Overview of the GREET™ Life-Cycle Analysis Model

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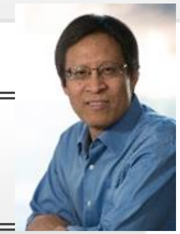
Societal effects of vehicle technologies and fuels

- Greenhouse gas (GHG)
- Energy security
- Air quality
- Other environmental effects (water, ecosystem services, etc.)

- The GREET model was developed to help evaluate these attributes

>30 researchers in Argonne's Systems Assessment Group study energy and environmental issues of transportation and energy systems

Systems Assessment Group, Energy Systems Division, Argonne National Laboratory



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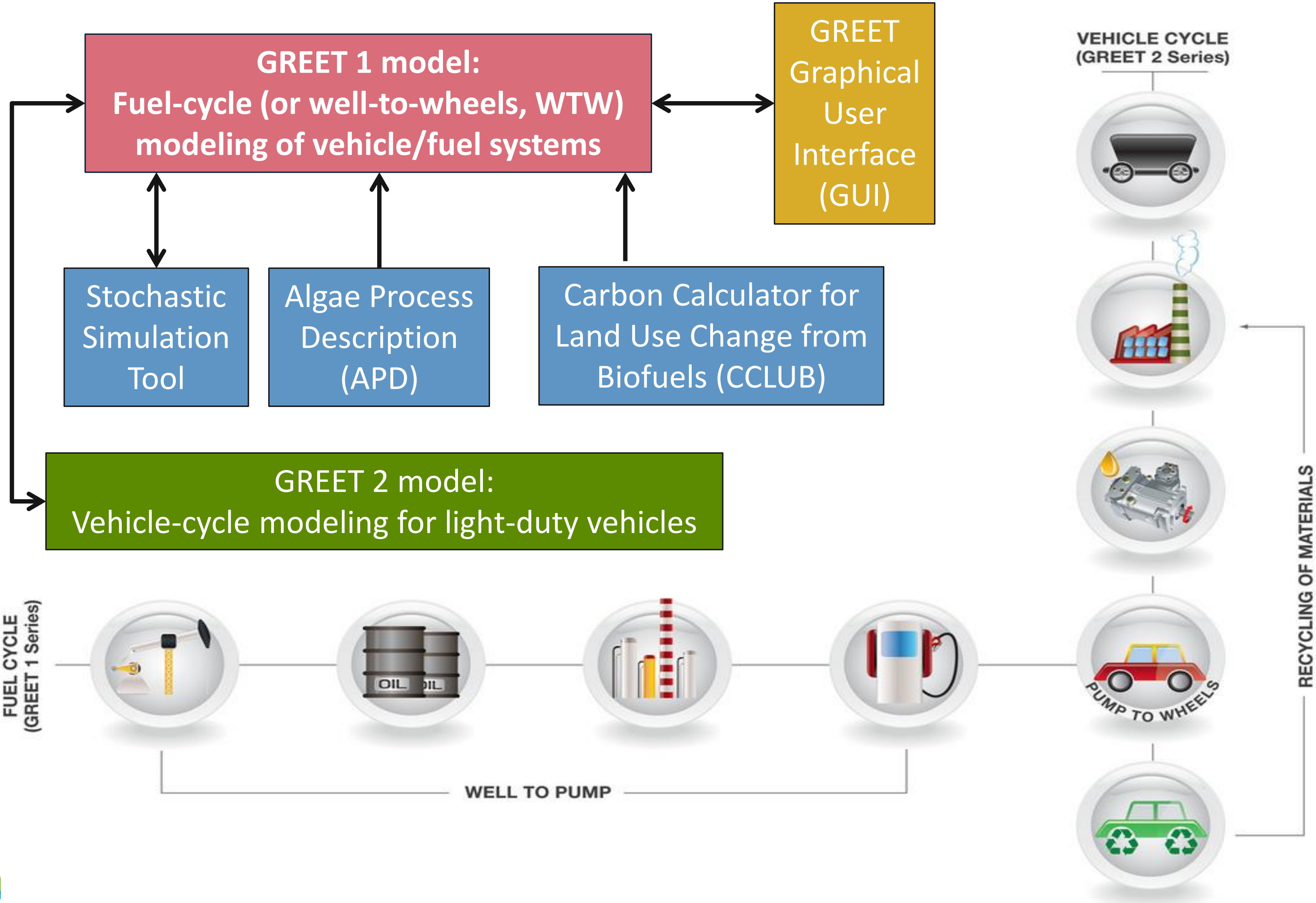
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model



GREET development has been supported by several DOE Offices since 1995

- Vehicle Technology Office (VTO)
- Fuel-Cell Technology Office (FCTO)
- Energy Policy and Systems Analysis (EPSA)
- Bioenergy Technology Office (BETO)
- Geothermal Technology Office (GTO)

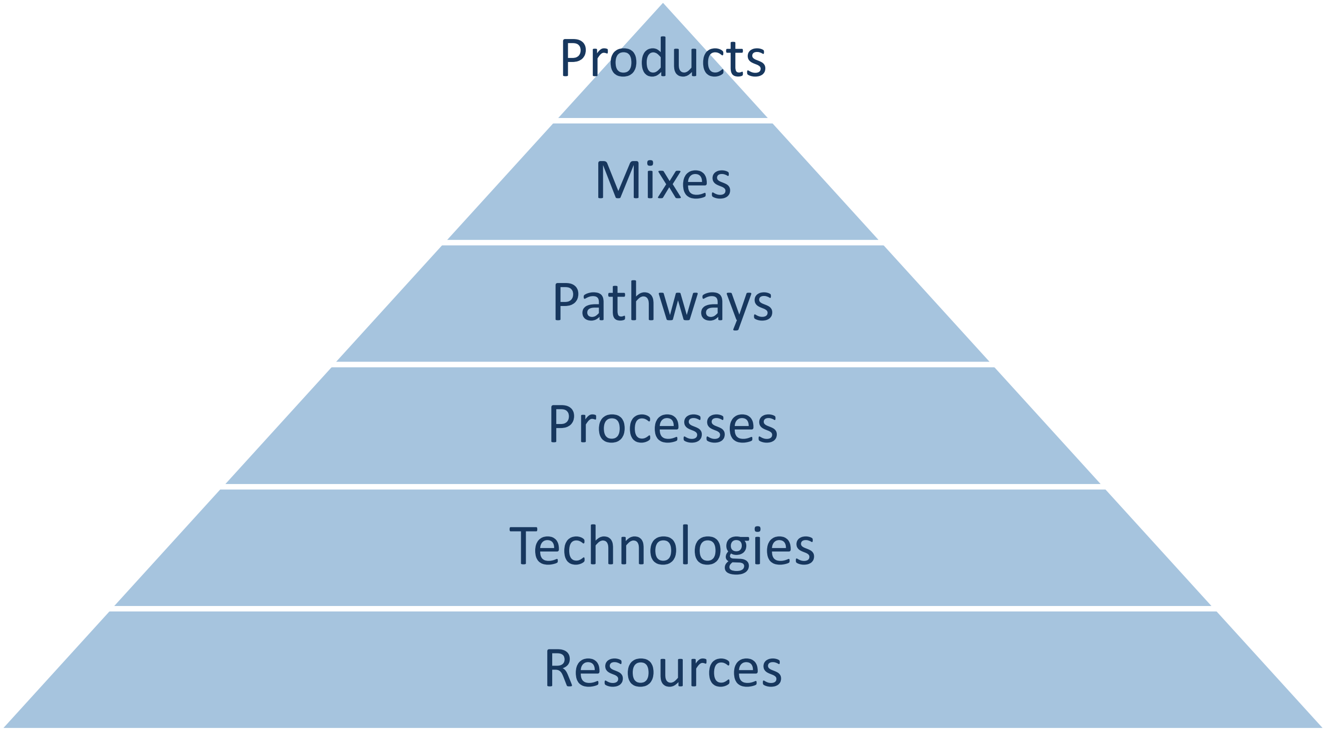
GREET has been in public domain and free of charge since it inception in 1995

Examples of major uses of GREET

- US EPA used GREET for RFS and vehicle GHG standard developments
- CARB developed CA-GREET for its Low-Carbon Fuel Standard compliance
- DOE, USDA, and the Navy use GREET for R&D decisions
- DOD DLA-Energy uses GREET for alternative fuel purchase requirements
- Auto industry uses it for R&D screening of vehicle/fuel system combinations
- Energy industry (especially new fuel companies) uses it for addressing sustainability of R&D investments
- Universities uses GREET for education on technology sustainability of various fuels

GREET.net platform integrates all GREET modules (originally developed in Excel) together

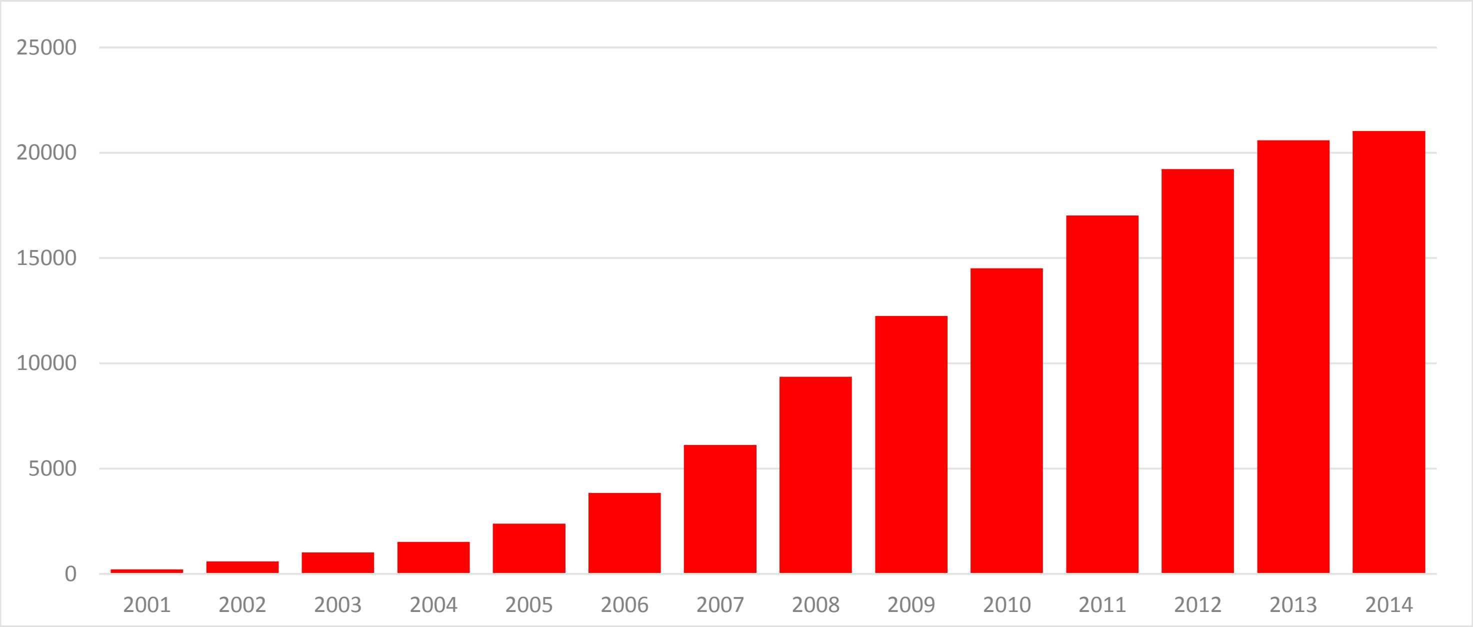
GREET.net hierarchy



GREET outputs include energy use, greenhouse gases, criteria pollutants and water consumption for vehicle and energy 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, N_2O, and black carbon
  - CO_2e of the three (with their global warming potentials)
- **Air 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)
- **Water consumption**
- **GREET LCA functional units**
  - Per mile driven
  - Per unit of energy (million Btu, MJ, gasoline gallon equivalent)
  - Other units (such as per ton of biomass)

There are more than 23,000 registered GREET users globally



- **Geographically, 71% in North America, 14% in Europe, 9% in Asia**
- **57% in academia and research, 33 % in industries, 8% in governments**

GREET includes more than 100 fuel production pathways from various energy feedstock sources

Feedstock	Fuel
Petroleum Conventional Oil Sands	Gasoline Diesel Jet Fuel Liquefied Petroleum Gas Naphtha Residual Oil
Coal	Hydrogen Fischer-Tropsch Diesel Fischer-Tropsch Jet Methanol Dimethyl Ether
Natural Gas North American Non-North American Shale gas **Renewable Natural Gas** Landfill Gas Animal Waste Waste water treatment	Compressed Natural Gas Liquefied Natural Gas Liquefied Petroleum Gas Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Jet Fischer-Tropsch Naphtha Hydrogen
Coke Oven Gas Petroleum Coke Nuclear Energy	Hydrogen

Feedstock	Fuel
Corn	Ethanol Butanol
Sugarcane	Ethanol
Soybeans Palm Rapeseed Jatropha Camelina Algae	Biodiesel Renewable Diesel Renewable Gasoline Hydroprocessed Renewabl
Cellulosic Biomass Switchgrass Willow/Poplar Crop Residues Forest Residues Miscanthus	Ethanol Hydrogen Methanol Dimethyl Ether Fischer-Tropsch Diesel Fischer-Tropsch Jet Pyro Gasoline/Diesel/Jet
Residual Oil Coal Natural Gas Biomass Other Renewables	Electricity

GREET examines more than 80 on-road vehicle/fuel systems for both LDVs and HDVs

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

Non-road transportation modes in GREET

- Air transportation
  - Globally, a fast growing sector with GHG reduction pressure
  - Interest by DOD, ICAO, FAA, and commercial airlines
  - GREET includes
    - Passenger and freight transportation
    - Various alternative fuels blending with petroleum jet fuels
- Marine transportation
  - Pressure to control air pollution in ports globally
  - Interest by EPA, local governments, IMO
  - Biodiesel and LNG are potential marine alternative fuels
  - GREET includes
    - Ocean and inland water transportation
    - Baseline diesel and alternative marine fuels
- Rail transportation
  - Interest by DOT, railroad companies
  - Potential for CNG/LNG to displace diesel

What is new in GREET2015: major expansions and updates

- Water consumption for
  - hydrogen from various sources
  - petroleum fuels
  - biofuels
  - hydro-electric power
- GHG emissions intensities of U.S. shale oil production from Bakken and Eagle Ford plays
- Updated GHG emission intensities for Canadian oil sands pathways
- High-octane fuel pathways with E10, E25, and E40 ethanol blends
- Land-management practices of cover crops and manure applications for corn-soy systems
- Expanded waste-to-energy pathways
- Updating and addition in vehicle cycle analysis
  - Aluminum
  - Molybdenum
  - Platinum
  - Zinc
  - Nickel
  - Silicon
  - Glass and glass fiber
  - Chilean copper

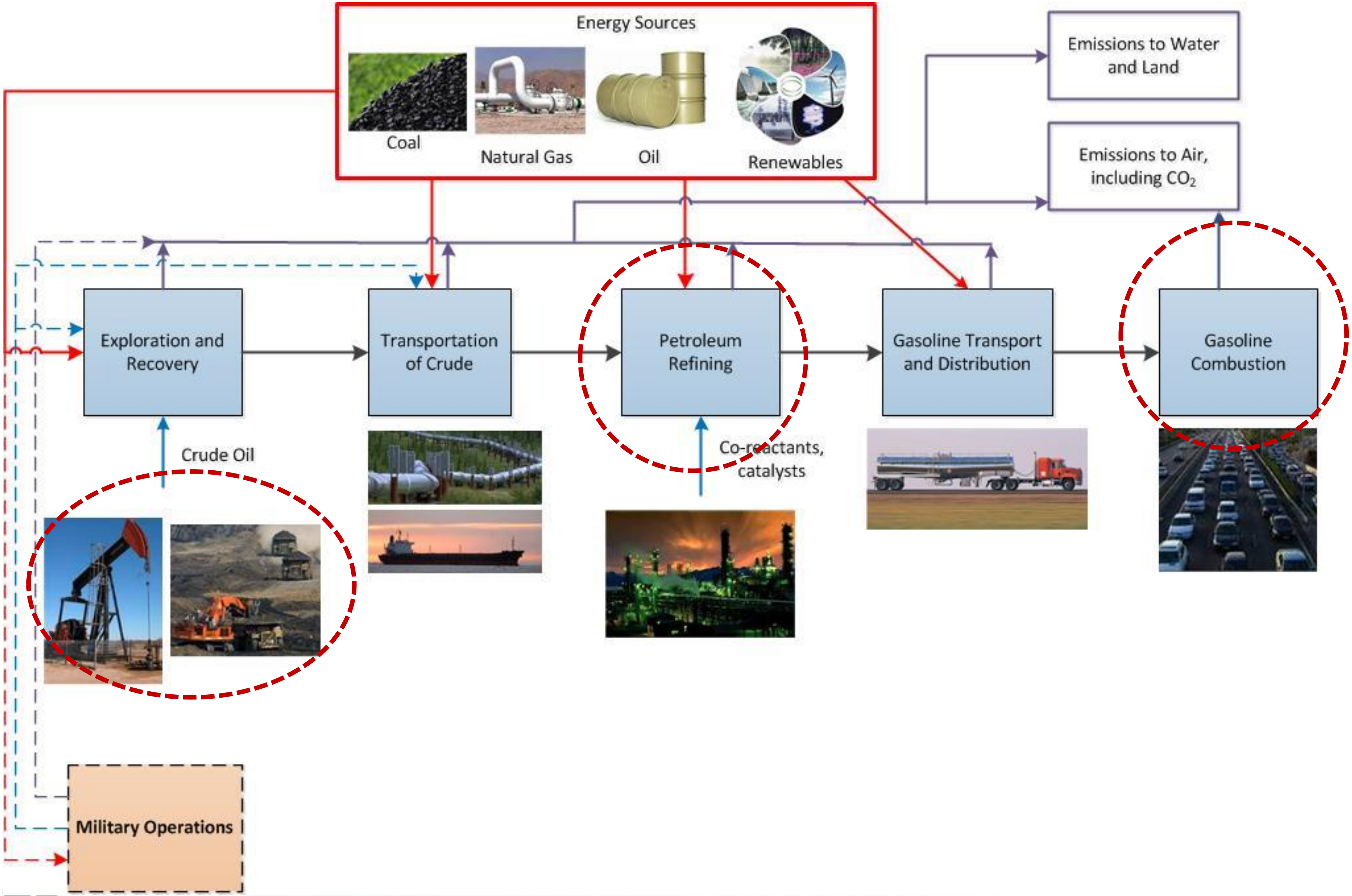
GREET Approach and data sources

- **Approach: build LCA modeling capacity with the GREET model**
  - Build a consistent LCA platform with reliable, widely accepted methods/protocols
  - Address emerging LCA issues
  - Maintain openness and transparency of LCAs by making GREET publicly available
  - Primarily process-based LCA approach (the so-called attributional LCA); some features of consequential LCA are incorporated
- **Data sources**
  - Open literature and results from other researchers
  - Simulations with models such as ASPEN Plus for fuel production and ANL Autonomie and EPA MOVES for vehicle operations
  - Fuel producers and technology developers for fuels and automakers and system components producers for vehicles
  - Baseline technologies and energy systems: EIA AEO projections, EPA eGrid for electric systems, etc.
  - Consideration of effects of regulations already adopted by agencies

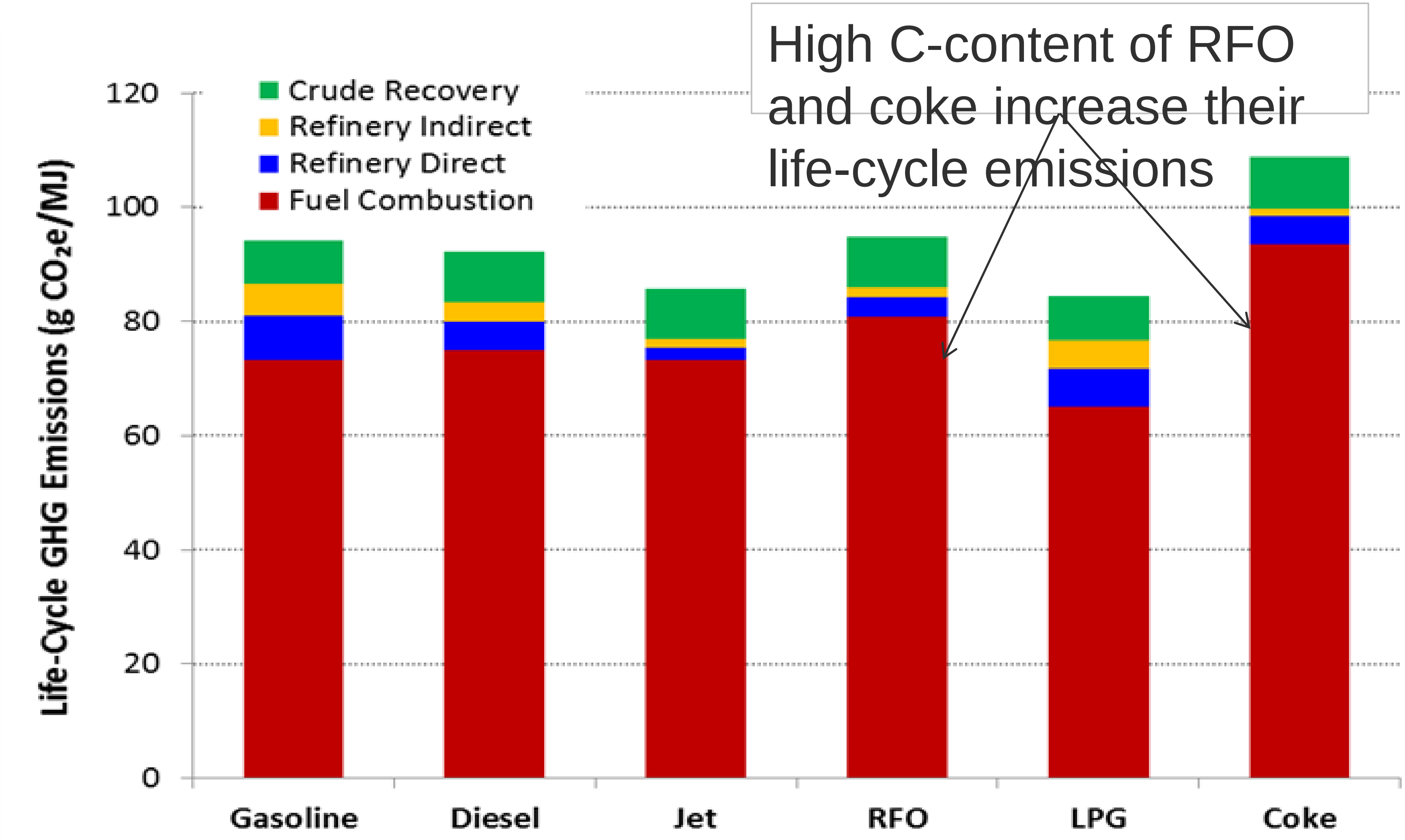
Main technical issues of GREET LCAs

- LCA system boundary – scope of LCA
  - Process-based LCA
  - Attributional vs. consequential LCA
- Co-product methods in LCA
- Data availability and representation
  - Temporal variation
  - Geographic variation
  - Sensitivity of LCA parameters and uncertainty analysis; GREET incorporates stochastic modeling features

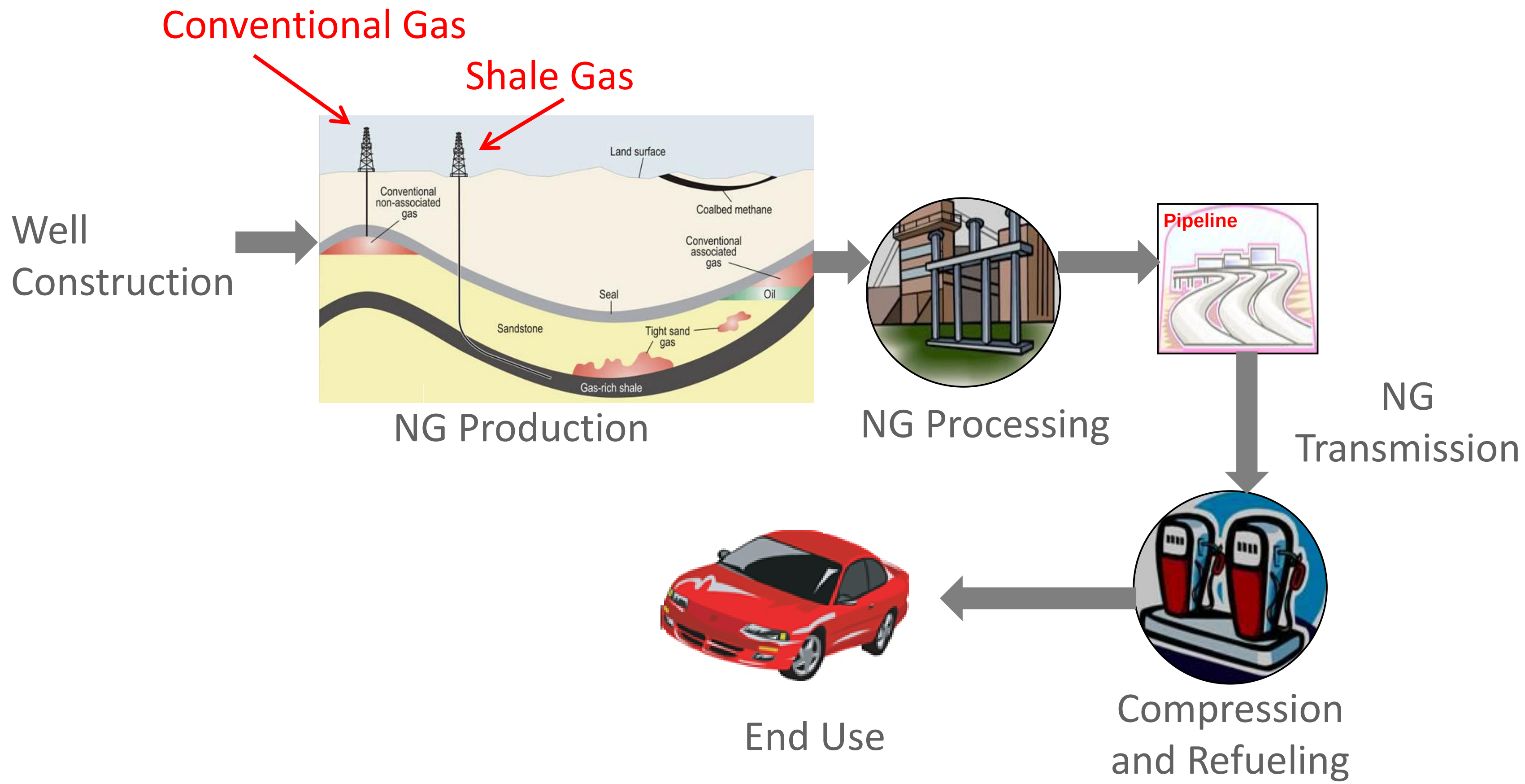
LCA system boundary: petroleum to gasoline



LCA GHG emissions of petroleum fuels is dominated by end use release of CO2; refinery emissions is a distant second



LCA system boundary: compressed natural gas

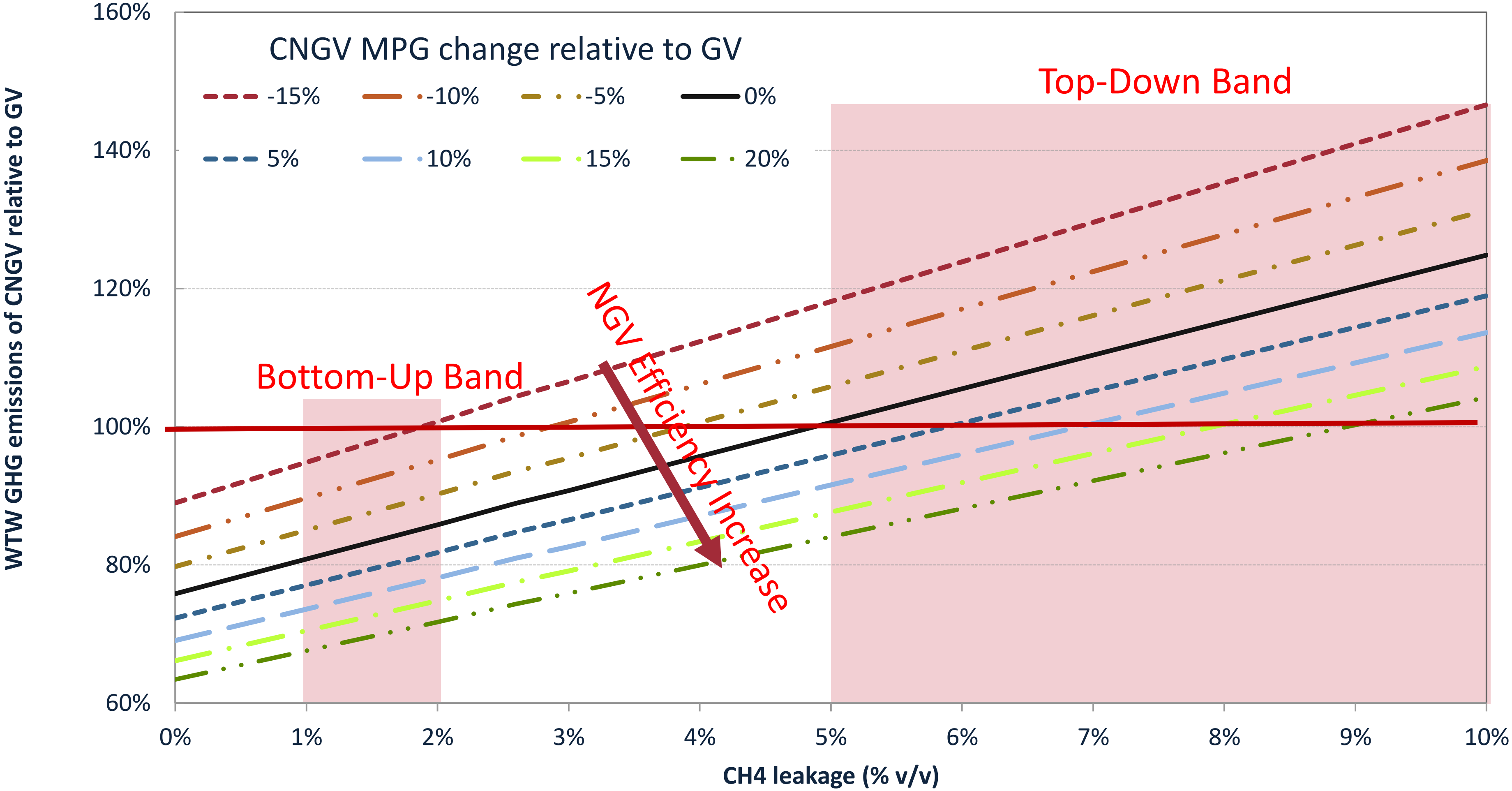


Methane leakage along NG supply chain is a major concern

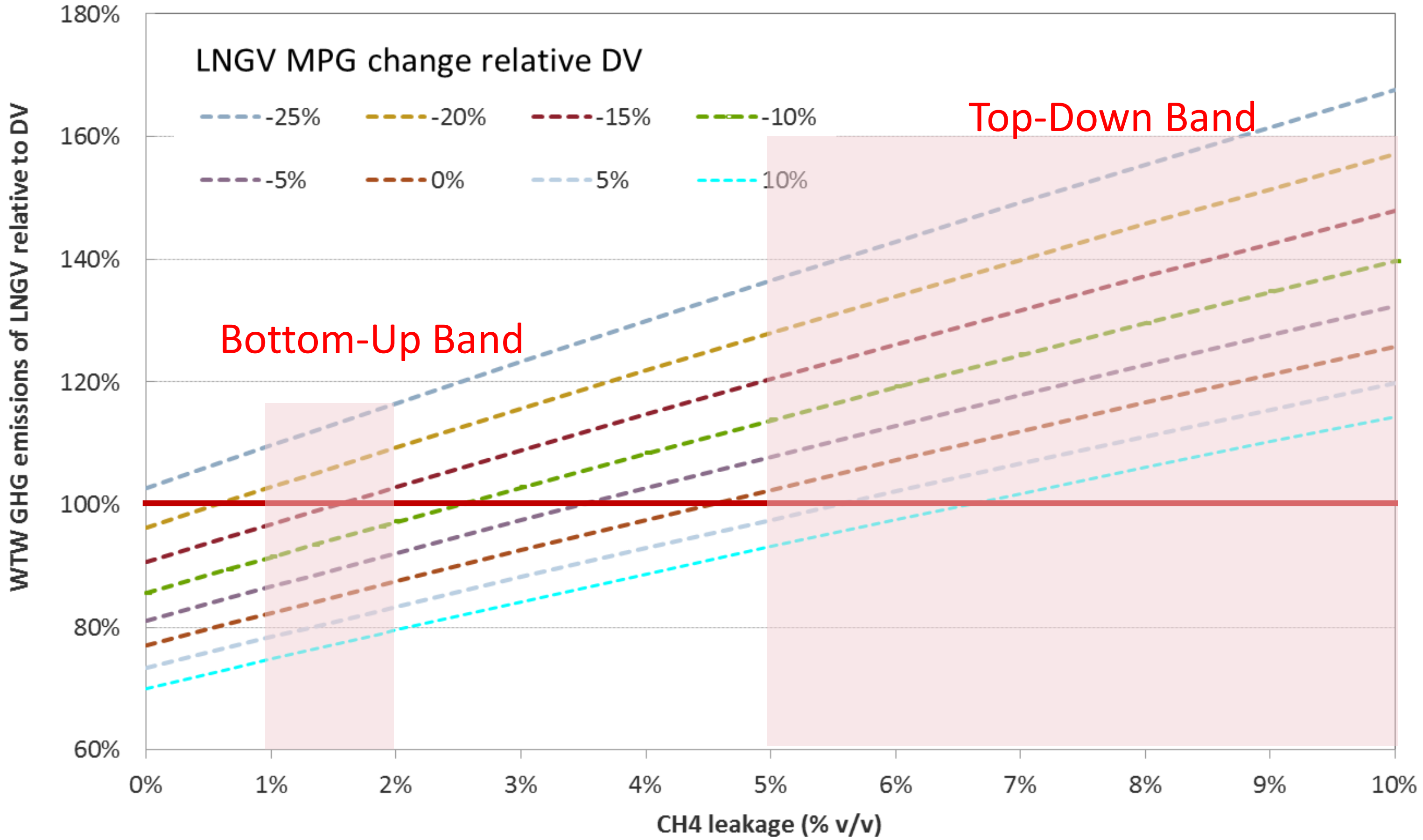
Sector	CH_4 Emissions: Percent of Volumetric NG Produced (Gross)												
	EPA - Inventory 5 yr avg (2011)	CMU - Marcellus Shale (2011)	NREL - Barnett Shale (2012)	API/ ANGA Survey (2012)	NOAA - DJ Basin (2012)	NOAA - Uintah Basin (2013)	Exxon Mobil (2013)	EPA - Inventory 2011 data (2013)	Univ. Texas (2013)	EPA - Inventory 2012 data (2014)	Stanford (2014)	IUP - Bakken (2014)	IUP - Eagle Ford (2014)
Gas Field	**1.18**		**0.9**	**0.75**	**2.3-7.7**	**6.2-11.7**	**0.6**	**0.44**	**0.42**	**0.33**		**2.8-17.4**	**2.9-15.3**
Completion/ Workover			0.7					0.17	0.03	0.04			
Unloading			0					0.04	0.05	0.05			
Other Sources			0.2					0.23	0.34	0.24			
Processing	**0.16**		**0**				**0.17**	**0.16**		**0.15**			
Transmission	**0.38**		**0.4**				**0.42**	**0.34**		**0.35**			
Distribution	**0.26**							**0.23**		**0.21**			
Total	**1.98**	**2.2**						**1.17**		**1.03**	**3.6-7.1**		

- Studies in **GREEN** are with bottom-up approach: measuring emissions of individual sources -> aggregating emissions along supply chain
- Studies in **RED** are with top-down approach: measuring CH4 concentration above or near fields/cities -> deriving CH4 emissions -> attributing emissions to NG-related activities

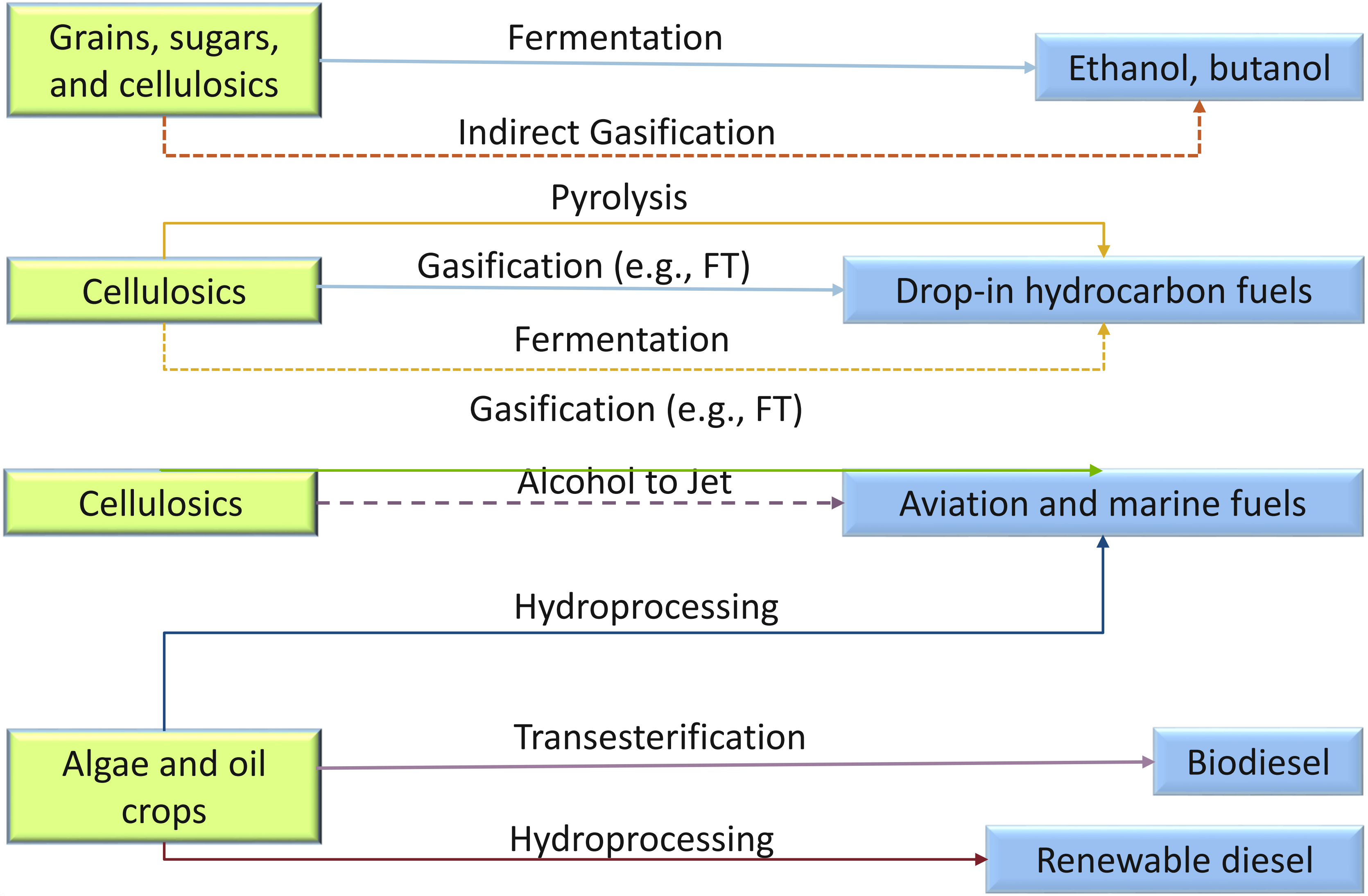
CNG vehicle efficiency and CH_4 leakage are two key factors of WTW GHG emissions of CNGVs vs. GVs



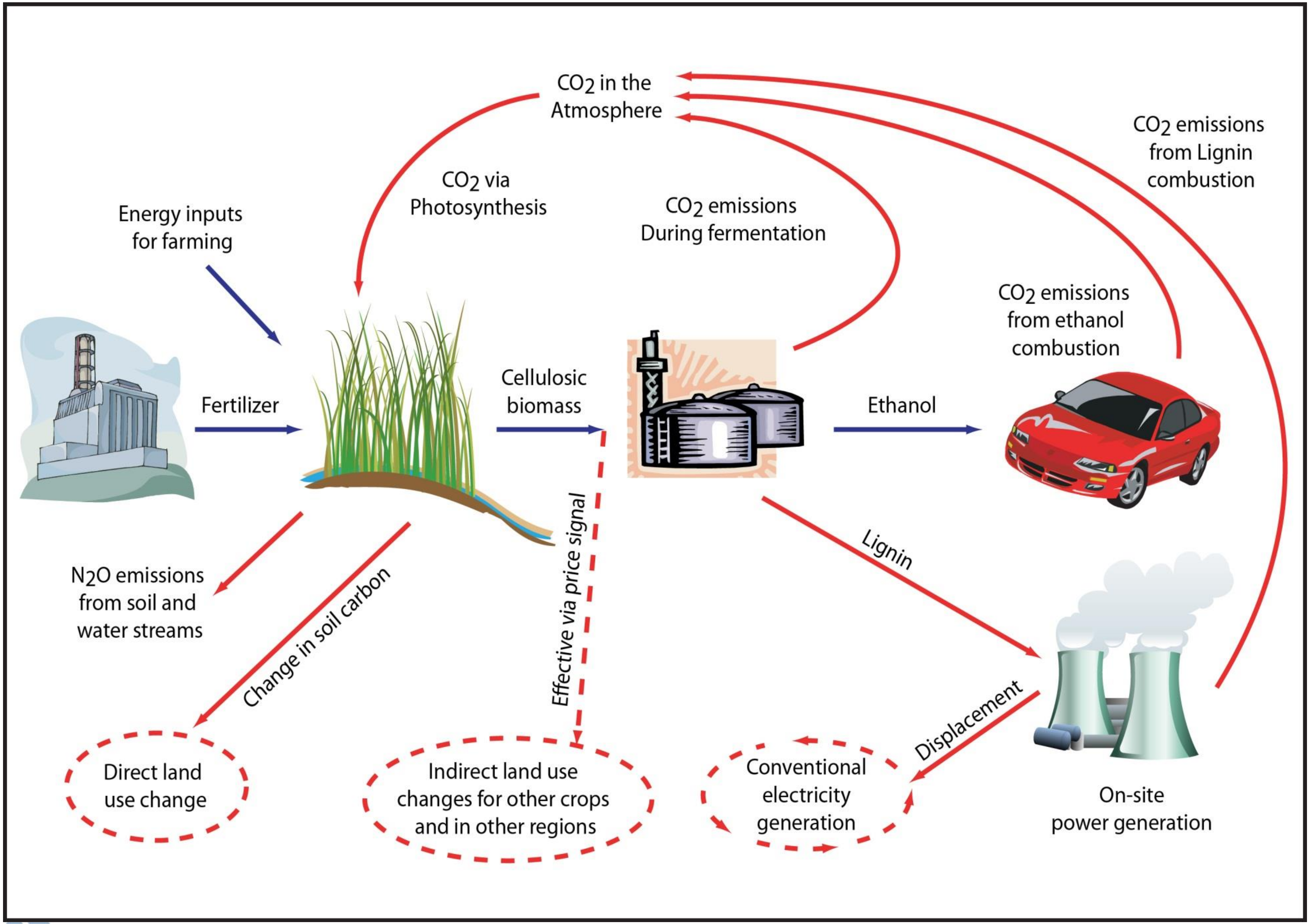
NGV efficiency and CH_4 leakage are two key factors of WTW GHG emissions of LNG HDVs vs. diesel HDVs



GREET includes various biomass feedstocks, conversion technologies, and liquid fuels



LCA system boundary: switchgrass to ethanol



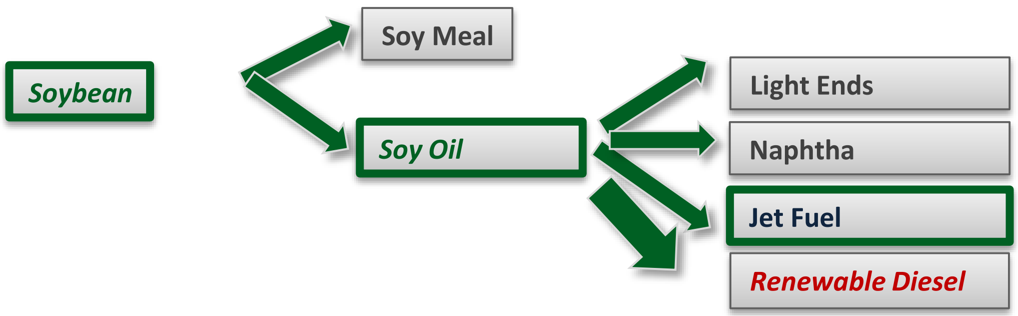
LCA co-product methods: benefits and issues

- Displacement method
  - Data intensive: need detailed understanding of the displaced product sector
  - Dynamic results: subject to change based on 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: results not entirely accurate, when coproducts are used in non-fuel applications
  - Market revenue based allocation: subject to price variation
- Process energy use approach
  - GREET method for petroleum refineries
  - Detailed engineering analysis is needed
  - Upstream burdens still need allocation based on mass, energy, or market revenue

Co-products and their treatment in GREET LCAs

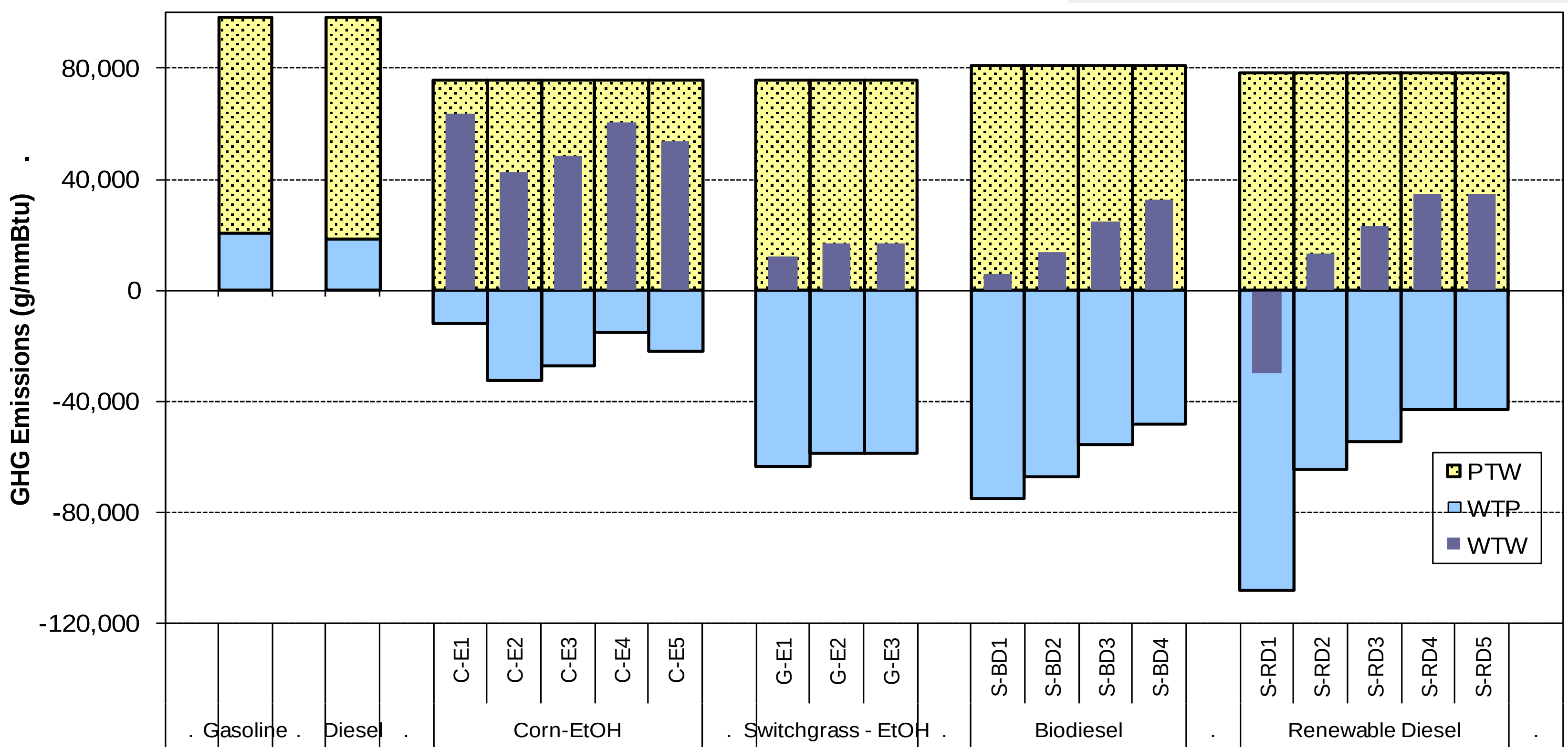
Pathway	Co-Product	Displaced Products	LCA Method in GREET	Alternative LCA Methods Available in GREET
Corn ethanol	DGS	Soybean, corn, and other animal feeds	Displacement	Allocation based on market revenue, mass, or energy
Sugarcane ethanol	Electricity from bagasse	Conventional electricity	Allocation based on energy	Displacement
Cellulosic ethanol (corn stover, switchgrass, and miscanthus)	Electricity from lignin	Conventional electricity	Displacement	Allocation based on energy
Petroleum gasoline	Other petroleum products	Other petroleum products	Allocation at refining process level based on energy	Allocation based on mass, market revenue

Choice of co-product methods can have significant LCA effects

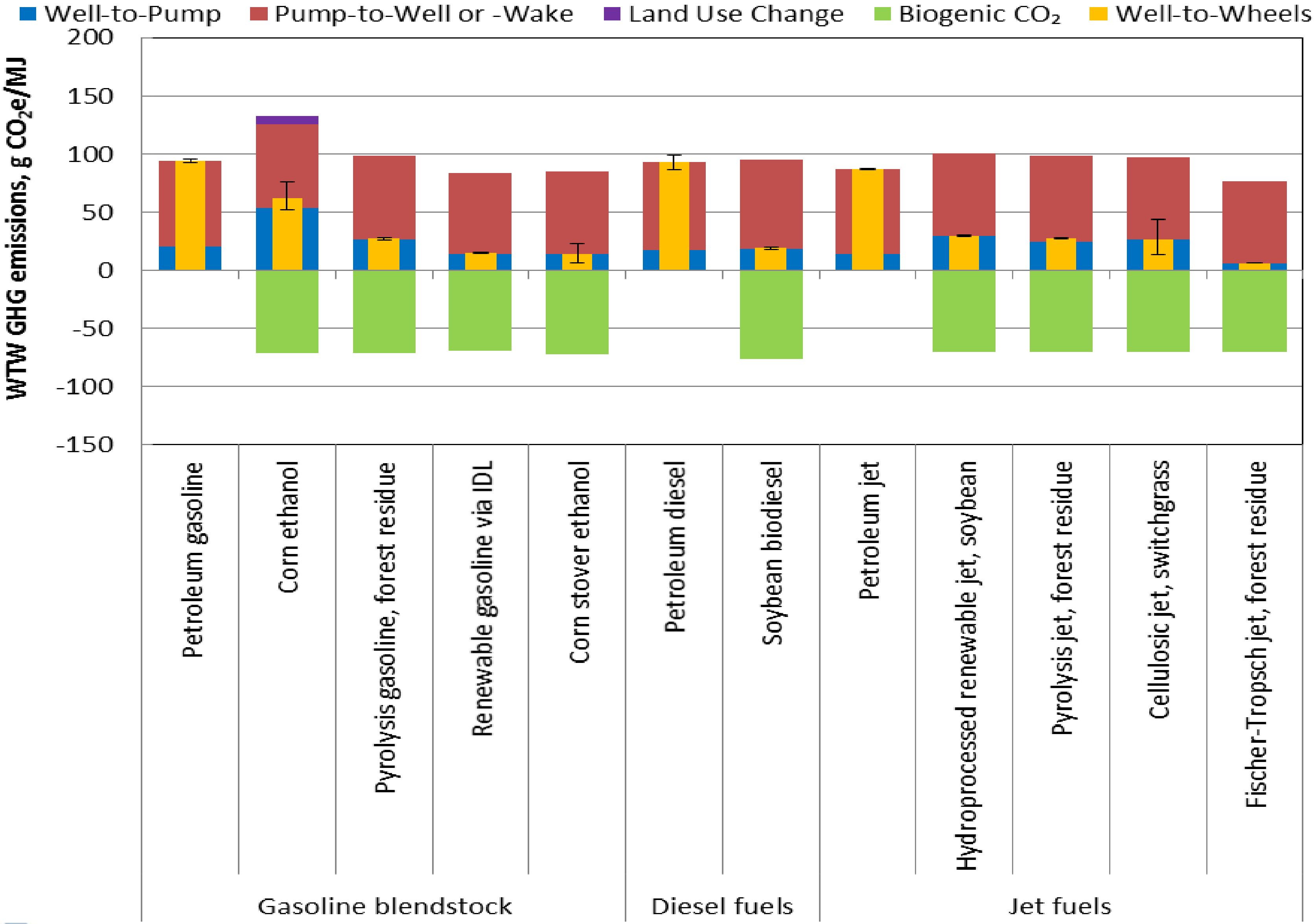


Biofuel production pathways and co-product methods included in this Study.

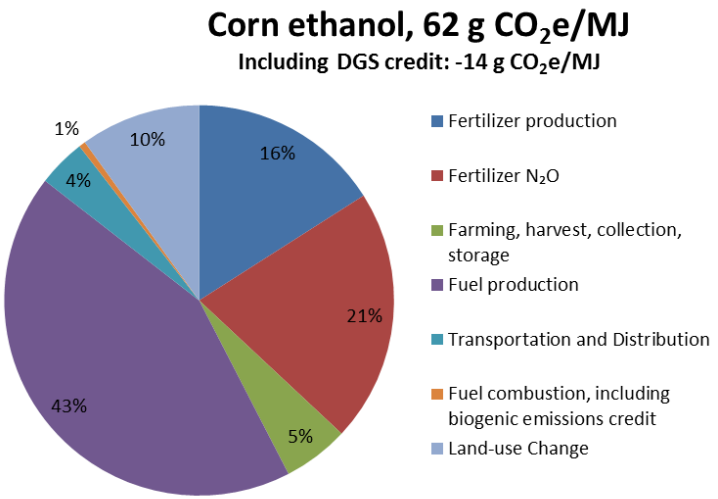
Biofuel Pathway	Method of Dealing with Multiple Products	Case Number
Corn to ethanol	Displacement	C-E1
	Mass	C-E2
	Energy content	C-E3
	Market value	C-E4
	Process purpose	C-E5
Switchgrass to ethanol	Displacement	G-E1
	Energy content	G-E2
	Market value	G-E3
Soybeans to biodiesel	Displacement	S-BD1
	Mass	S-BD2
	Energy content	S-BD3
	Market value	S-BD4
Soybeans to renewable diesel	Displacement	S-RD1
	Mass	S-RD2
	Energy content	S-RD3
	Market value	S-RD4
	Hybrid allocation	S-RD5

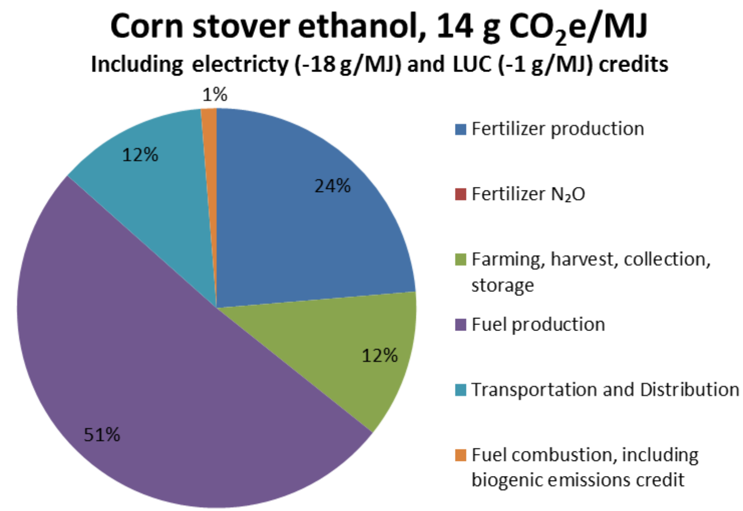


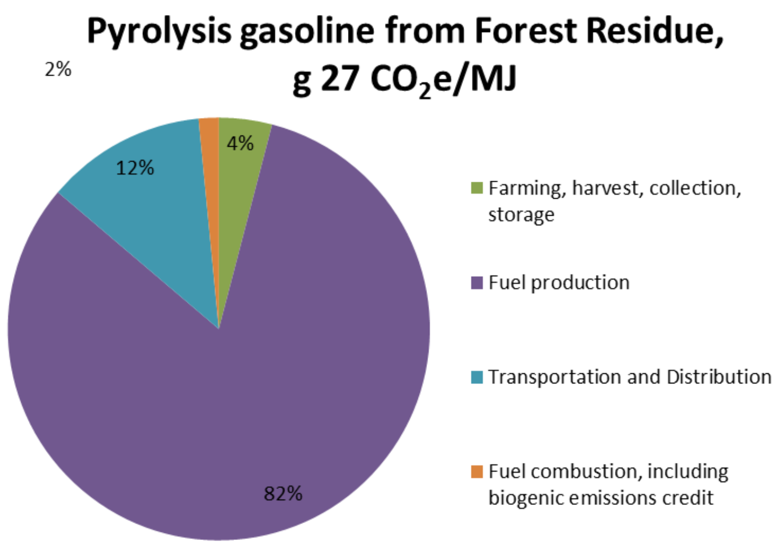
Life-cycle GHG emissions of selected biofuels

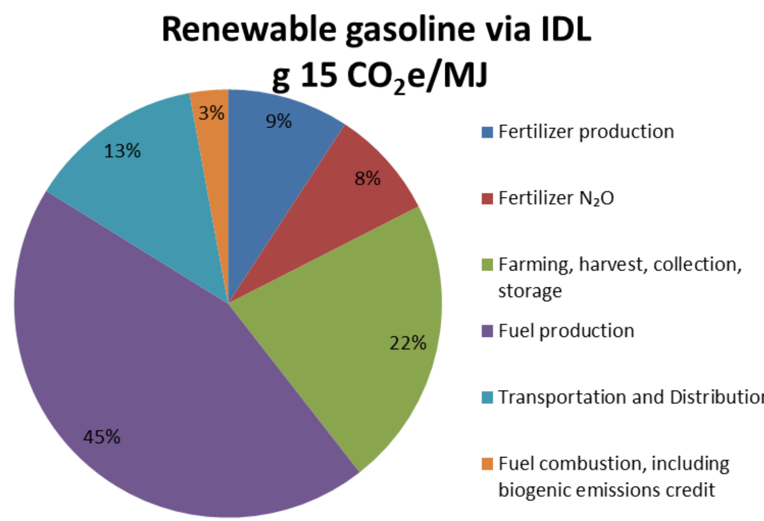


Emission breakout for different biofuels









Electricity Generation Systems in GREET

1. Coal: Steam Boiler and IGCC
Coal mining & cleaning
Coal transportation
Power generation

2. Natural Gas: Steam boiler, Gas Turbine, and NGCC
NG recovery & processing
NG transportation
Power generation

3. Nuclear: light water reactor
Uranium mining
Yellowcake conversion
Enrichment
Fuel rod fabrication
Power generation

4. Petroleum: Steam Boiler
Oil recovery & transportation
Refining
Residual fuel oil transportation
Power generation

5. Biomass: Steam Boiler
Biomass farming & harvesting
Biomass transportation
Power generation

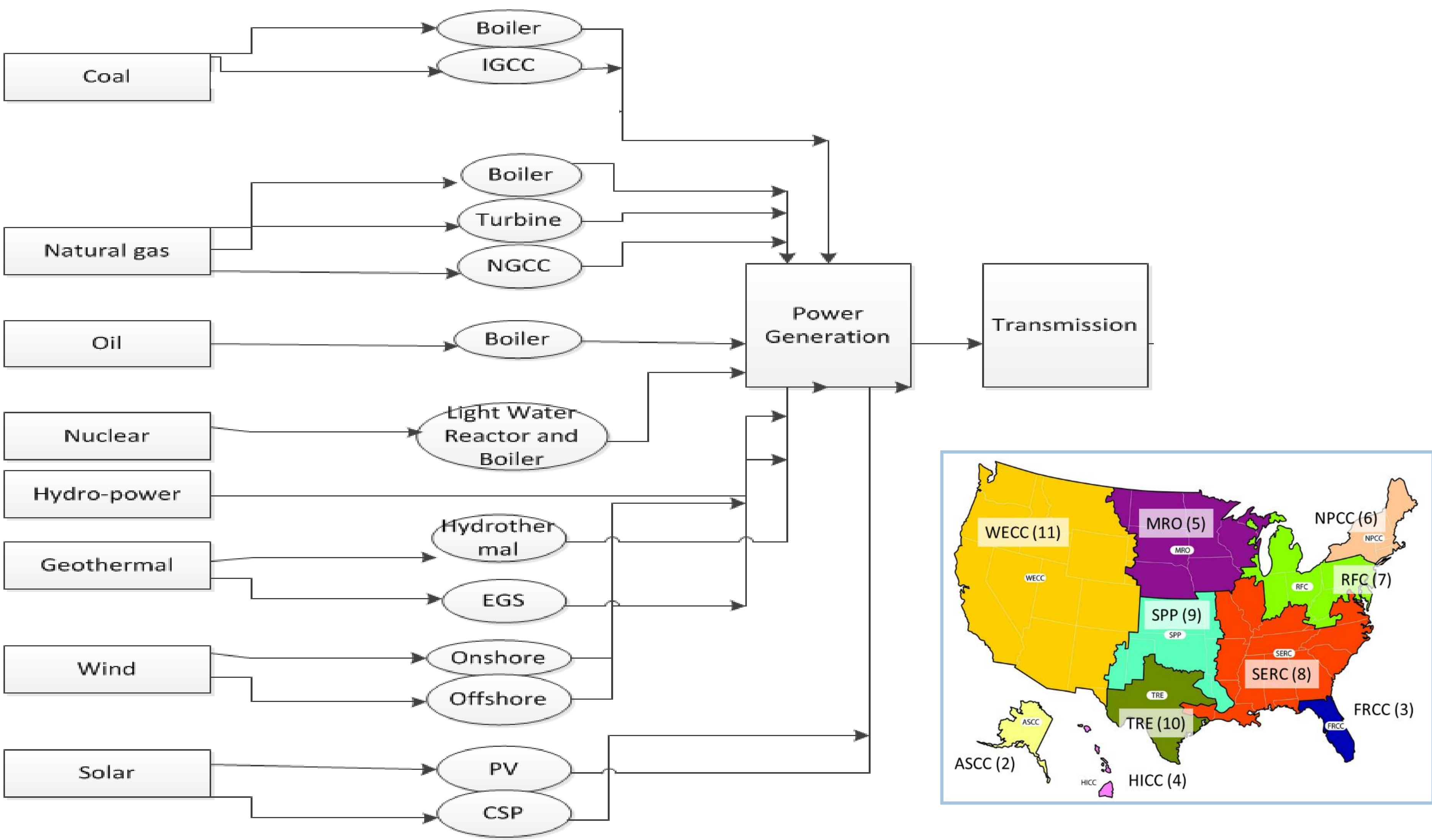
6. Hydro-Power

7. Wind Turbine

8. Solar PV and CSP

9. Geothermal

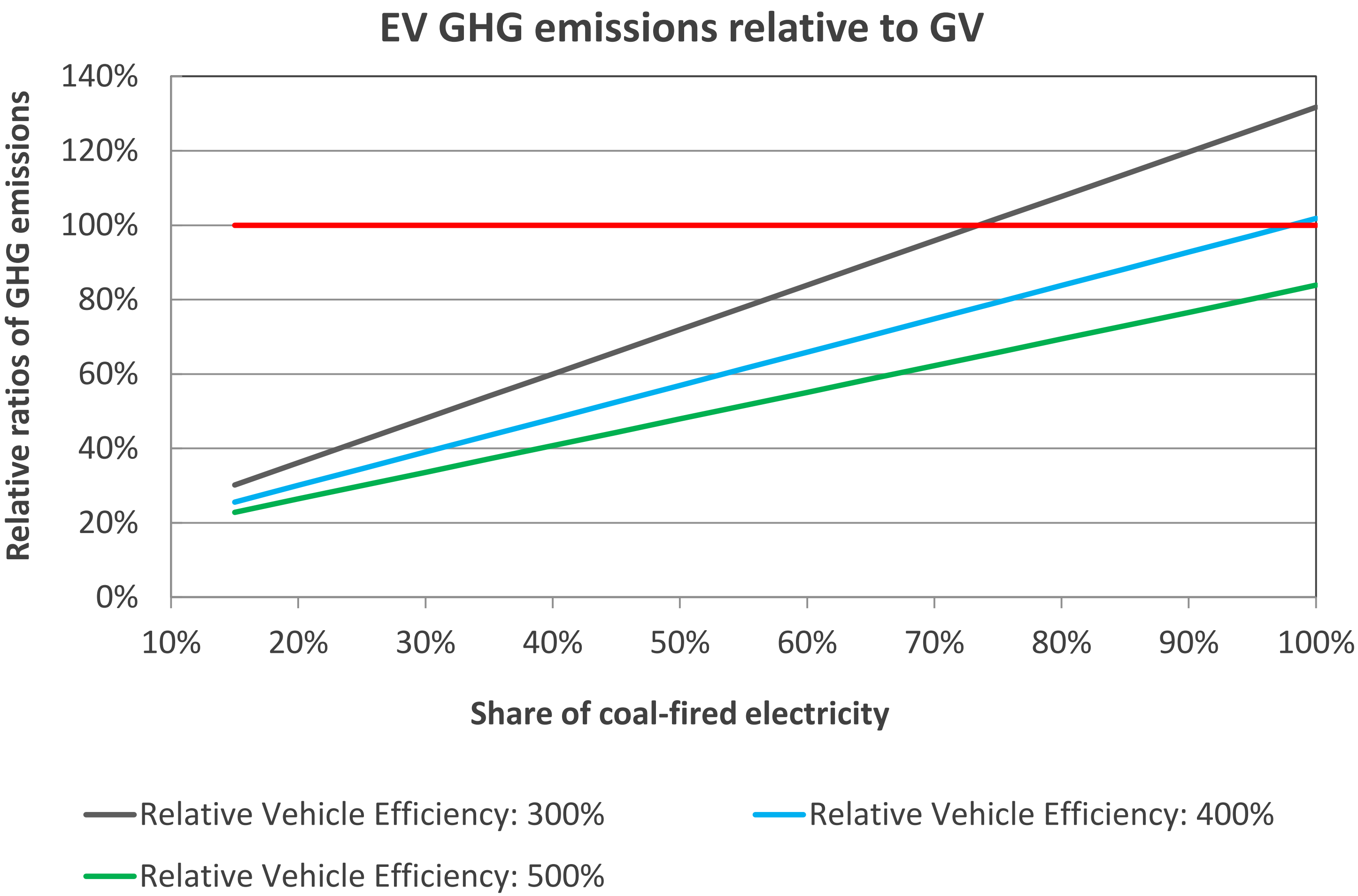
GREET models electricity generation mix at national, state and utility region levels



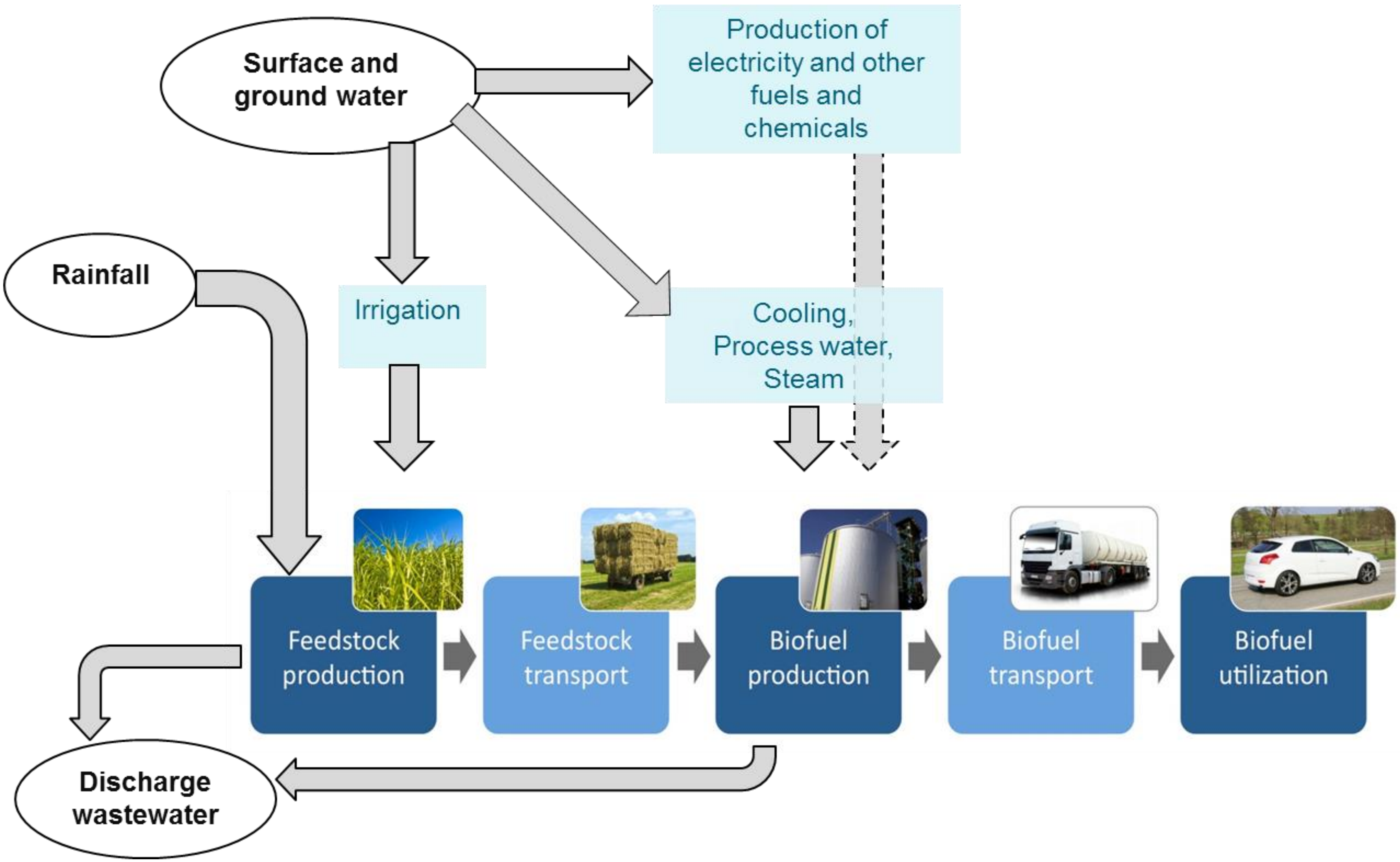
Data and methods for GREET electricity modeling

- **Electricity generation mixes**
  - EIA's Annual Energy Outlook
- **Thermal efficiencies**
  - EIA's electric generating unit-level performance data (EIA Form 923 and 860 data)
- **GHG emission factors**
  - CH_4 and N_2O emissions are estimated by multiplying the fuel specific heat input in MMBtu by appropriate EFs from Table C-2 of EPA's Final Mandatory Reporting of Greenhouse Gases Rule (EPA, 2009)
  - CO_2 emissions calculated from fuel carbon intensity and fuel consumption
- **Criteria air pollutants emission factors**
  - SOx and NOx emission data from the EPA's AMPD database
  - PM emissions for various EGUs by emissions control technologies in AMPD

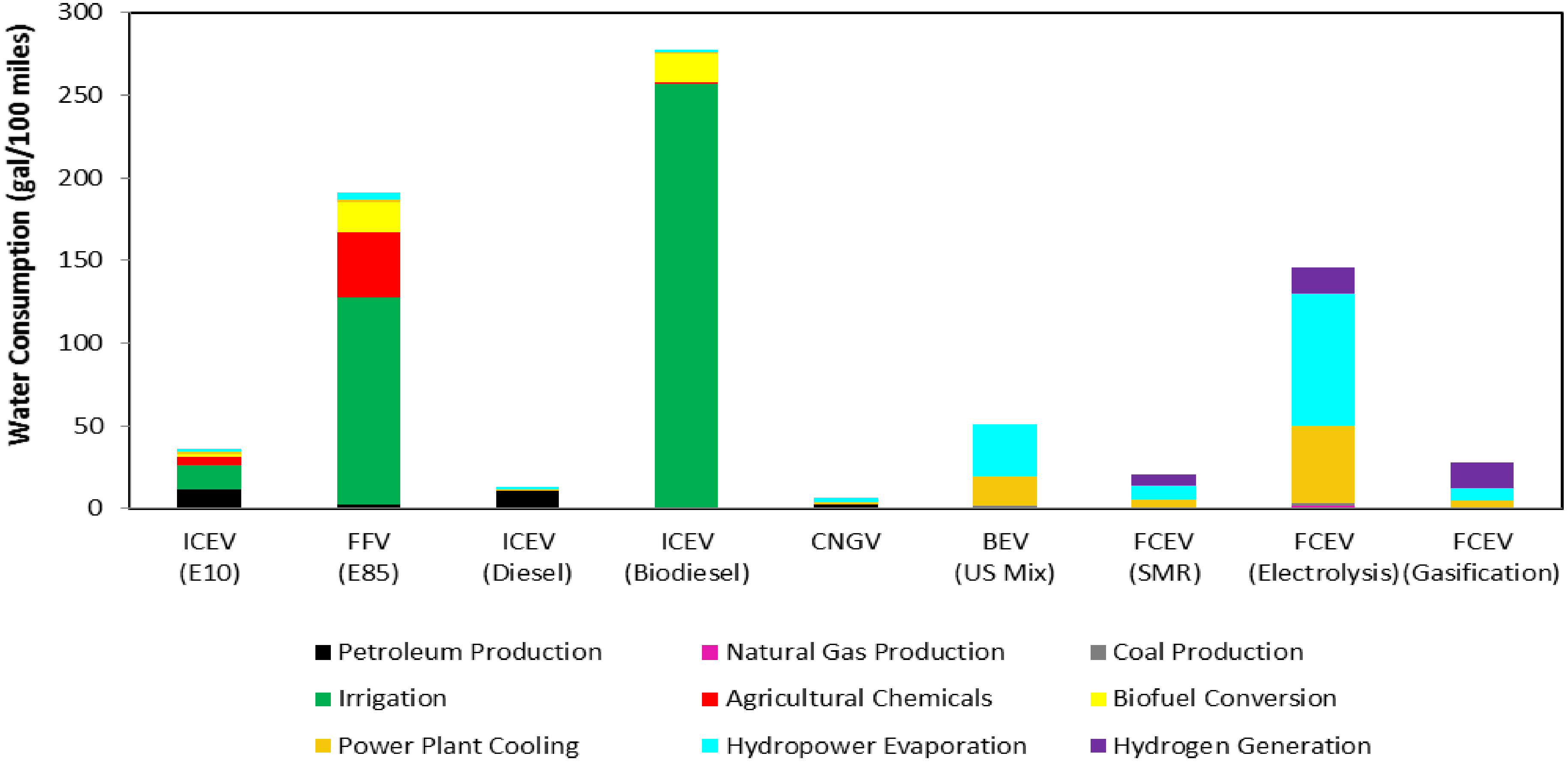
GREET quantifies effects of electric generation mix and relative EV efficiency on EV GHG performance



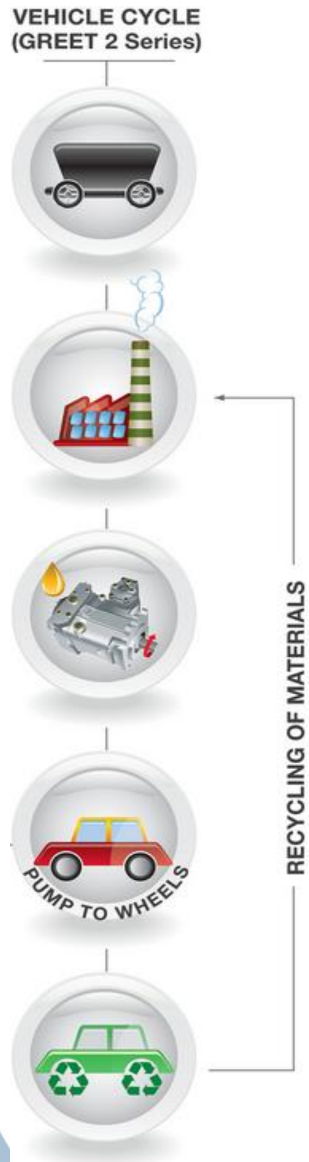
Example: biofuel pathway water use accounting



Life-cycle water consumption is dominated by electricity use and irrigation for biofuels

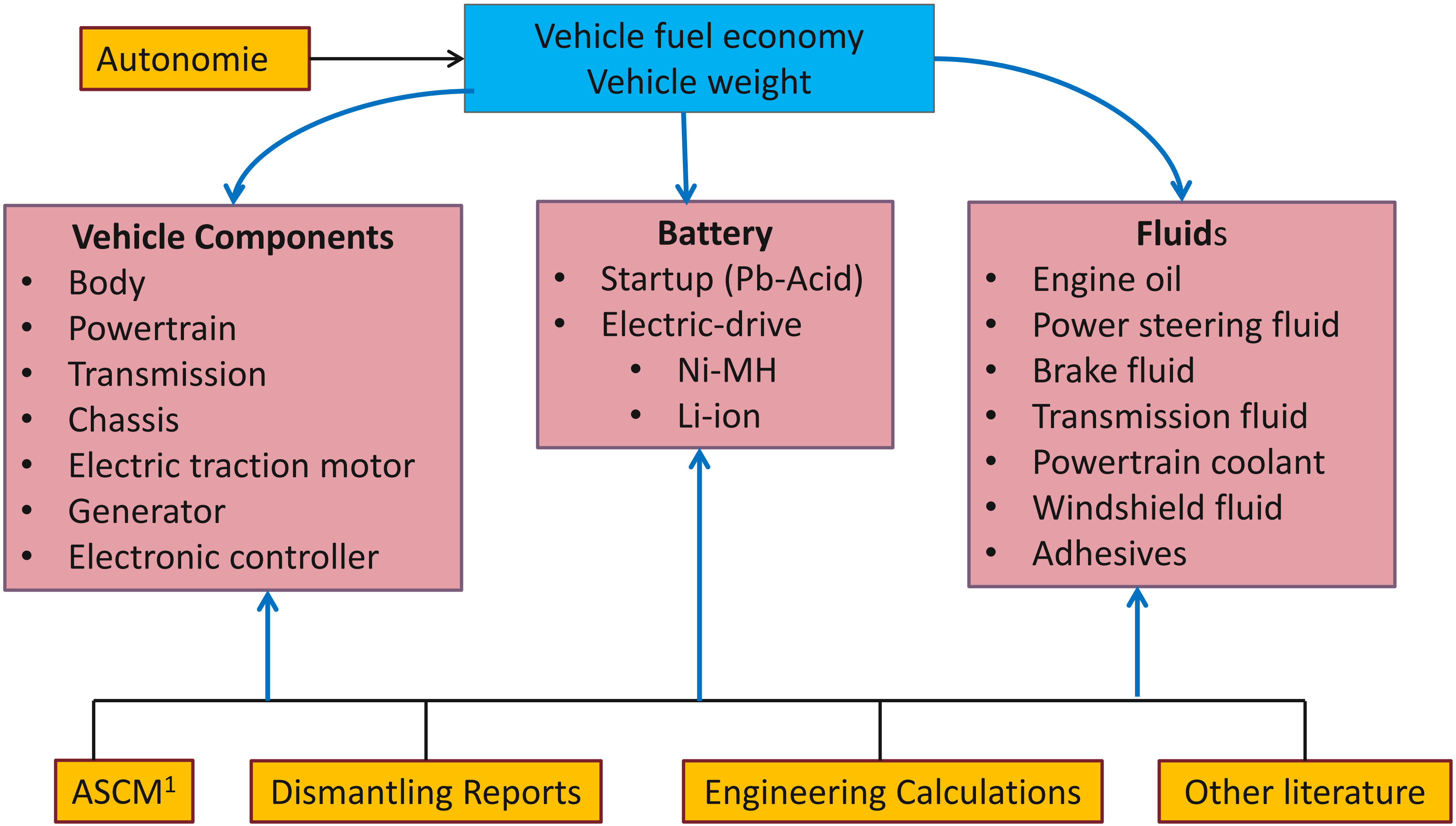


GREET 2 simulates vehicle cycle energy use and emissions from material recovery to vehicle disposal



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

Developing a materials inventory for vehicles



1. Automotive System Cost Model, IBIS Associates and Oak Ridge National Laboratory

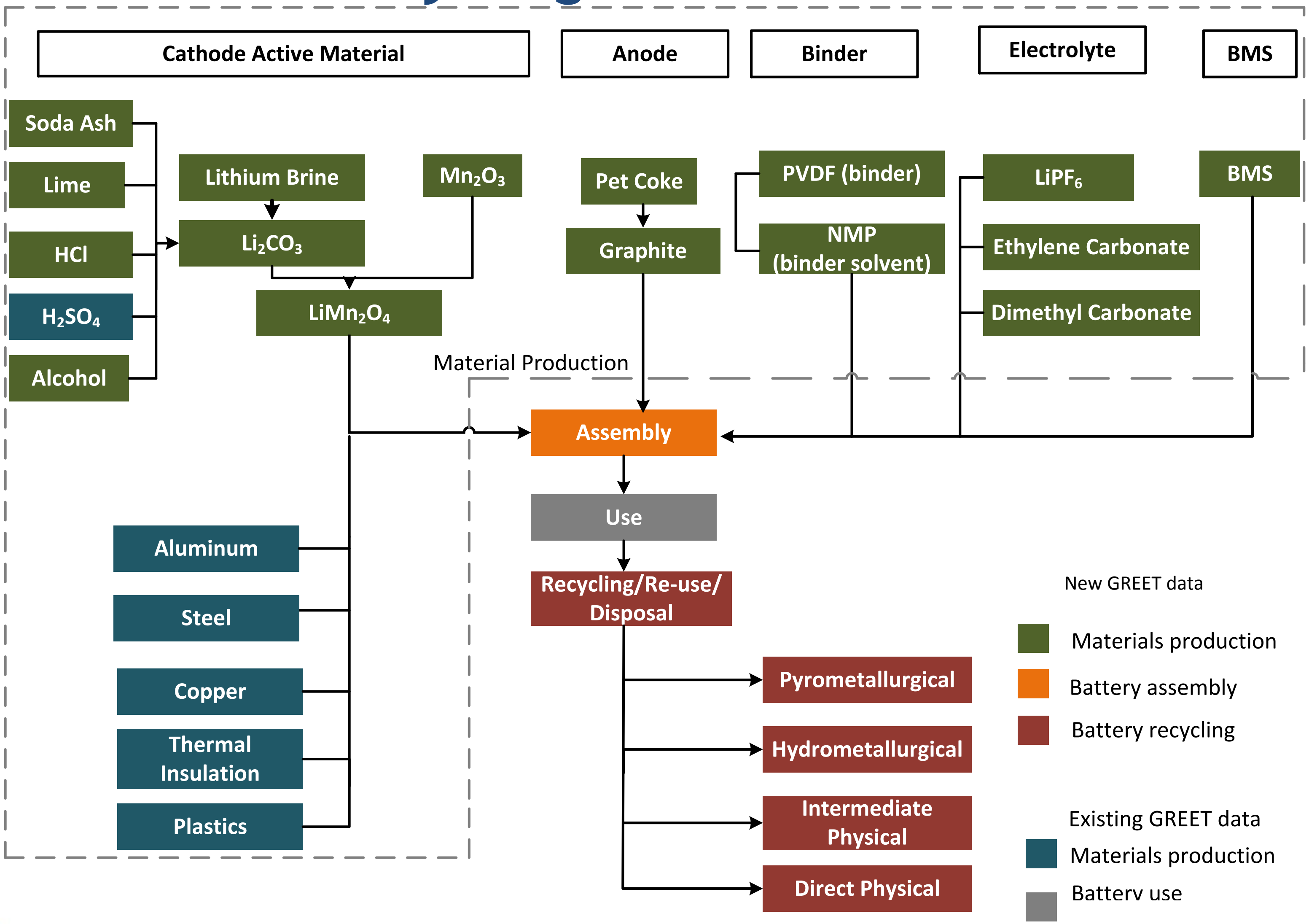
Life Cycles of 60+ materials are included in GREET 2

Material Type	Number in GREET	Examples
Ferrous Metals	3	Steel, stainless steel, iron
Non-Ferrous Metals	12	Aluminum, copper, nickel, magnesium
Plastics	23	Polypropylene, nylon, carbon fiber reinforced plastic
Vehicle Fluids	7	Engine oil, windshield fluid
Others	17	Glass, graphite, silicon, cement
Total	**62**	

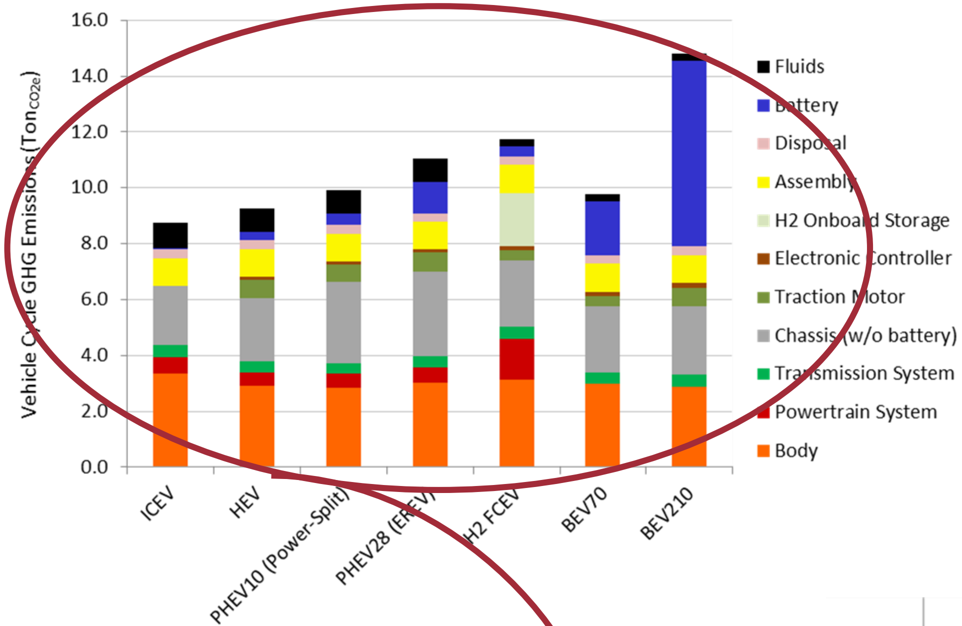
Key issues in vehicle-cycle analysis

- ❑ Use of virgin vs. recycled materials
- ❑ Vehicle weight and lightweighting
- ❑ Vehicle lifetime, component rebuilding/replacement

GREET battery LCA module contains life-cycle inventory of lithium-ion batteries including battery production and recycling

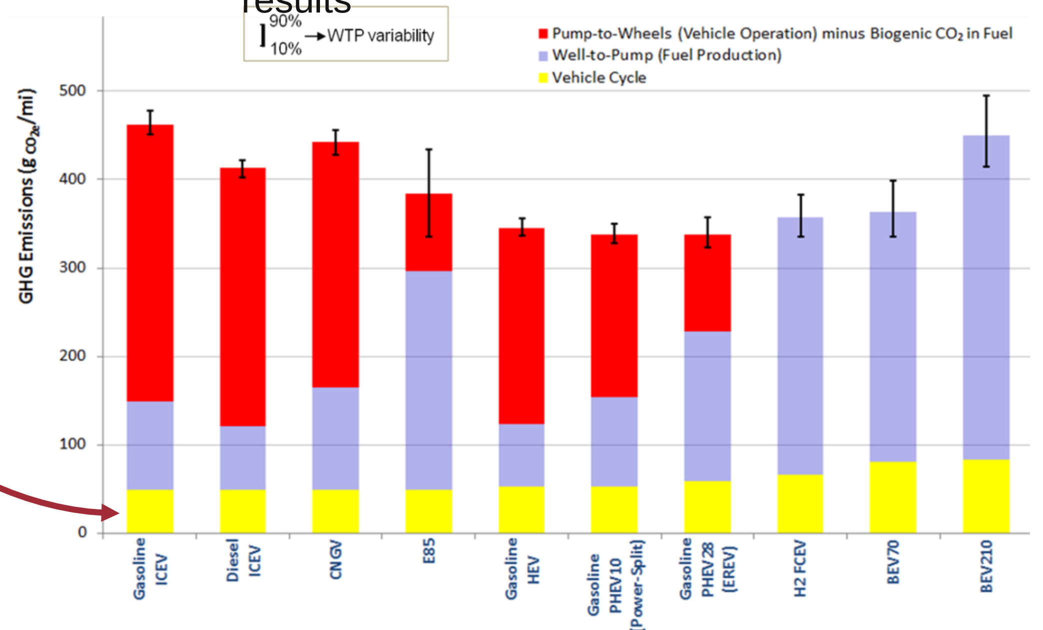


Battery LCA to Vehicle LCA to Vehicle/Fuel LCA



Battery contributes to 1-8% of total results for PEVs

Vehicle cycle contributes to 10-22% of total results



Please visit greet.es.anl.gov for:

- ***GREET models***
- ***GREET documents***
- ***LCA publications***
- ***GREET-based tools and calculators***