Life-cycle Analysis of Vehicle/Fuel Systems Using the GREET Model

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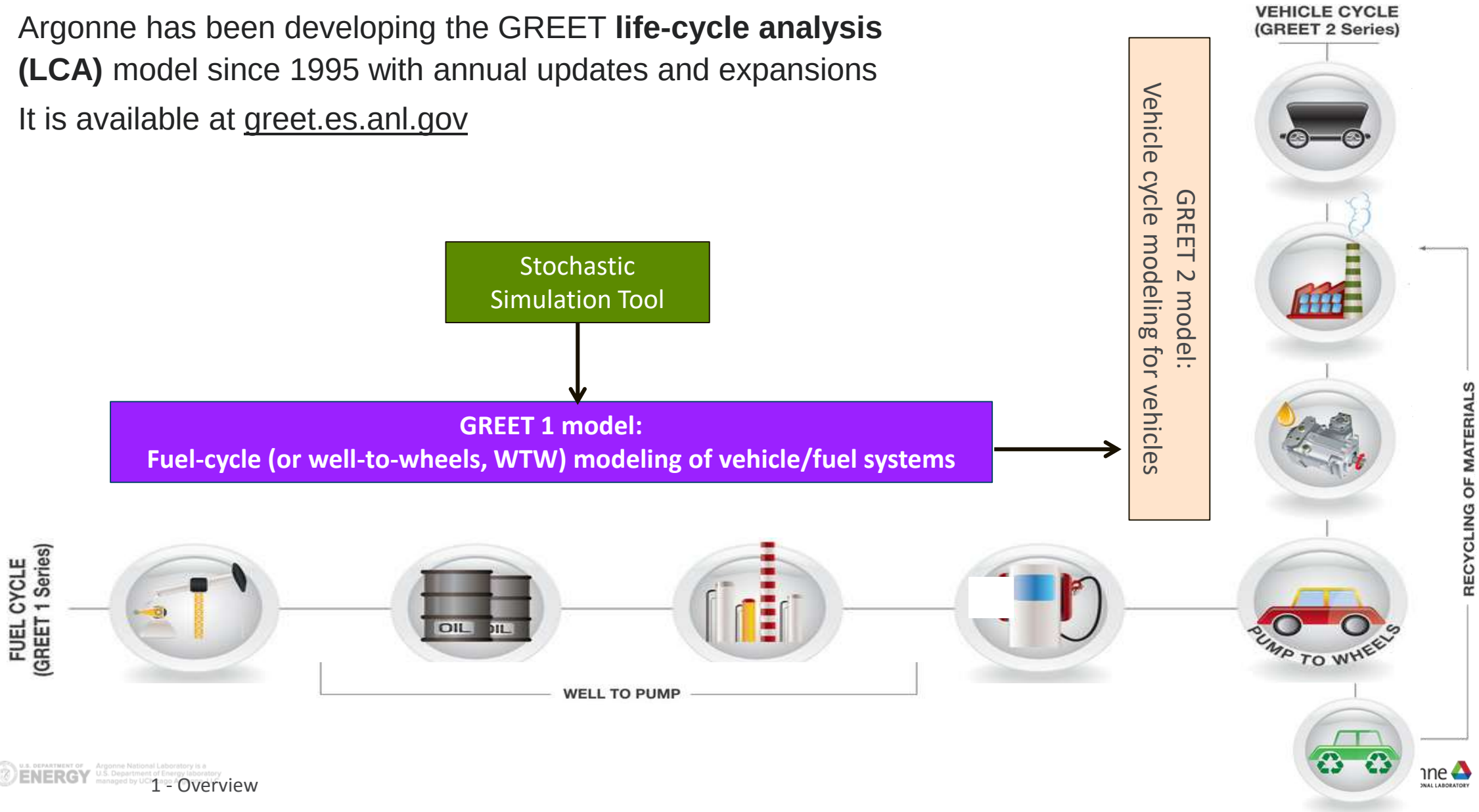
LIFE CYCLE ASSESSMENT METHODS TO SUPPORT INDIA'S EFFORTS TO DECARBONISE TRANSPORT

WORKSHOP UNDER THE DTEE AND NDC-TIA PROJECTS

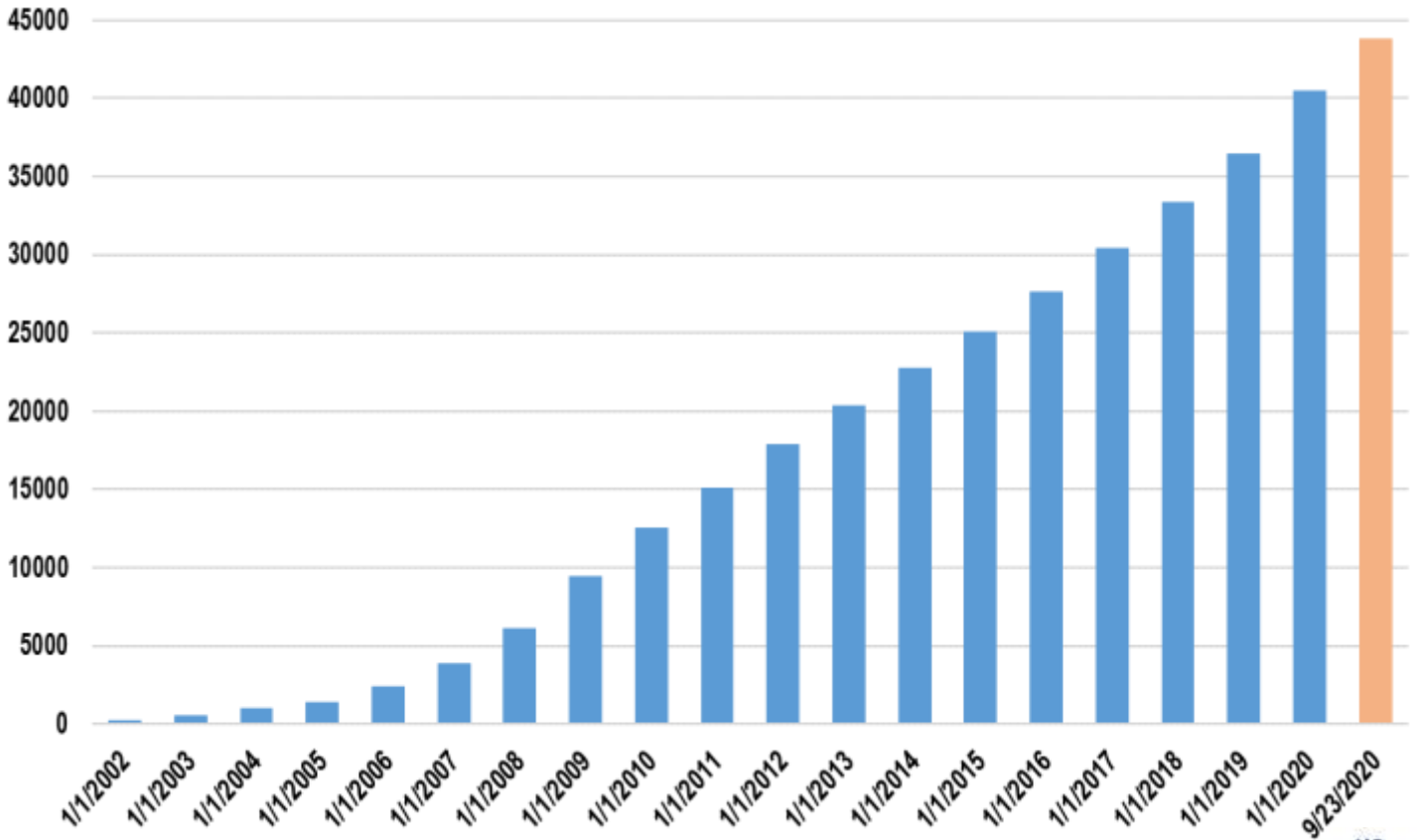
April 13 2021

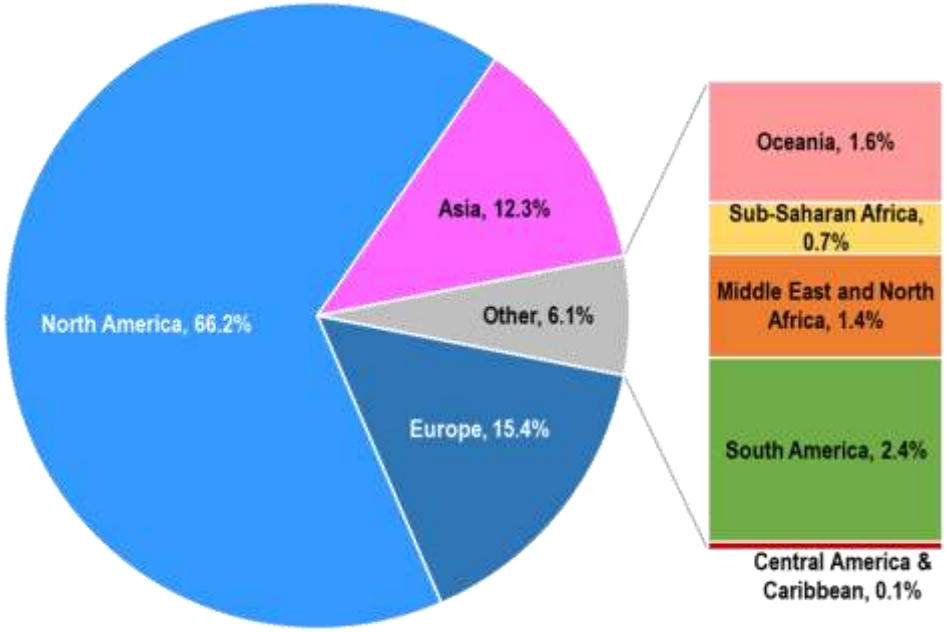
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model Framework

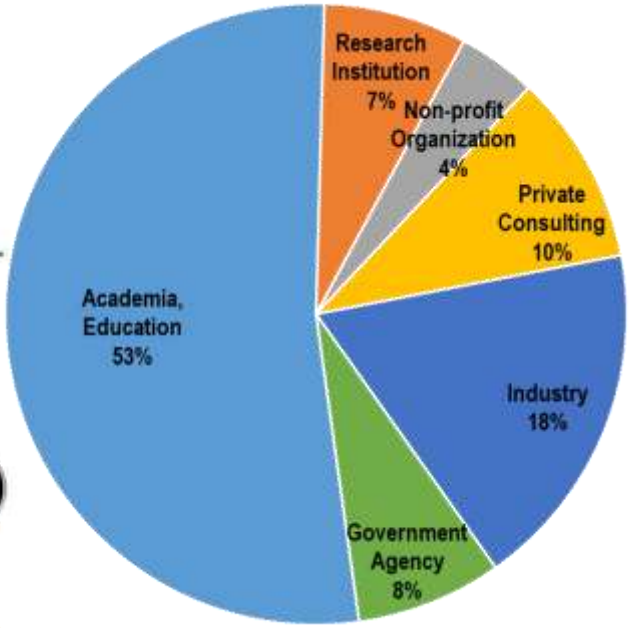
- Argonne has been developing the GREET **life-cycle analysis (LCA)** model since 1995 with annual updates and expansions
- It is available at greet.es.anl.gov



~ 43,800 Registered GREET Users Globally







GREET includes a suite of models and tools

- GREET coverage
  - ✓ GREET1: fuel cycle (or WTW) model of vehicle technologies and transportation fuels
  - ✓ GREET2: vehicle manufacturing cycle model of vehicle technologies
- Modeling platform
  - ✓ Excel
  - ✓ .net
- GREET derivatives
  - ✓ ICAO-GREET by ANL, based on GREET1
  - ✓ China-GREET by ANL, with support of Aramco
  - ✓ CA-GREET by CARB, based on GREET1
  - ✓ AFLEET by ANL: alternative-fuel vehicles energy, emissions, and cost estimation
  - ✓ EverBatt by ANL: energy, emissions, and cost modeling of remanufacturing and recycling of EV batteries

GREET applications by agencies

California Environmental Protection Agency Air Resources Board CA-GREET3.0 built based on and uses data from ANL GREET

DEQ Oregon Dept of Environ. Quality Clean Fuel Program

EPA RFS2 used GREET and other sources for LCA of fuel pathways; GHG regulations

NHTSA National Highway Traffic Safety Administration (NHTSA) fuel economy regulation

FAA and ICAO AFTF using GREET to evaluate aviation fuel pathways

USDRIVE GREET was used for the US DRIVE Fuels Working Group Well-to-Wheels Report

MARAD LCA of renewable marine fuel options to meet IMO 2020 sulfur regulations for the DOT MARAD

USDA US Dept of Agriculture: ARS for carbon intensity of farming practices and management; ERS for food environmental footprints; Office of Chief Economist for bioenergy LCA

GREET sustainability metrics include energy use, criteria pollutants, greenhouse gases, and water consumption

Energy use

- Total energy: fossil energy and renewable energy
- Fossil energy: petroleum, natural gas, and coal
- Renewable energy: biomass, nuclear energy, hydro-power, wind power, and solar energy

Air pollutants

- VOC, CO, NOx, PM_{10}, $PM_{2.5}$, and SOx
- Estimated separately for total and urban (a subset of the total) emissions

Greenhouse gases

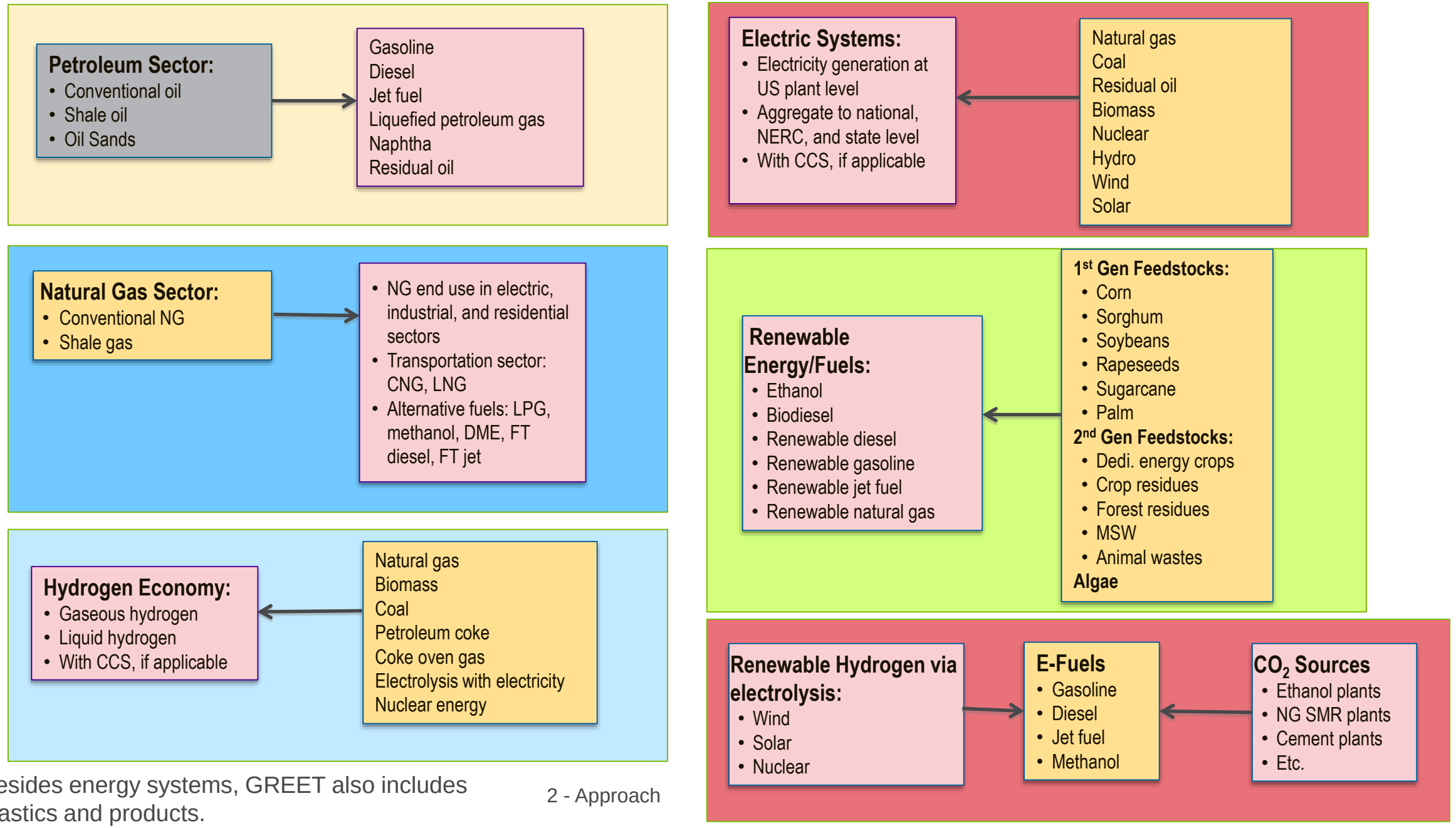
- CO_2, CH_4, N_2O, black carbon, and albedo
- CO_{2e} of the five (combined with their global warming potentials)

Water consumption

- Addressing water supply and demand (energy-water nexus)

- GREET LCA functional units
  - Per service unit (e.g., mile driven, ton-mile, passenger-mile)
  - Per unit of output (e.g., million Btu, MJ, gasoline gallon equivalent)
  - Per units of resource (e.g., per ton of biomass)

GREET covers many groups of energy systems



Besides energy systems, GREET also includes plastics and products.

GREET includes key propulsion technologies for light-duty and heavy-duty vehicles

Conventional Spark-Ignition Engine Vehicles
- Liquid and gaseous fuels

Spark-Ignition, Direct-Injection Engine Vehicles
- Liquid and gaseous fuels

Compression-Ignition, Direct-Injection Engine Vehicles
- Liquid fuels

Hybrid Electric Vehicles (HEVs)
- Spark-ignition engines:
- Compression-ignition engines

Plug-in Hybrid Electric Vehicles (PHEVs)
- Spark-ignition engines:
- Compression-ignition engines

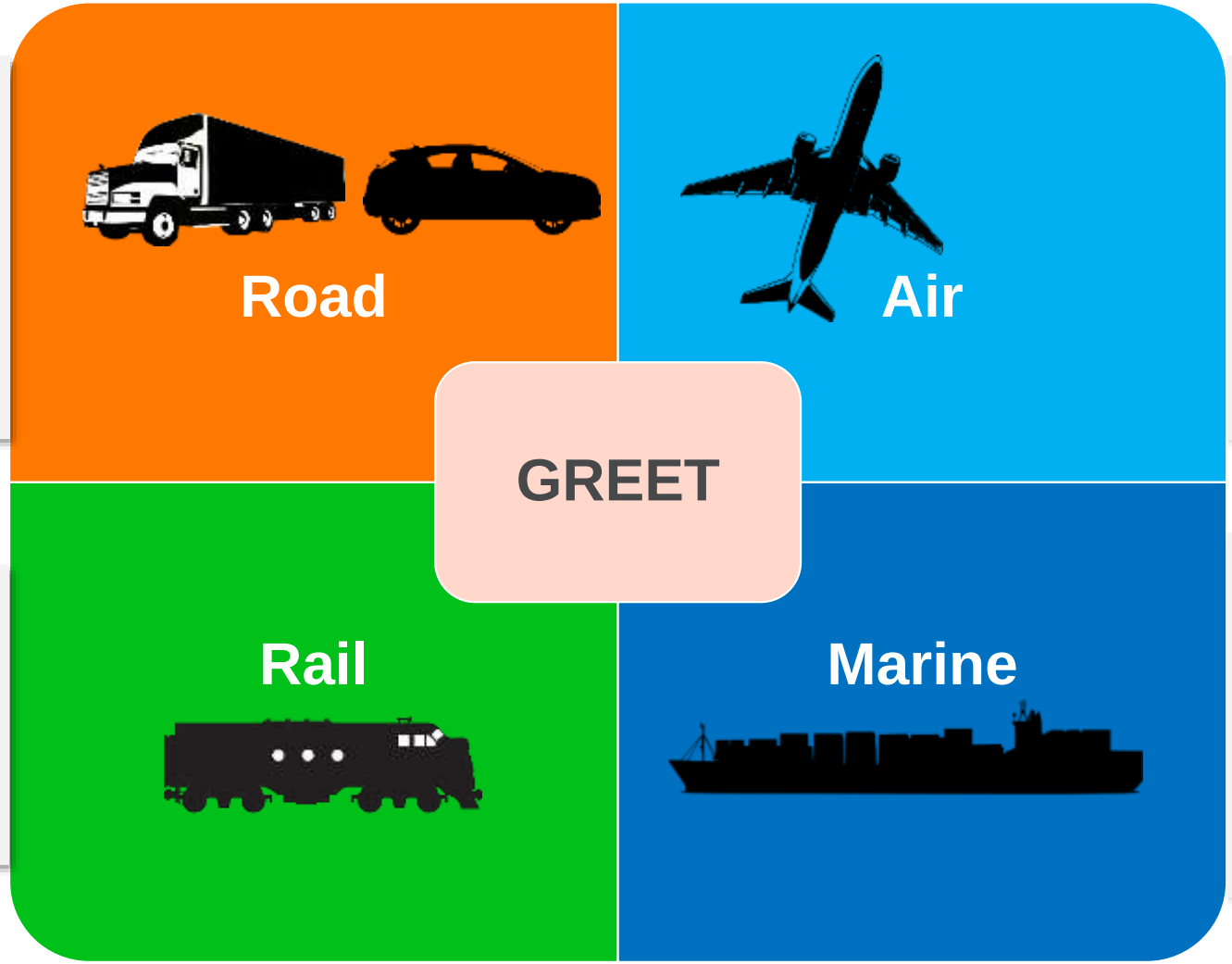
Battery-Powered Electric Vehicles
- Various electricity generation sources

Fuel Cell Vehicles
- Hydrogen and on-board hydrocarbon reforming to hydrogen

GREET includes all transportation subsectors

(It is now expanded to include LCA of buildings and building technologies)

- Light-duty vehicles
- Medium-duty vehicles
- Heavy-duty vehicles
- Various powertrains:
  - Internal combustion
  - Battery electric
  - Fuel cells



Globally, a fast growing sector with GHG reduction pressure. GREET includes

- Passenger and freight transportation of various alternative fuels blended with petroleum jet fuels

Freight transportation GREET includes

- Diesel
- Electricity
- CNG/LNG

The sector is under pressure to reduce air emissions and GHG emissions. GREET includes

- Ocean and inland water transportation
- Baseline diesel and alternative marine fuels

GREET LCA modeling framework

- Build LCA modeling capacity
- Build a consistent LCA platform with reliable, widely accepted methods/protocols
- Address emerging LCA issues
- Access to primary data sources and conduct detailed analysis
- Document sources of data, modeling and analysis approach, and results/conclusions
- Maintain openness and transparency of LCAs by making GREET and its documentation publicly available
- Primarily process-based LCA approach (the so-called attributional LCA); some features of consequential LCA are incorporated

GREET relies on a variety of data sources

Baseline technologies and systems

- Energy Information Administration's data and its Annual Energy Outlook projections
- EPA eGrid for electric systems
- US Geology Services for water data

Field operation data

- Oil sands and shale oil operations
- Ethanol plants energy use
- Farming data from USDA

Simulations with models

- ASPEN Plus for fuel production
- ANL Autonomie for fuel economy
- EPA MOVES for vehicle emissions, EPA AMPD for stationary emissions
- LP models for petroleum refinery operations
- Electric utility dispatch models for marginal electricity analysis

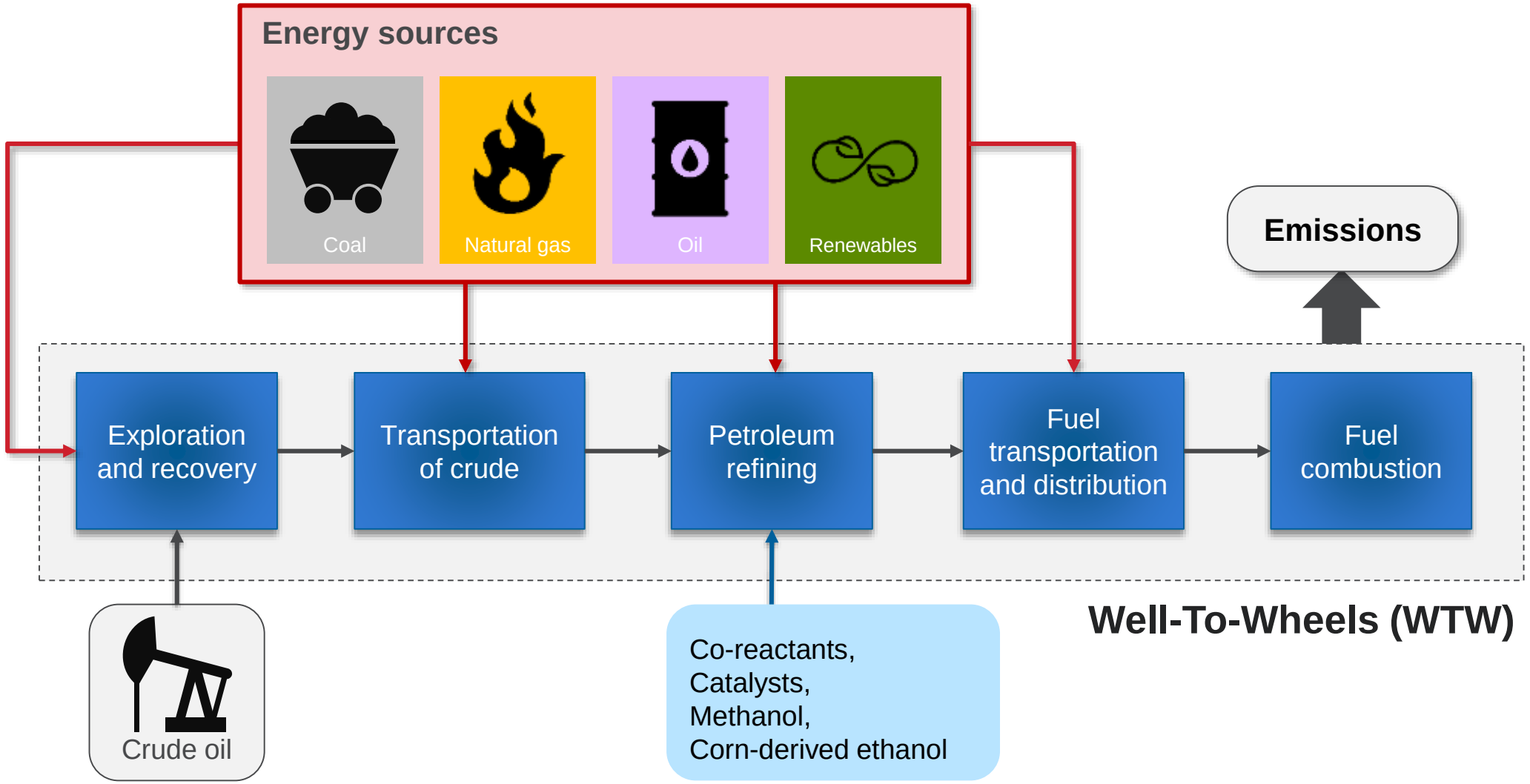
Collaboration with other national laboratories

Industry inputs

- Fuel producers and technology developers on fuels
- Automakers and system components producers on vehicles

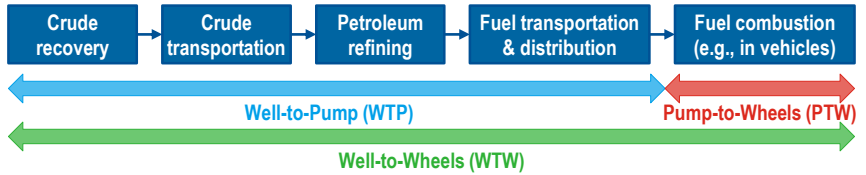
Life cycle of petroleum fuels

- GREET covers from petroleum recovery to fuel use (combustion) by including all energy inputs and emissions for each stage.

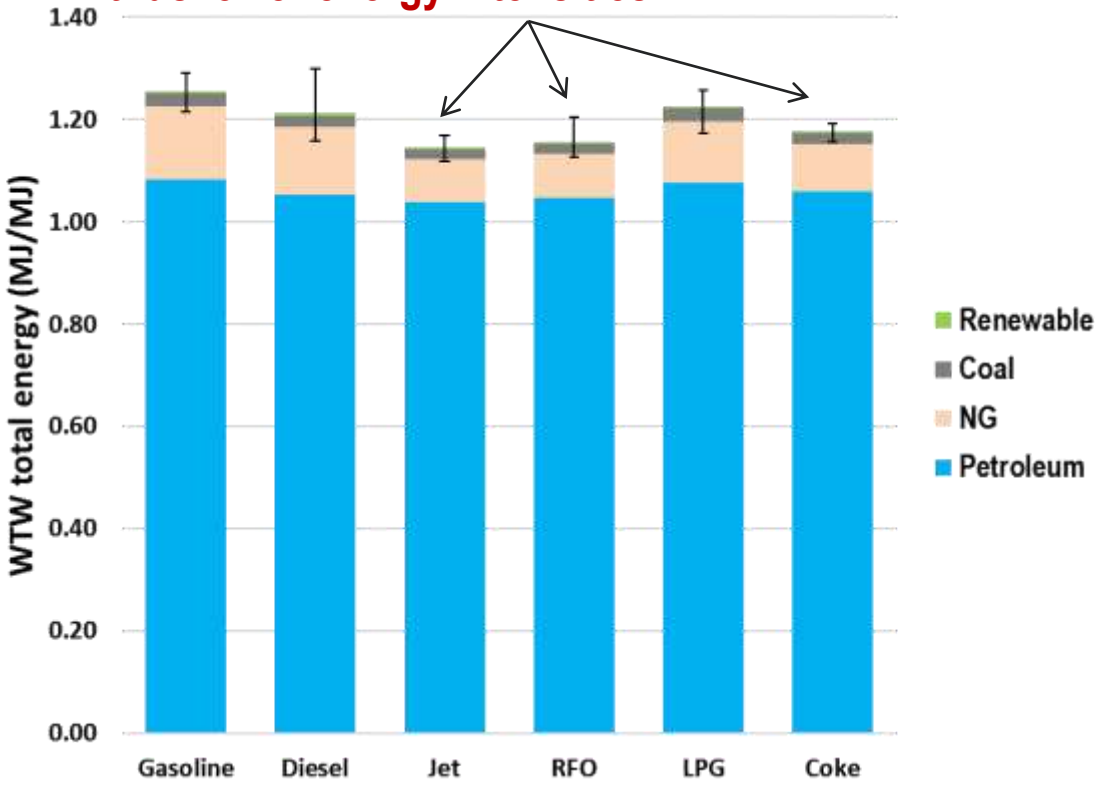


Petroleum product well-to-wheels results

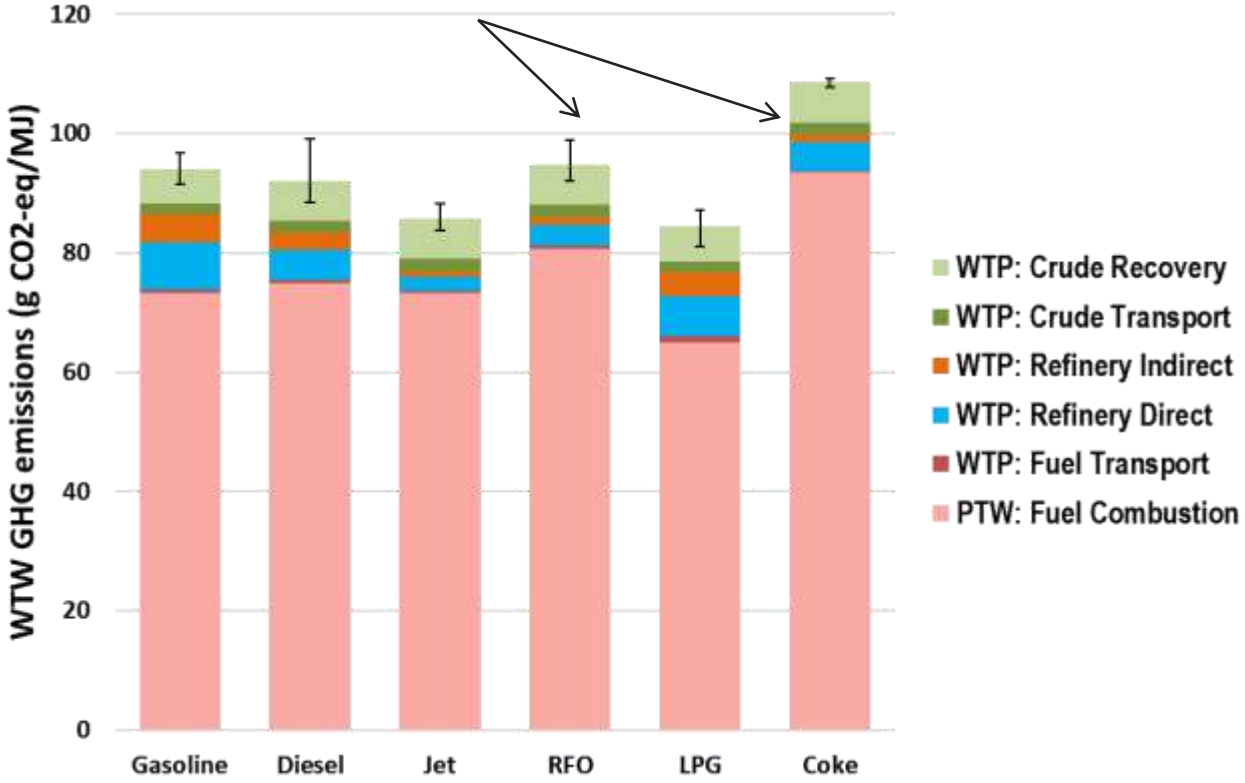
- WTW GHG emissions of petroleum fuels are dominated by end use release of CO_2; refinery direct/indirect emissions a distant second



Jet, RFO, and coke are less processed fuels, thus lower energy intensities

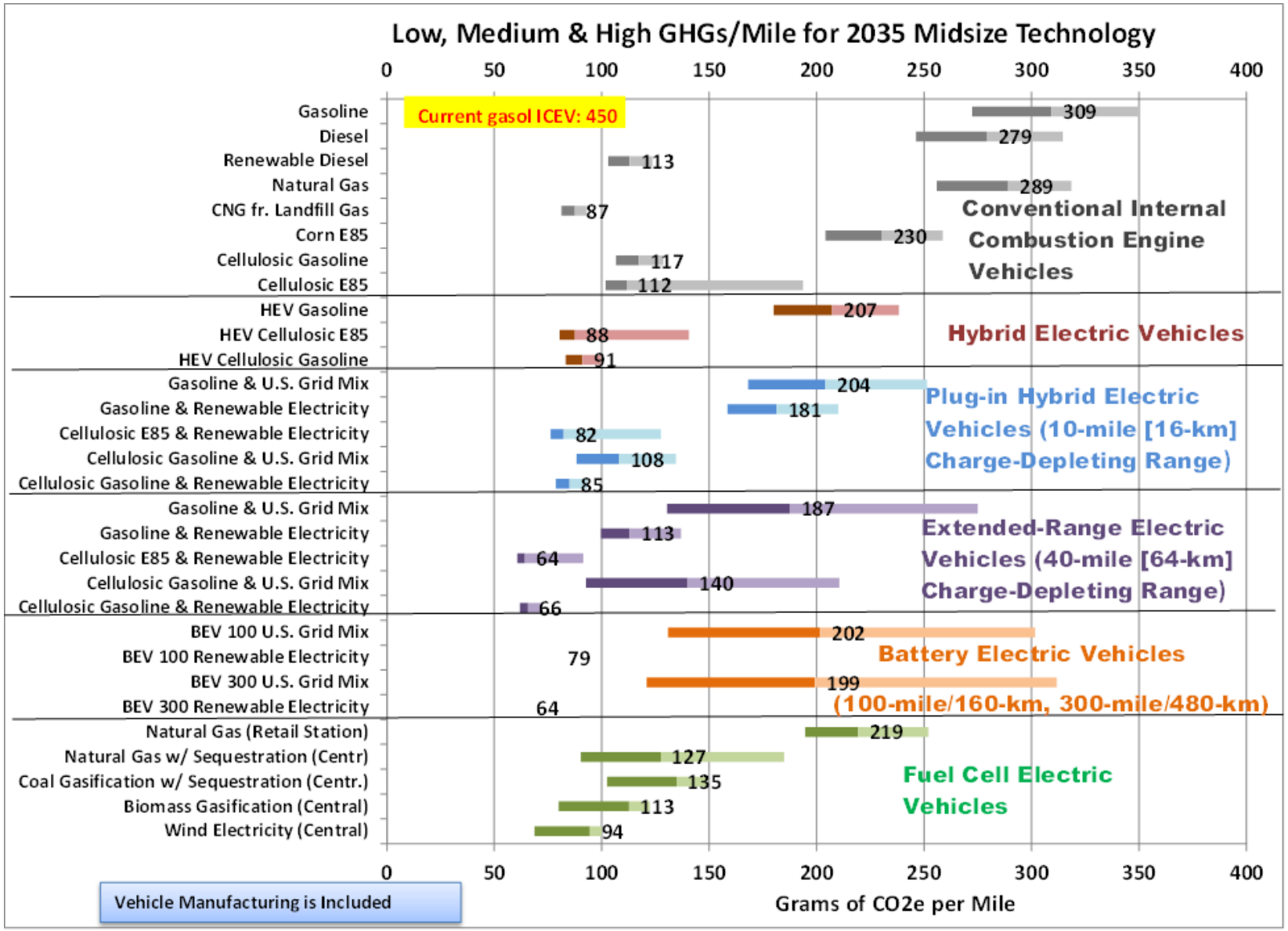


High C-content of RFO and coke increases their WTW GHG emission intensities



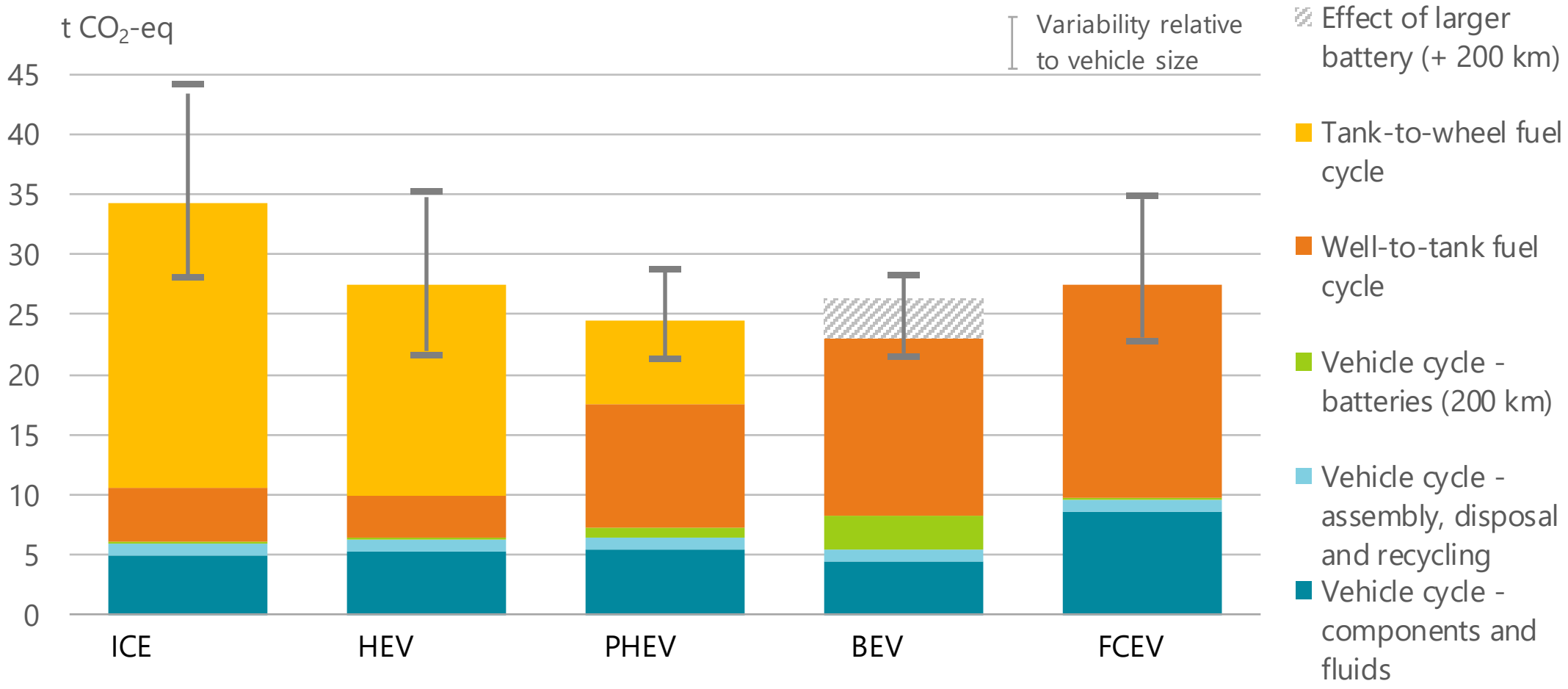
GREET results inform various DOE offices and programs

(DOE EERE December 23, 2016, Record 16008)



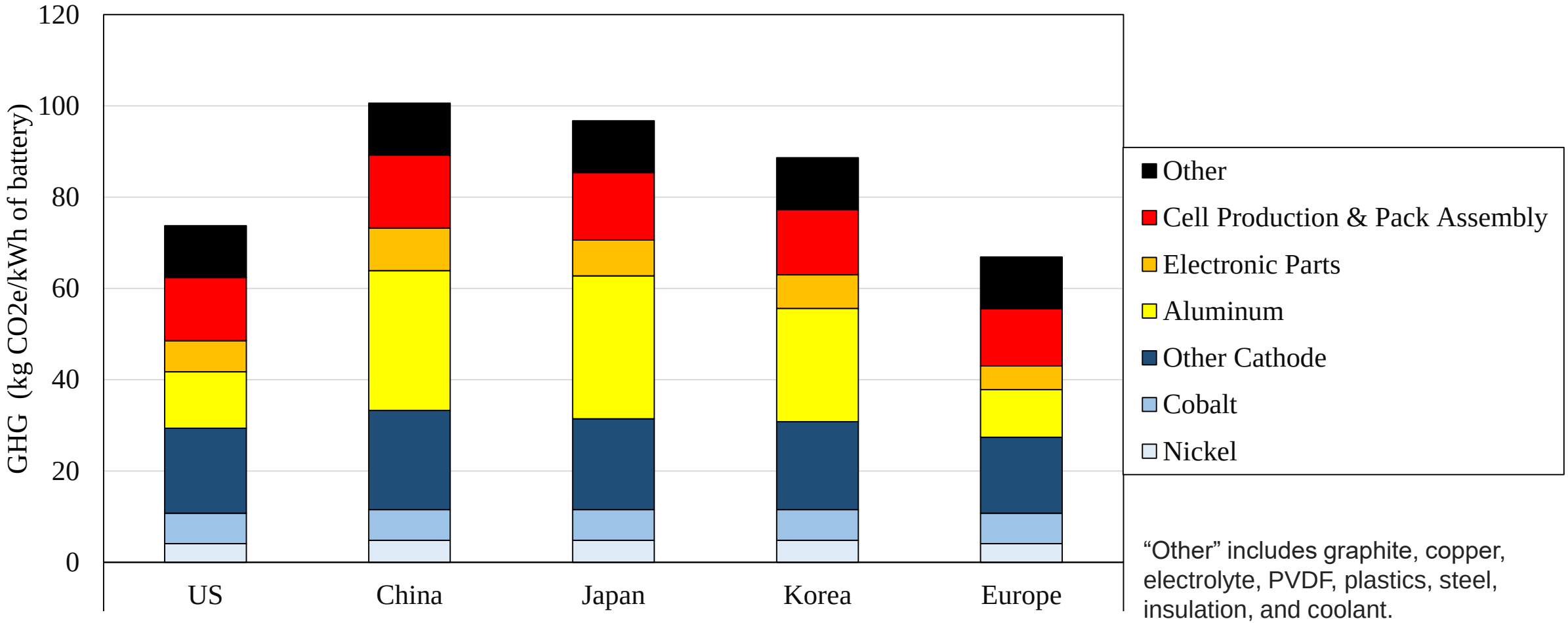
Low/high band: sensitivity to uncertainties associated with projected fuel economy values and selected fuel pathway parameters

Comparative life-cycle GHG emissions of a mid-size global average car by powertrain, 2018 (tonnes per vehicle lifetime)



Source: IEA (2019), "Global EV Outlook 2019", IEA, Paris

Li-Ion battery LCA result regional variation: country specific GHG emissions

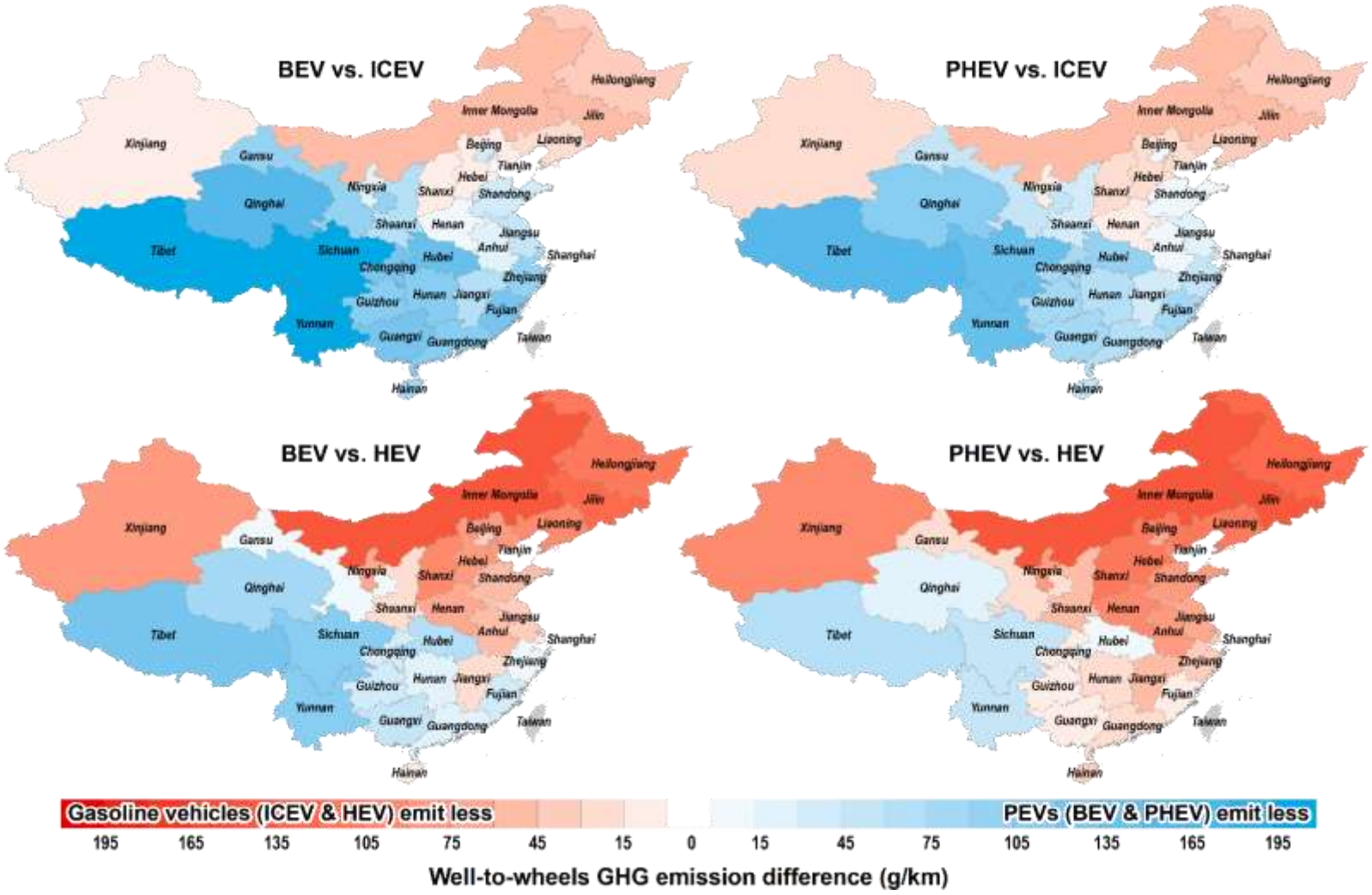


"Other" includes graphite, copper, electrolyte, PVDF, plastics, steel, insulation, and coolant.
"Other Cathode" includes process energy use and non-Ni/Co reagents.

Source: Kelly *et al.*, Mitigation and Adaptation Strategies for Global Change, 2019.

WTW GHG Emission Comparison of ICEV, HEV, BEV, and PHEV in China

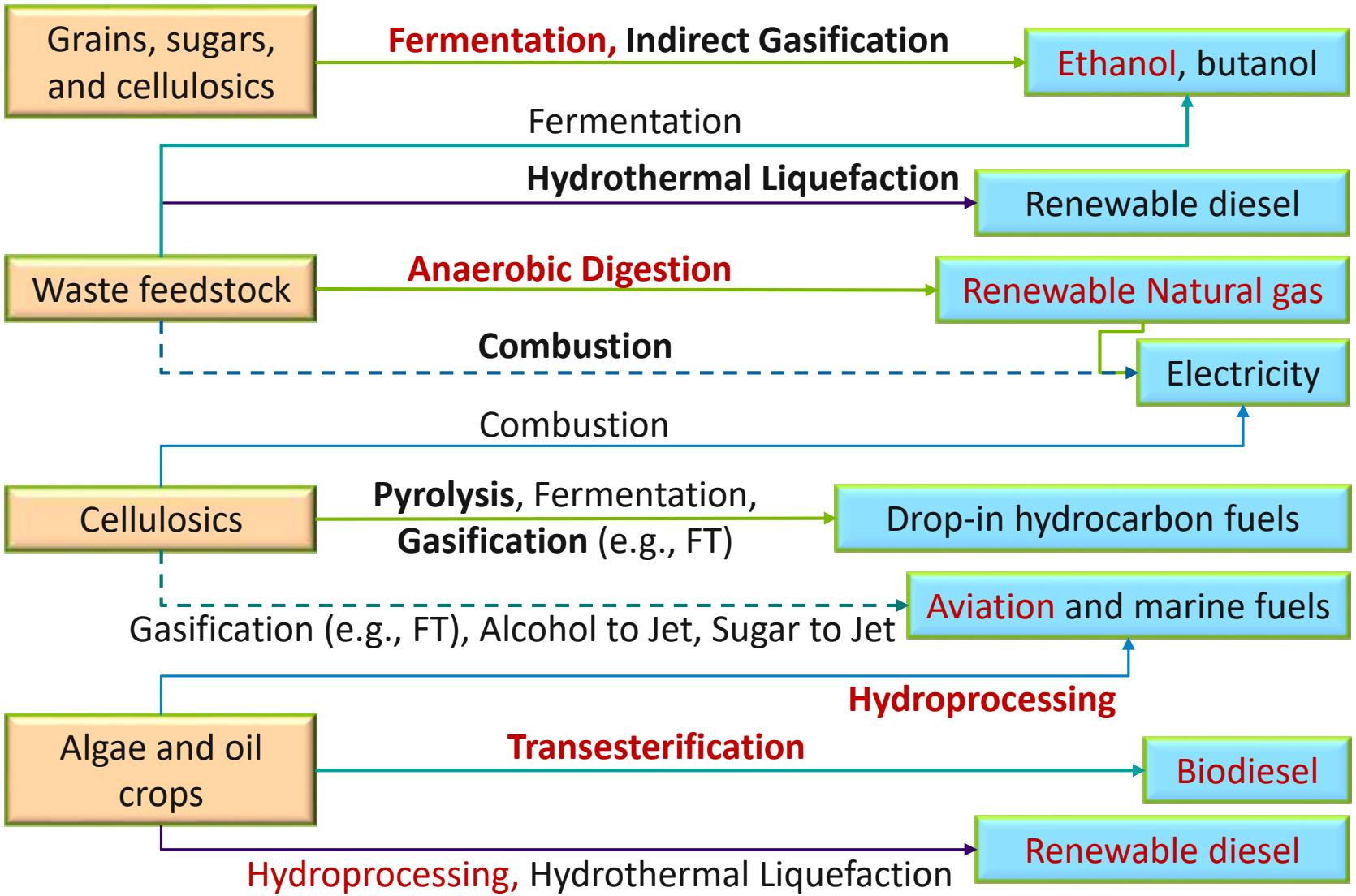
China-GREET model & Consumption-based provincial electricity GHG intensities



- **WTW GHG intensities of BEVs and PHEVs are higher than gasoline ICEVs in 7 and 10 northern provinces due to the GHG-intensive coal-based electricity and cold weather**
- **Gasoline HEVs have lower WTW GHG emissions than BEVs in 18 provinces, and PHEVs in 26 provinces**

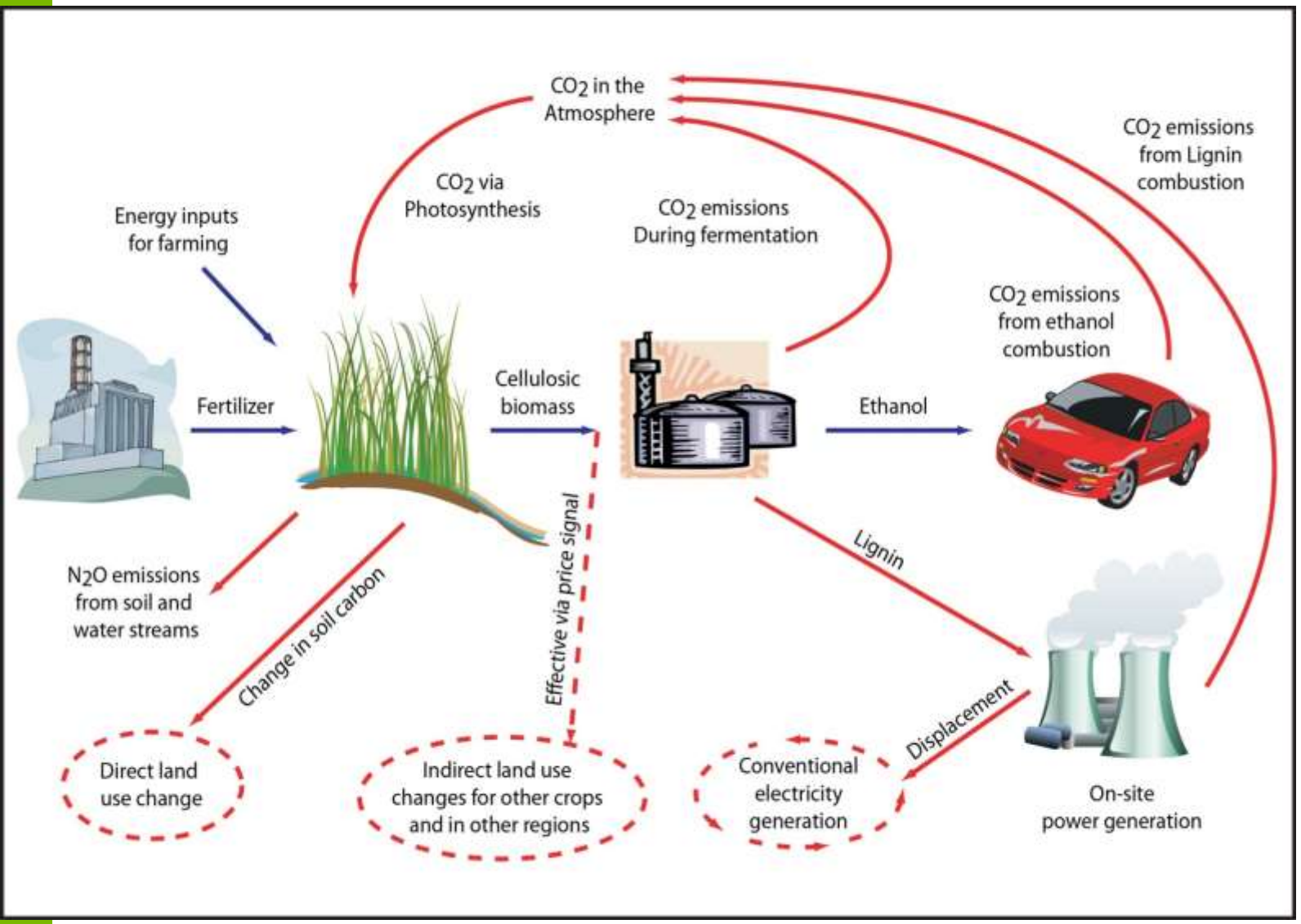
Gan et al. "Provincial Greenhouse Gas Emissions of Gasoline and Plug-in Electric Vehicles in China: Comparison from the Consumption-Based Electricity Perspective", under review, 2021

A variety of biofuel production pathways are covered in GREET



- **The highlighted options have significant volumes in LCFS and RFS**
- **Ethanol accounts for >15 billion gallons nationwide, and >1.1 billion gallons in CA**

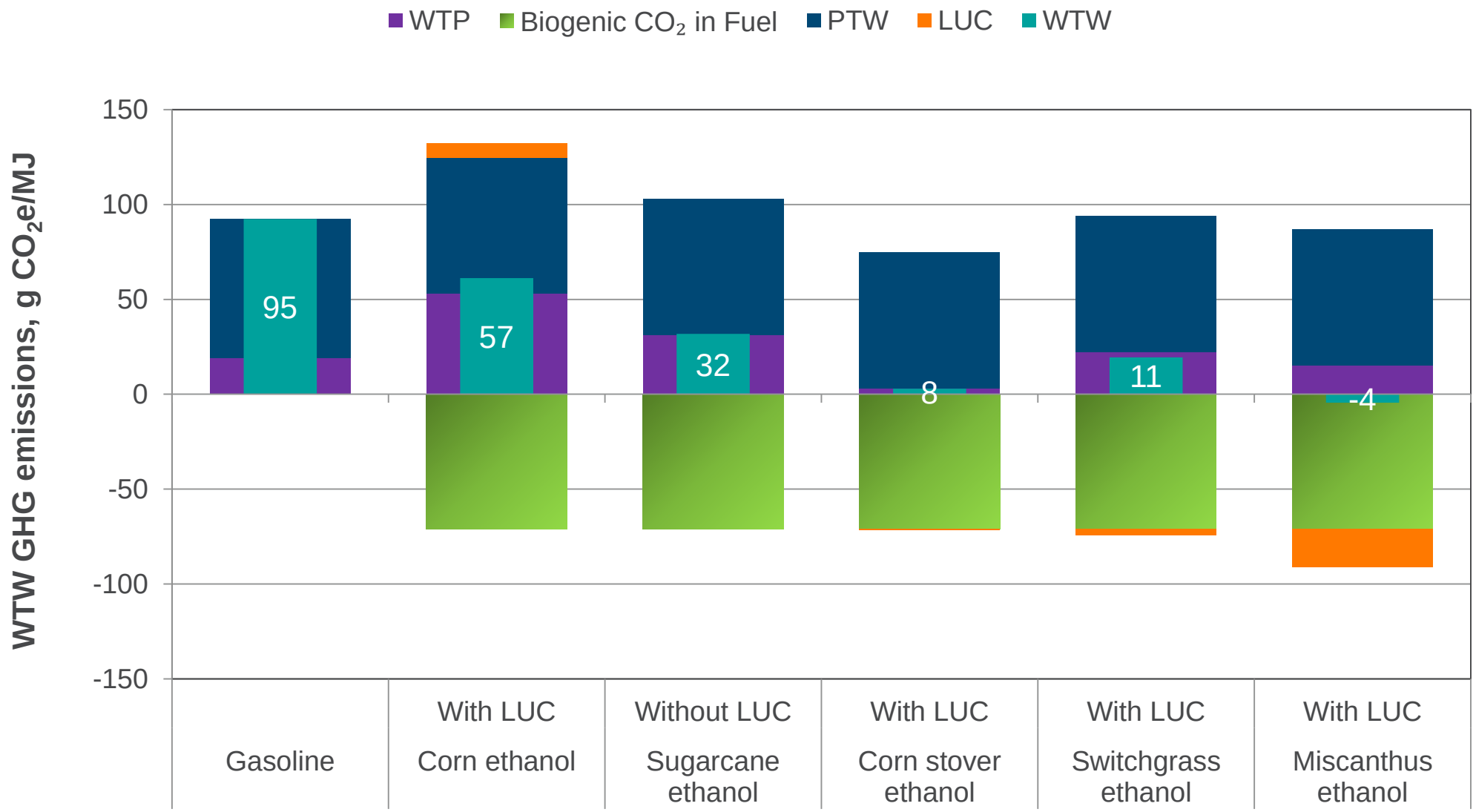
GREET system boundary for biofuel LCA: direct activities and indirect effects are included



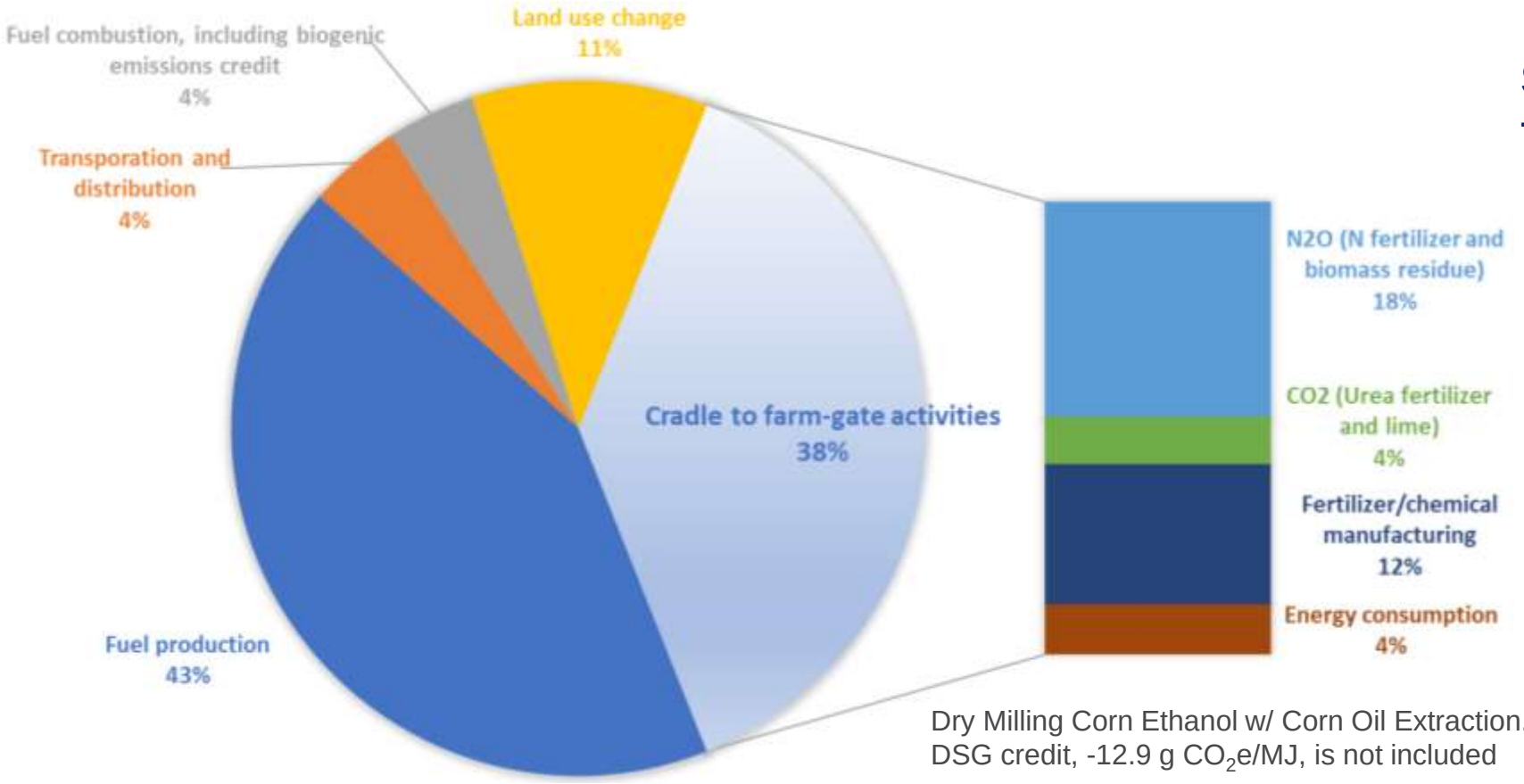
Key factors determining biofuel LCA results

- ❑ LCA system boundary
- ❑ Feedstock types
- ❑ Conversion technologies: energy balance and materials inputs such as enzyme and catalyst
- ❑ Technology improvement over time
- ❑ Biorefineries with distinctly different products: co-product methods
- ❑ Direct and indirect land use changes

GREET life-cycle GHG emissions of ethanol: feedstock is the main driver

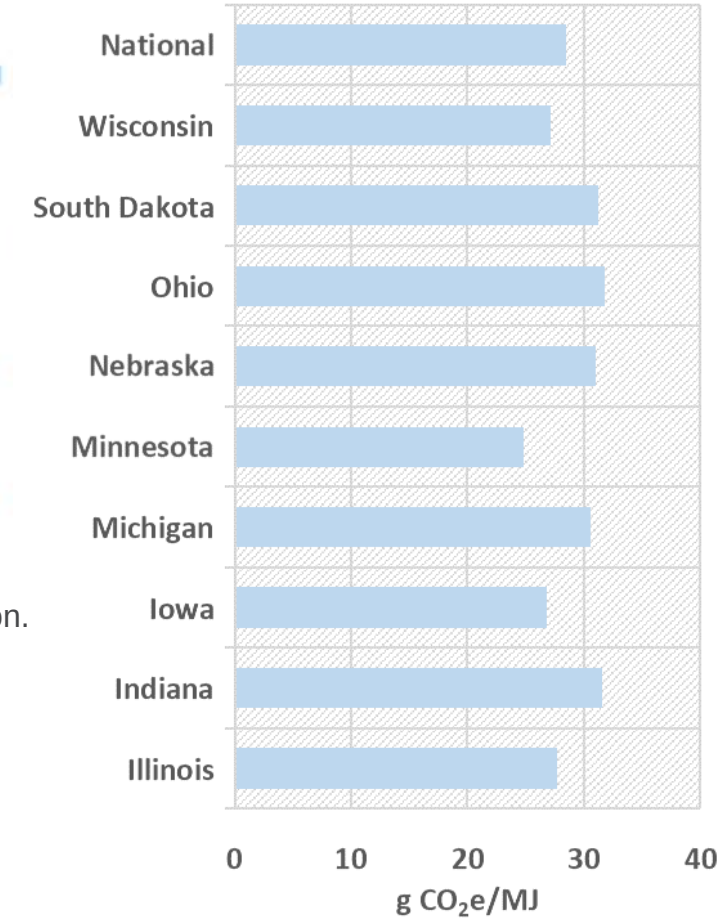


Feedstock is a significant contributor to corn ethanol LCA GHGs: 38% of corn ethanol CI, in addition to 11% from land use change GHGs



Dry Milling Corn Ethanol w/ Corn Oil Extraction.
DSG credit, -12.9 g CO_2e/MJ, is not included

Significant variation exists in feedstock CI among regions



Argonne Previous and Ongoing Works in India

- **Previous works**
  - Developed detailed inventory of SO_2 and carbonaceous aerosol (i.e., black carbon and organic carbon) emissions from anthropogenic sources in India with a technology-based methodology

    Lu et al. Atmos. Chem. Phys. 11, 9839-9864, 2011; Streets et al. Geophys. Res. Lett. 40, 4409-4414, 2013; etc.
  - Developed unit-based NO_x and SO_2 emission inventory for Indian thermal power sector and compared the emission estimates with the satellite observations of NO_2 and SO_2

    Lu and Streets, Environ. Sci. Tech. 46, 7463-7470, 2012; Lu et al. Environ. Sci. Tech. 47, 13993-14000, 2013; etc.
  - Studied the transportation of black carbon from India to the Himalayas and Tibetan Plateau

    Lu et al. Geophy. Res. Lett., 39, L01809, 2012

- **Ongoing works (focus on the power and the coal sectors)**
  - Develop detailed unit-based energy and emission datasets for the entire power sector in India at the monthly level from 2005 to now
  - Develop coal transportation matrix from Indian coal producers to individual coal-fired power plants
  - Develop electricity transmission matrix among Indian power regions

Questions?

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