Overview of Life-Cycle Analysis with the GREET Model

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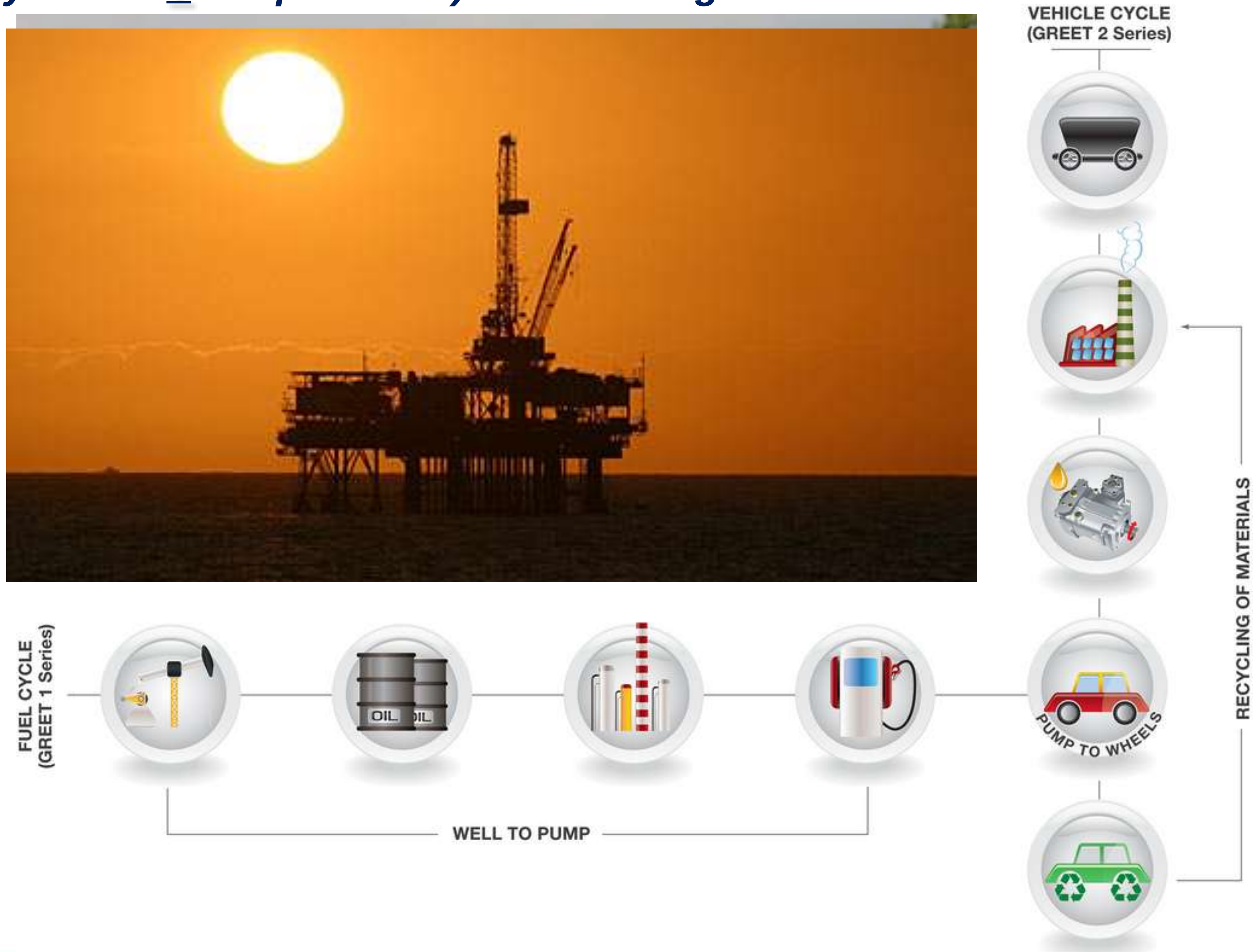
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model at Argonne National Lab



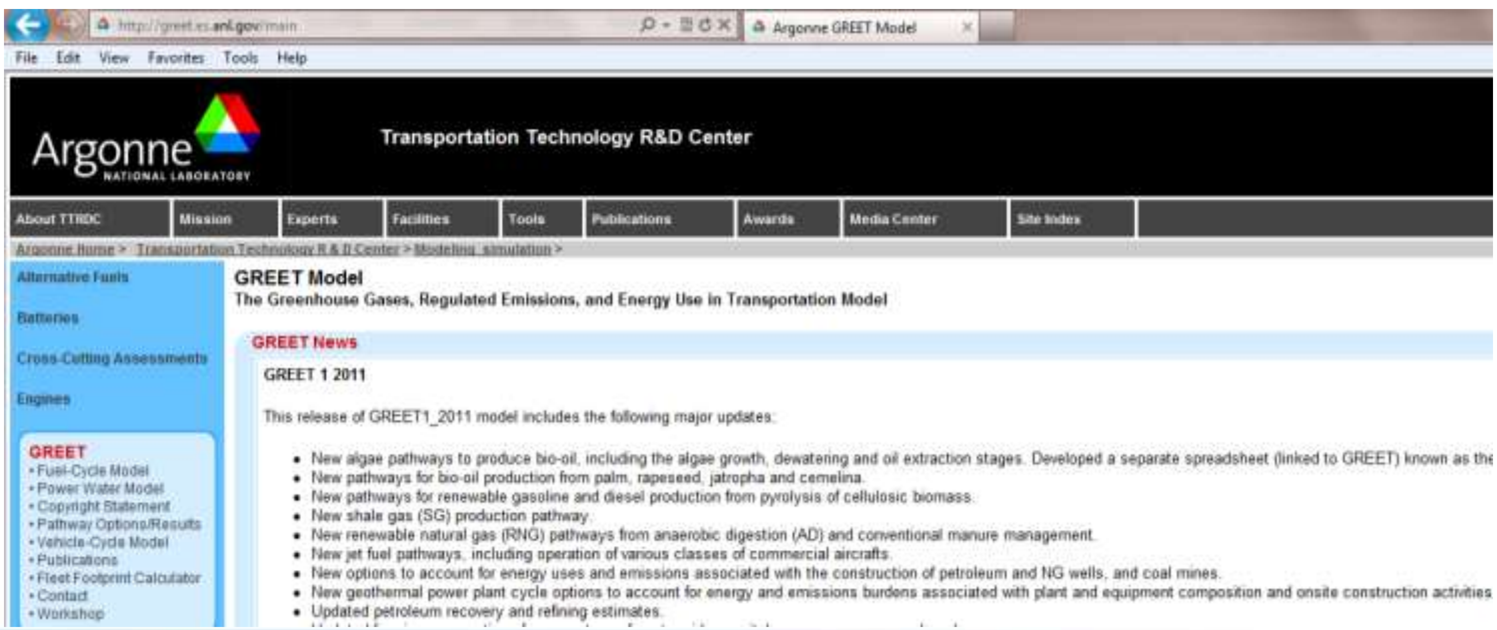
Life-Cycle Analysis (LCA) Models Available Worldwide for Transportation Fuel Examination

- The GREET model at Argonne National Laboratory
- The lifecycle emission model (LEM) at University of California at Davis
- Canadian GHGenius model
- LBST's E3 database in Europe
- 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 or the world

GREET Development Has Been Supported by U.S. Department of Energy

- Four DOE EERE programs have been GREET sponsors
  - Vehicle Technology Program: formerly Phil Patterson and now Jake Ward; Kevin Stork
  - Office of Biomass Program: Zia Haq
  - Fuel Cell Technology Program: Fred Joseck
  - Geothermal Technology Program: Arlene Anderson

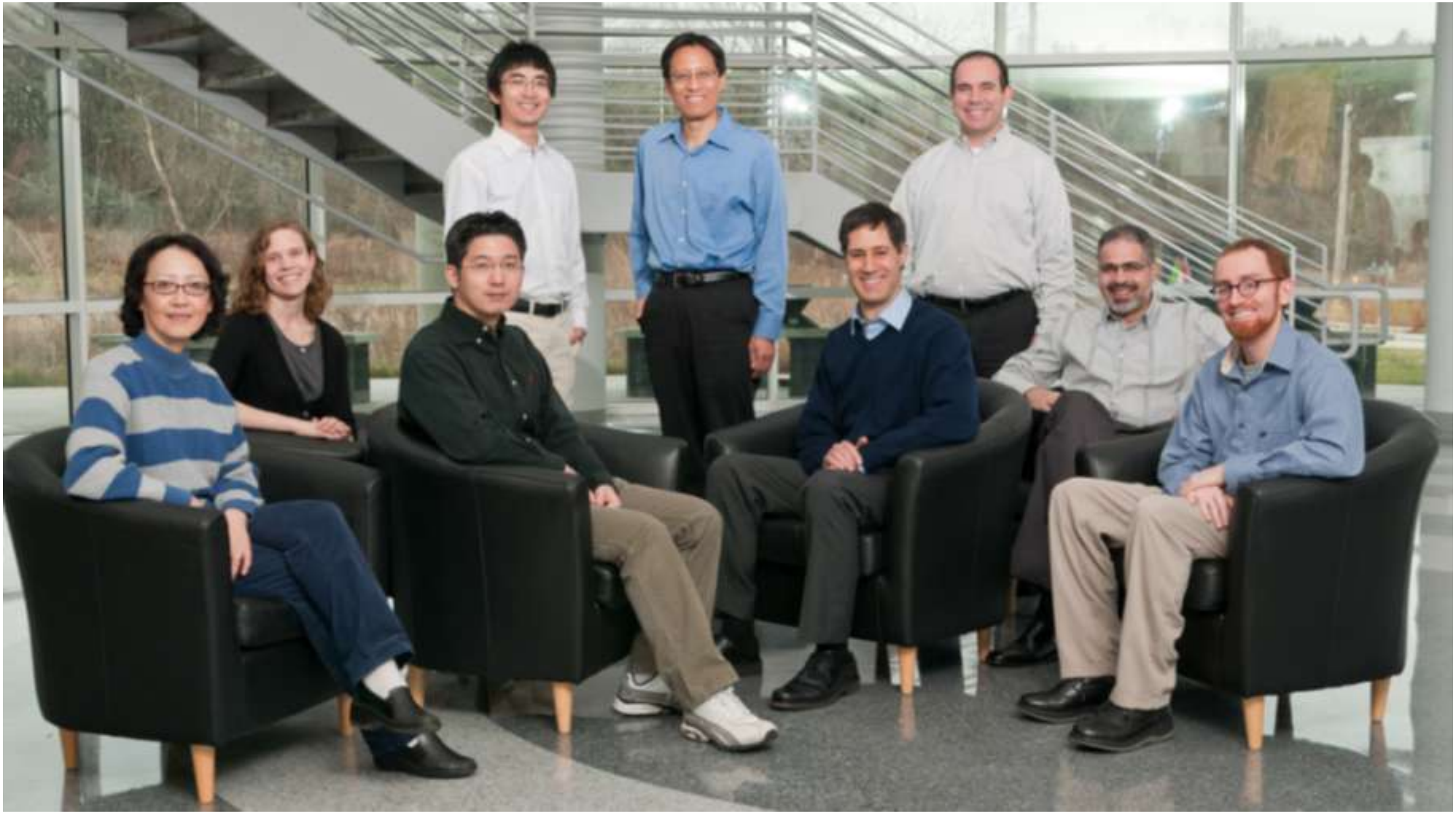
- The most recent GREET version (GREET1_2011) was released in Oct. 2011
- GREET and its documents are available at the GREET website



GREET Team at Argonne

- 11 staff on LCA research and GREET development
  - Dr. Michael Wang: group leader
  - Mr. Andy Burnham: vehicle cycle analysis, and natural gas pathways, and GREET user help
  - Dr. Corrie Clark: geothermal and shale gas process analysis and water resource/quality assessment
  - Dr. Jennifer Dunn: biofuels, soil carbon, batteries, and GREET applications
  - Dr. Amgad Elgowainy: hydrogen fuel vehicles, plug-in electric vehicles, GREET development
  - Dr. Ed Frank: algae-based biofuels, electric power generation systems
  - Dr. Jeongwoo Han: renewable natural gas, pyrolysis, vehicle technologies, GREET development
  - Ms. Marianne Mintz: renewable natural gas pathways
  - Dr. Ignasi Palou-Rivera: biofuels and petroleum fuels process modeling and LCA applications
  - Dr. John Sullivan: vehicle cycle analysis and geothermal and conventional power systems
  - Dr. May Wu: biofuels and water resource/quality assessment
- Two post-doctoral researchers on GREET LCA
- Four GREET .net programmers
- Other organizations who help Argonne
  - Massachusetts Institute of Technology
  - Purdue University
  - University of Illinois at Chicago and at Urbana-Champaign
  - University of Michigan at Ann Arbor
  - The Great Plains Institute

Argonne LCA Research and GREET Development Team



In the picture (Left to right): May Wu, Jennifer Dunn, Jeongwoo Han, Hao Cai, Michael Wang, Ed Frank, Ignasi Palou-Rivera, Amgad Elgowainy, Andy Burnham

Not in the picture: Corrie Clark, Marianne Mintz, and John Sullivan

Argonne GREET .net Programming Team

In the picture (Left to right): Michael Wang, Raja Sabbisetti, Amgad Elgowainy, David Dieffenthaler, Azeam Anjum, Vadim Sokolov

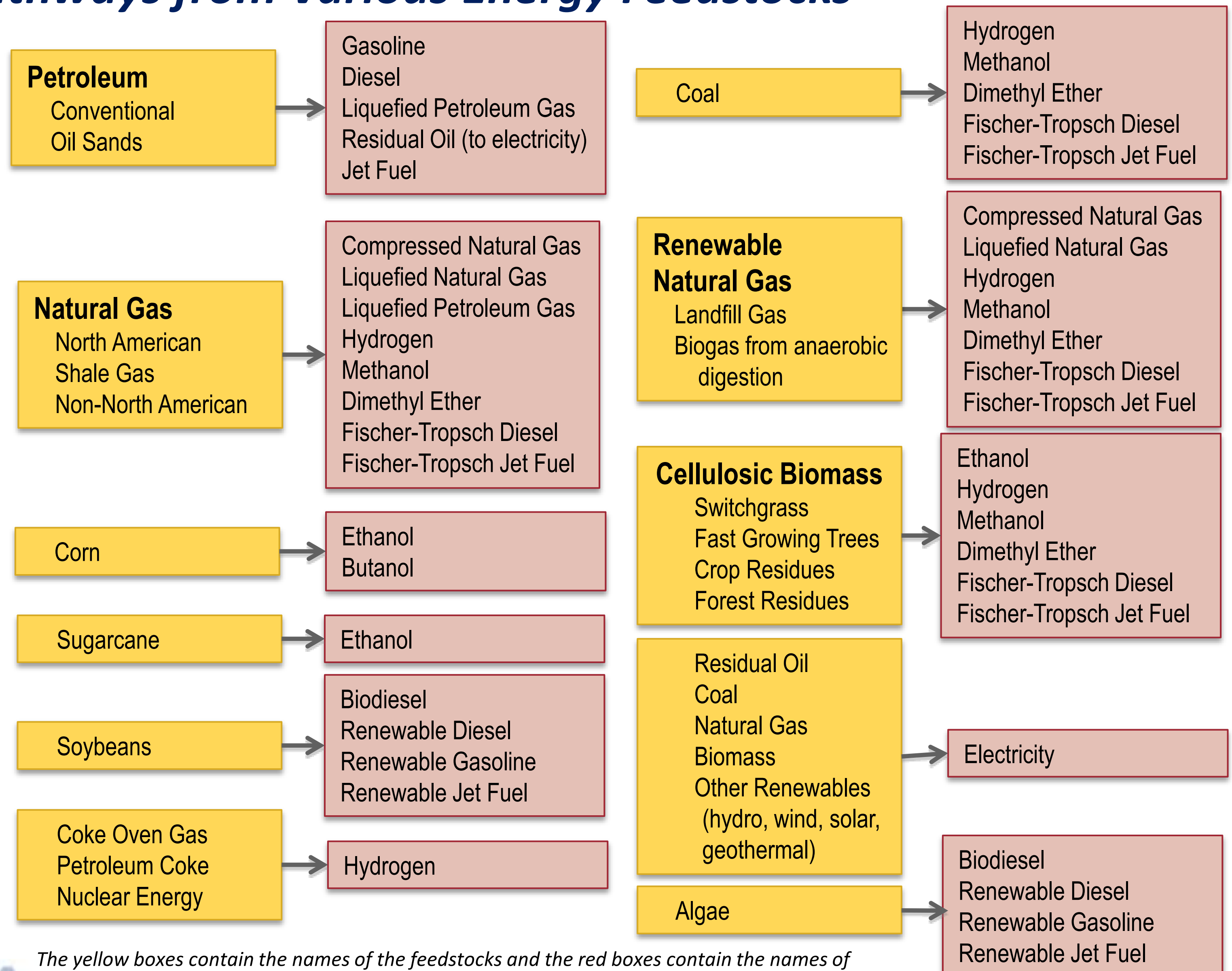
What Is New in GREET1_2011?

- Algae biofuel pathways, with the algae process description (APD) with detailed assumptions of the key stages of the algae pathways
- Pyrolysis pathways from cellulosic biomass to renewable gasoline and diesel
- Shale gas pathway and updated natural gas pathways
- Renewable natural gas pathways from anaerobic digestion of animal waste
- Jet fuel pathways, including operation of various classes of commercial aircrafts
- Optional inclusion of energy uses and emissions associated with the construction of petroleum and natural gas wells, coal mines, and various electric power generation systems
- Geothermal power plant options, including both operation and construction phases
- Updated petroleum recovery and refining efficiencies
- Updated farming assumptions for corn stover, forest residue, switchgrass, sugarcane and soybean

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



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

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

- Cellulosic biomass via pyrolysis to
  - Gasoline
  - Diesel

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

- Corn to butanol

- Soybeans to
  - Biodiesel
  - Renewable diesel
  - Renewable gasoline
  - Renewable 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**

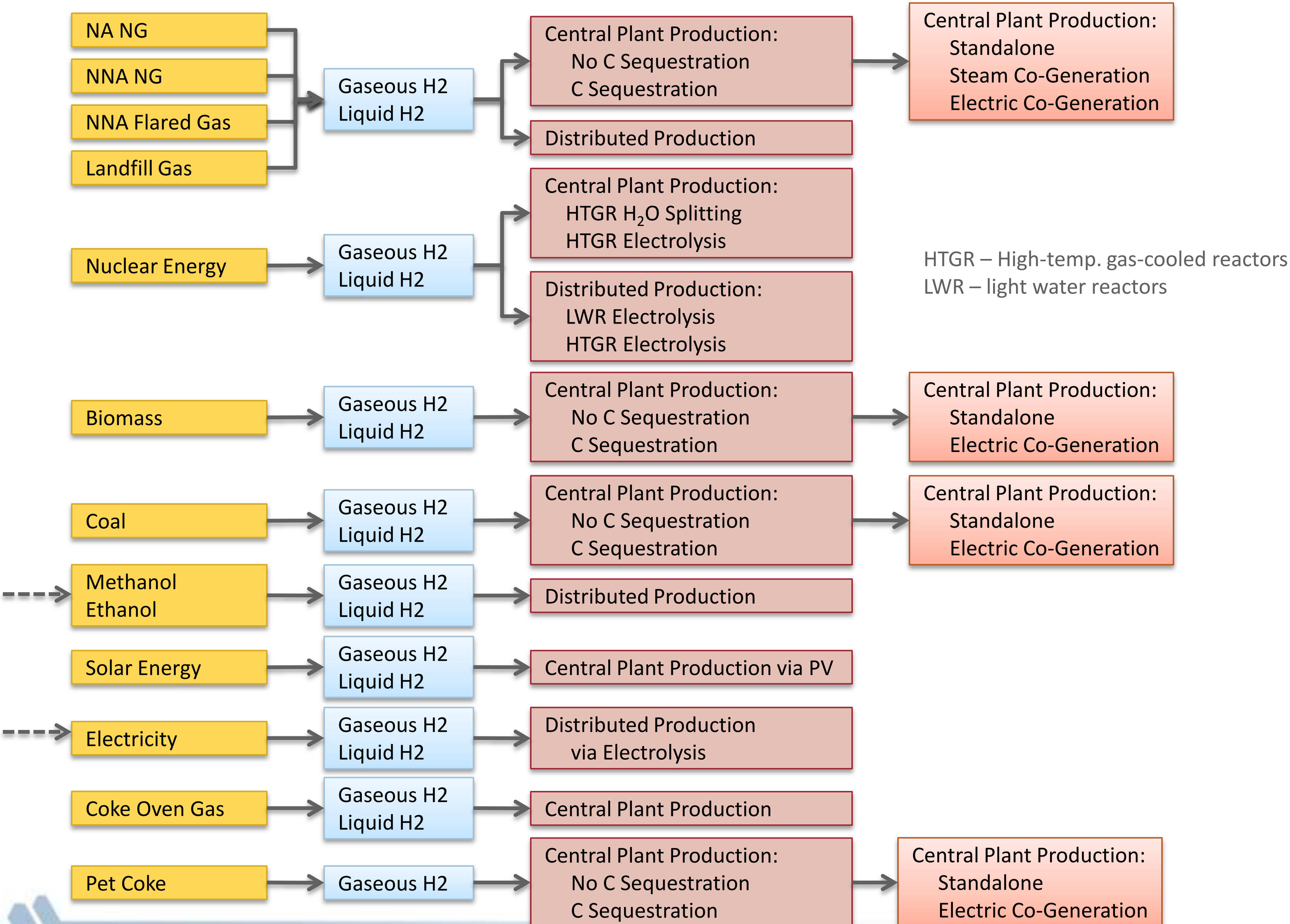
- **Wind Power**

- **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



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

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

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

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

Aviation Fuel Options in GREET1_2011

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

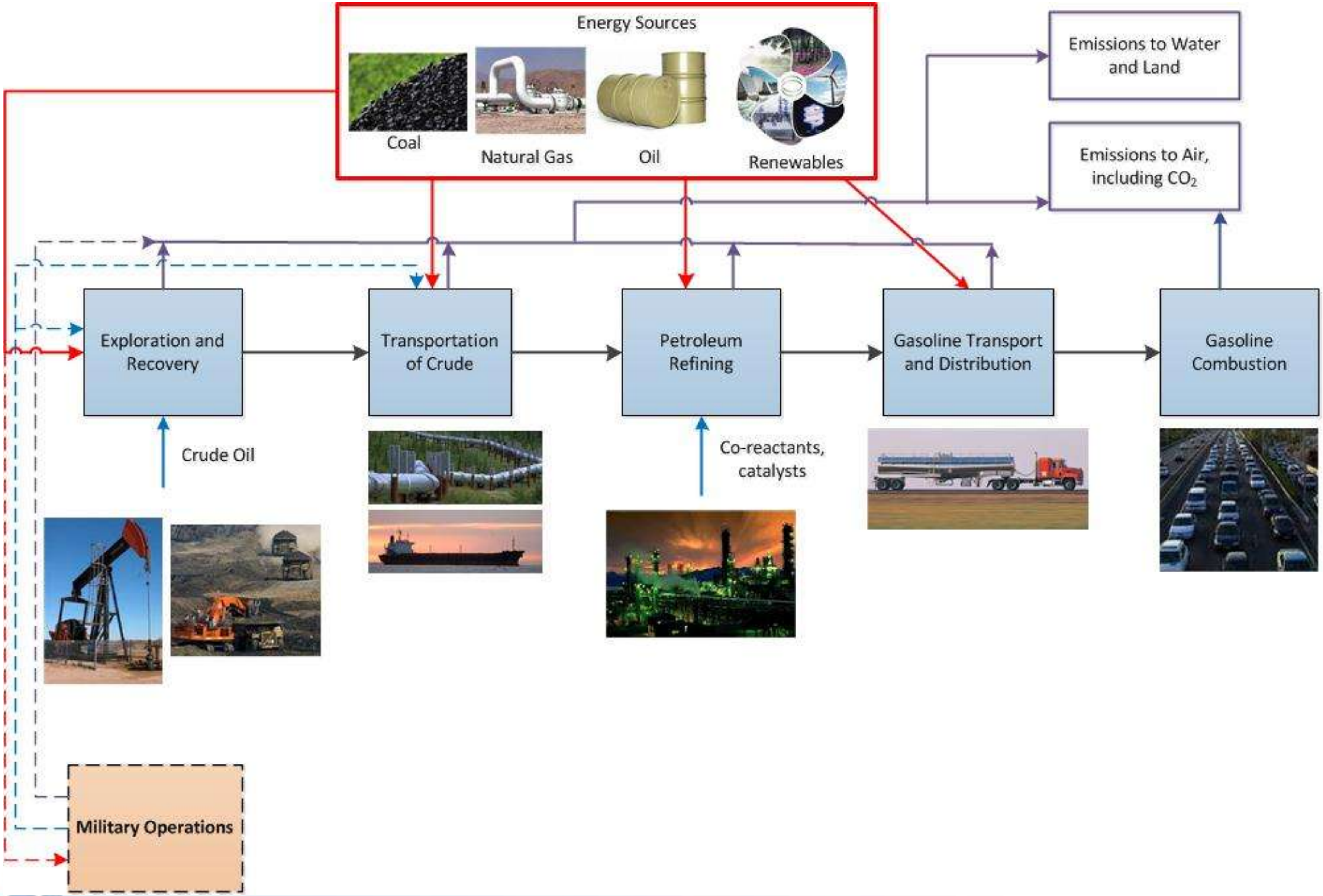
- **Passenger Aircraft**
  - Single Aisle
  - Small Twin Aisle
  - Large Twin Aisle
  - Large Quad
  - Regional Jet
  - Business Jet
- **Freight Aircraft**
  - Single Aisle
  - Small Twin Aisle
  - Large Twin Aisle
  - Large Quad
- **LCA Functional Units**
  - Per MJ of fuel
  - Per kg-km
  - Per passenger-km

(In collaboration with MIT PARTNER)

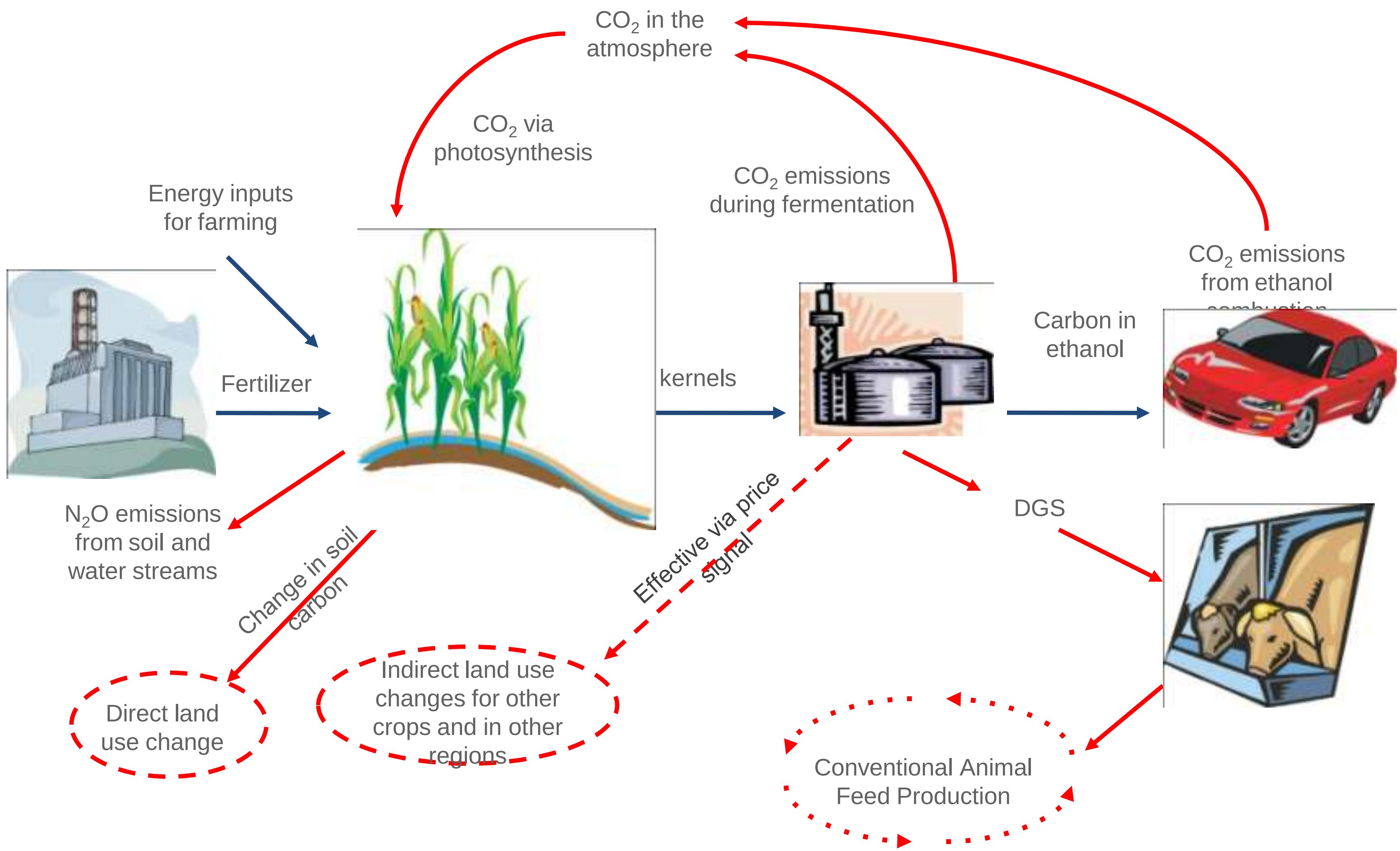
Key LCA Issues

- 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 stages
    - Existing vs. emerging
    - Environmental sustainability vs. economic viability
  - Inter- and intra-pathway technology choices result in many options; cherry-picking results from singular dimension can result in erroneous conclusions
- Methods of addressing co-products of transportation fuels
- Life-cycle analysis methodologies
  - Attributional LCA: GREET approach
  - Consequential LCA

Life-Cycle Analysis System Boundary: Petroleum to Gasoline



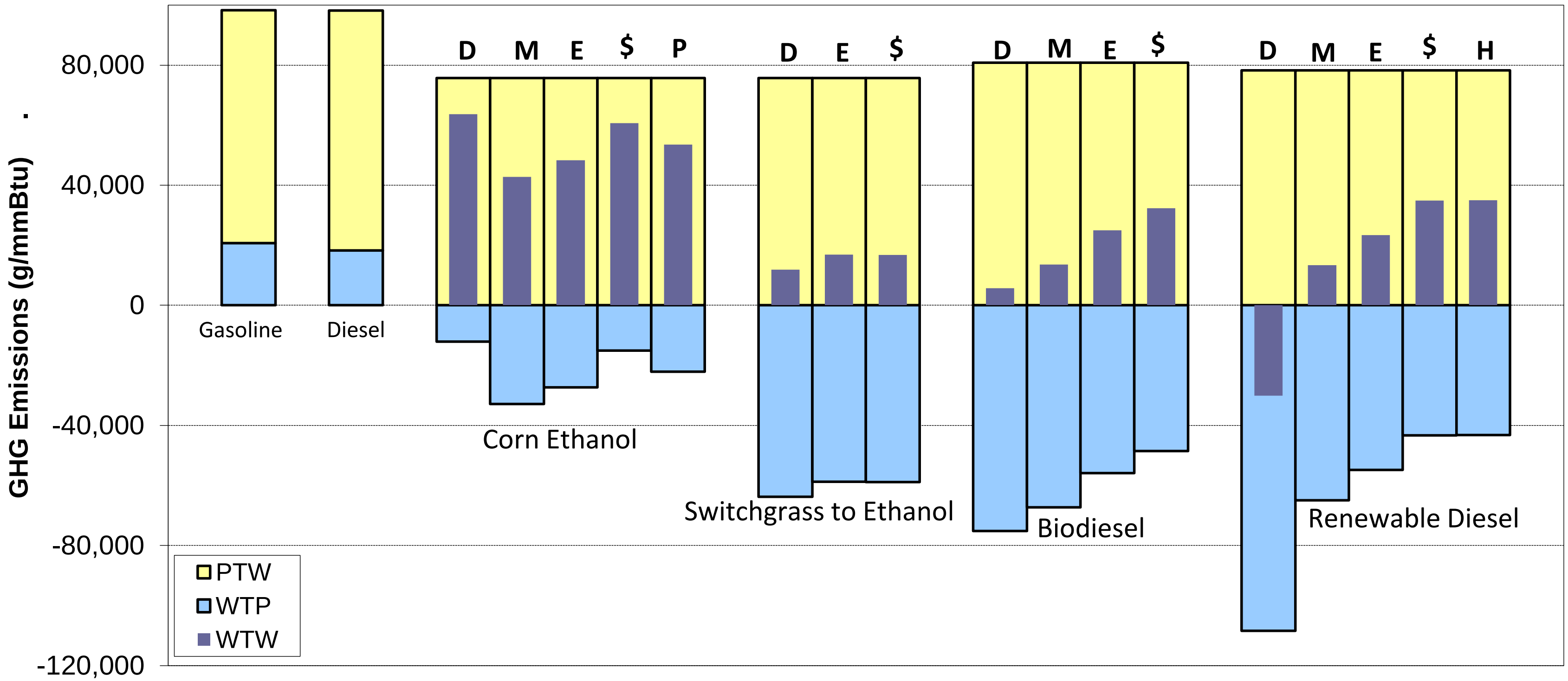
Life-Cycle Analysis System Boundary: Corn to Ethanol



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

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



D: Displacement
M: Mass based
E: Energy Based

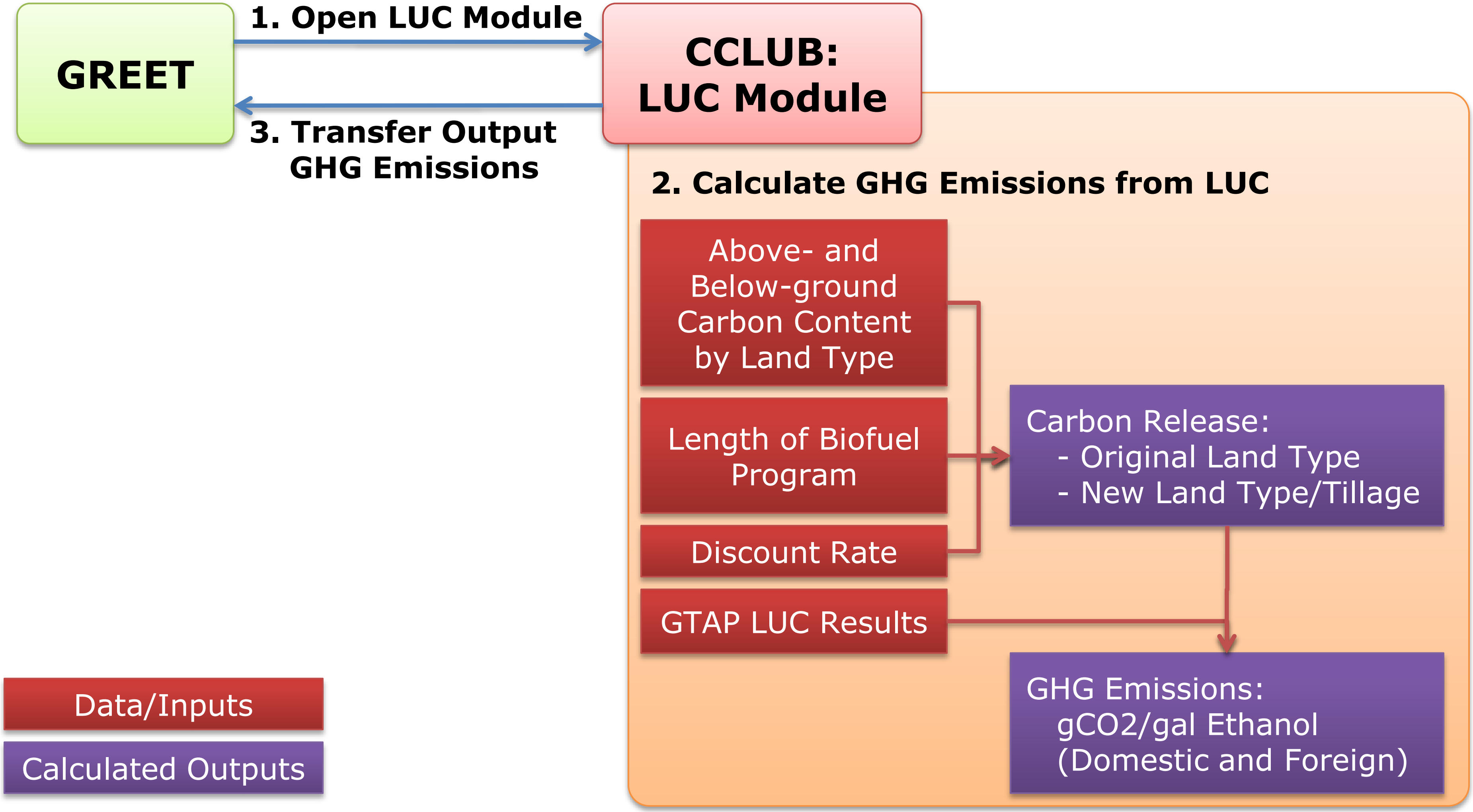
$: Market Value
P: Process Purpose
H: Hybrid Allocation

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

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

- Simulations of potential land use changes (in collaboration with Purdue)
  - Significant efforts have been made in the past three years to improve existing computational general equilibrium (CGE) models
  - More efforts are being made to address additional biomass feedstocks
- Carbon profiles of major land types (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 (e.g., the DAYCENT model) but others are very coarse (e.g., the IPCC data)
  - There are mismatches between CGE simulated land types and land types in available carbon databases: satellite data with ground truthing

Interface between GREET and Biofuel LUC Module



CCLUB was developed by Dr. Steffen Mueller of University of IL at Chicago and Argonne National Laboratory

Issues with Vehicle Operation Simulations in GREET

- Lab-tested emissions and fuel economy results vs. on-road results for vehicles
  - Driving cycle adjustment factors
  - Part of GREET research issues; pre-entry of 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

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 Separates a Vehicle 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 (heavy-duty vehicle engines), and component replacement cycle (battery)
- New vehicle components, especially for electric drive technologies
  - Batteries
  - Fuel cells
  - Motors

Main Effort and Challenge of LCAs: Data, Data, Data – 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

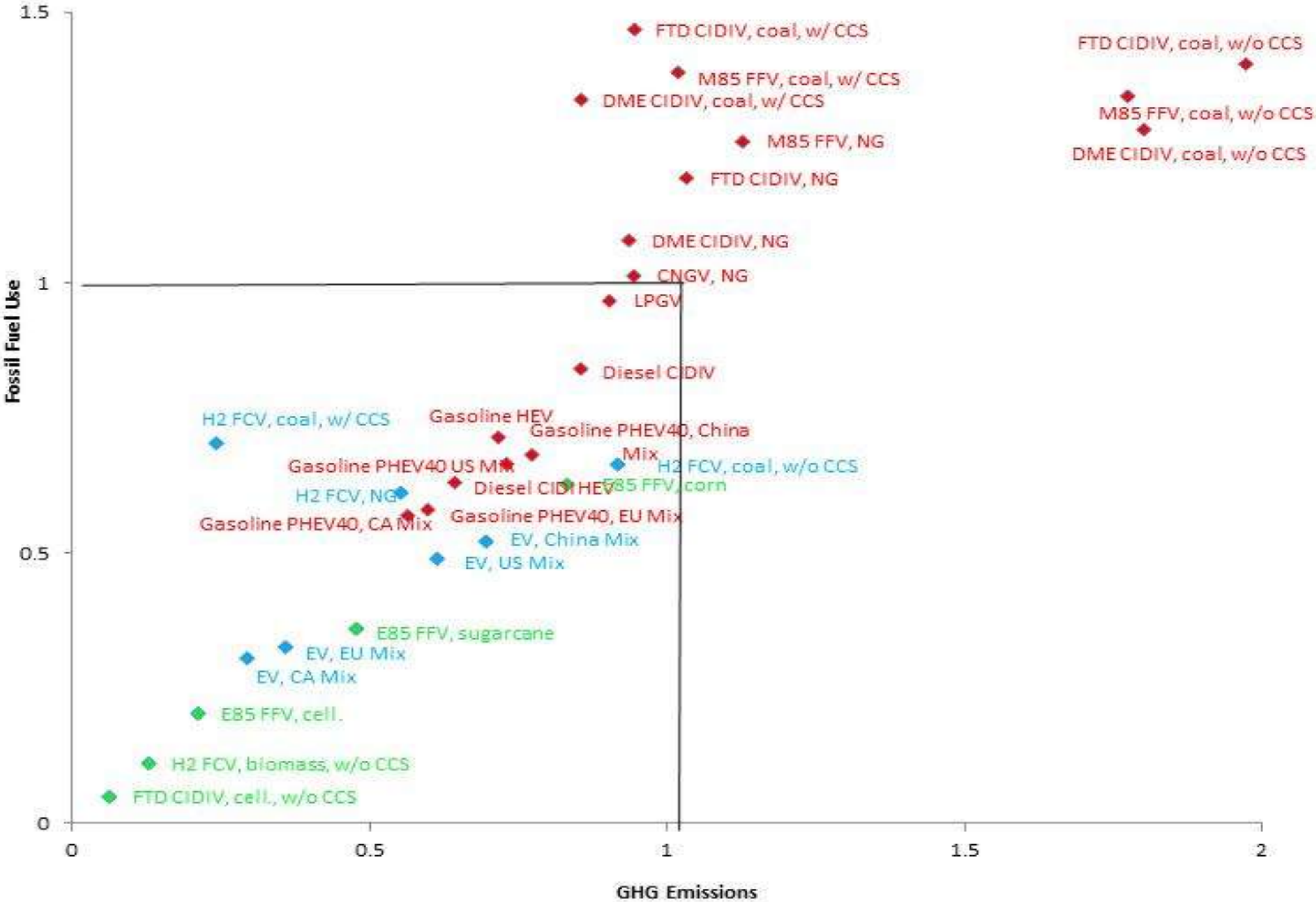
- System uncertainties
  - LCA methodology inconsistency: attributional vs. consequential
  - System boundary selection: a moving target
  - Treatment of co-products
  - These issues cause inconsistencies among LCA studies and results
- Technical uncertainties related to data availability and quality
  - 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

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

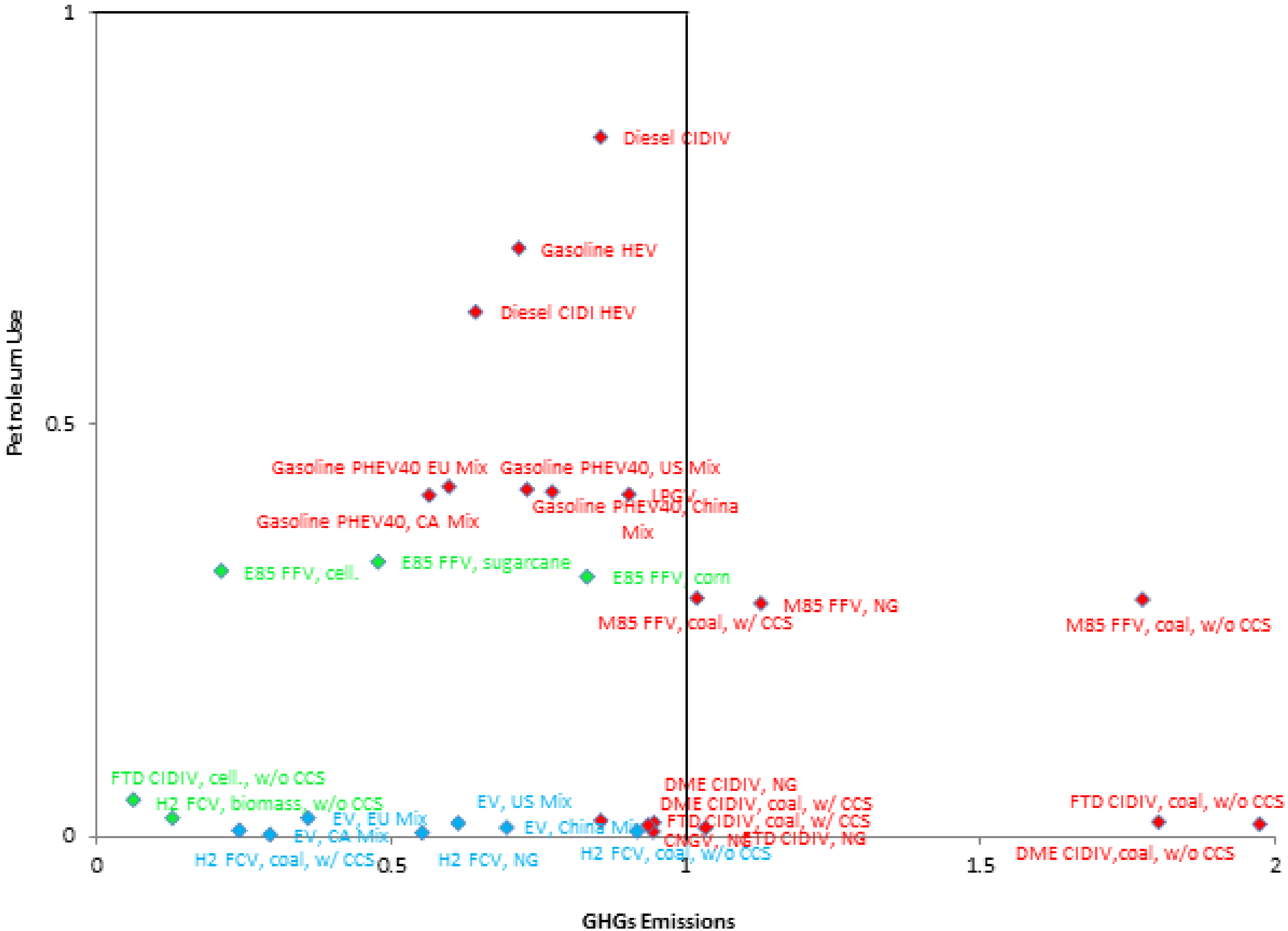
Download GREET results mini-tool to browse the results and generate comparison tables and charts here

Sample GREET WTW Results for Selected Vehicle/Fuel Options: Fossil vs. GHGs



From Wang et al. (forthcoming)

Sample GREET WTW Results for Selected Vehicle/Fuel Options: Petroleum vs. GHGs



From Wang et al. (forthcoming)

Near-Future GREET Upgrades and Updates

- An upgraded CCLUB for biofuel LUC GHG emissions
- Expansion on construction of fuels production and distribution infrastructure
- An upgraded and updated GREET2 vehicle cycle version
  - A detailed battery LCA module
  - Updated energy and emission profiles of key vehicle materials
  - A detailed module on vehicle assembling, disposal, and recycling
- Alpha and beta testing of GREET .net version
- Parallel development of GREET Excel and .net versions

Questions and Suggestions Regarding Argonne LCA Research and GREET?

Email to greet@anl.gov Or any of us