductions by FT Diesel from Different Feedstocks



Outstanding Life-Cycle Analysis Issues

- Land use changes and resultant GHG emissions for biofuel production
- 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 1.8 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)