Overview of Life Cycle Analysis (LCA) with the GREET® Model

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The GREET Introduction Workshop
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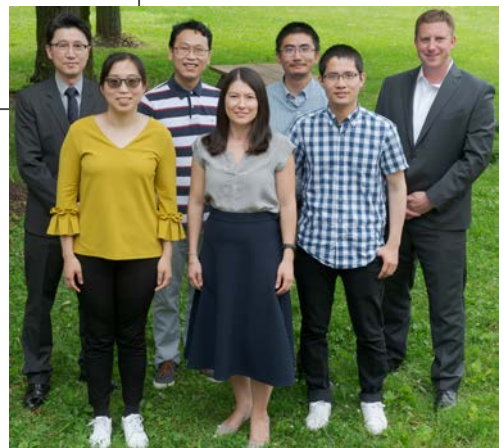

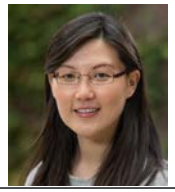

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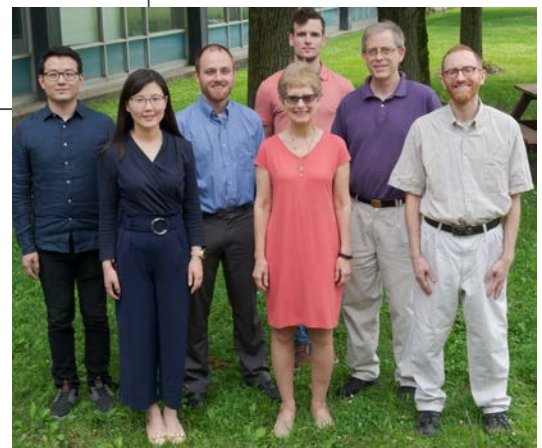
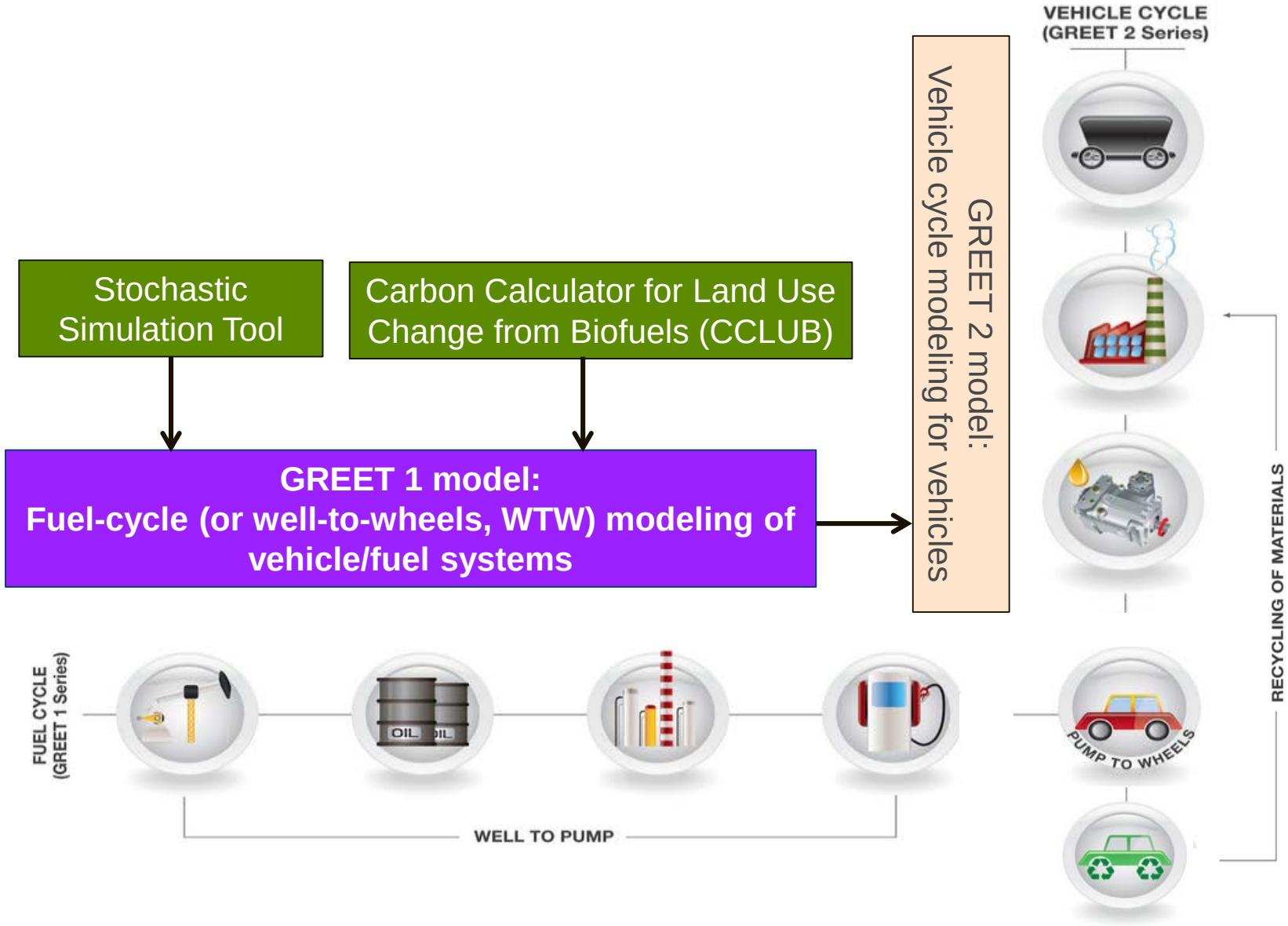


The GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model



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
  - ✓ 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
  - ✓ ICAO-GREET by ANL, based on GREET1
  - ✓ China-GREET by ANL, with support of Aramco
  - ✓ CA-GREET by CARB, based on GREET1
- CARB developed CA-GREET for its Low-Carbon Fuel Standard compliance

GREET annual release in each October

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ANL/ESD-19/6

Summary of Expansions and Updates in GREET® 2019

prepared by
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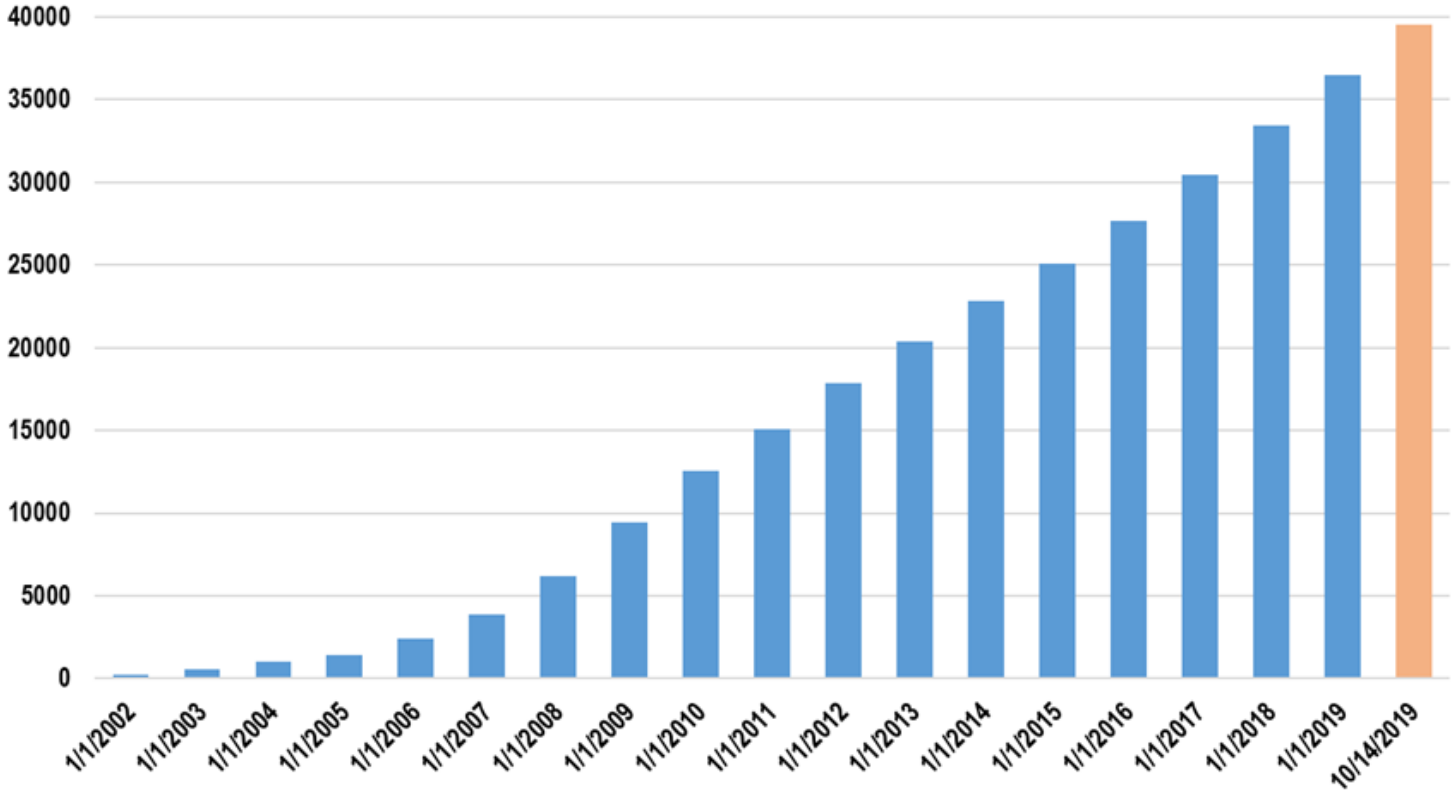
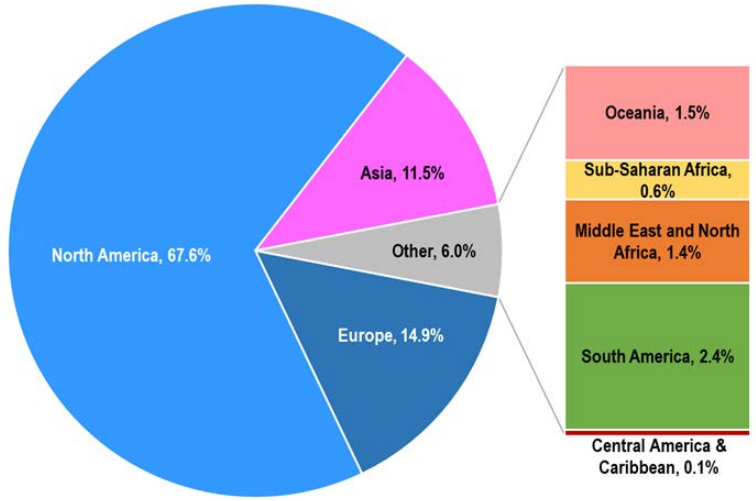
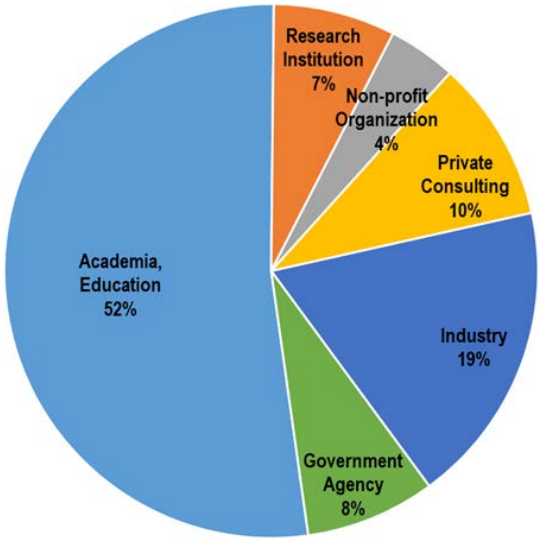
October 2019

There are ~ 40,000 registered GREET users globally

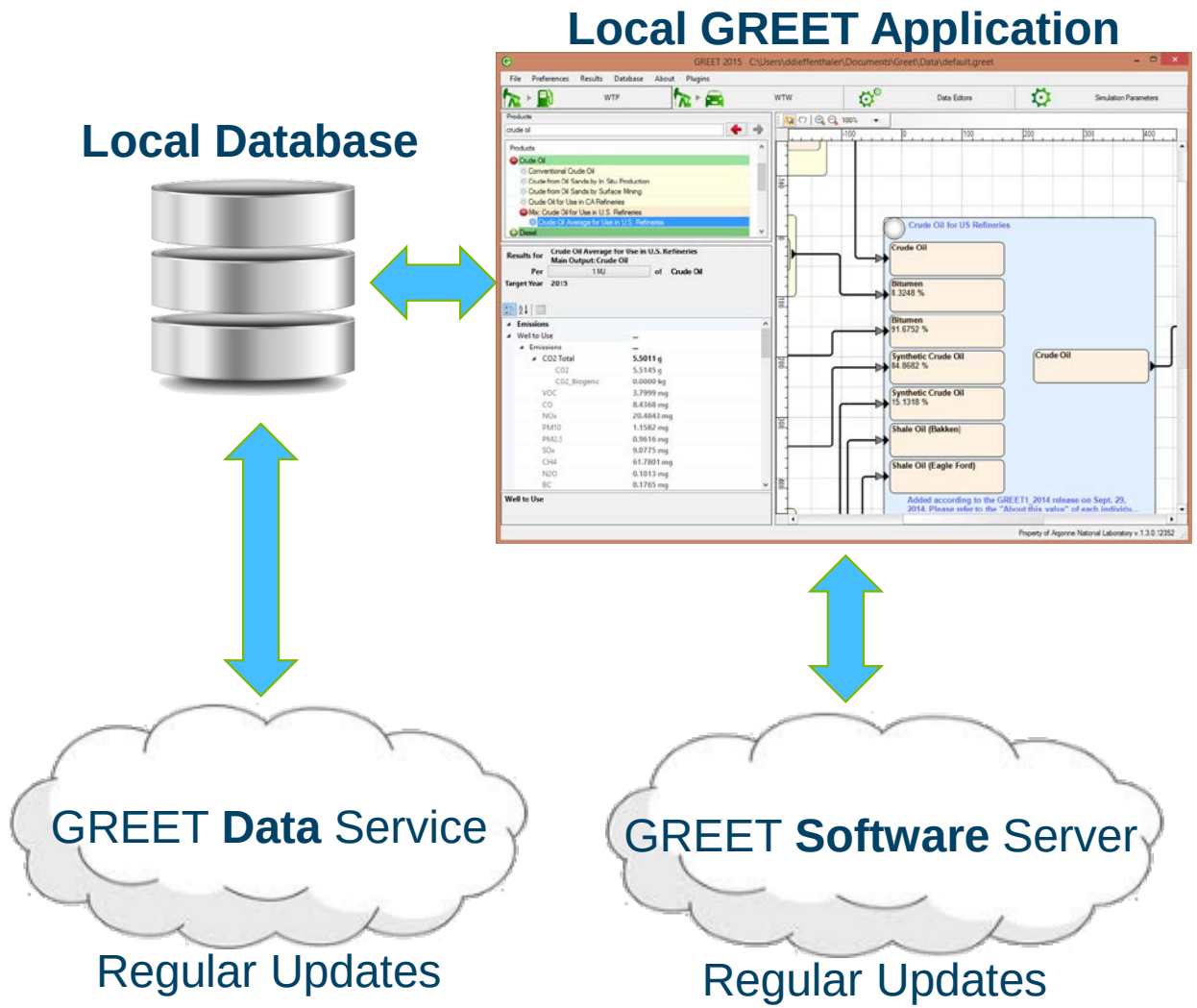


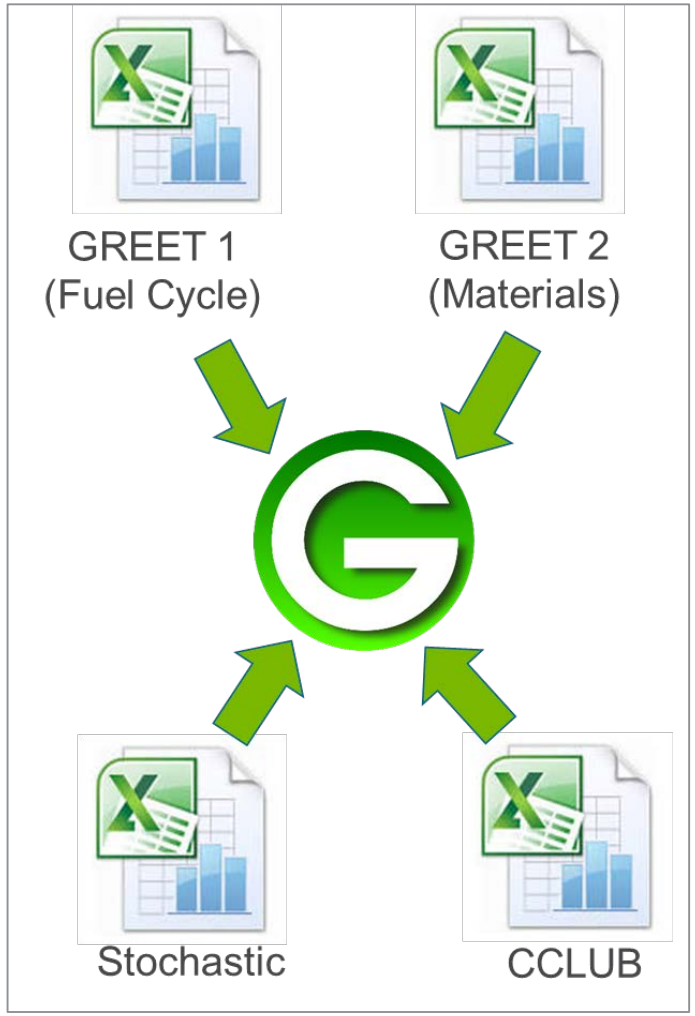




While GREET Excel version is completely transparent, GREET.net offers a modular user interface with structured database

- Provides efficient and standardized LCA modeling platform and enables database sharing





GREET development has been supported by several U.S. DOE Offices since 1995

- Vehicle Technology Office (VTO)
- Fuel-Cell Technology Office (FCTO)
- Advanced Research Projects Agency–Energy (ARPA-E)
- Building Technologies Office (BTO)
- Bioenergy Technology Office (BETO)
- Strategic Priorities & Impact Analysis (SPIA)

GREET has been in public domain and free of charge since it inception in 1995- Updated and expanded annually (https://greet.es.anl.gov)

Examples of major uses of GREET

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

GREET includes all transportation subsectors

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

Road transportation

Air transportation

Globally, a fast growing sector with GHG reduction pressure

GREET includes

- Passenger and freight transportation

Various alternative fuels blended with petroleum jet fuels

Rail transportation

- Freight transportation
- GREET includes
  - ✓ Diesel
  - ✓ Electricity
  - ✓ CNG/LNG

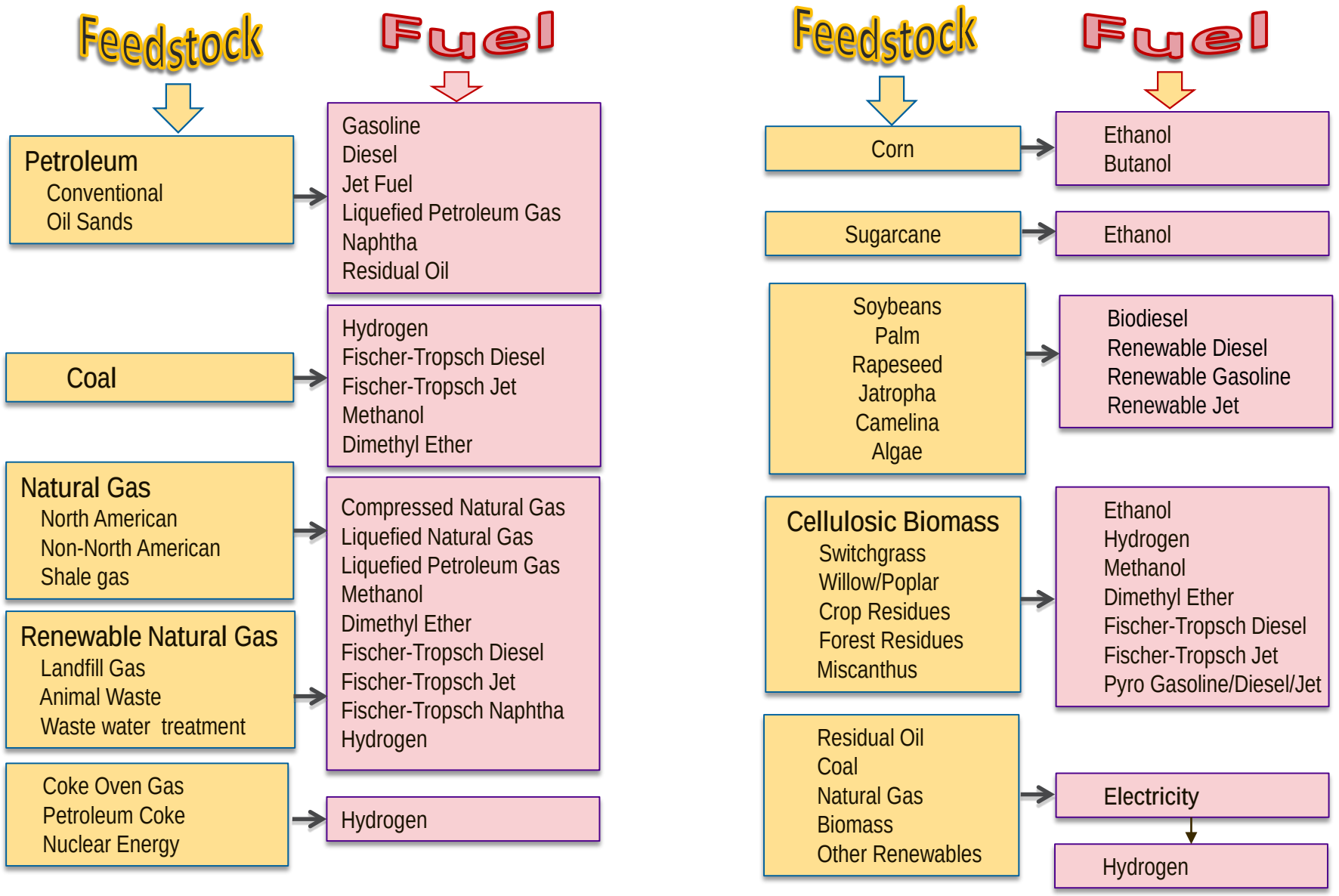
Marine transportation

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

- **Energy use – addressing energy diversity/security**
  - 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
- **Air pollutants – addressing air pollution**
  - 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)
- **Greenhouse gases (GHGs) – addressing climate change**
  - CO_2, CH_4, N_2O, black carbon, and albedo
  - CO_{2e} of the five (with their global warming potentials)
- **Water consumption – addressing fresh 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 includes more than 100 fuel production pathways from various energy feedstock sources



GREET examines more than 80 on-road vehicle/fuel systems for both light-duty and heavy-duty vehicles

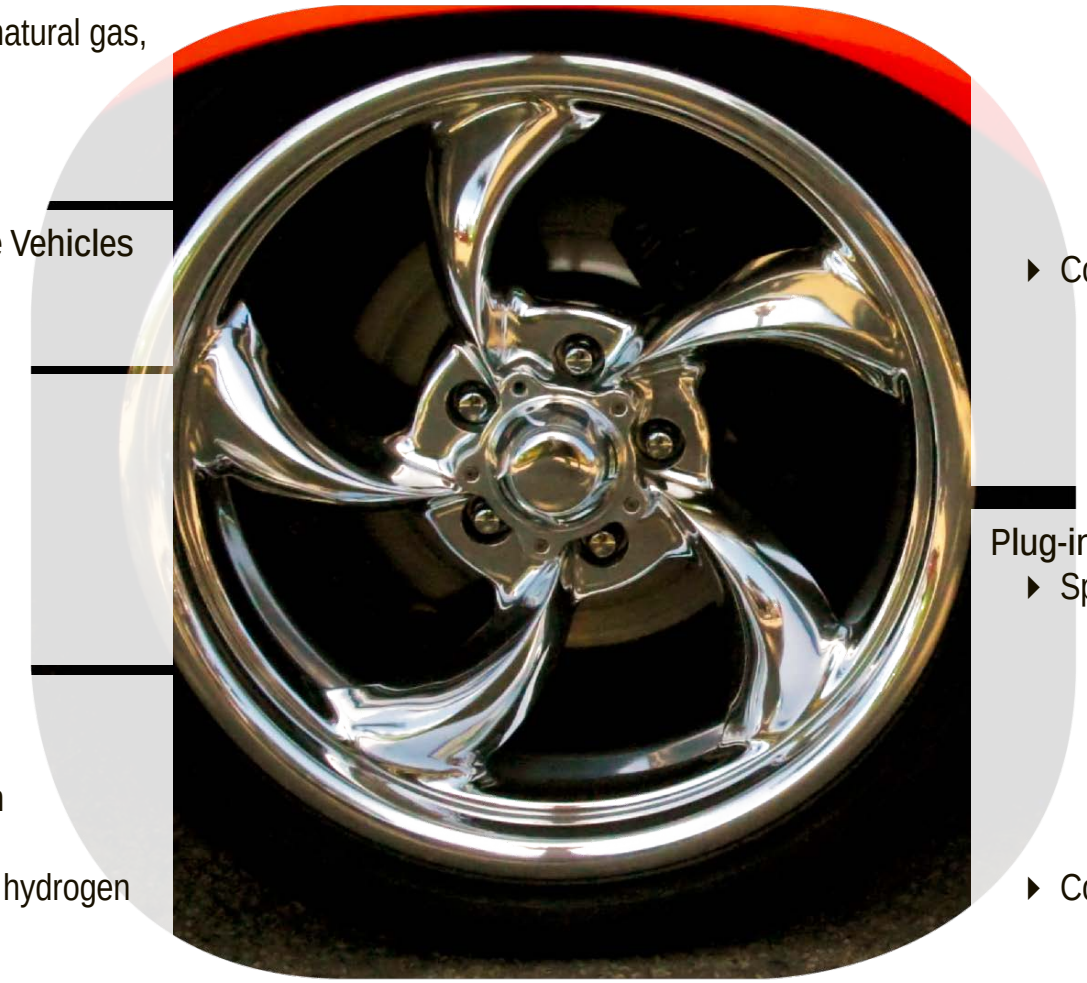
Conventional Spark-Ignition Engine Vehicles
- Gasoline
- Compressed natural gas, liquefied natural gas, and liquefied petroleum gas
- Gaseous and liquid hydrogen
- Methanol and ethanol

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

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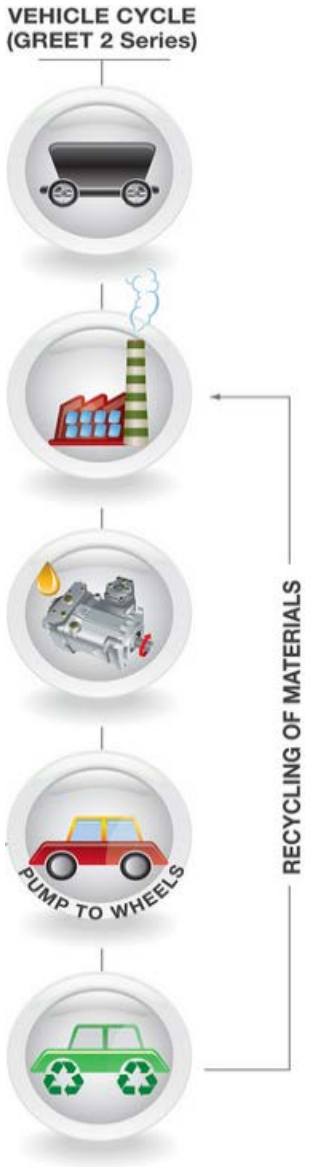
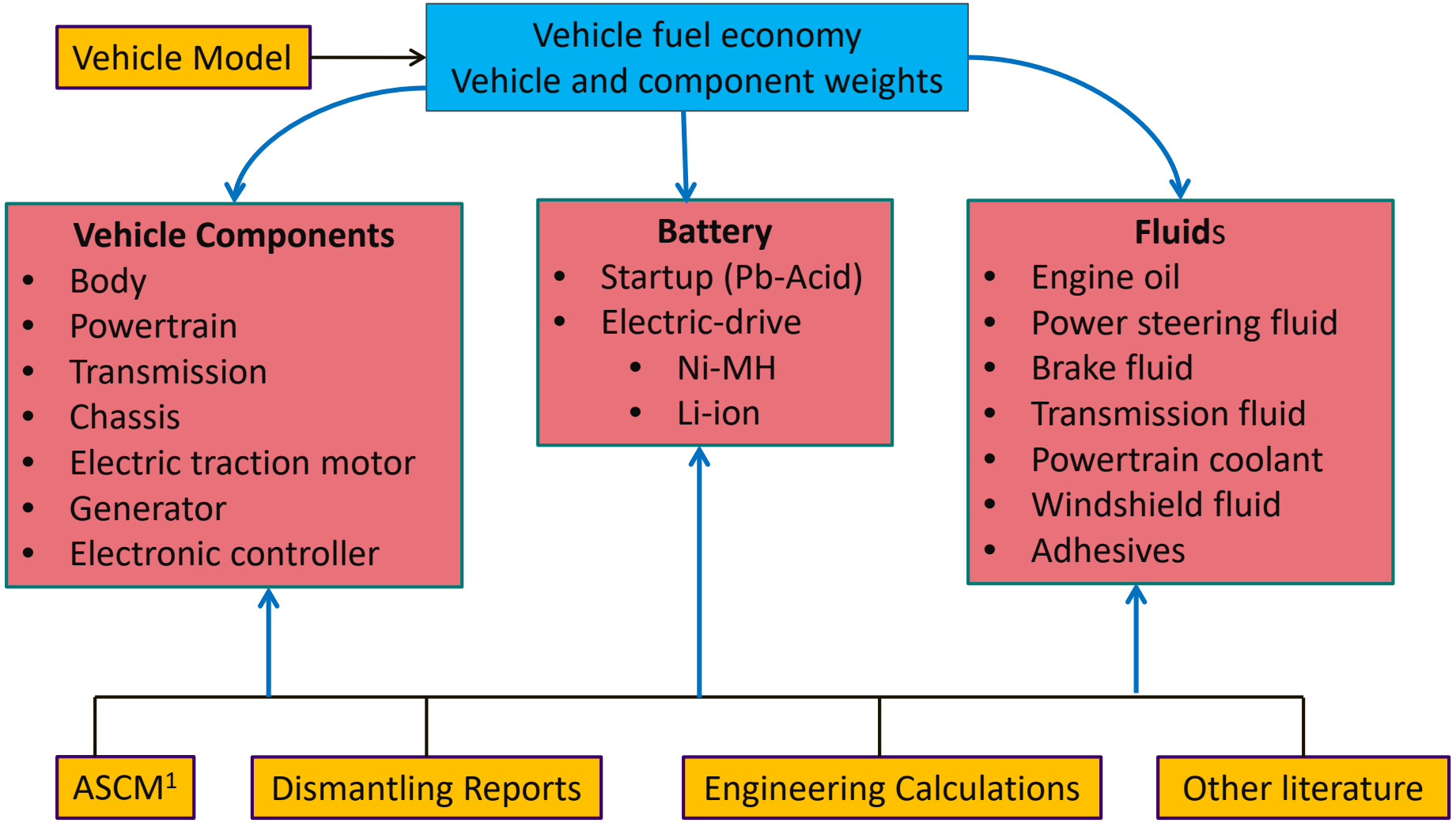
GREET simulates vehicle cycle from material recovery to vehicle disposal



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

Approach to developing a materials inventory for vehicles



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

GREET includes life-cycle inventories of 60+ materials

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

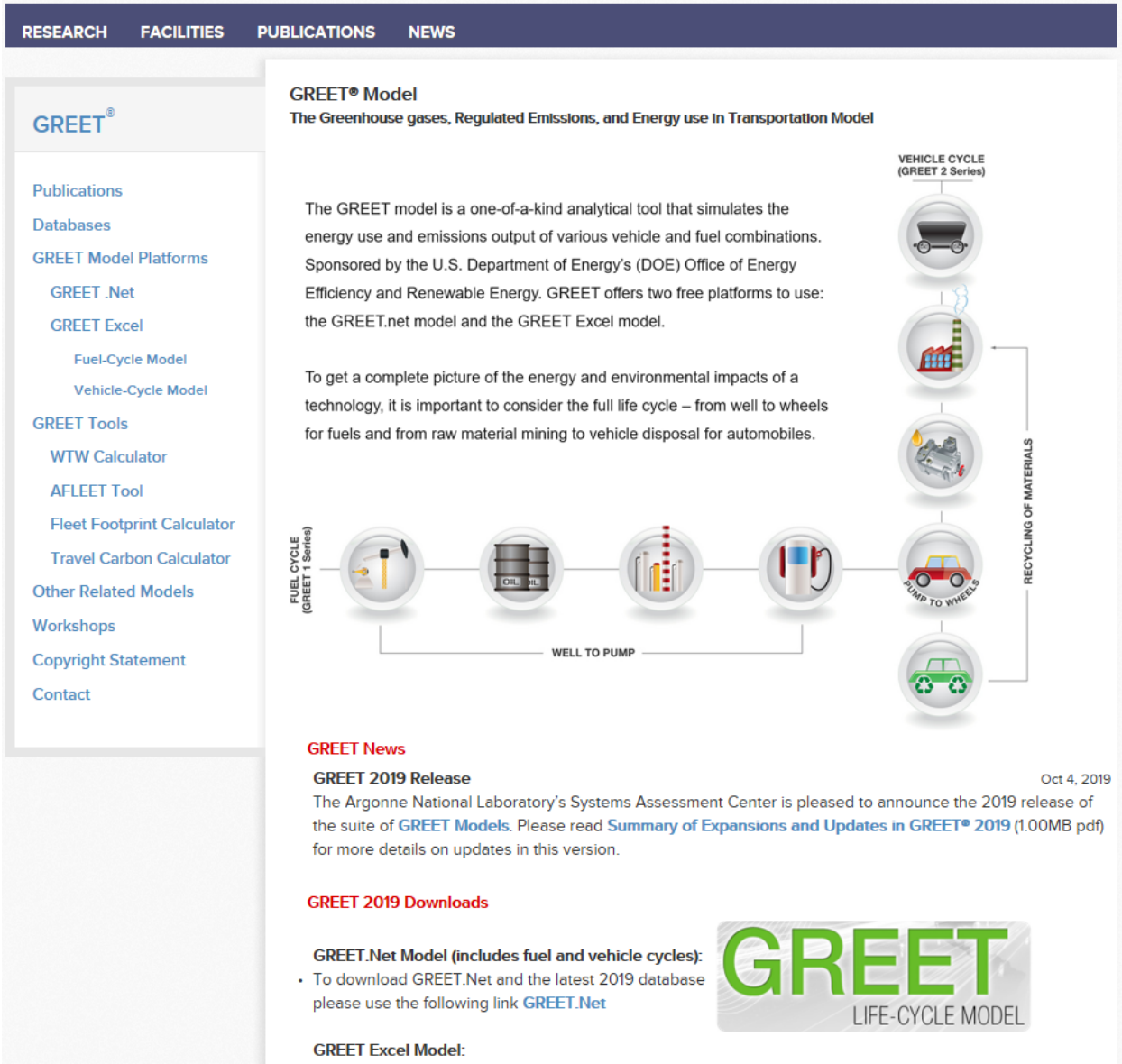
- Use of virgin vs. recycled materials
- Vehicle weight and lightweighting
  - lightweighting with aluminum, magnesium, carbon fiber reinforced plastics, and high strength steel
- Vehicle lifetime, component rebuilding/replacement

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

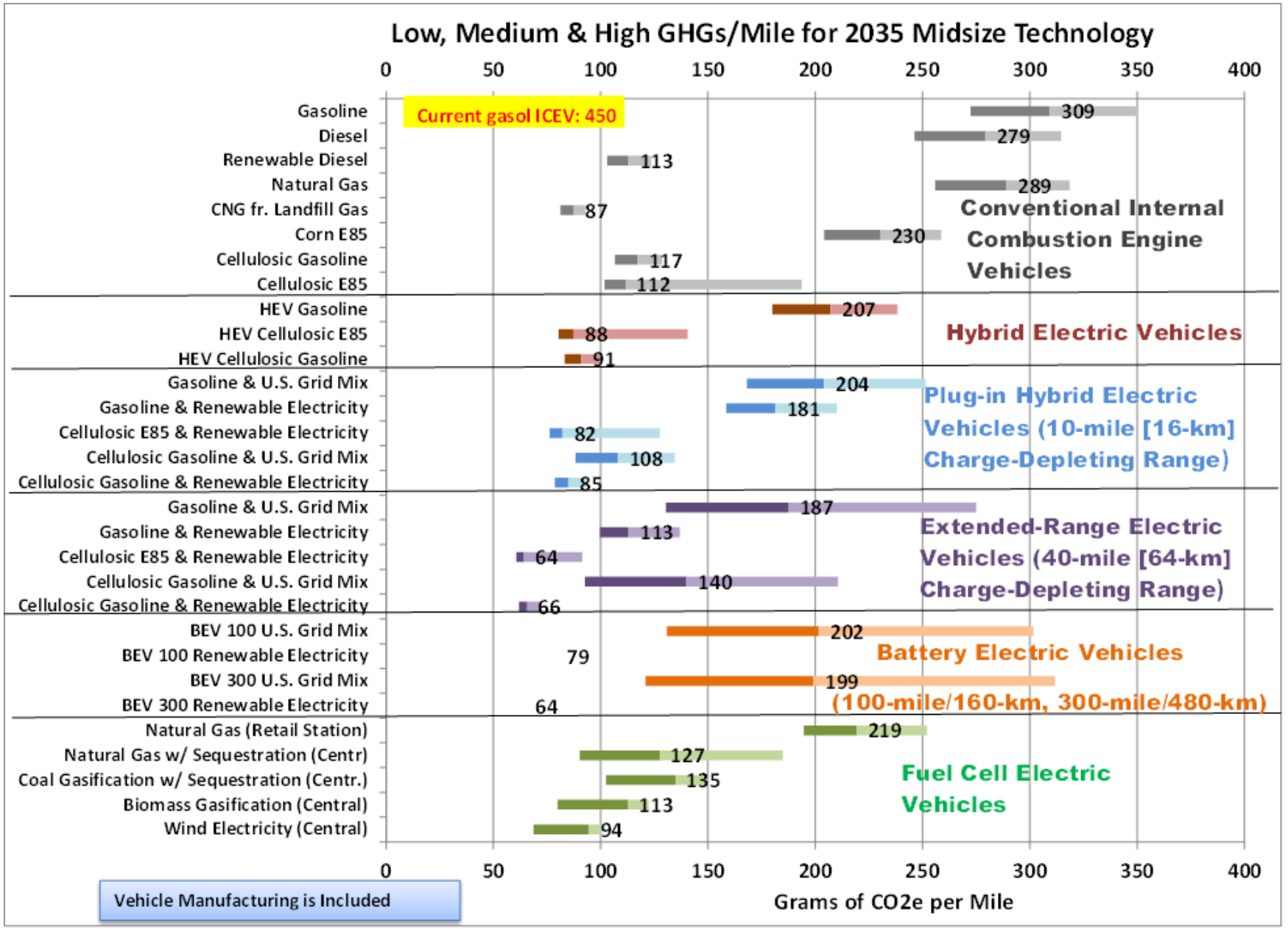
GREET models, publications and tutorials are accessible online

http://greet.es.anl.gov/greet/



GREET Model Tutorial Videos

Informing various DOE offices and programs



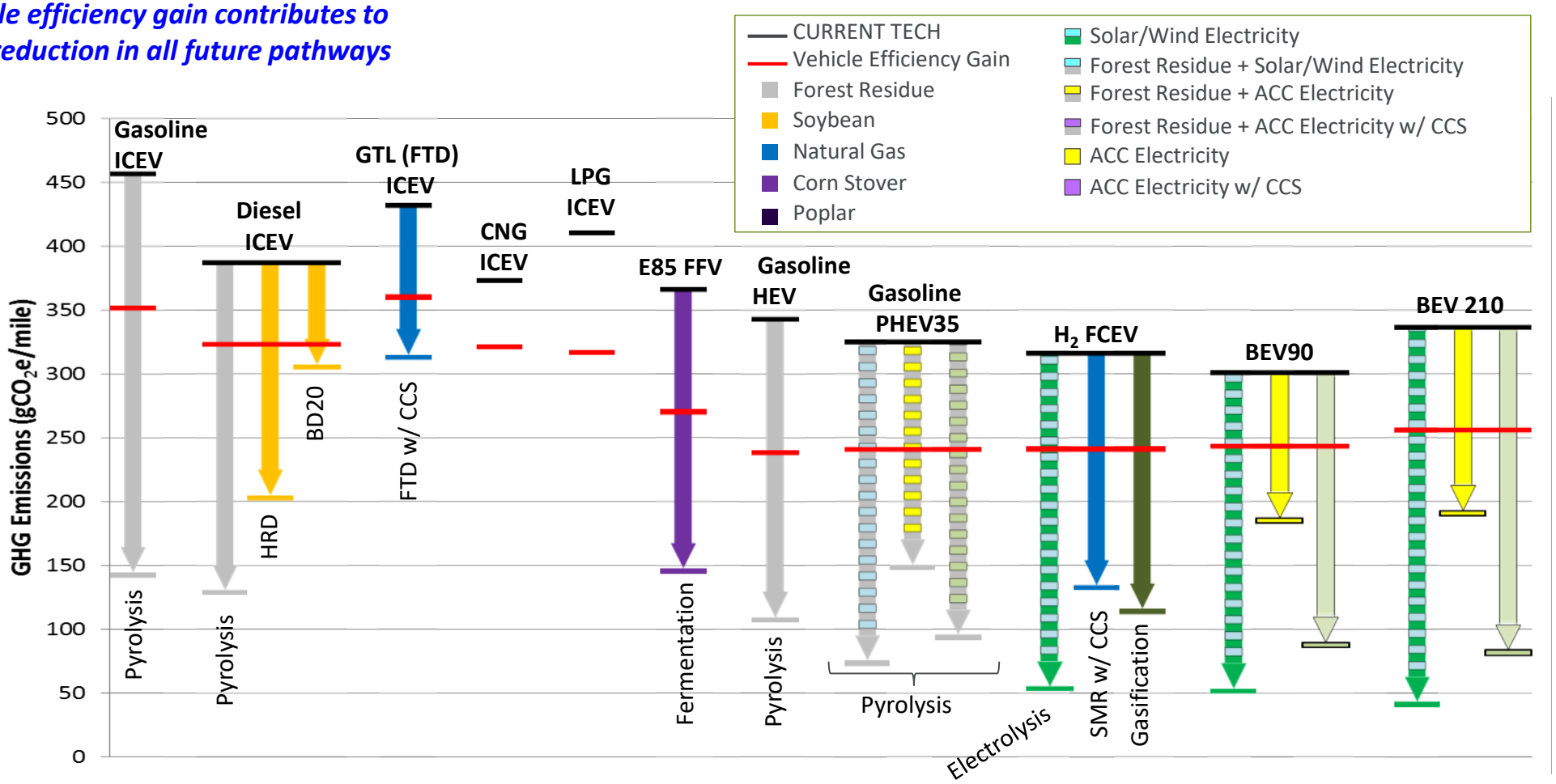
(DOE EERE December 23, 2016, Record 16008)

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

Collaborating with industry: C2G GHG emissions for current and future vehicle-fuel pathways (US DRIVE partnership study)

Large GHG reductions for light-duty vehicles are challenging and require consideration of the entire lifecycle, including vehicle manufacture, fuel production, and vehicle operation.

***Note**: Vehicle efficiency gain contributes to GHG reduction in all future pathways*



https://greet.es.anl.gov/publication-c2g-2016-report
https://pubs.acs.org/doi/abs/10.1021%2Fes302420z

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Please visit

http://greet.es.anl.gov

for:

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

Major updates in GREET 2019

- **Updated emission factors of petroleum production pathways**
  - added four pathways for propane, butane, asphalt, and propylene
- **Expanded the marine module with pathways of low-sulfur conventional fuels, LNG, and biofuels**
- **Updated CCLUB and the direct nitrogen fertilizer-induced nitrous oxide (N_2O) emission factor**
- **Incorporated the Regional Soil Carbon Observations for Renewable Energy and Agriculture (ReSCORE-A)**
  - A new database that refines estimates of soil organic carbon (SOC) changes in CCLUB
- **Added new bio-derived plastic pathways for polylactic acid (PLA) and polyethylene terephthalate (PET) production**
- **Updated energy efficiency and emission factors for hydrogen production with steam methane reforming (SMR)**
- **Expanded battery LCA modelling using regional supply chain data**
- **Added pathways for various classes of medium- and heavy-duty battery electric vehicles (BEVs)**
  - updated the fuel economy values for baseline diesel ICEVs and hydrogen fuel cell electric vehicles (FCEVs)
- **Updated methane emissions throughout natural gas supply chain**
- **Updated the cement and concrete pathways**

https://greet.es.anl.gov/files/greet-2019-summary

Acronyms

AD	Anaerobic digestion
AEZ	Agricultural Ecological Zone
ATJ	Alcohol-To-Jet
BAU	Business-as-usual
BEV	Battery Electric Vehicle
BG	Billion Gallons
C	Carbon
CARB	California Air Resources Board
CCLUB	Carbon Calculator for Land Use change from Biofuels production
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSP	Concentrated Solar Power
EtOH	Ethanol
FCEV	Fuel Cell Electric Vehicle
FT	Fischer-Tropsch
FTJ	Fischer-Tropsch jet
FY	Fiscal Year
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GTAP	Global Trade Analysis Project
HFO	Heavy Fuel Oil
HRJ	hydroprocessed Renewable Jet
HTL	Hydrothermal liquefaction
ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
LCA	Life-Cycle Analysis
LMC	Land Management Chance
LNG	Liquefied Natural Gas
LUC	Land Use Change
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MSW	Municipal Solid Waste
NG	Natual Gas
NGCC	Natural Gas Combined Cycle
NREL	National Renewable Energy Laboratory
PEV	Plug-in Electric Vehicle
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
S	Sulfur
SIP	Synthesized Iso-Paraffins
SMR	Steam Methane Reforming
SOC	Soil Organic Carbon
STJ	Sugar-To-Jet
SVO	Straight Vegetable Oil
UN	United Nations
US	United States
USDA	United States Department of Agriculture
WTE	Waste-to-Energy
WTR	Well-to-Refinery
WTW	Well-to-Wheels