GREET Life-Cycle Analysis Approach and Key Issues

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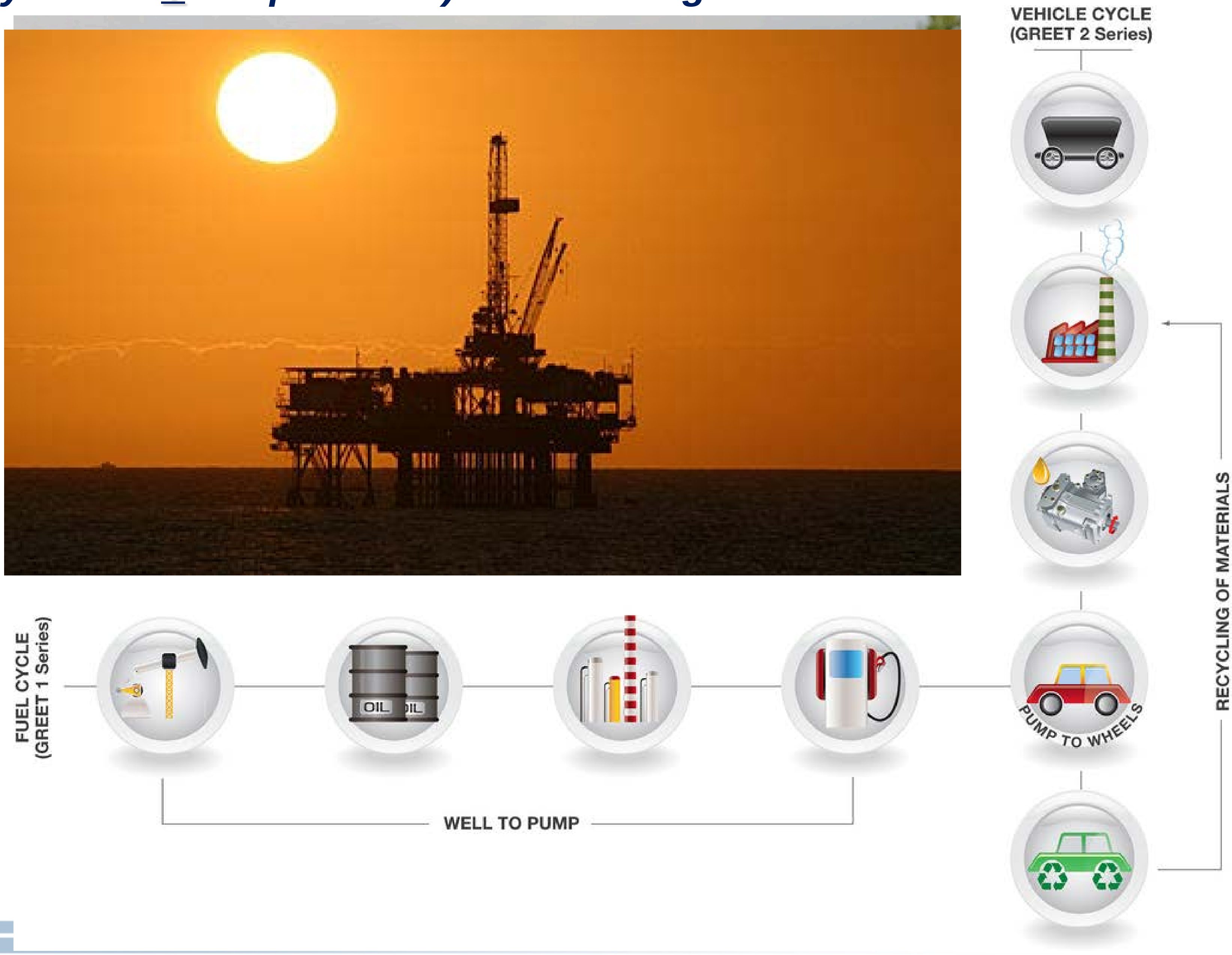
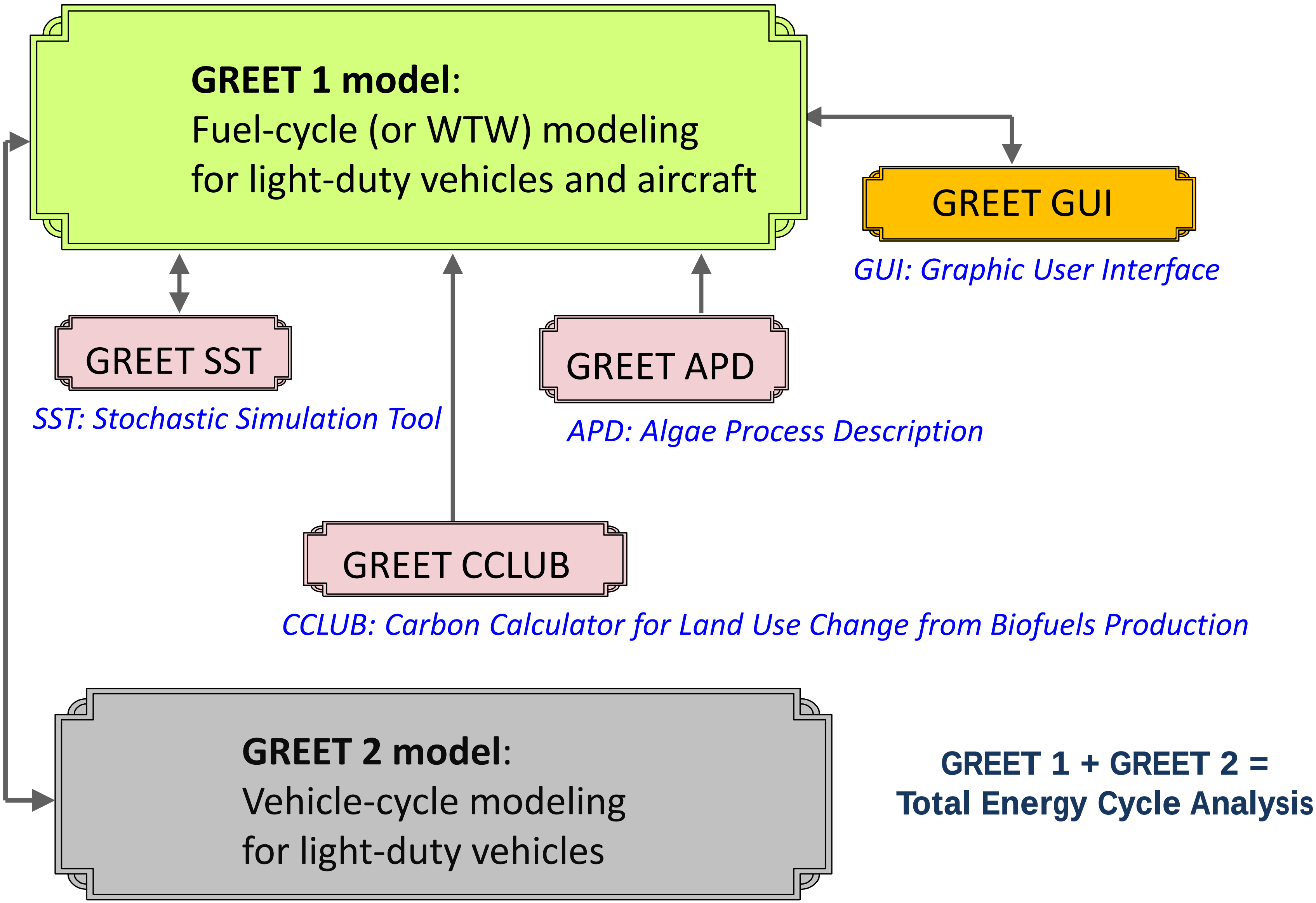
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model at Argonne National Lab

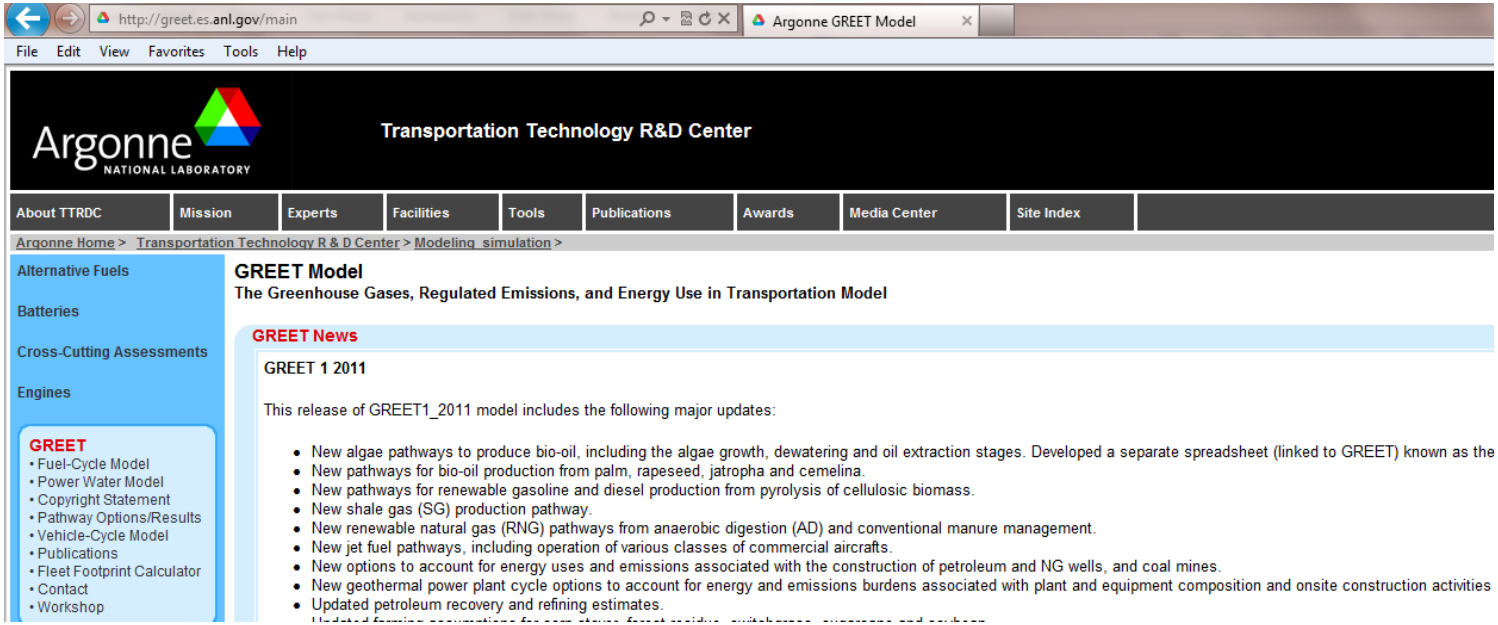


The Suite of GREET Models

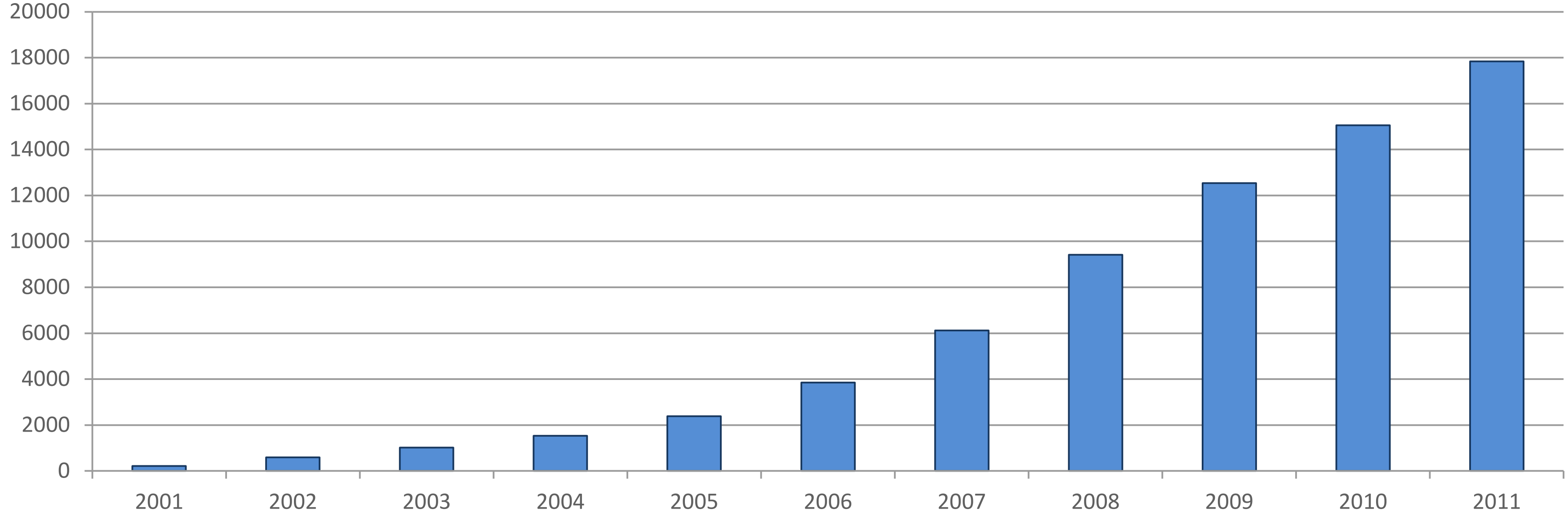


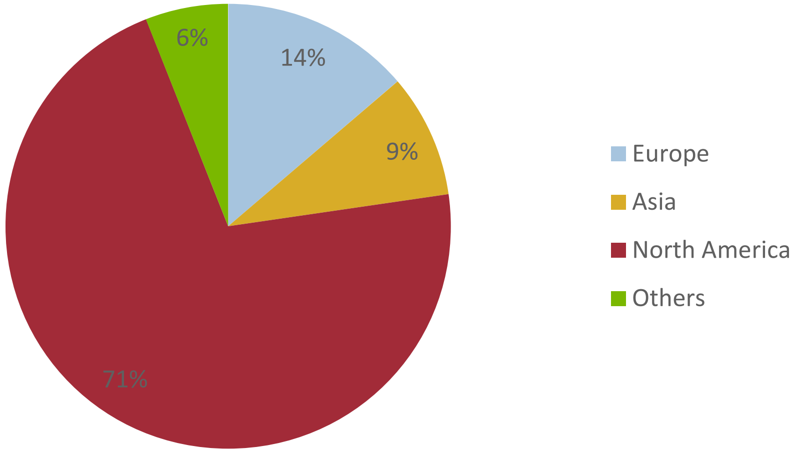
GREET Development Has Been Supported by Several DOE EERE Programs

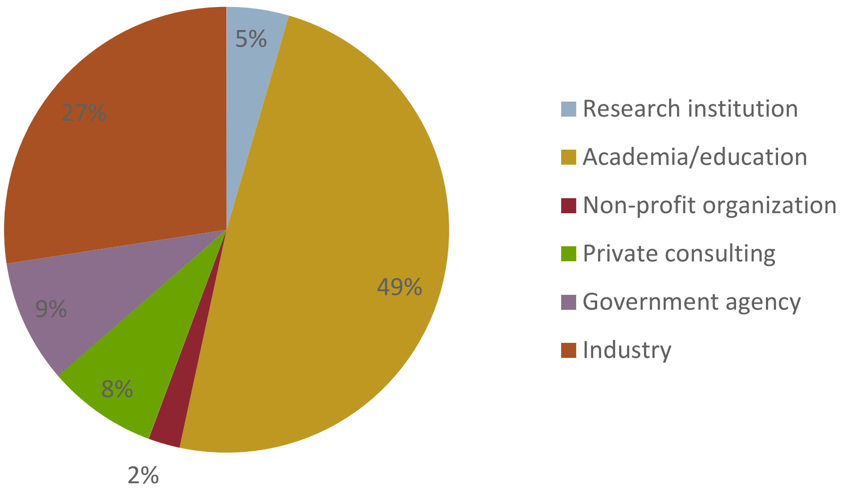
- Four DOE EERE program sponsors
  - Vehicle Technology Program
  - Office of Biomass Program
  - Fuel Cell Technology Program
  - Geothermal Technology Program
- The most recent GREET version (GREET1_2011) was released in Oct. 2011
- GREET and its documents are available at the GREET website



There Are More Than 18,000 Registered GREET Users Worldwide







Life-Cycle Analysis (LCA) Models Available Worldwide for Transportation Fuel Examination

- The GREET model at Argonne National Laboratory
  - CARB LCFS
  - One of a suite of models of EPA RFS2
- The lifecycle emission model (LEM) at University of California at Davis
- Canadian GHGenius model
- LBST’s E3 database in Europe
  - EU Renewable Energy Directive (RED) and Fuel Quality Directive (FQD)
- Other generic LCA models that can be applied to examine transportation fuels and vehicle technologies
- Newly emerging consequential LCA methods based on economic interactions within a country and/or in the world

The GREET Model Estimates Energy Use and Emissions of GHGs and Criteria Pollutants for Vehicle/Fuel Systems

- Energy use
  - Total energy: fossil energy and renewable energy
    - Fossil energy: petroleum, natural gas, and coal (they are estimated separately)
    - Renewable energy: biomass, nuclear energy, hydro-power, wind power, and solar energy
- Greenhouse gases (GHGs)
  - $CO_{2,}$ $CH_{4,}$ and N_2O
  - CO_2e of the three (with their global warming potentials)
- Criteria pollutants
  - VOC, CO, $NO_{x,}$ $PM_{10,}$ $PM_{2.5,}$ and SO_x
  - They are estimated separately for
    - Total (emissions everywhere)
    - Urban (a subset of the total)

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

Feedstocks	Fuels
Petroleum Conventional Oil Sands	Gasoline Diesel Liquefied Petroleum Gas Residual Oil (to electricity) Jet Fuel
Natural Gas North American Shale Gas Non-North American	Compressed Natural Gas Liquefied Natural Gas Liquefied Petroleum Gas Hydrogen Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Jet Fuel
Corn	Ethanol Butanol
Sugarcane	Ethanol
Soybeans	Biodiesel Renewable Diesel Renewable Gasoline 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 Biogas from anaerobic digestion	Compressed Natural Gas Liquefied Natural Gas Hydrogen Methanol Dimethyl Ether Fischer-Tropsch Diesel 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 (hydro, wind, solar, geothermal)	Electricity
Algae	Biodiesel Renewable Diesel Renewable Gasoline Renewable Jet Fuel

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.

GREET Includes Many Biofuel Production Pathways

- Ethanol via fermentation from
  - Corn
  - Sugarcane
  - Cellulosic biomass
    - Crop residues
    - Dedicated energy crops
    - Forest residues

- Renewable natural gas from
  - Landfill gas
  - Anaerobic digestion of animal wastes

- Corn to butanol

- Cellulosic biomass via gasification to
  - Fischer-Tropsch diesel
  - Fischer-Tropsch jet fuel

- Soybeans to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable jet fuel

- Cellulosic biomass via pyrolysis to
  - Gasoline
  - Diesel
  - Jet fuel

- Algae to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable jet fuel

Electricity Generation Systems in GREET

- **Coal: Steam Boiler and IGCC**
  - Coal mining and cleaning
  - Coal transportation
  - Power generation

- **Natural Gas: Steam Boiler, Gas Turbine, and NGCC**
  - NG recovery and processing
  - NG transmission
  - Power generation

- **Biomass: Steam Boiler**
  - Biomass farming and harvesting
  - Biomass transportation
  - Power generation

- **Nuclear: Light Water Reactor**
  - Uranium mining
  - Yellowcake conversion
  - Enrichment
  - Fuel rod fabrication
  - Power generation

- **Hydro Power**

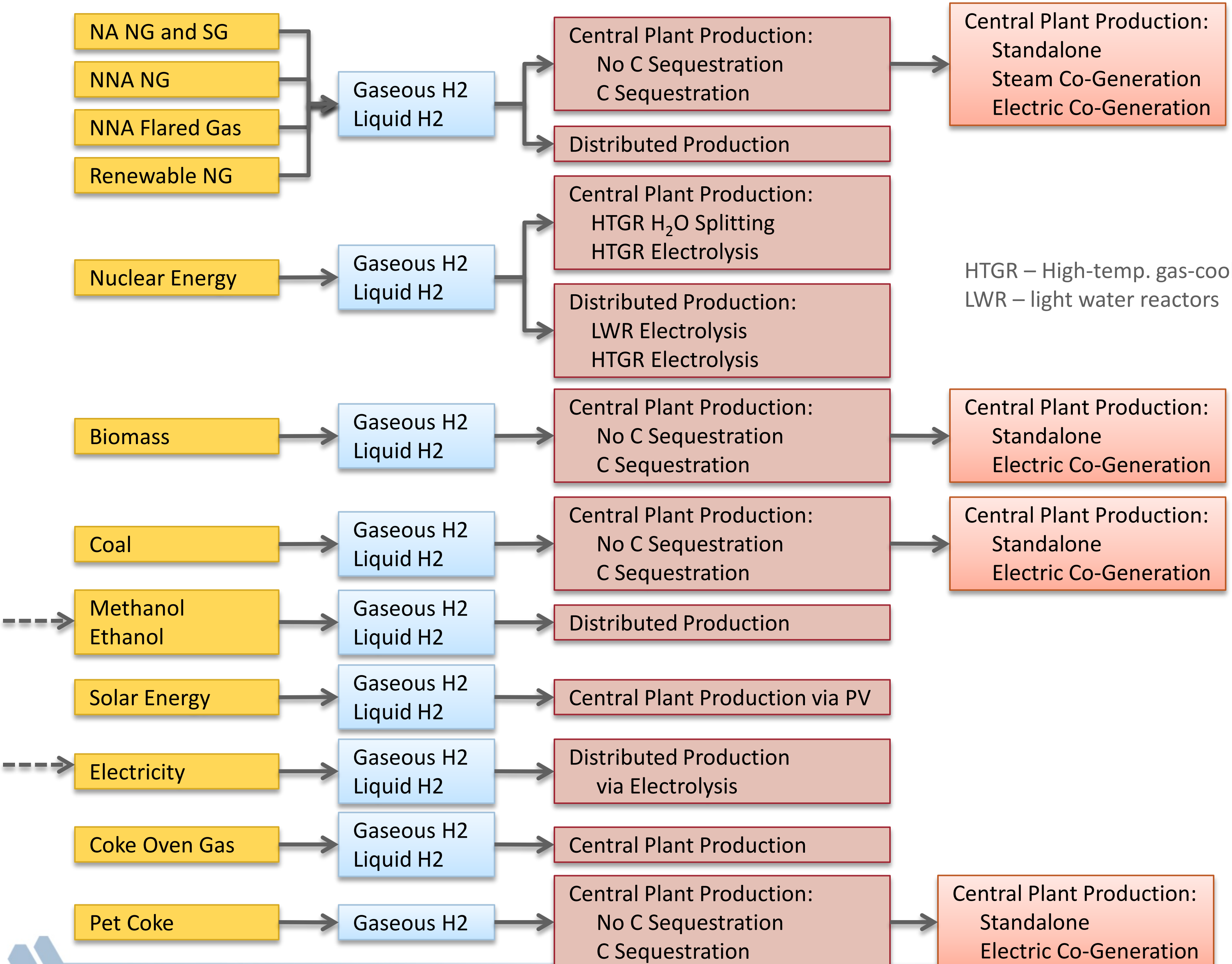
- **Wind Power**

- **Residual Oil: Steam Boiler**
  - Oil recovery and transportation
  - Oil refining
  - Residual oil transportation
  - Power generation

- **Solar Power via Photovoltaics**

- **Geothermal Power**

Many Hydrogen Production Pathways Are Included in GREET



HTGR – High-temp. gas-cooled reactors
LWR – light water reactors

GREET Examines
More Than 80 Vehicle/Fuel Systems

Conventional Spark-Ignition Engine Vehicles
- Gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol
- Renewable gasoline
- Pyrolysis-based gasoline

Spark-Ignition, Direct-Injection Engine Vehicles
- Gasoline
- Methanol and ethanol

Compression-Ignition, Direct-Injection Engine Vehicles
- Diesel
- Fischer-Tropsch diesel
- Dimethyl ether
- Biodiesel
- Renewable diesel
- Pyrolysis-based diesel

Fuel Cell Vehicles
- On-board hydrogen storage
  – Gaseous and liquid hydrogen from various sources
- On-board hydrocarbon reforming to hydrogen

Battery-Powered Electric Vehicles
- Various electricity generation sources

Hybrid Electric Vehicles (HEVs)
- Spark-ignition engines:
  – Gasoline
  – Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  – Gaseous and liquid hydrogen
  – Methanol and ethanol
- Compression-ignition engines
  – Diesel
  – Fischer-Tropsch diesel
  – Dimethyl ether
  – Biodiesel

Plug-in Hybrid Electric Vehicles (PHEVs)
- Spark-ignition engines:
  – Gasoline
  – Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
  – Gaseous and liquid hydrogen
  – Methanol and ethanol
- Compression-ignition engines
  – Diesel
  – Fischer-Tropsch diesel
  – Dimethyl ether
  – Biodiesel
- Fuel cell
  – Gaseous and liquid hydrogen from various sources

Vehicle Operation Simulations in GREET

- Three vehicle classes
  - Passenger cars
  - LDT1 (GVW < 6000 lb)
  - LDT2 (6000 lb < GVW <= 8500 lb)
- Lab-tested emissions and fuel economy results vs. on-road results for vehicles
  - Driving cycle adjustment factors: adjusted for on-road fuel economy
    - ✓ EPA (post 2008 MY) mpg-based formulae
    - ✓ 43/57 City/HWY split
    - ✓ Special treatment for electric drive technologies (PHEVs, BEVs, and FCVs)
  - Part of GREET research issues; entry of processed data into GREET
- Modeling of model-year vehicle technologies in a calendar year
  - Snapshot modeling of vehicle lifetime performance
  - Built Inside GREET
  - The latter is 5 years after the former
- Fuel blends (e.g., E10 and B5) for use in vehicles vs. effects of pure fuel (e.g., ethanol and biodiesel) to displace baseline fuels
  - Need extra step in the GREET *Results* sheet
- Per-mile WTW results from drivers' point of view vs. per-unit fuel results from fuel providers' point of view
  - Need extra step in the GREET *Results* sheet

Aviation Fuel Options in GREET

Fuels and Feedstocks

- ❑ **Petroleum Jet Fuel**
  - Conventional Crude
  - Oil Sand
- ❑ **Pyrolysis Oil Jet Fuel**
  - Crop Residues
  - Forest Residues
  - Dedicated Energy Crops
- ❑ **Hydrotreated Renewable Jet Fuel**
  - Soybeans
  - Palm Oil
  - Rapeseeds
  - Jatropha
  - Camelina
  - Algae
- ❑ **Fischer-Tropsch Jet Fuel**
  - North American Natural Gas
  - Non-North American Natural Gas
  - Renewable Natural Gas
  - Shale Gas
  - Biomass via Gasification
  - Coal via Gasification
  - Coal/Biomass via Gasification

Aircraft Types

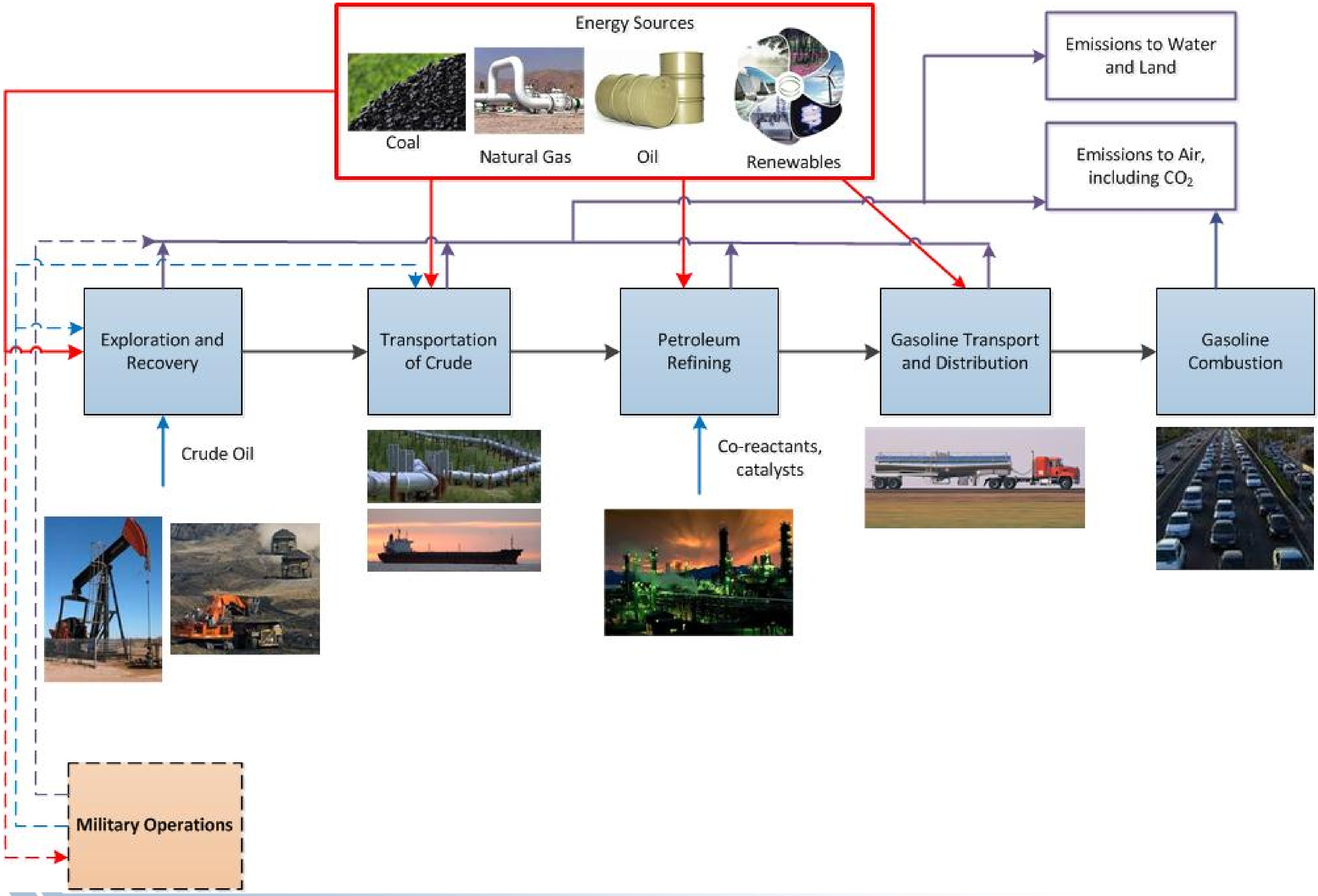
- ❑ **Passenger Aircraft**
  - Single Aisle
  - Small Twin Aisle
  - Large Twin Aisle
  - Large Quad
  - Regional Jet
  - Business Jet
- ❑ **Freight Aircraft**
  - Single Aisle
  - Small Twin Aisle
  - Large Twin Aisle
  - Large Quad
- ❑ **LCA Functional Units**
  - Per MJ of fuel
  - Per kg-km
  - Per passenger-km

(In collaboration with MIT PARTNER)

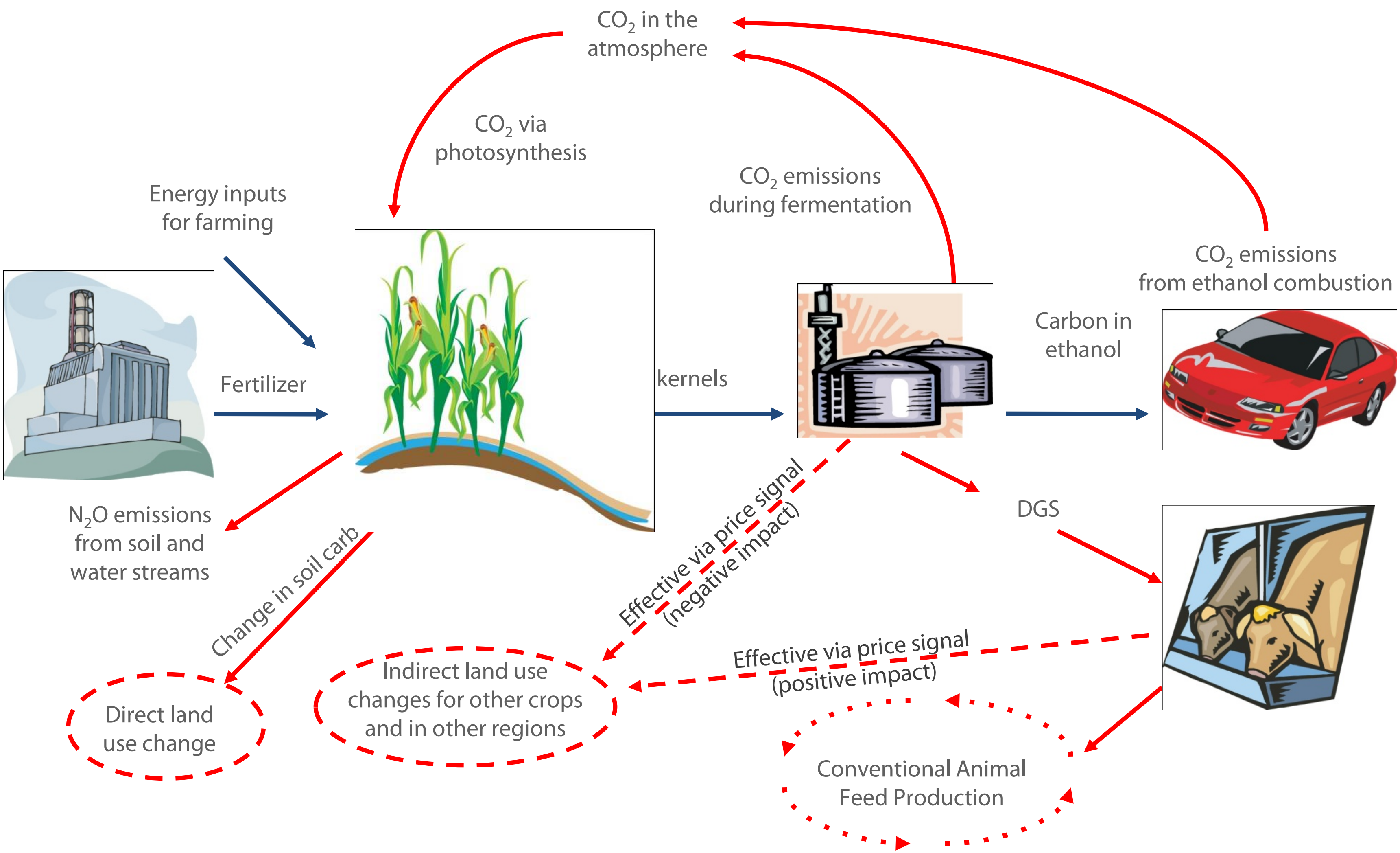
Key LCA Issues

- System boundary
  - Construction of infrastructure vs. operation stages of the complete life cycle
  - Indirect effects primarily via market/pricing effects
- Technology choices for LCAs
  - LCA comparison among pathway technologies
    - ✓ Fuel production: commercial ones vs. emerging ones still at the R&D stage
    - ✓ Vehicle technologies: performance equivalency
  - Pathway definition: technology options for pathway processes
    - ✓ Existing vs. emerging
    - ✓ Environmental sustainability vs. economic viability
  - Inter- and intra-pathway technology choices result in many options
- Methods of addressing co-products of transportation fuels
- Life-cycle analysis methodologies
  - Attributional LCA: GREET approach (with supplement of consequential LCA results)
  - Consequential LCA

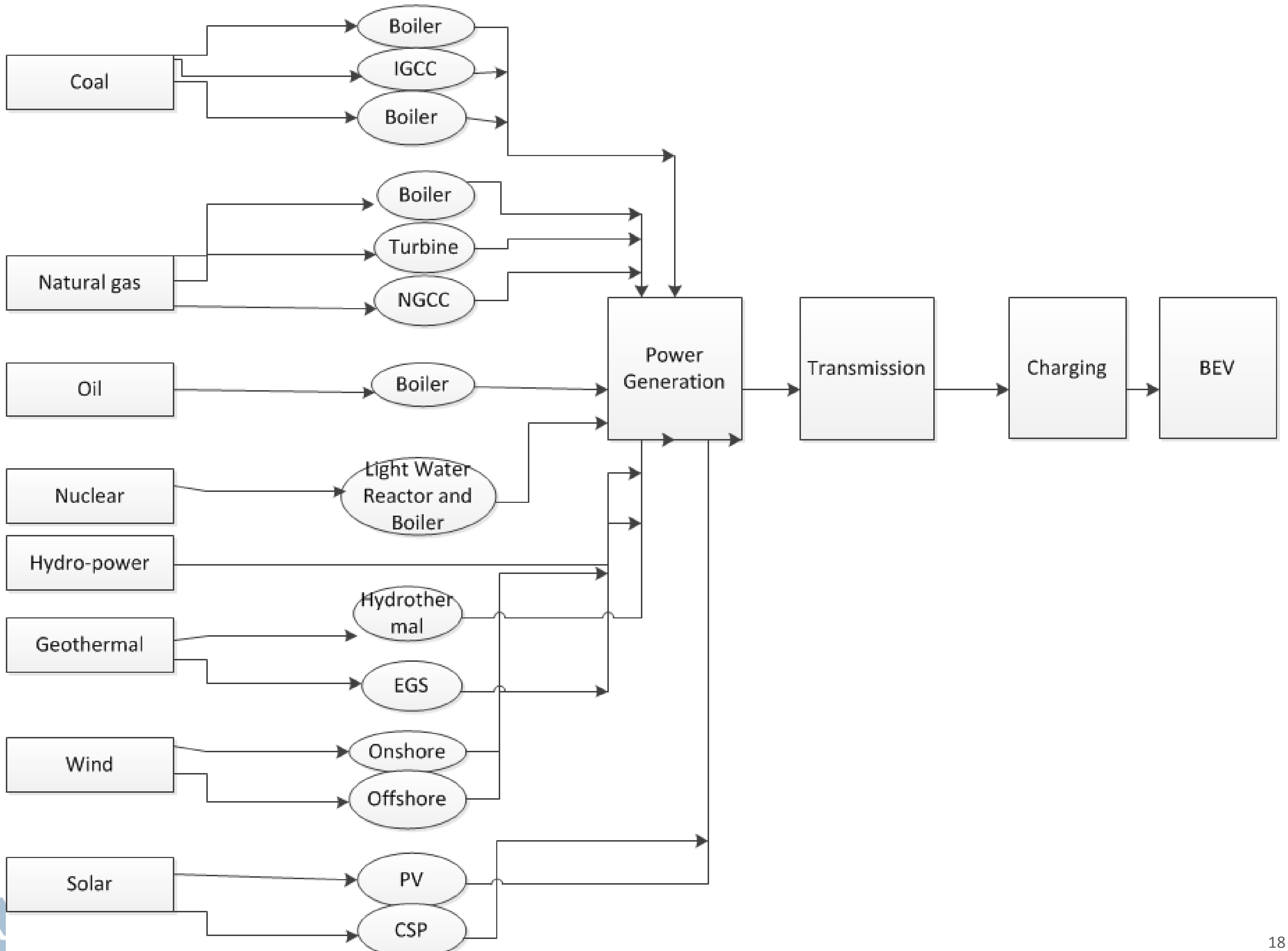
LCA System Boundary: Petroleum to Gasoline



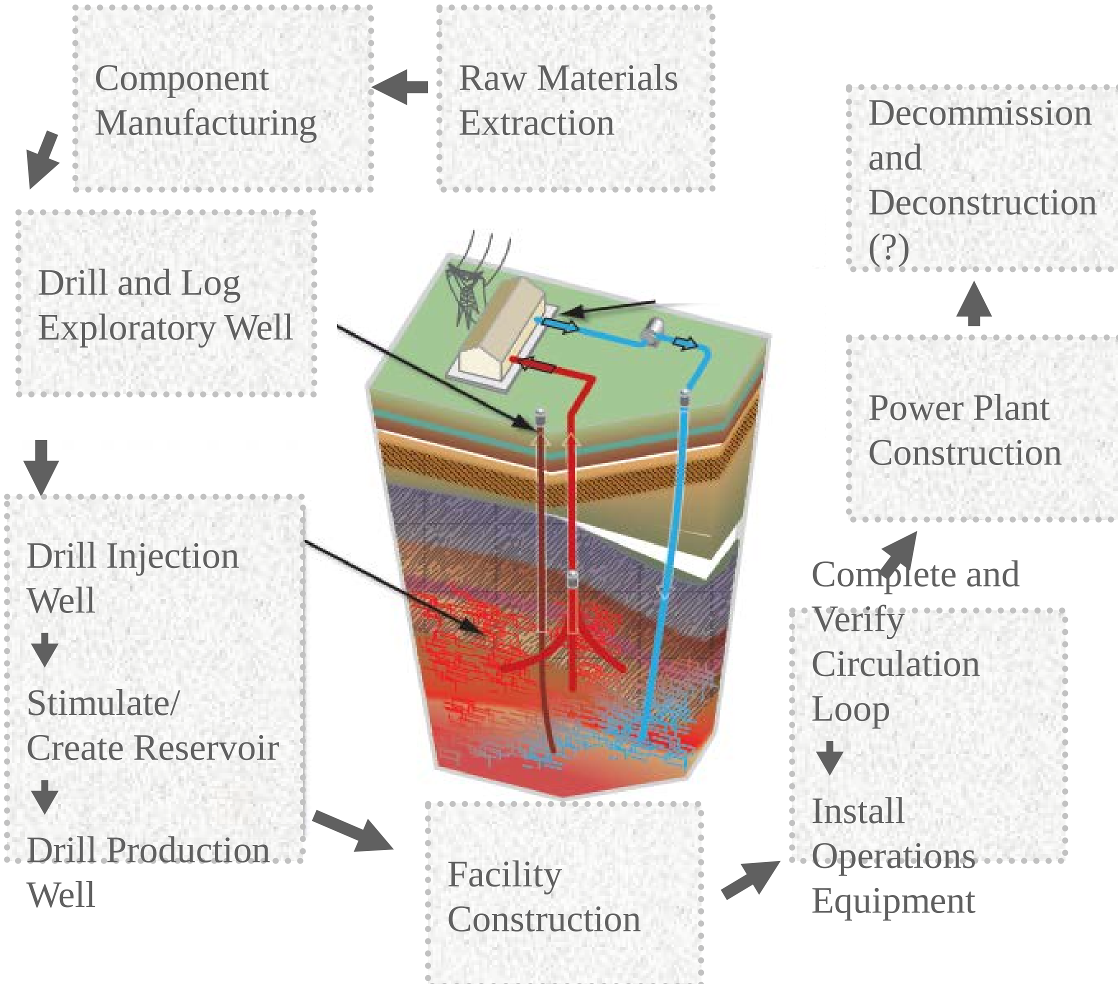
LCA System Boundary: Corn to Ethanol



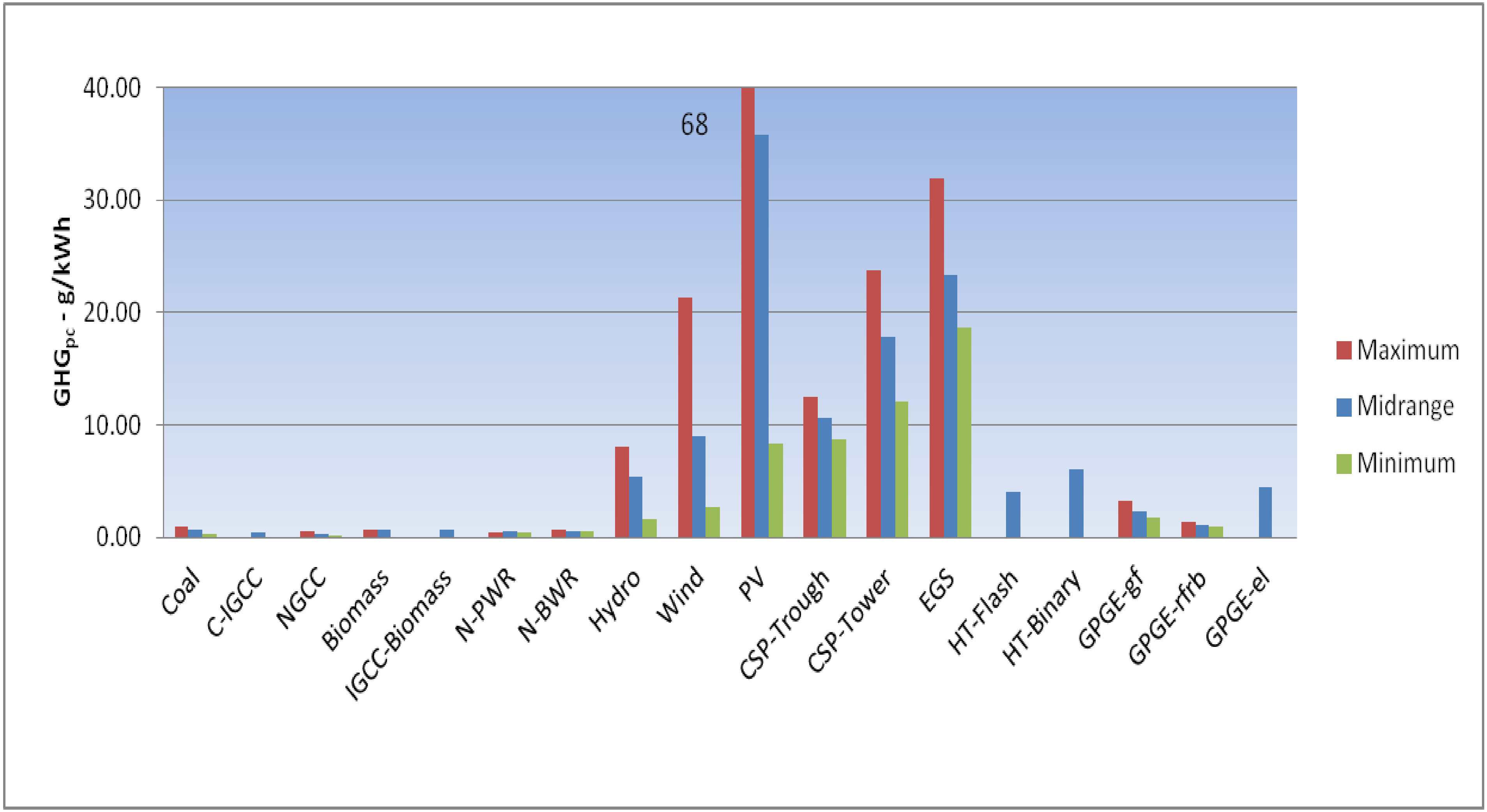
Life-Cycle Analysis of Electricity



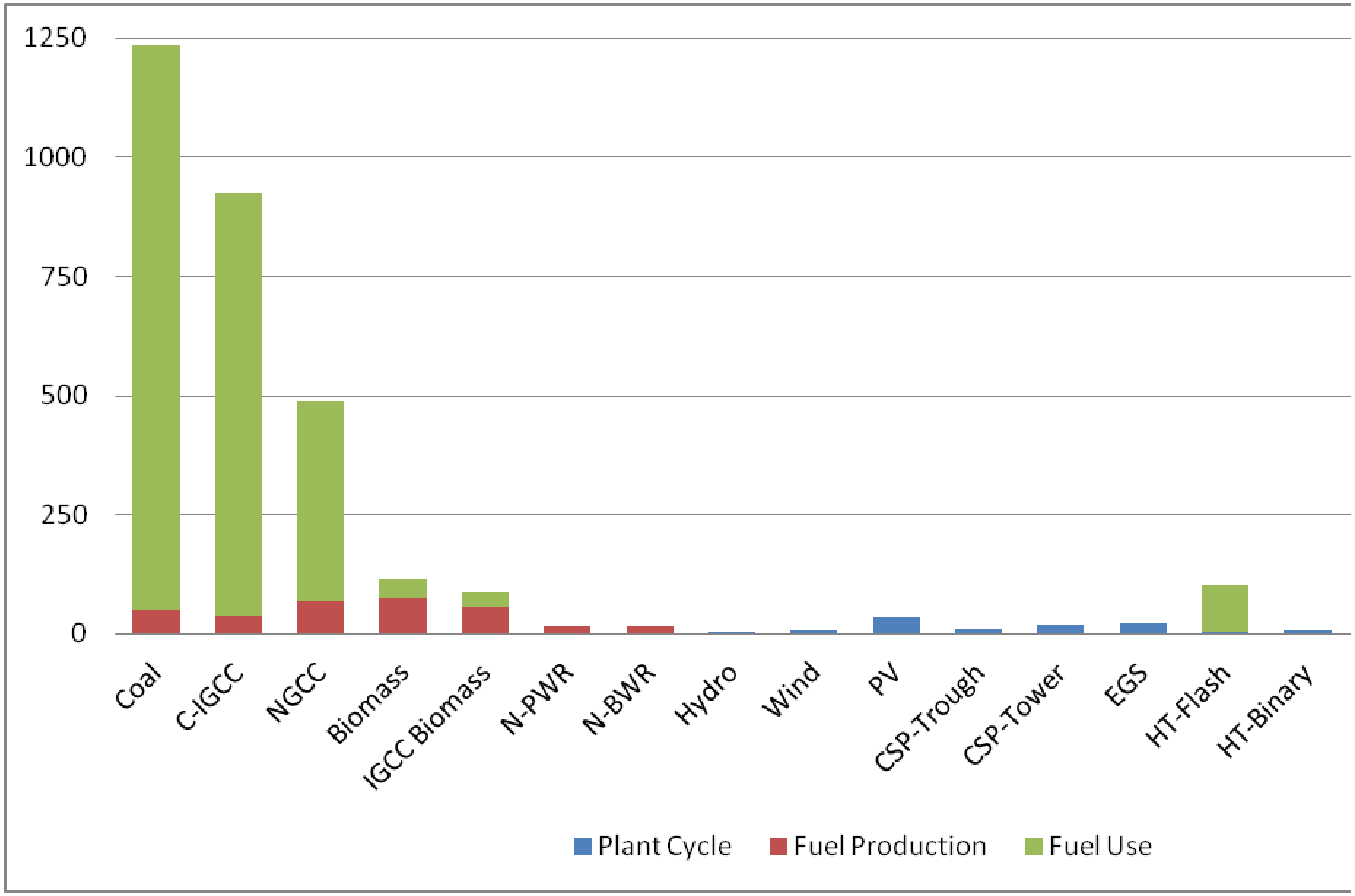
LCA Approach for Geothermal Power Technologies: Construction of Geothermal Facilities



Facility Construction GHG Emissions of Different Electric Power Systems



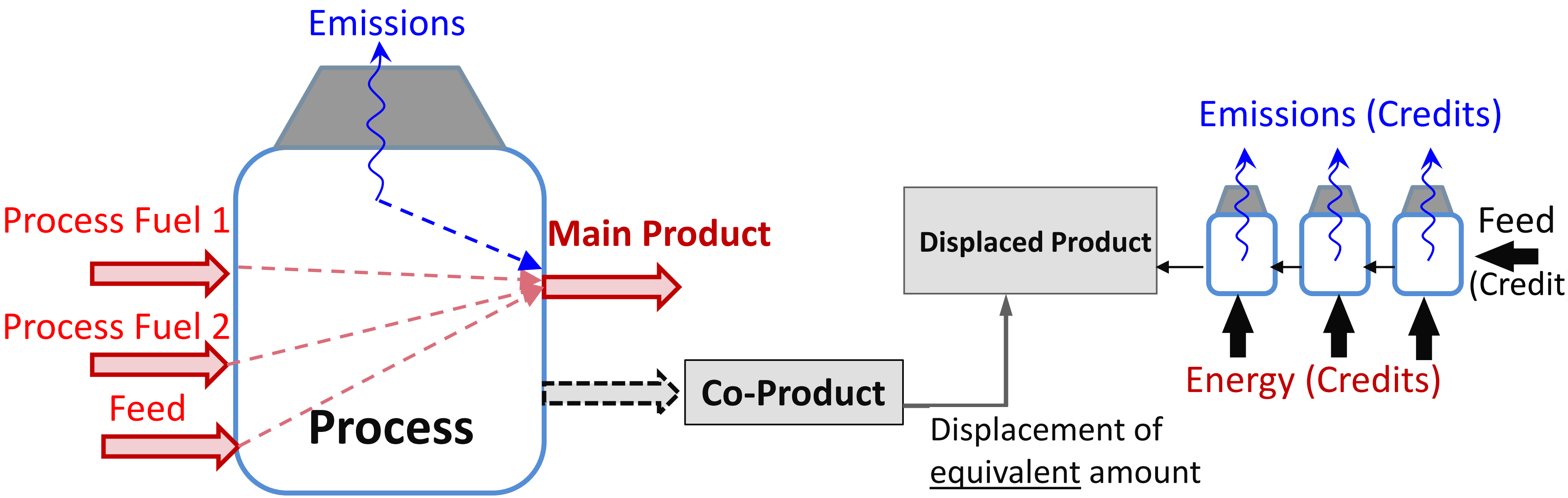
Plant Construction and Operation GHG Emissions of Different Power Systems (g of CO2e per kWh)



Co-Product Methods: Benefits and Issues

- Displacement method
  - Data intensive: need detailed understanding of the displaced product sector
  - Dynamic results: fluctuate with economic and market modifications
- Allocation methods: based on mass, energy, or market revenue
  - Easy to use
  - Frequent updates not required for mature industry, e.g. petroleum refineries
  - Mass-based allocation: not applicable for certain cases
  - Energy-based allocation: less accurate with non-fuel co-products
  - Market revenue based allocation: subject to price variation
- Process energy use approach
  - Requires detailed engineering analysis
  - Must allocate upstream burdens based on mass, energy, or market revenue
- There is no consensus in policy and research arena on which method is the most appropriate; GREET offers several methods for users to select

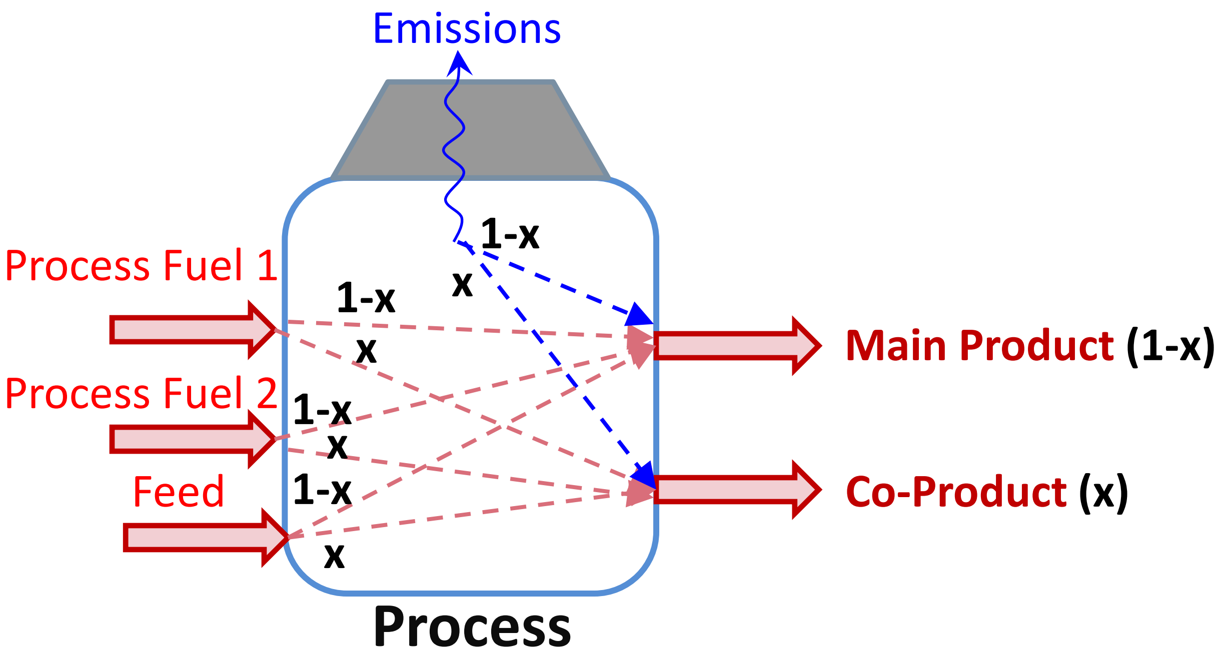
Co-Product *Displacement* of Equivalent Product



Important Notes:

- Main product carry the burden of all process energy and emissions
- Co-product does not carry any burden
- Displaced product is identical or equivalent to co-product
  - ✓ If not identical, a displacement ratio may apply
- All life-cycle energy and emissions of the displaced product are credited to main product
- For large co-product/main product ratio, credits may overwhelm main process emissions

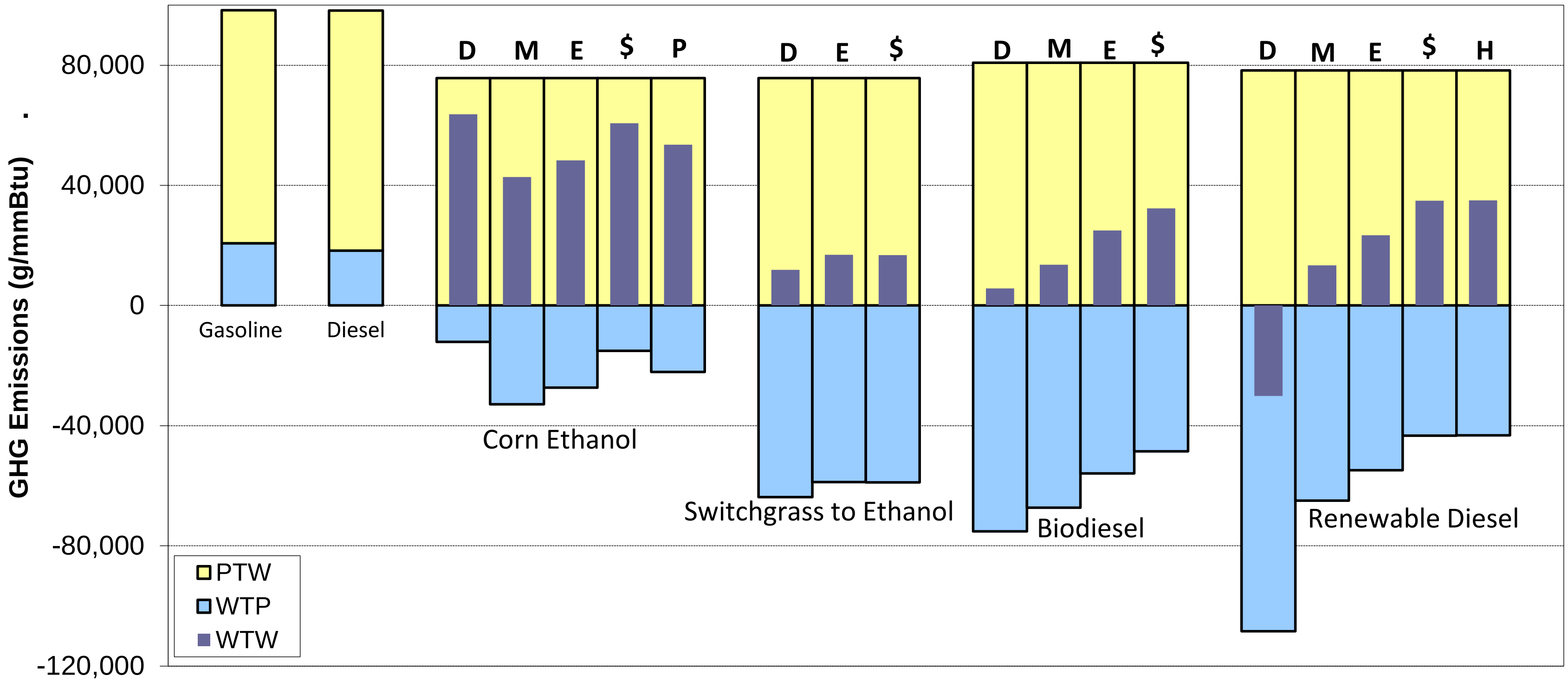
Allocation of Process Energy and Emissions to Co-Products



Important Notes:

- **x** is the ratio of co-product in all products by mass, energy, or market value
- Main product and co-product carry energy and emissions burden based on their ratios in the total products
- The main product and co-product are equivalent (function at end use, quality, etc.)
- Same process efficiency applies to all products for energy allocation (implied)

Choice of Co-Product Methods Can Have Significant LCA Effects for Biofuels

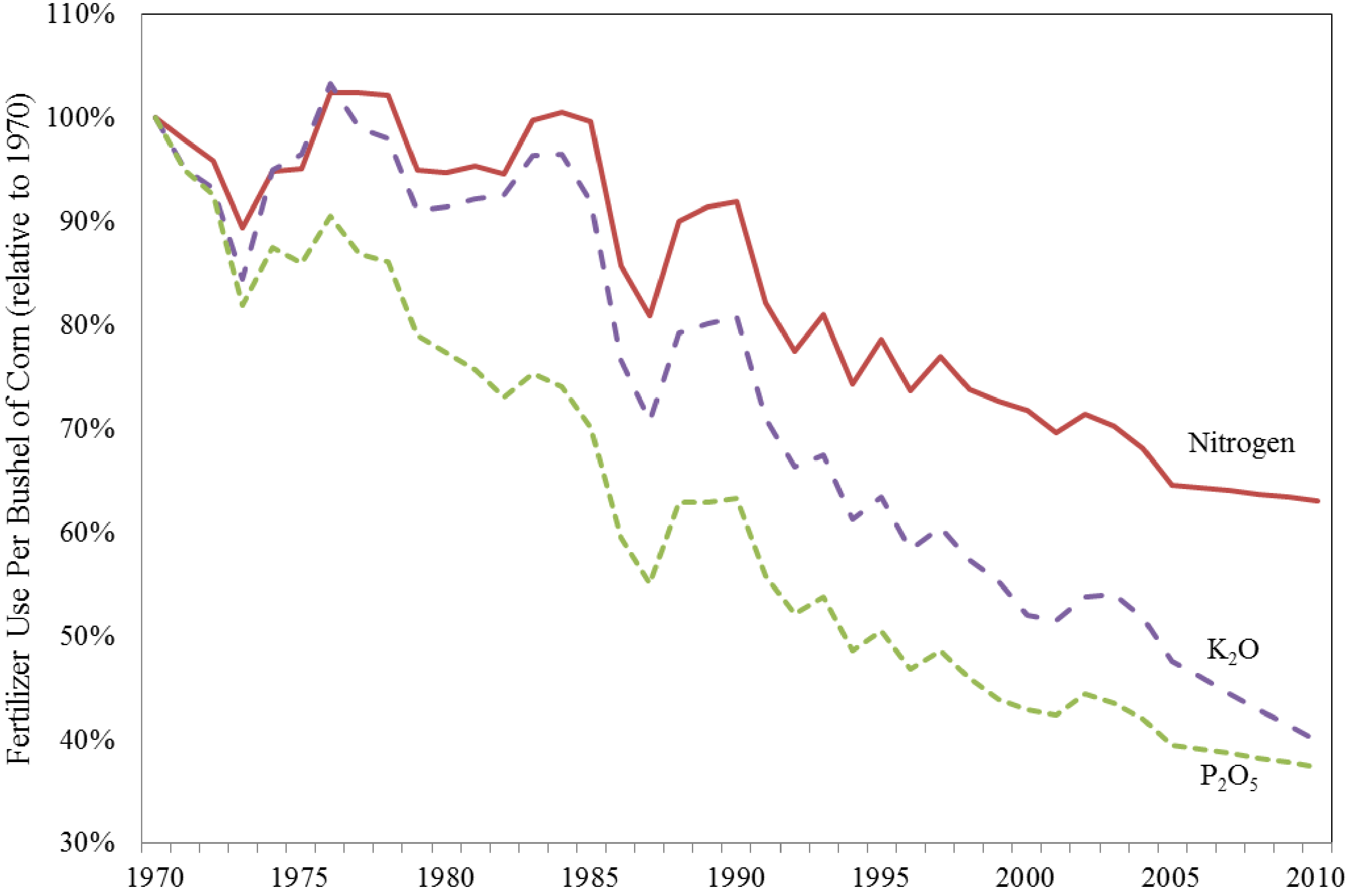


D: Displacement
M: Mass based
E: Energy Based

$: Market Value
P: Process Purpose
H: Hybrid Allocation

In Wang et al. (Energy Policy J., 2011)

Fertilizer Use in U.S. Corn Farming Has Reduced Significantly in the Past 40 Years



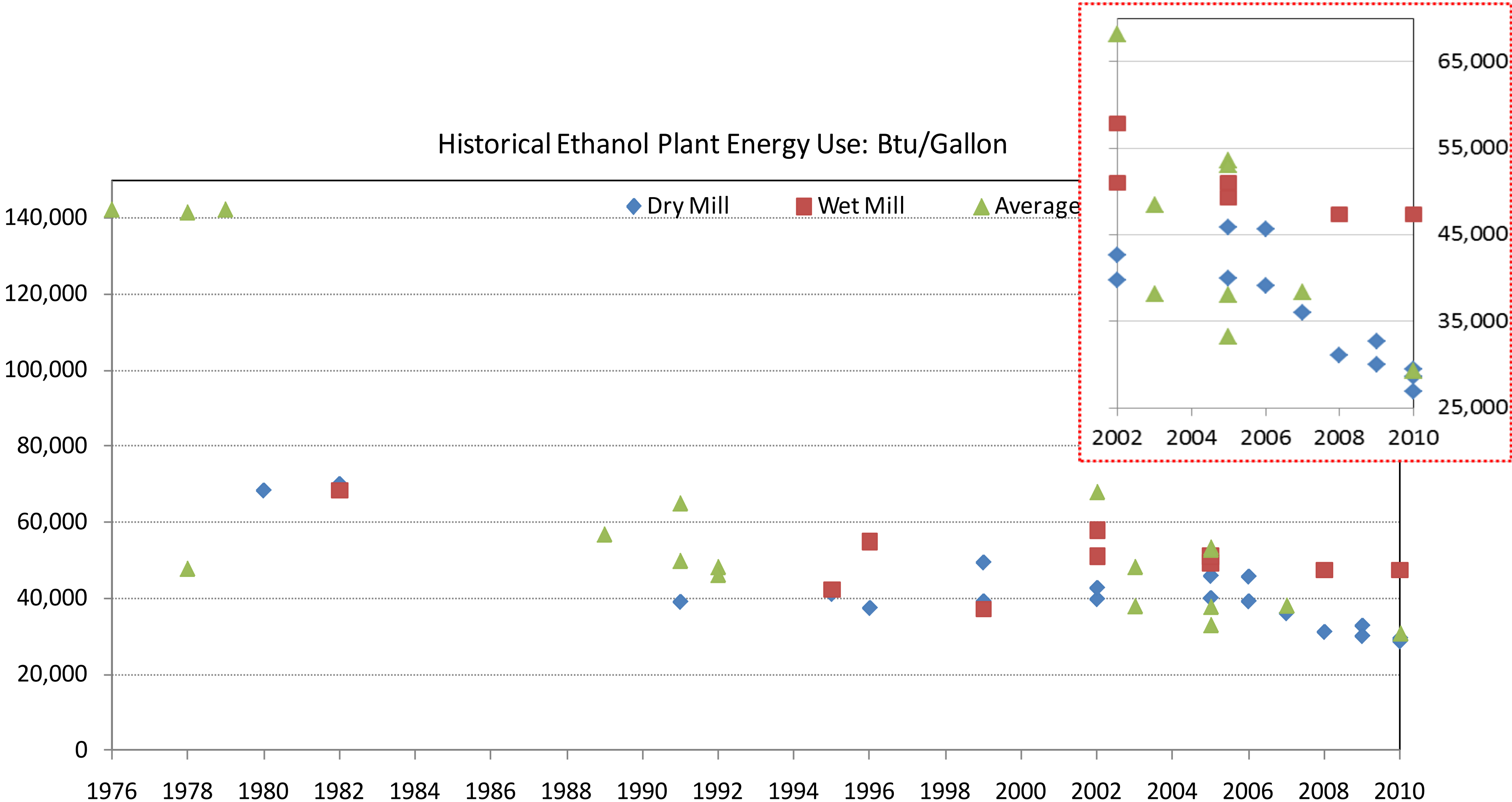
Intensity of Fertilizer Use in U.S. Corn Farming and Energy Use and GHG Emissions of Fertilizer Production and Use

	Nitrogen	Phosphate	Potash	Lime
Fertilizer Use Intensity: **lb of nutrient per bushel of corn**	**0.96**	**0.34**	**0.40**	**2.44**
Energy Use for Fertilizer Production: **Btu/lb of nutrient**	**20,741**	**5,939**	**3,719**	**3,398**
GHG Emissions of Fertilizer Production: **g CO_{2e}/lb of nutrient**	**1,359**	**460**	**302**	**274**
GHG Emissions from Fertilizer in Field: **g CO_{2e}/lb of nutrient**	**2,965**[a]	**0**	**0**	**200**[b]
Total GHG Emissions: **g CO2e/lb of fertilizer nutrient**	**4,324**	**460**	**302**	**474**
Total GHG Emissions: **g CO2e/bushel of corn**	**4,151**	**156**	**121**	**1,157**

[a] This is CO_{2e} emissions of N_2O from nitrification and denitrification of nitrogen fertilizer in cornfields.

[b] This is CO_2 emissions of converting calcium carbonate (limestone) to calcium oxide (burnt lime) in cornfields.

Trend of 35 Studies in the Past 35 Years: Energy Use in U.S. Corn Ethanol Plants Has Decreased Significantly



In Wang et al. (2011), Biomass and Bioenergy Journal

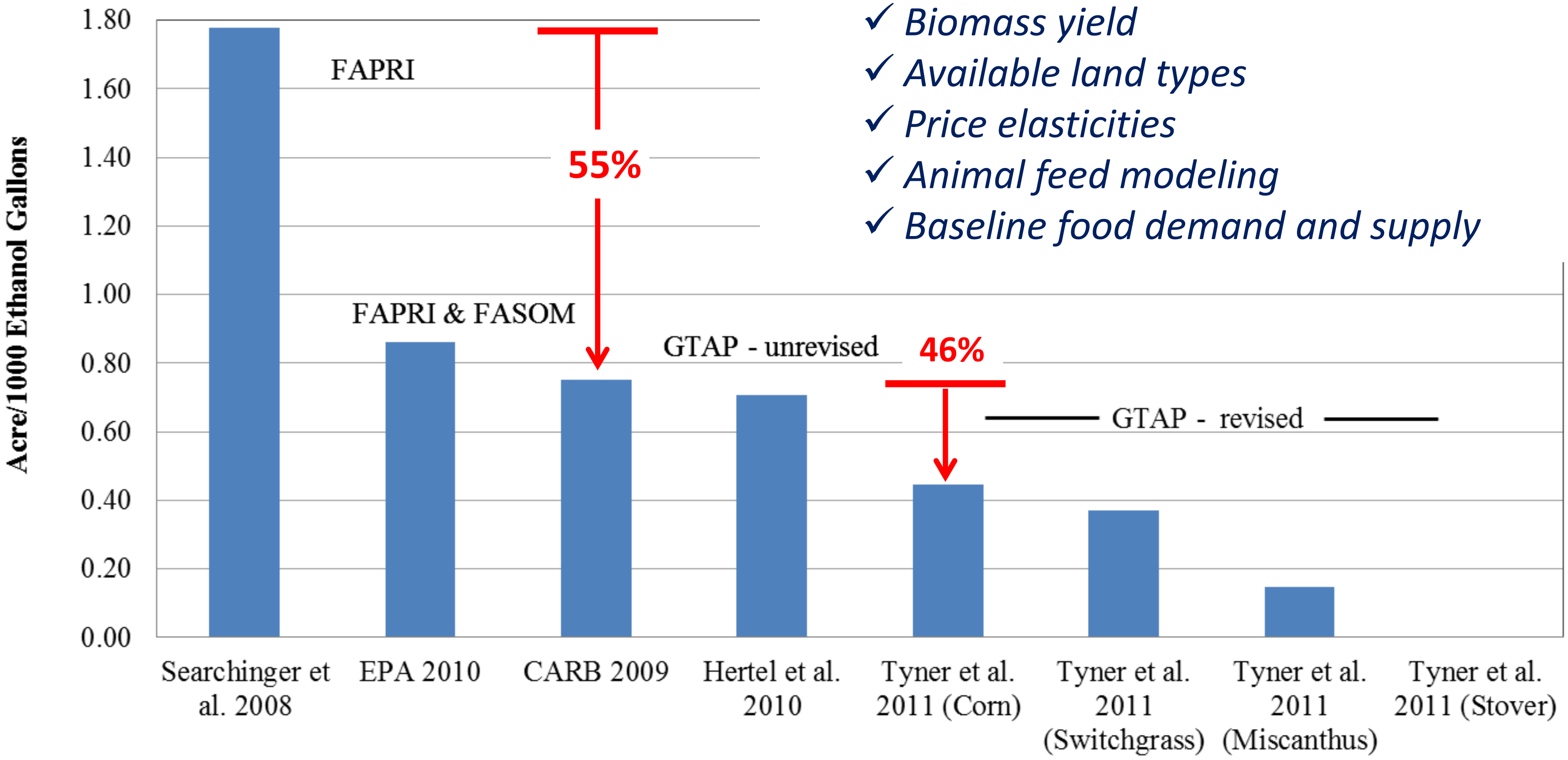
Key Steps to Address GHG Emissions of Potential Land Use Changes by Large-Scale Biofuel Production

- Simulations of potential land use changes (ANL in collaboration with Purdue)
  - Significant efforts have been made to improve existing computational general equilibrium (CGE) models
  - Completed GTAP updates and upgrades
    - ✓ Land availability in key countries
    - ✓ Yields in response to elevated commodity price
    - ✓ Future grain supply and demand trends without ethanol production
    - ✓ Substitution of conventional animal feed with biofuel animal feeds
    - ✓ Inclusion of cellulosic biomass (stover, switchgrass, and miscanthus)
- Carbon profiles of major land types (ANL in collaboration with UIC and UIUC)
  - Both above-ground biomass and soil carbon are being considered
  - Of the available data sources, some are very detailed but others are very coarse (e.g., the IPCC data)
    - ✓ UIUC is conducting DAYCENT modeling for US soil types
  - There are mismatches between CGE simulated land types and land types in available carbon databases:
    - ✓ UIC is using USDA detailed data, satellite data with ground truthing

Land Use Change Simulated for US Biofuel Production from Some Completed Studies

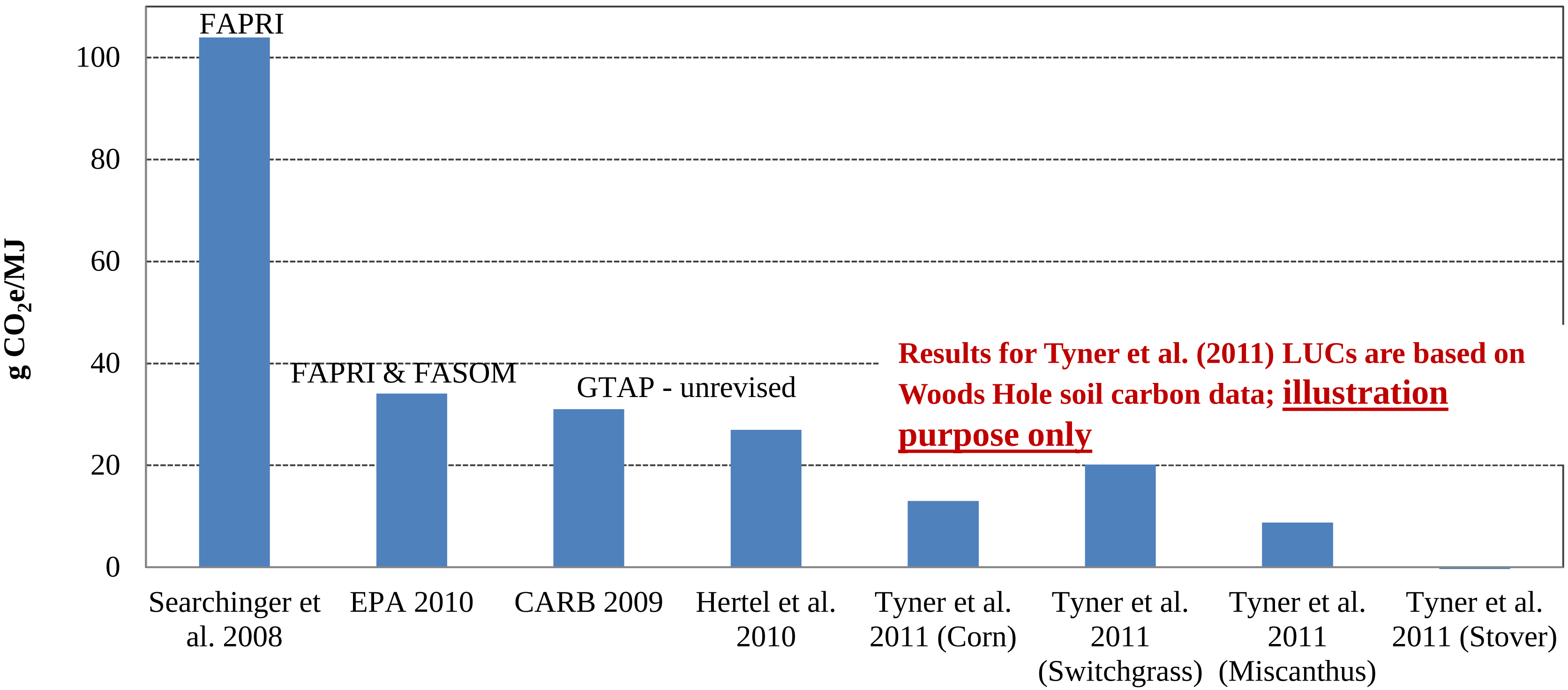
Effects of several critical factors in CGE models:

- ✓ *Biomass yield*
- ✓ *Available land types*
- ✓ *Price elasticities*
- ✓ *Animal feed modeling*
- ✓ *Baseline food demand and supply*



CGE – Computable General Equilibrium
GTAP – Global Trade Analysis Project (Purdue University)
FAPRI – Food and Agricultural Policy Research Institute (Iowa State)
FASOM – Forest and Agricultural Sector Optimization Model (Texas A&M)

GHG Emissions of LUCs Estimated for US Biofuel Production from Some Completed Studies



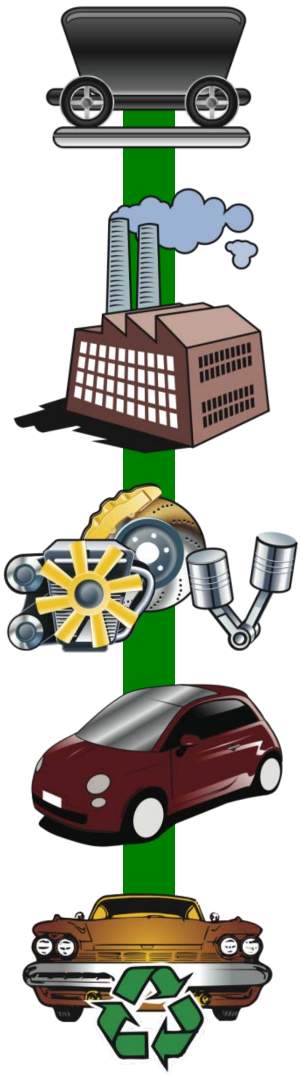
GTAP 2011 LUC Results: Pasture vs. Forest Conversion

	Corn	Miscanthus	Switchgrass
Pasture	89%	50%	20%
Forest	11%	50%	80%

GTAP 2011 LUC Results: U.S. vs. Rest of the World

	Corn: pasture	Miscanthus	Switchgrass: forest
U.S.	35%	33%	93%
ROW	65%	67%	7%

GREET 2 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

GREET 2 Vehicle-Cycle Technology Options

- Vehicle propulsion technologies
  - Internal combustion engine vehicle (ICEV)
  - Regular hybrid electric vehicle (HEV)
  - Fuel cell vehicle (FCV) with hybrid configuration
  - Plug-in hybrid electric vehicle (PHEV)
  - Battery electric vehicle (EV)
- Evaluate vehicle material compositions
  - Conventional
  - Lightweighting (LW)
- Vehicle types
  - Light-duty vehicles: passenger car, SUV, pick-up truck

GREET 2 Separates Vehicle-Cycle Analysis Into Four Categories

1. Components
   - Includes powertrain (engine or fuel cell), transmission, chassis, traction motor, generator, electronic controller, fuel cell auxiliaries (H2 tank, piping, etc.), and body
2. Batteries
   - Startup: lead-acid
   - Motive: Ni-MH or Li-Ion
3. Fluids; can affect criteria pollutant emissions significantly
   - Engine oil, power steering fluid, brake fluid, transmission fluid, powertrain coolant, windshield fluid, adhesives
   - Replacement frequency during vehicle lifetime
4. Vehicle assembly, disposal, and recycling

Key Issues in GREET Vehicle-Cycle Analysis

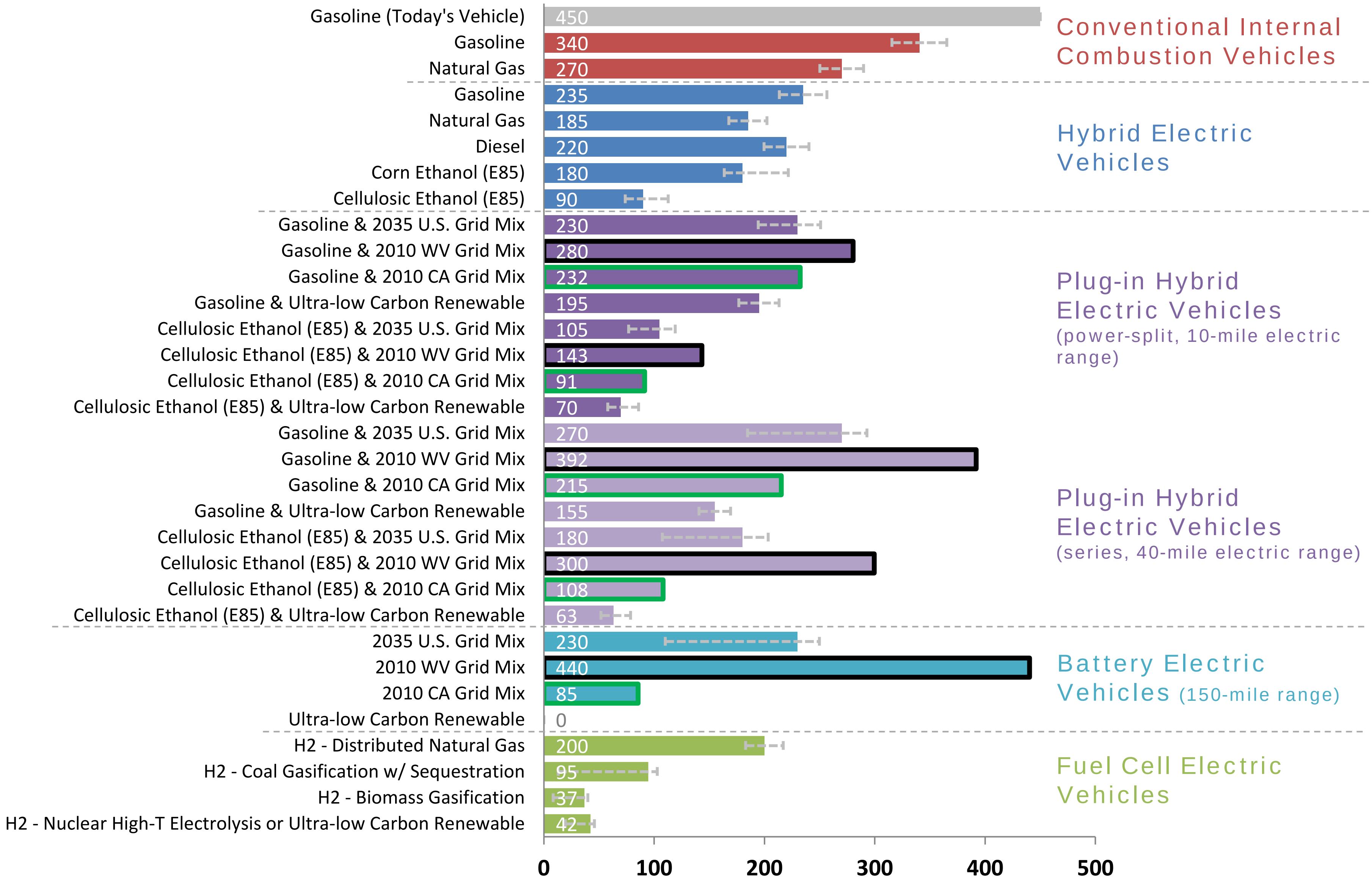
- Energy and emission burdens for key vehicle materials (steel, aluminum, etc.)
- Use of virgin vs. recycled materials
- Vehicle weight and lightweighting options
- Vehicle lifetime, component rebuilding (e.g., heavy-duty vehicle engines), and component replacement cycle (e.g., battery)
- New vehicle components, especially for electric drive technologies
  - Batteries
  - Fuel cells
  - Motors

GREET Can Serve as A Helpful Reference and Resource

- Emission factors of combustion technologies
  - Argonne's efforts of processing data from a variety of sources
  - By fuel type and combustion technology
- Fuel and energy product specifications
  - Energy content; carbon content, sulfur content, density, etc.
- Transportation logistics for feedstocks and fuels (the *T&D* sheet)
- A free stochastic add-on in Excel for other stochastic simulations
- GREET publications available at its website
  - GREET model reports
  - Technical reports
  - Journal articles (only abstracts)
  - Presentation materials
- Argonne default GREET simulation results in http://greet.es.anl.gov/results

  Download GREET results mini-tool to browse the results and generate comparison tables and charts here

WTW emissions (g CO_2-eq/mile) (DOE EERE Record)



Sample GREET WTW Results for Selected Vehicle/Fuel Options: Petroleum vs. GHGs (relative per-mile results)

From Wang et al. (2011)

Upcoming GREET1 Upgrades and Updates

- An upgraded CCLUB for biofuel LUC GHG emissions
- Expansion on construction of fuels production and distribution infrastructure
  - Petroleum refineries
  - Hydrogen production plants
- Updating of criteria air pollutant emissions in GREET1
- Alpha and beta testing of GREET .net version
- Parallel development of GREET Excel and .net versions

Main Effort and Challenge of LCAs: Data Collection and Reliability -- General Data Sources for GREET

- Open literature: transparent but much variation in data quality
- Process modeling (such as Argonne's own ASPEN Plus and Autonomie simulations): sometime speculative for yet developed commercial technologies
- Companies and technology developers: often proprietary and less transparent
- Engagement of the whole community (LCA practitioners, researchers, developers, agencies, etc.) and data source transparency are critical

Two Distinctly Different Uncertainties in LCAs

- System uncertainties
  - LCA methodology inconsistency: attributional vs. consequential
  - System boundary selection: a moving target
  - Treatment of co-products
  - These issues cause inconsistencies among LCA studies and results
- Technical uncertainties related to data availability and quality
  - Variation in input parameters and output results
  - Stochastic simulation feature is incorporated in GREET
- Model and LCA analysis transparency can help advance understanding and consensus building

Questions and Suggestions Regarding Argonne LCA Research and GREET?

Email to greet@anl.gov

Or any of us