Jan. 8, 2026
Presentation to the Strong PHEV Coalition

GREET Life Cycle Analysis Model Introduction

Michael Wang, Ph.D., Director

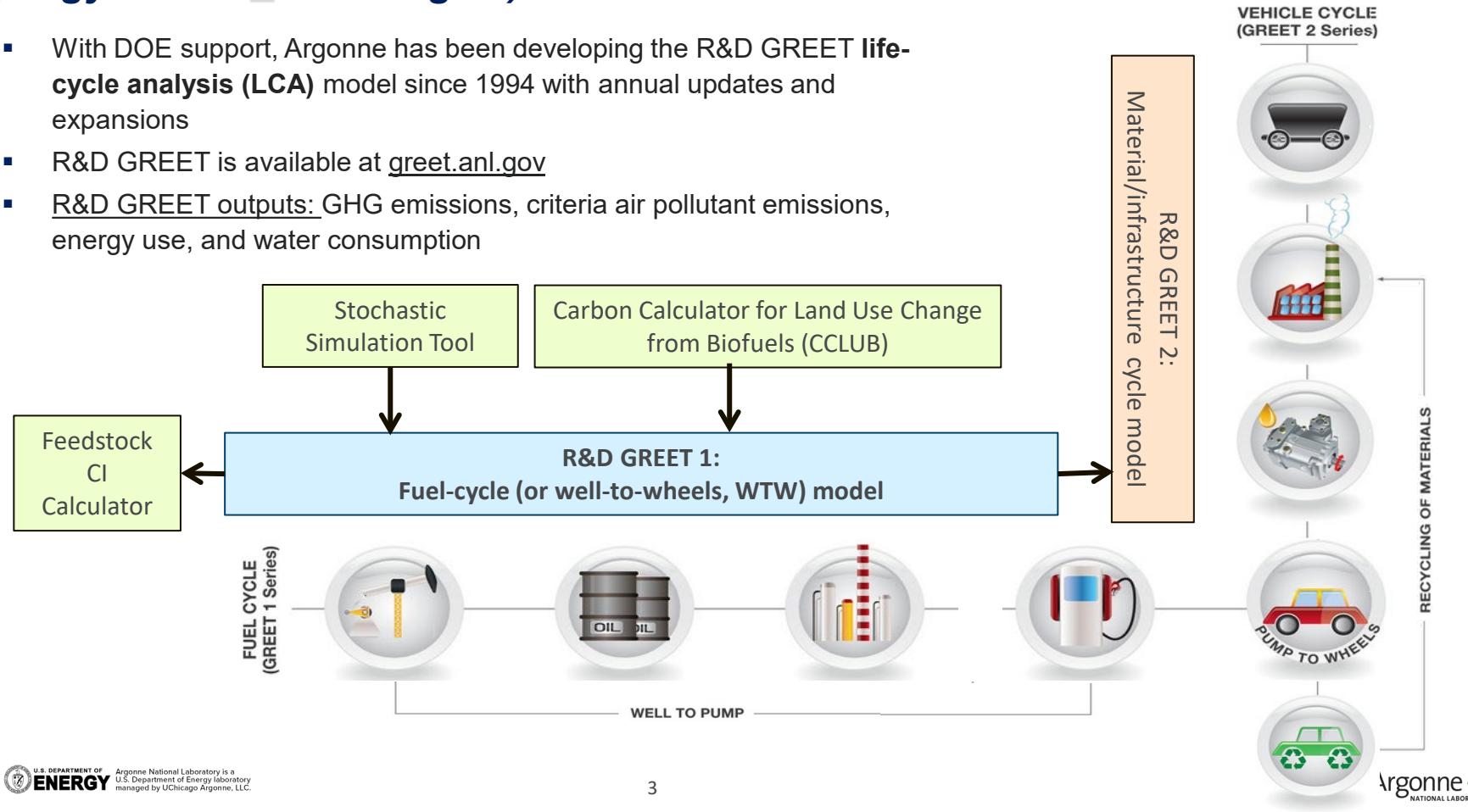
Life Cycle Analysis and Technology Assessment Department
Energy Systems and Infrastructure Assessment Division
Argonne National Laboratory

The R&D GREET effort at Argonne National Laboratory is supported by the Office of Critical Minerals and Energy Innovation, the Hydrocarbons and Geothermal Energy Office, the Office of Technology Commercialization, the Office of Nuclear Energy, and ARPA-E of the US Department of Energy (DOE) under contract DE-AC02-06CH11357. The views and opinions expressed herein do not necessarily state or reflect those of the US government or any agency thereof. Neither the US government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

Argonne's R&D GREET is to inform the life cycle analysis of technical community. Not all pathways and data in R&D GREET are appropriate for use in circumstances where a high level of quantitative certainty or precision is required. GREET is referenced in numerous independent state and federal compliance and incentive programs (including solicitations, rulemakings, and tax incentives), but it is important to note that R&D GREET is not the version used by any of these specific programs. Argonne does not warrant that use of R&D GREET is consistent with the requirements of any particular regulatory or incentive program.

The R&D GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model framework

- With DOE support, Argonne has been developing the R&D GREET **life-cycle analysis (LCA)** model since 1994 with annual updates and expansions
- R&D GREET is available at greet.anl.gov
- R&D GREET outputs: GHG emissions, criteria air pollutant emissions, energy use, and water consumption



R&D GREET LCA objectives

- Tracks life cycle performance of technologies to present their value proposition and inform R&D and business decisions by agencies and corporations
- Build LCA modeling capacity for Department of Energy, other agencies, and R&D community
- Build a consistent LCA platform with reliable, widely accepted methods/protocols
- Address emerging LCA issues
- Conduct detailed LCA and to document data sources, modeling and analysis approaches, and results/conclusions
- Maintain openness and transparency of LCAs by making R&D GREET, its data, and publications publicly available

R&D GREET relies on a variety of data sources to address the challenge of data availability, representation, and reliability

Background data for baseline technologies and systems

- Energy Information Administration's data and its Annual Energy Outlook projections
- EPA eGrid for electric systems, GHGRP, and other databases
- US Geology Services for water data
- USDA agricultural sector statistics

Field operation data (primary sources for foreground data)

- Oil sands and shale oil operations
- Ethanol plants energy use
- Farming operations, facility operations, etc.

Simulations with models (secondary sources for foreground data)

- ASPEN Plus for technologies at facility level
- Argonne Autonomie for fuel economy of vehicle operations
- EPA MOVES for vehicle emissions, EPA CAMPD for stationary equipment emissions
- Linear programming models for petroleum refinery operations
- Electric utility dispatch models for marginal electricity analysis of EV recharging

Collaboration with universities, national labs (primary/secondary sources for foreground data)

Industry inputs (primary sources for foreground data)

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

R&D GREET sustainability metrics include energy use, criteria air pollutants, GHG, and water consumption

Energy use

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

Resource availability and energy security

Air pollutants

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

Air quality and human health

Greenhouse gases

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

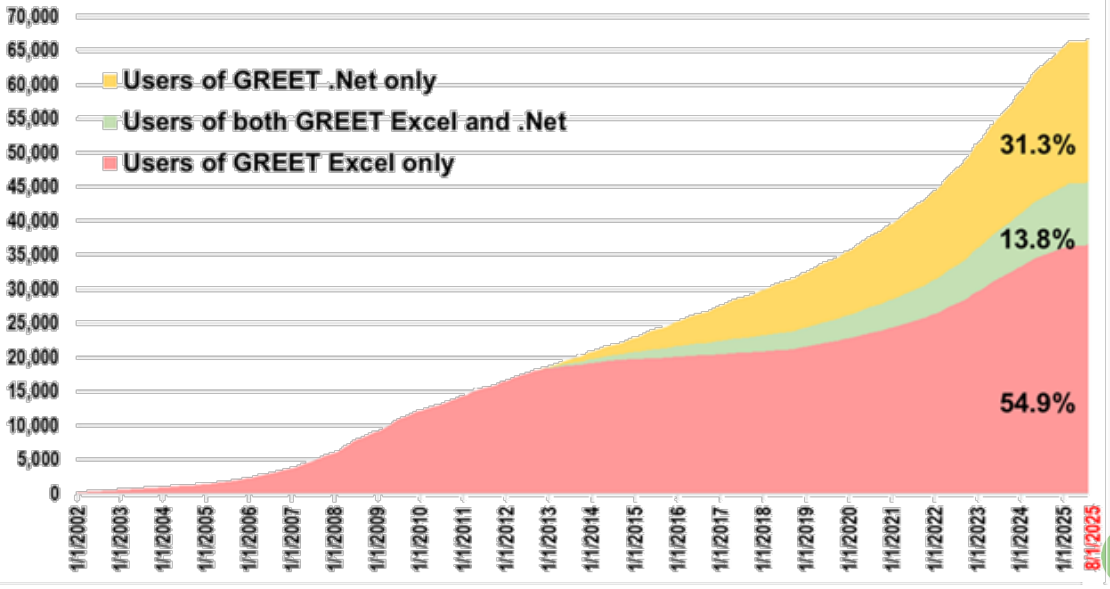
Global warming impacts

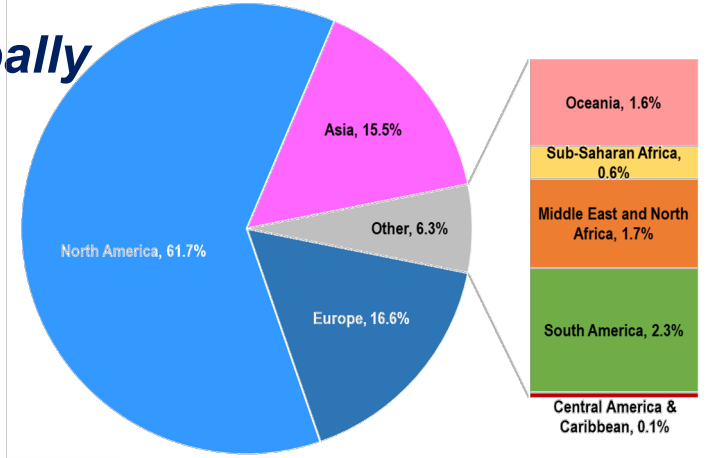
Water consumption

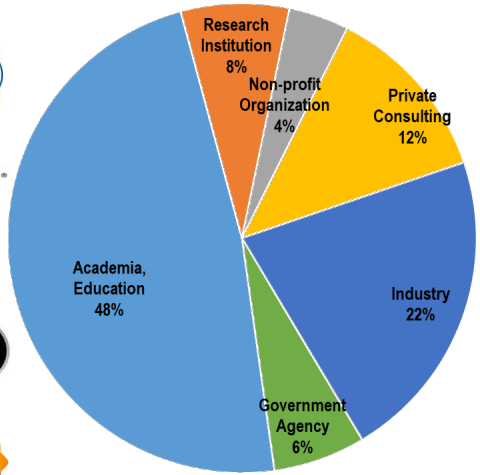
- Addressing water supply and demand (energy-water nexus)

Regional/seasonal water stress impacts

>66,000 Registered R&D GREET Users Globally

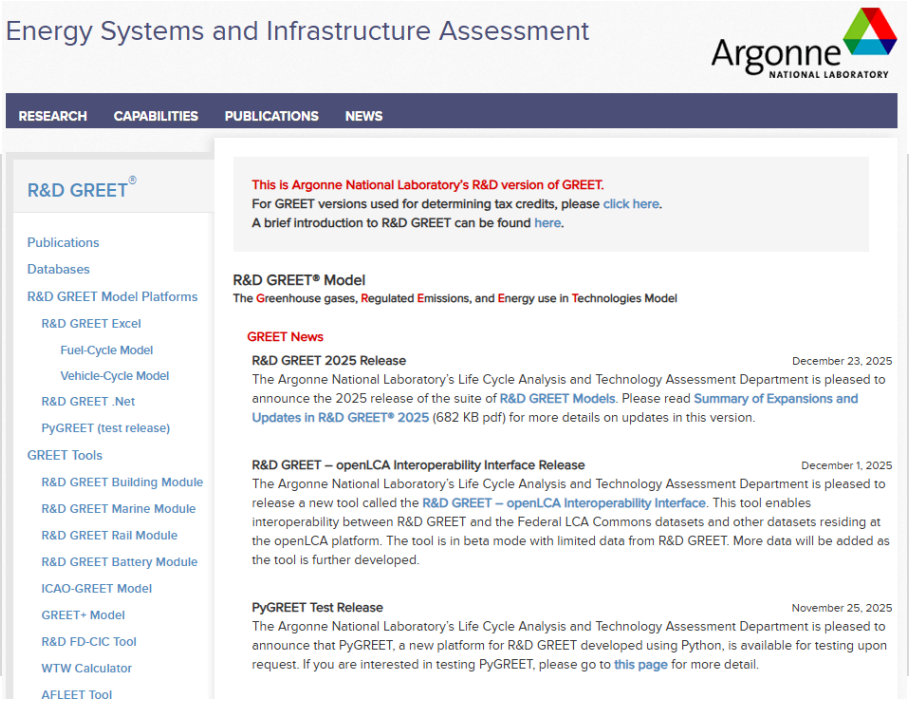






ARGONNE GREET WEBSITE

Has R&D GREET, Technical Reports, Journal Articles, and Technical Memos



ANL/ESIA-25/16

Summary of Expansions and Updates in R&D GREET® 2025

Prepared by

Michael Wang, Hao Cai, Longwen Ou, Amgad Elgowainy, Pahola Thathiana Benavides, Livia Benvenutti, Utkarsh S. Chaudhari, Thai Ngan Do, Jacob Englander, Masum Farhad, Yu Gan, Arna Ganguly, Ulises R. Gracida-Alvarez, Rakesh Krishnamoorthy Iyer, Jarod Kelly, Taemin Kim, Christopher P. Kolodziej, Hoyoung Kwon, Kyuha Lee, Uisung Lee, Branden E. Leonhardt, Juin Yau Lim, Xinyu Liu, Yi Ran Lu, Zifeng Lu, Sofia Martinez, Francisco Medel, Ahmad Naquash, Clarence Ng, Ishan Pandey, Ramsharan Pandey, Kang Shen, Siddharth Shukla, Pingping Sun, Tom Sykora, Shashwat Tripathi, Pradeep Vyawahare, Yiling Xu, Rufan Zhou

Energy Systems and Infrastructure Assessment Division
Argonne National Laboratory
December 2025

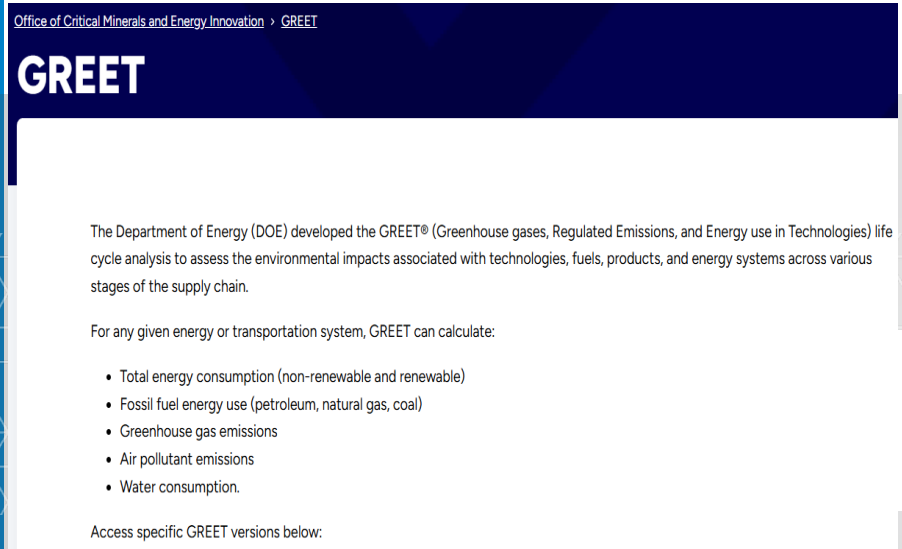
ARGONNE'S R&D GREET MODE

https://greet.anl.gov

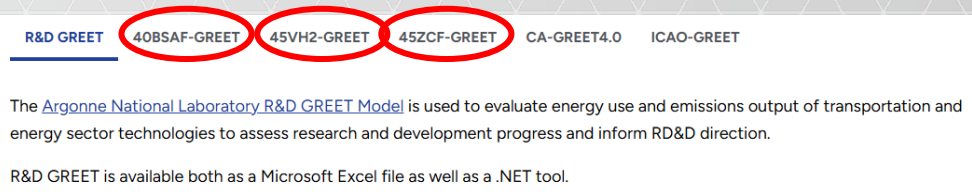
GREET informs policies and regulations

- **California Low-Carbon Fuel Standard** uses CA-GREET, an adaptation of Argonne GREET model
- **Oregon Clean Fuels Program** uses an adaptation of Argonne's GREET model
- **State of Washington Clean Fuel Regulation** relies on CA-GREET
- **State of New Mexico Clean Transportation Fuel Program** relies on Argonne's GREET
- **U.S. EPA** uses GREET with other sources for **Renewable Fuels Standard** pathway evaluations
- **National Highway Traffic Safety Administration** for fuel economy regulation
- **Federal Aviation Administration** and **International Civil Aviation Organization** using GREET to evaluate aviation fuel pathways
- **Canadian Clean Fuel Regulation** for Environment and Climate Change Canada fuel pathways
- LCA results for use in provisions of the 2022 **Inflation Reduction Act** and the 2025 **One Big Beautiful Bill Act (OBBBA)**

DOE Policy GREET Website (https://www.energy.gov/cmei/greet)



DOE GREET website provides links to R&D GREET at ANL and hosts tax credit GREET models and documentation.



R&D 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

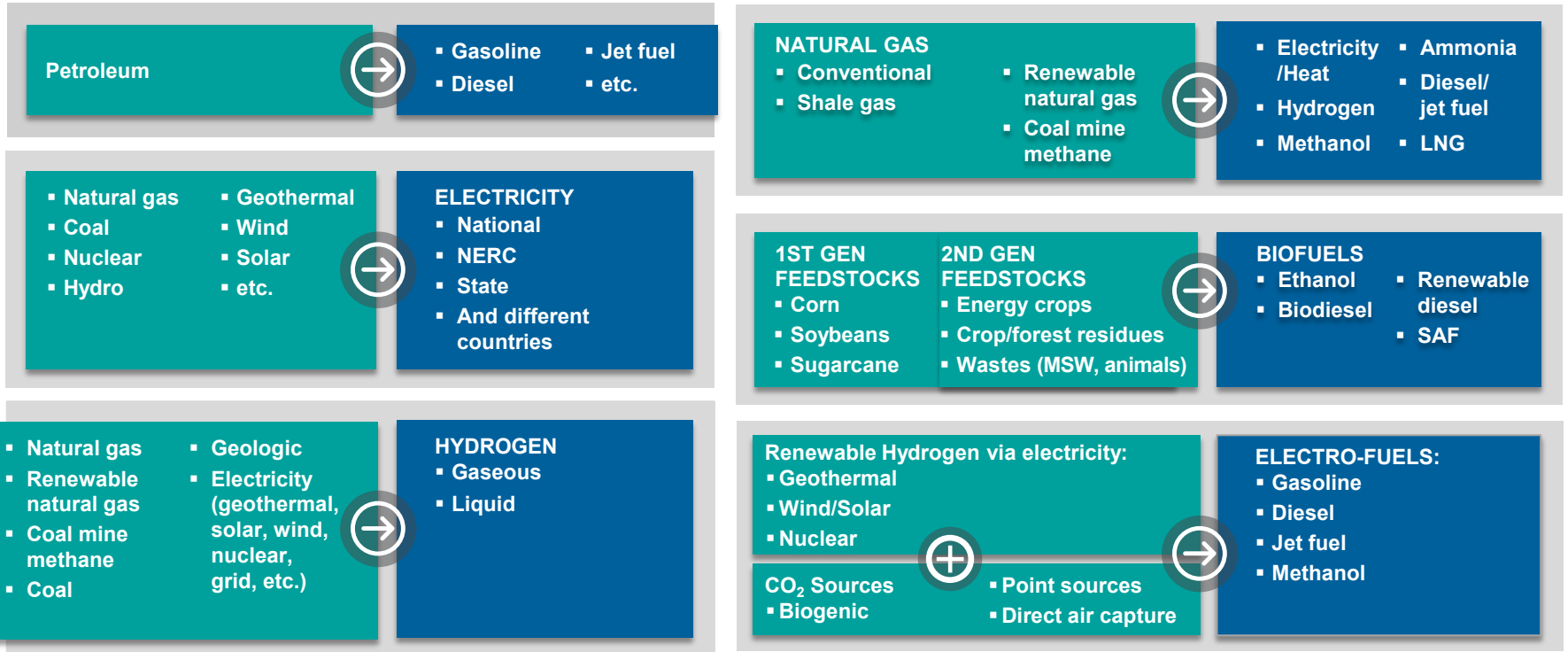
Hybrid Electric Vehicles (HEVs)
- Spark-ignition engines:
- Compression-ignition engines

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

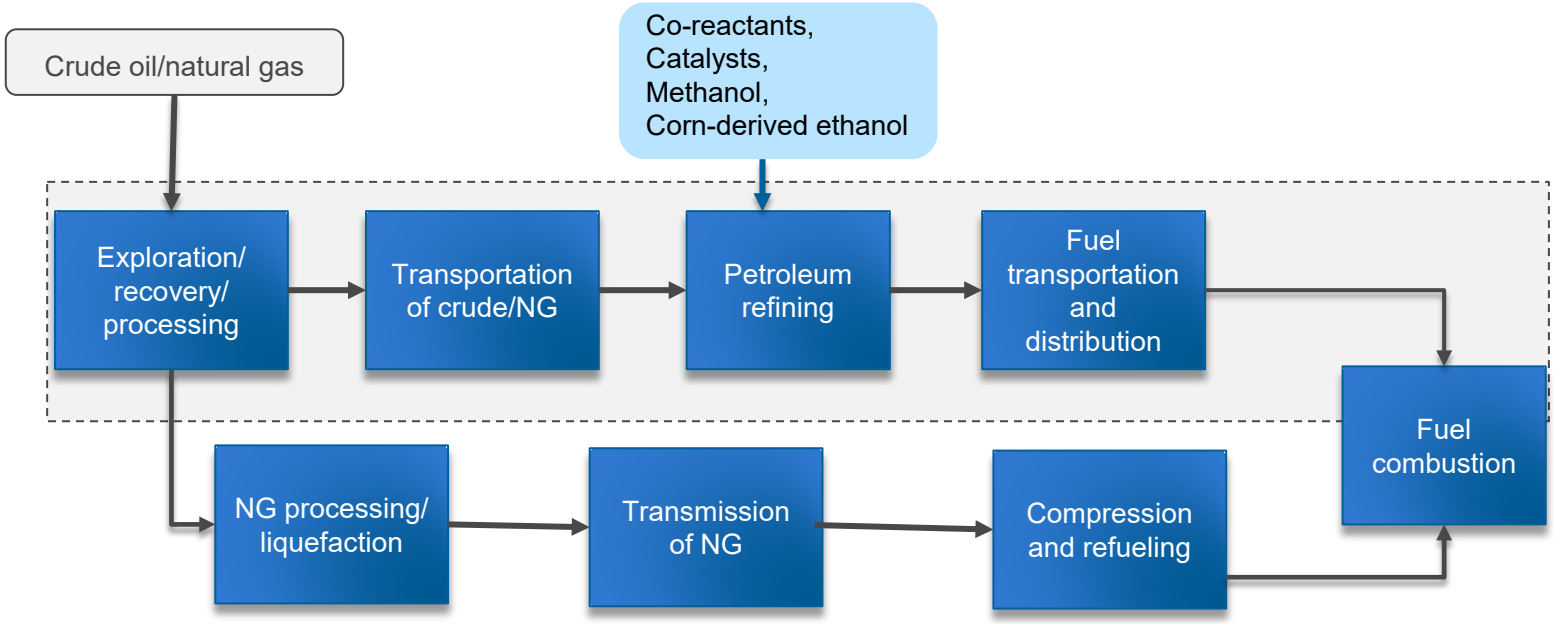
Battery-Powered Electric Vehicles
- Various electricity generation sources

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

R&D GREET HAS EXTENSIVE LIST OF ENERGY SYSTEMS



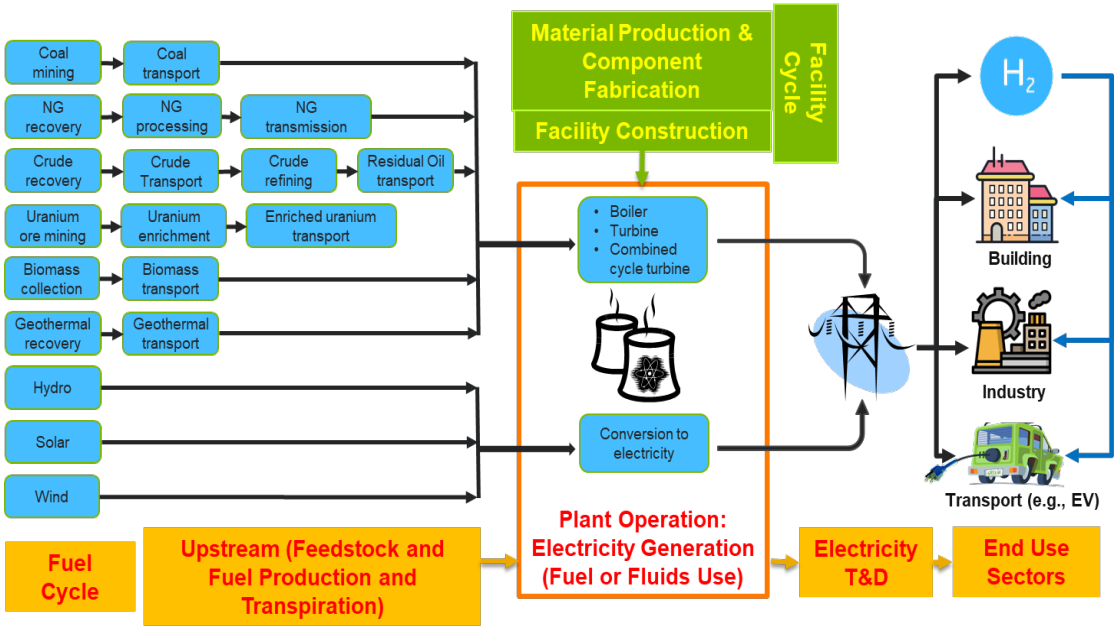
Life cycle of fuels from petroleum and natural gas



- All direct activities and emissions in the above flowcharts are included
- **Land disturbance** of oil/NG recovery was assessed and included in R&D GREET (up to 2 g/MJ)
- Methane leakage of the NG supply chain is based on combined bottom-up (EPA GHG Inventory) and top-down (individual studies) approach

R&D GREET COVERS ELECTRICITY GENERATION FROM VARIOUS SOURCES

Over 30 Power Generation Technologies, Including Facility Life-Cycle (Embodied) Emissions



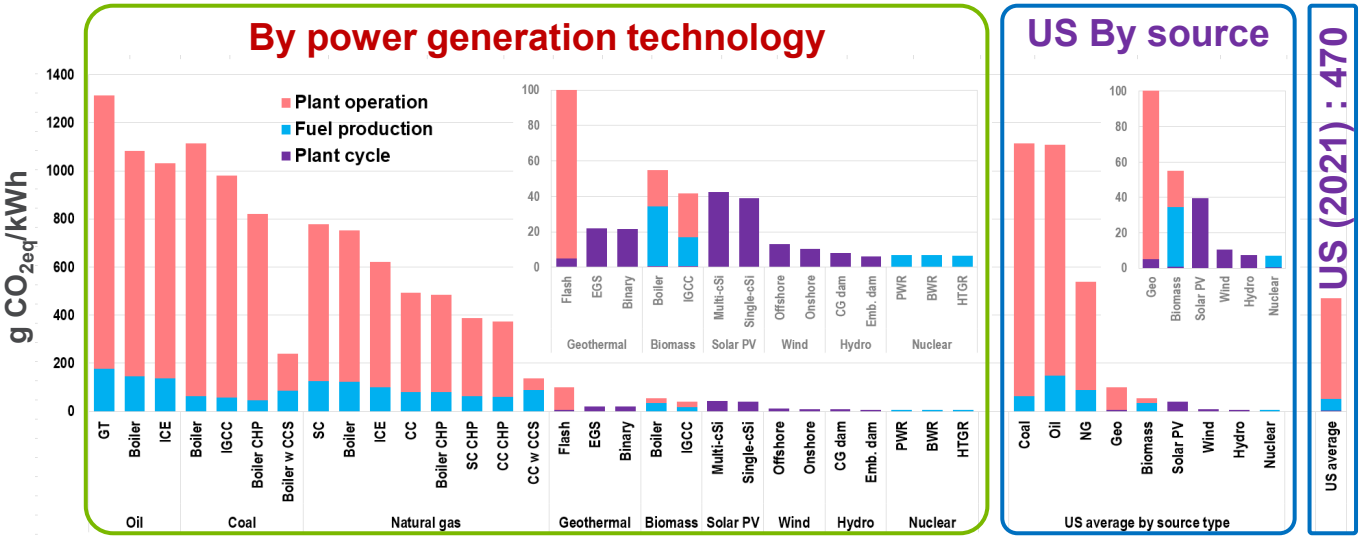
Key parameters, methods, and data sources for R&D GREET electricity LCA

- **Plant operation in the US**
  - Thermal efficiencies
    - Unit-level performance data (EIA 923, 860)
    - Aggregated to technology, regional, and national levels
  - GHG emission factors
    - CH_4 and N_2O: GHG reporting rule (EPA, 2009)
    - CO_2: fuel's carbon content and carbon balance
  - Criteria air pollutants
    - Plant-level emissions (EPA NEI 2017, e-GRID)
  - Water use
    - EIA and USGS's plant-level data
- **Transmission losses**
  - EIA Electricity Profiles (US)
  - World Bank Database (other countries)
- **Electricity generation mixes**
  - Unit-level generation data (EIA 923)
    - Aggregated to technology, regional, and national levels
  - EIA's Annual Energy Outlook (future projection)
  - IEA's Electricity Information (other countries)
- **Upstream**
  - Plant fuels are linked to their upstream production pathways in GREET, e.g.,
    - Coal: coal mining, cleaning, transportation
    - Gas: NG recovery, processing, transportation
    - Oil: crude recovery, transportation, refining, fuel oil transportation
    - Biomass: farming, harvesting, transportation
    - Nuclear: uranium mining, yellowcake conversion, enrichment, fuel rod fabrication

LIFE-CYCLE GHG EMISSIONS OF ELECTRICITY VARY AMONG TECHNOLOGIES

Thermal power plants (coal, gas, oil, biomass) results are dominated by GHG emissions from plant operation and plant fuel production stages

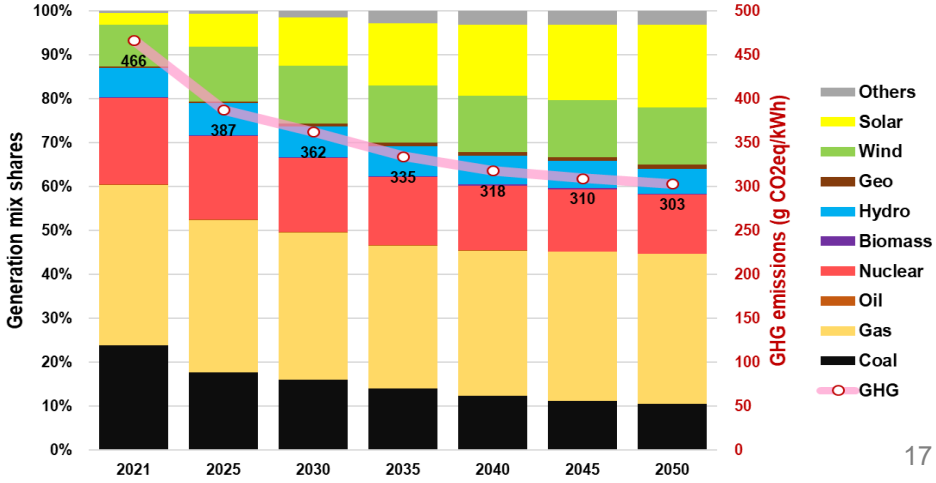
Facility cycle GHG emissions of renewable power infrastructure are higher than those of fossil-fired and nuclear plants

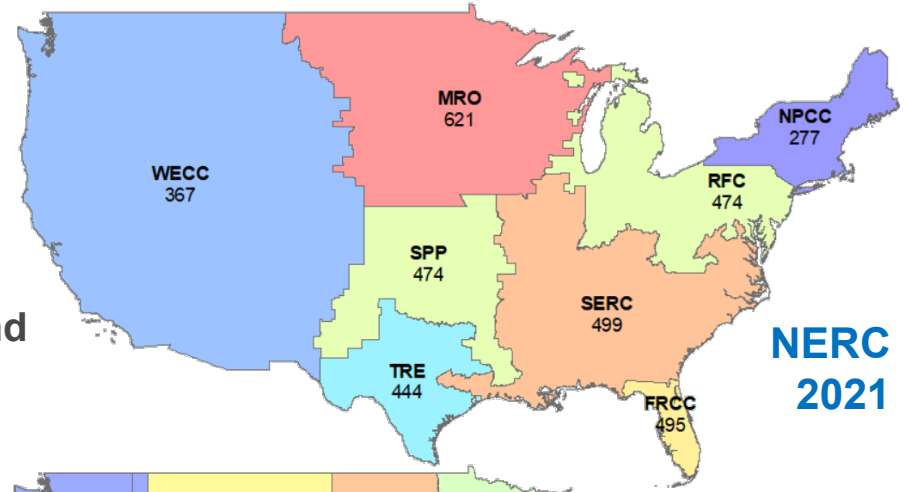


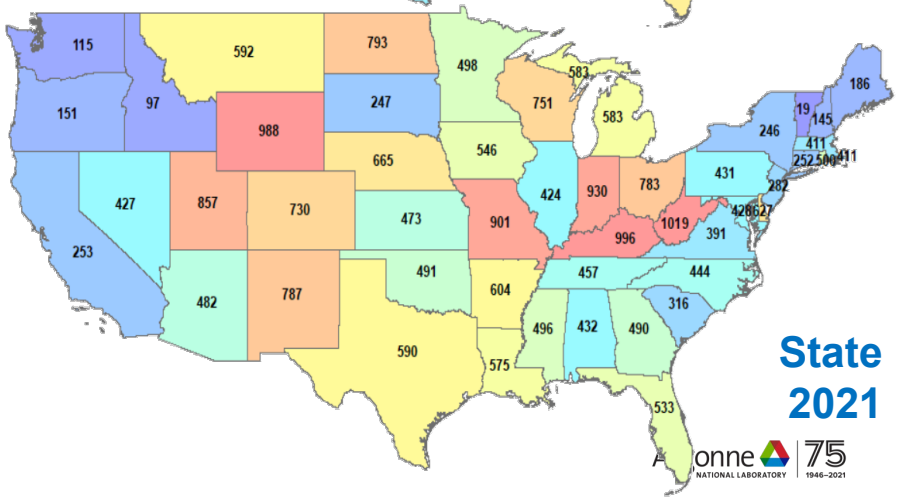
Fuel-cycle GHG emissions of U.S. electricity by year and region

- **2021 U.S. electricity GHG intensity**
  - 466 g $CO_{2\ eq}$/kWh at the plug
  - Generation mix

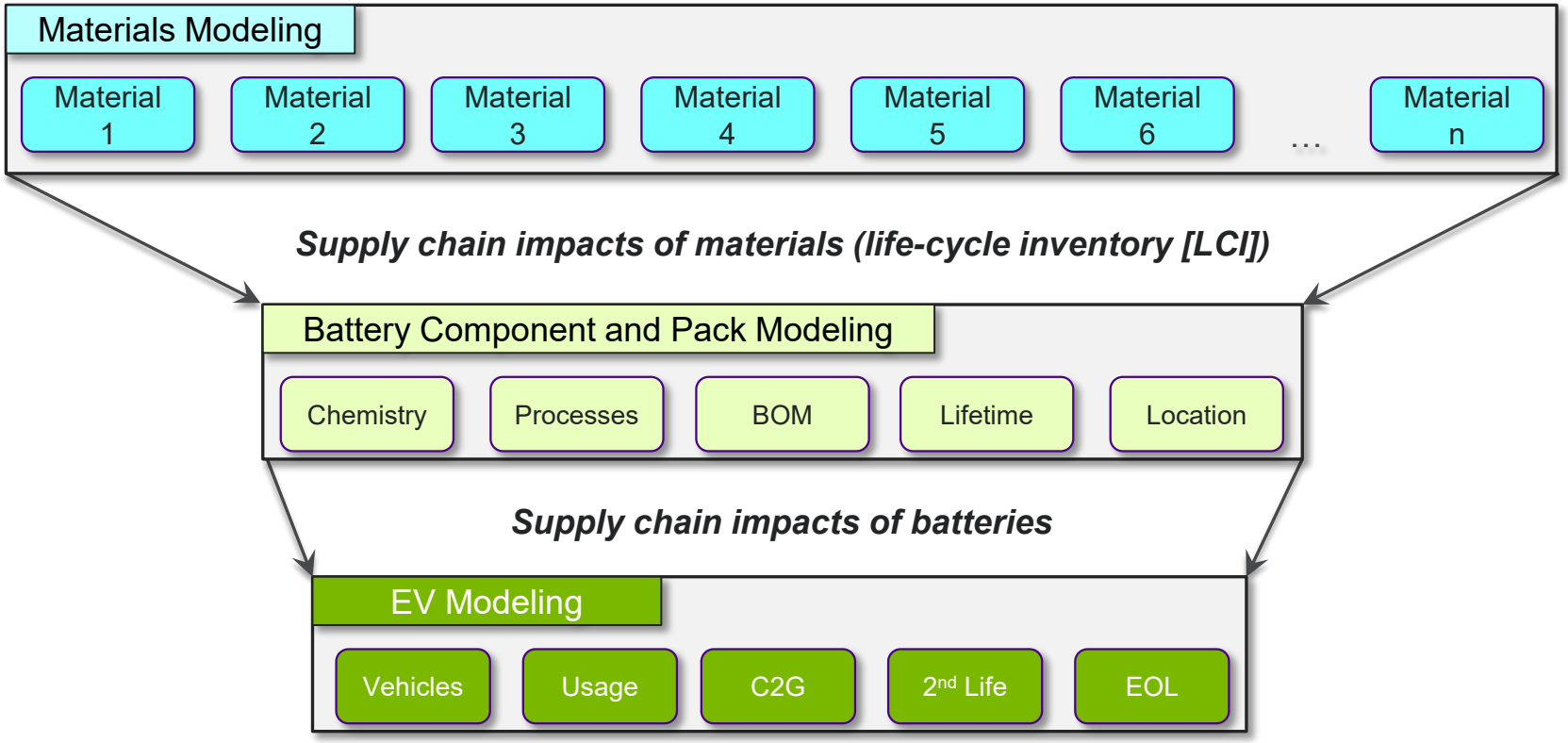
    Gas 36%, coal 24%, nuclear 20%, renewable 19%
- **Electricity generation intensities are low in the east and west coast and high in the Mountain and central US**



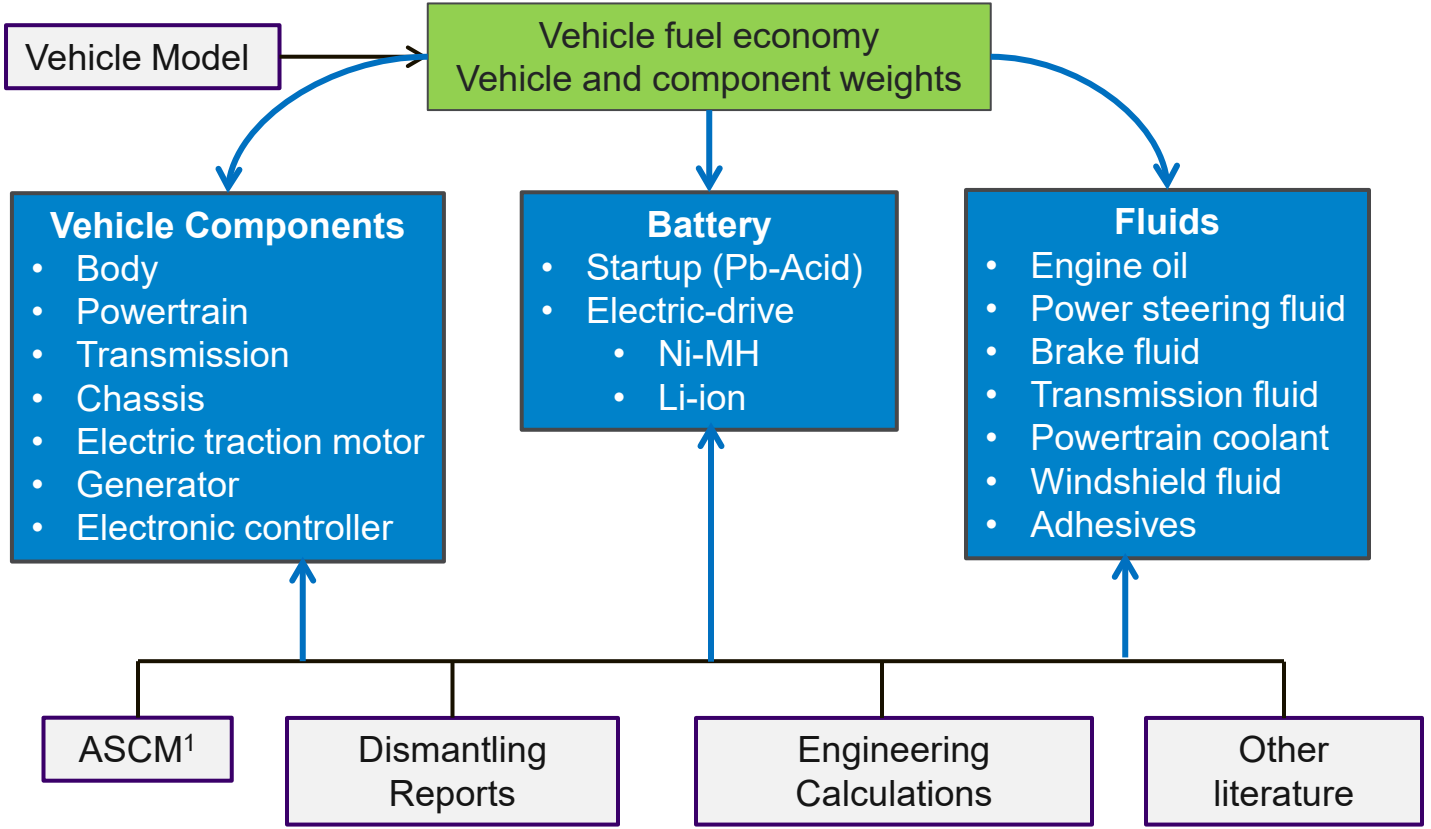




Framework of vehicle cycle analysis: example of EVs – from materials, to batteries, and to EVs



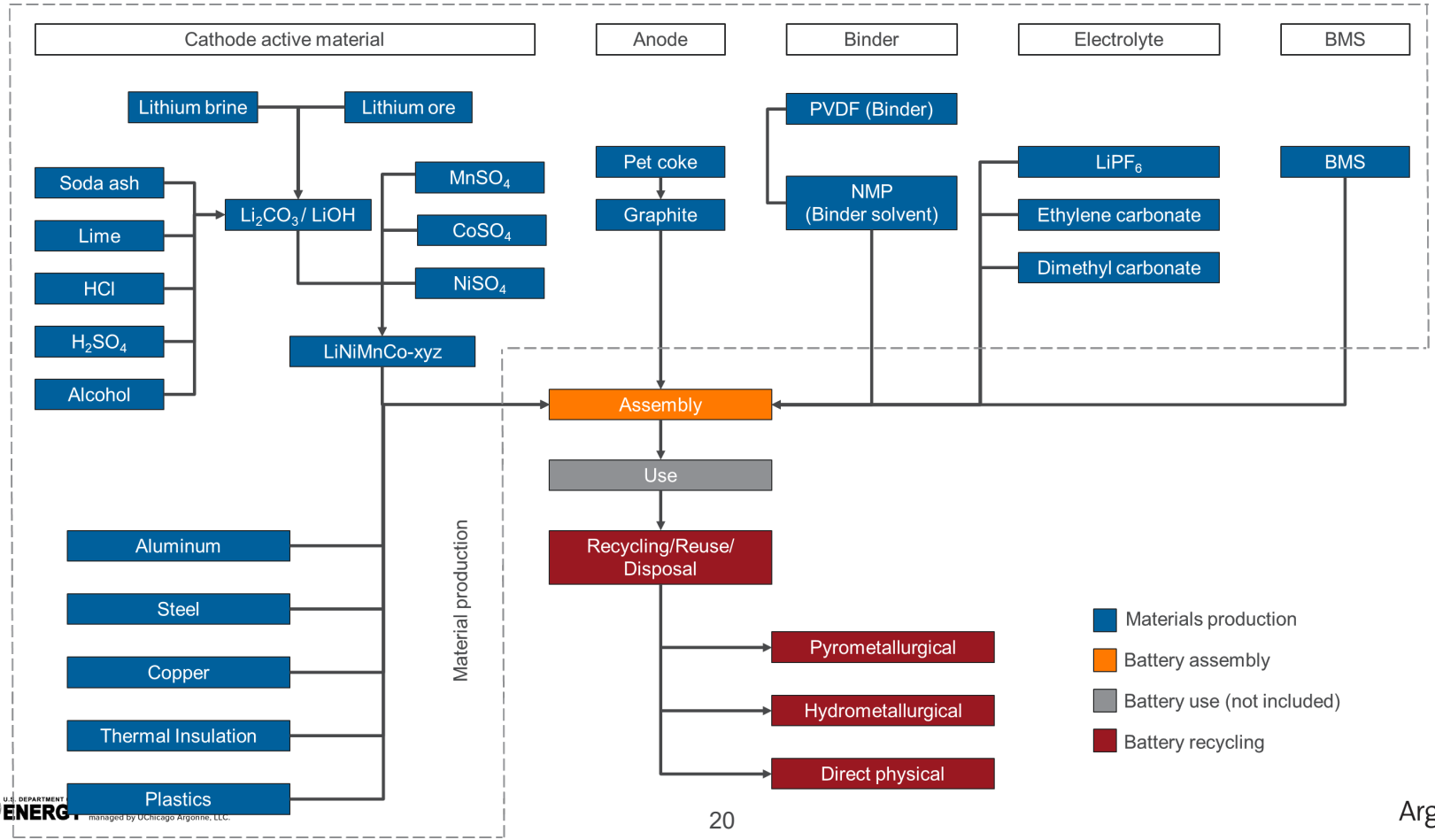
Approach to developing a materials inventory (bill of materials) for vehicles in R&D GREET2



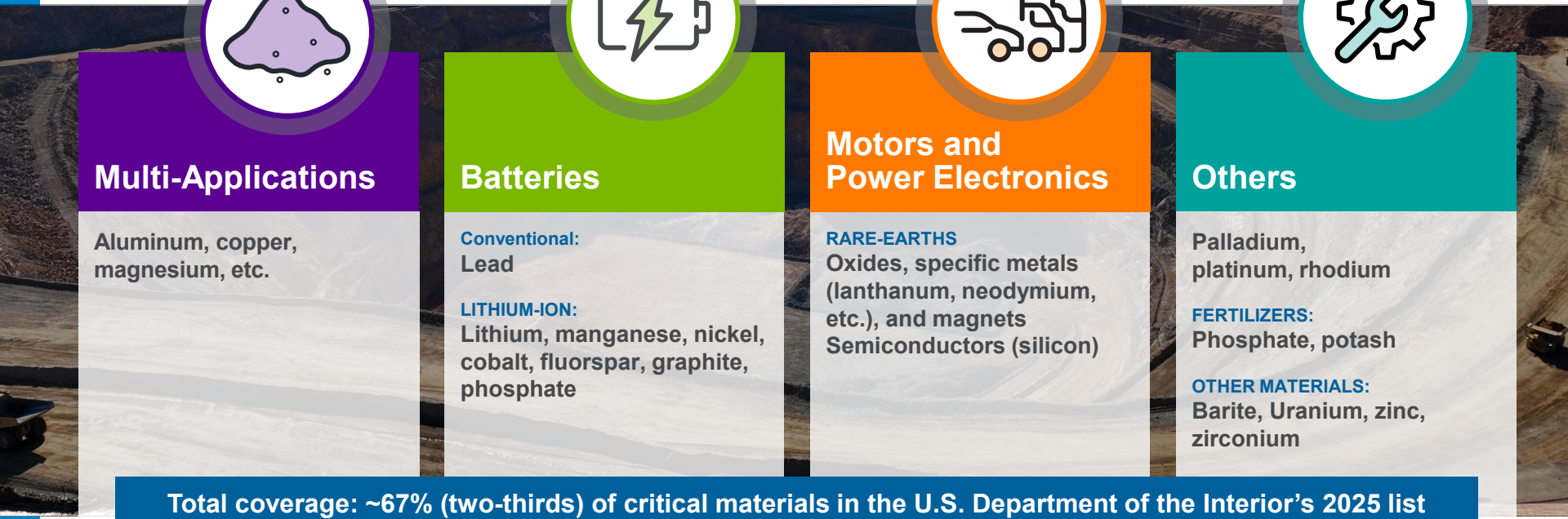
1. Automotive System Cost Model, IBIS Associates and Oak Ridge National Laboratory

19

Battery LCA coverage in R&D GREET



R&D GREET INCLUDES EXTENSIVE LISTS OF CRITICAL MATERIALS/MINERALS



Multi-Applications

Aluminum, copper, magnesium, etc.

Batteries

Conventional:
Lead

LITHIUM-ION:
Lithium, manganese, nickel, cobalt, fluorspar, graphite, phosphate

Motors and Power Electronics

RARE-EARTHS
Oxides, specific metals (lanthanum, neodymium, etc.), and magnets
Semiconductors (silicon)

Others

Palladium, platinum, rhodium

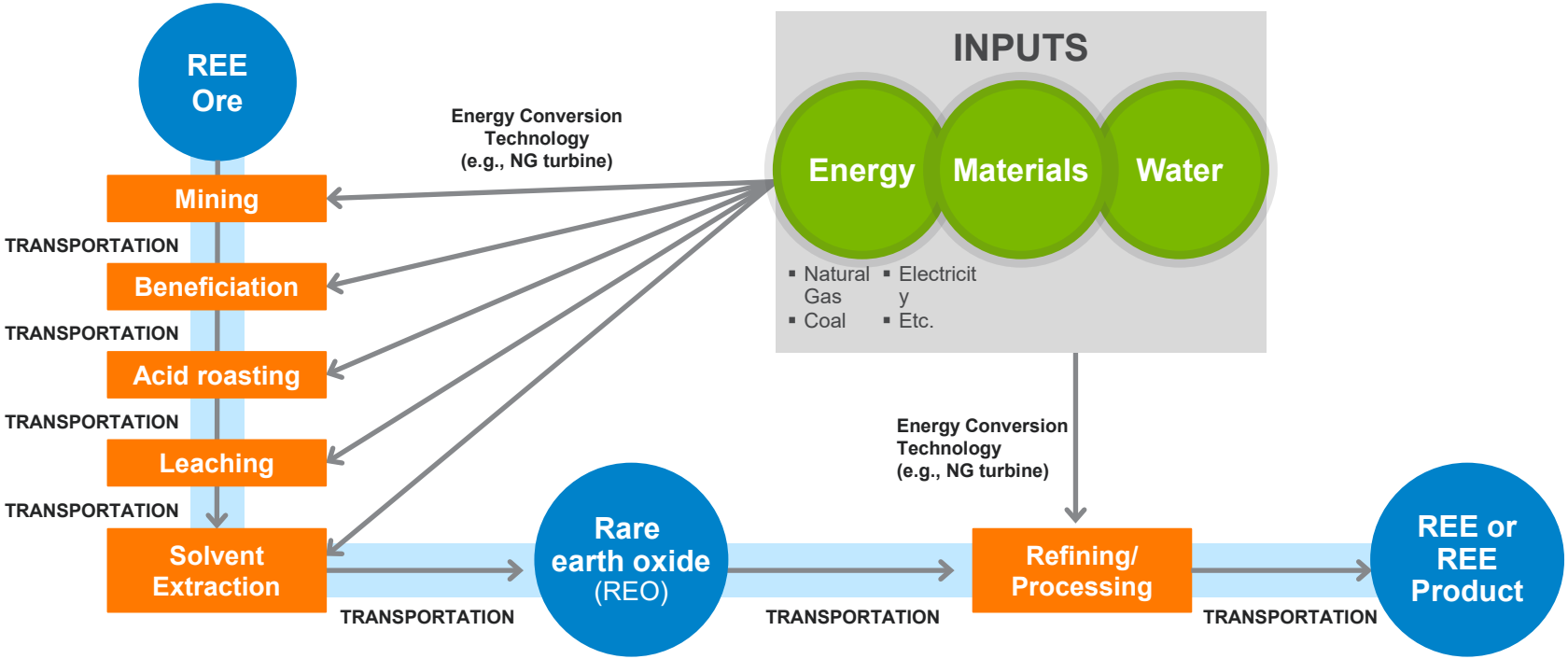
FERTILIZERS:
Phosphate, potash

OTHER MATERIALS:
Barite, Uranium, zinc, zirconium

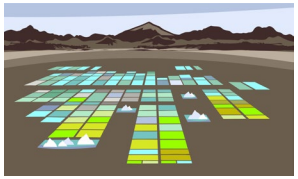
Total coverage: ~67% (two-thirds) of critical materials in the U.S. Department of the Interior's 2025 list

R&D GREET LCA APPROACH

Rare-earth Elements (REE) from Bastnasite/Monazite Ores



Detailed supply chain for lithium LCA



Brine recovery

Brine concentration

Truck transport

Li_2CO_3 / LiOH production

Truck transport

Ocean transport

Land transport

Brine-based Li Production

Ore-based Li Production

Ore mining

Spodumene concentration

Truck transport

Ocean transport

Land transport

Li_2CO_3 / LiOH production

Land Transport

Transport

Cathode production

Cell production

Transport

Module production

Transport

Pack production

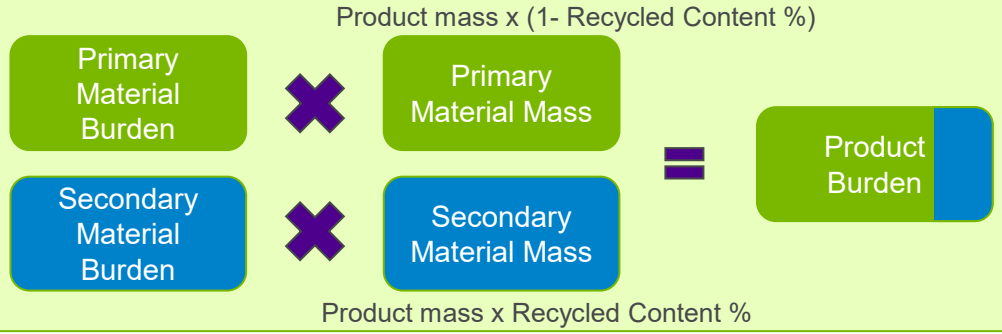
Transport

EV production

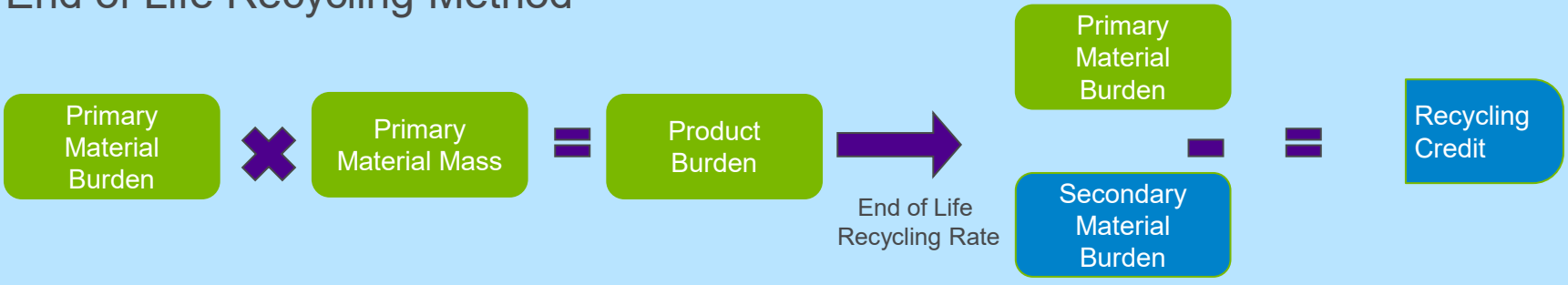
Battery Production

Treatment of recycled materials in vehicle cycle analysis

Recycled Content Method

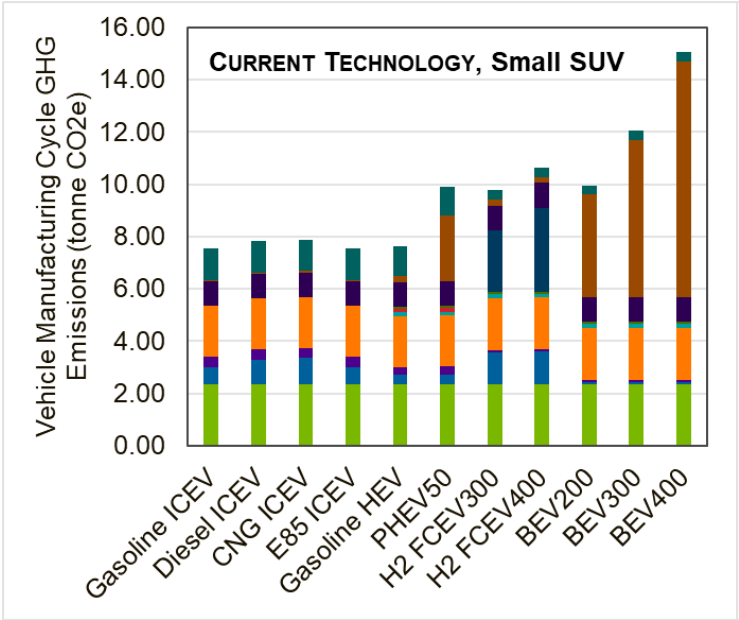


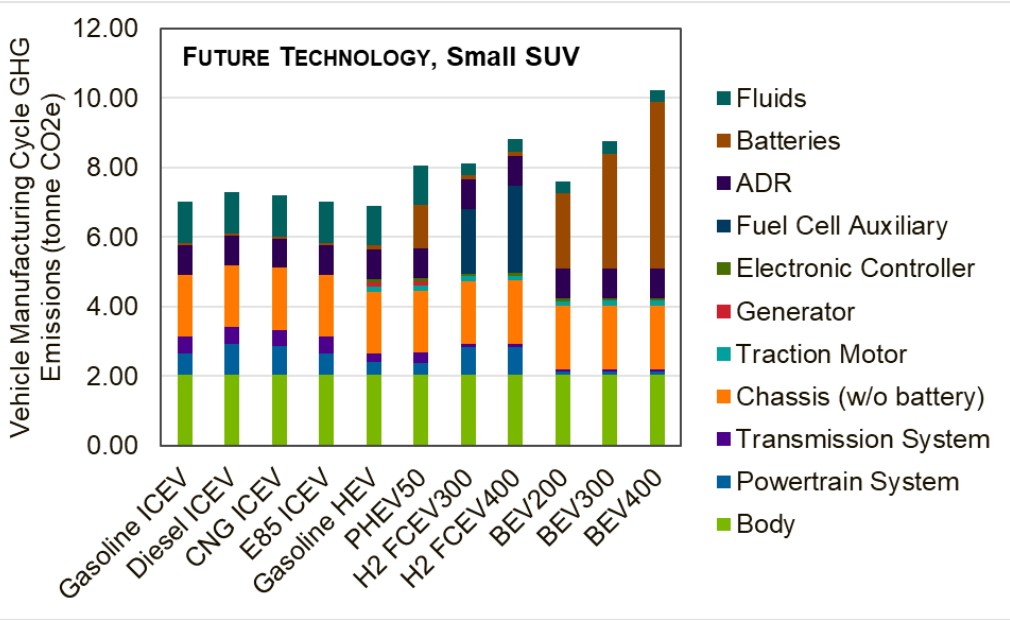
End of Life Recycling Method



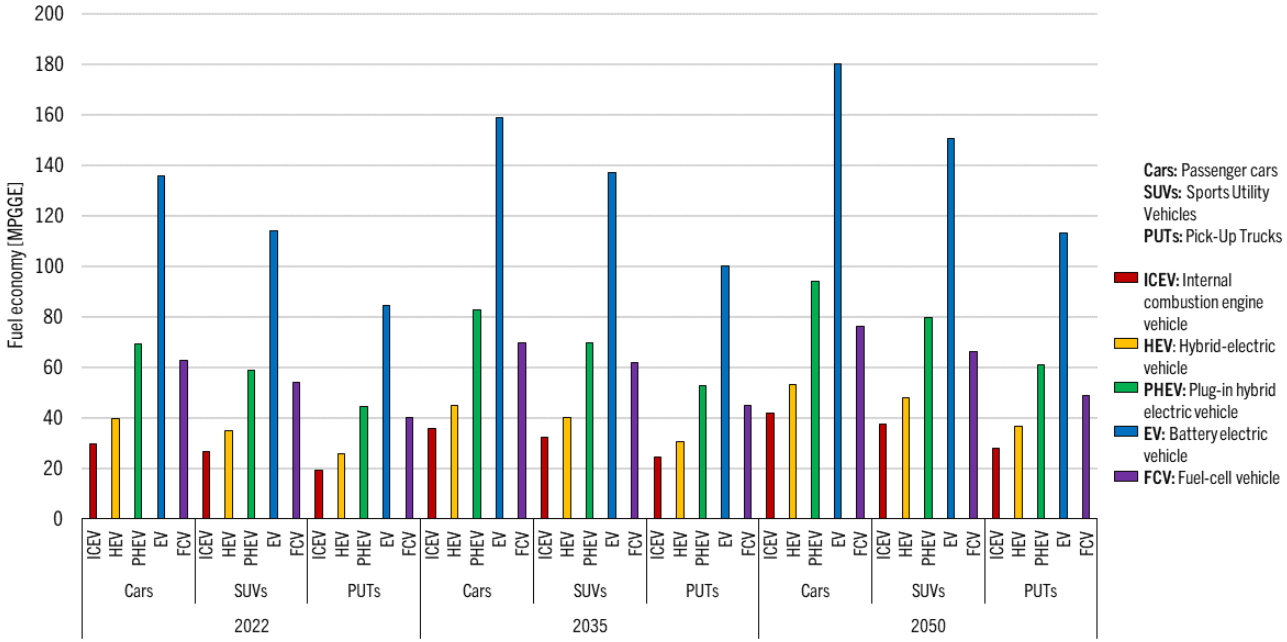
Zooming in on the vehicle cycle

- How will a transition to alternative powertrains impact the vehicle cycle?
- CURRENT TECHNOLOGY shows larger GHG impact from alternative powertrains than FUTURE



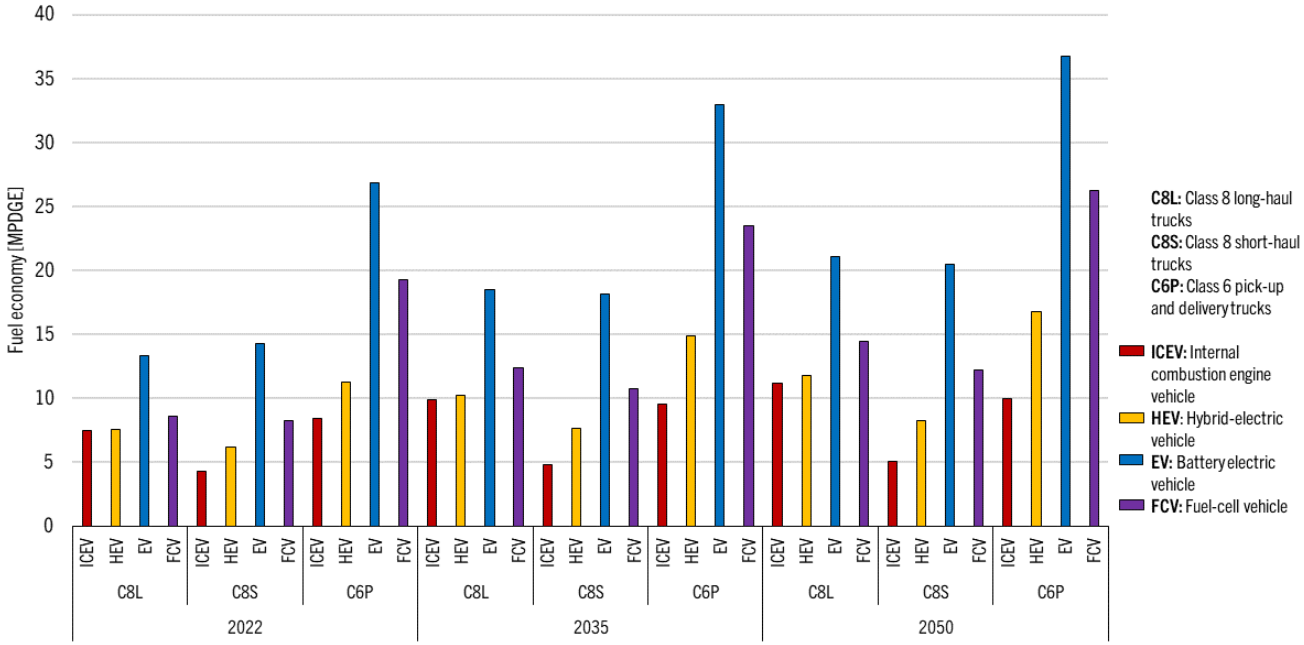


SAE PAPER 2024-01-2830:
LIGHT DUTY VEHICLE FUEL ECONOMY



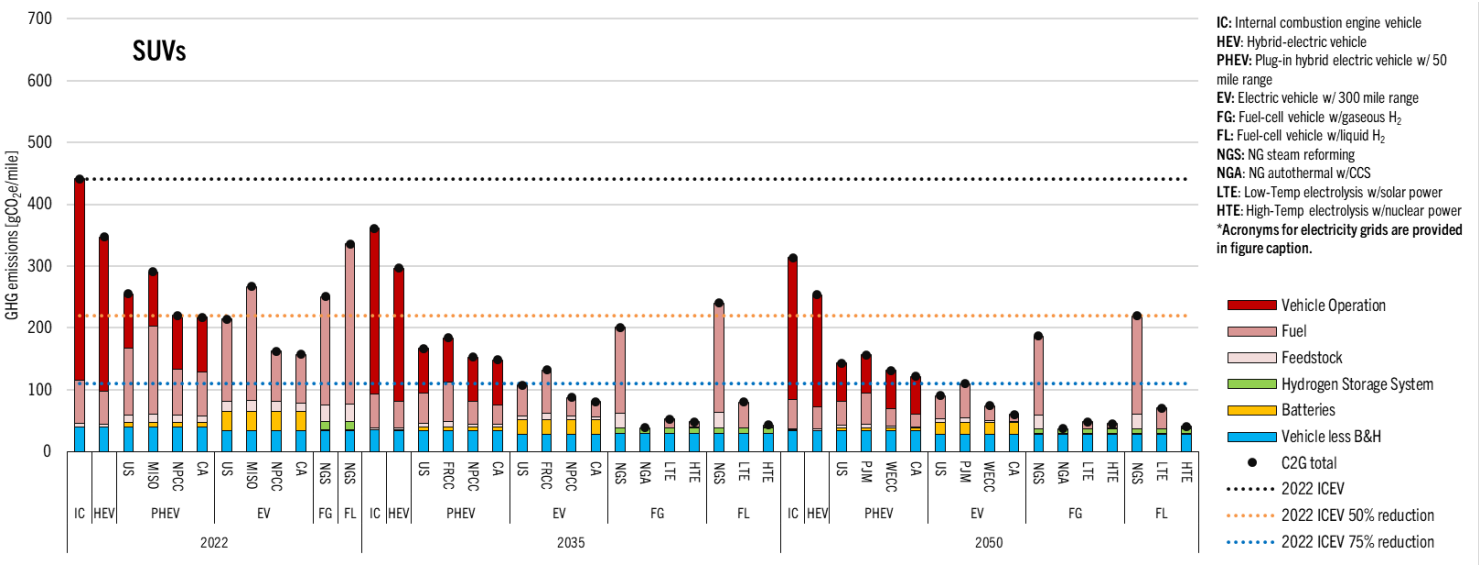
- All five powertrain options are projected to have improved future fuel economies

MEDIUM- AND HEAVY-DUTY VEHICLE FUEL ECONOMY



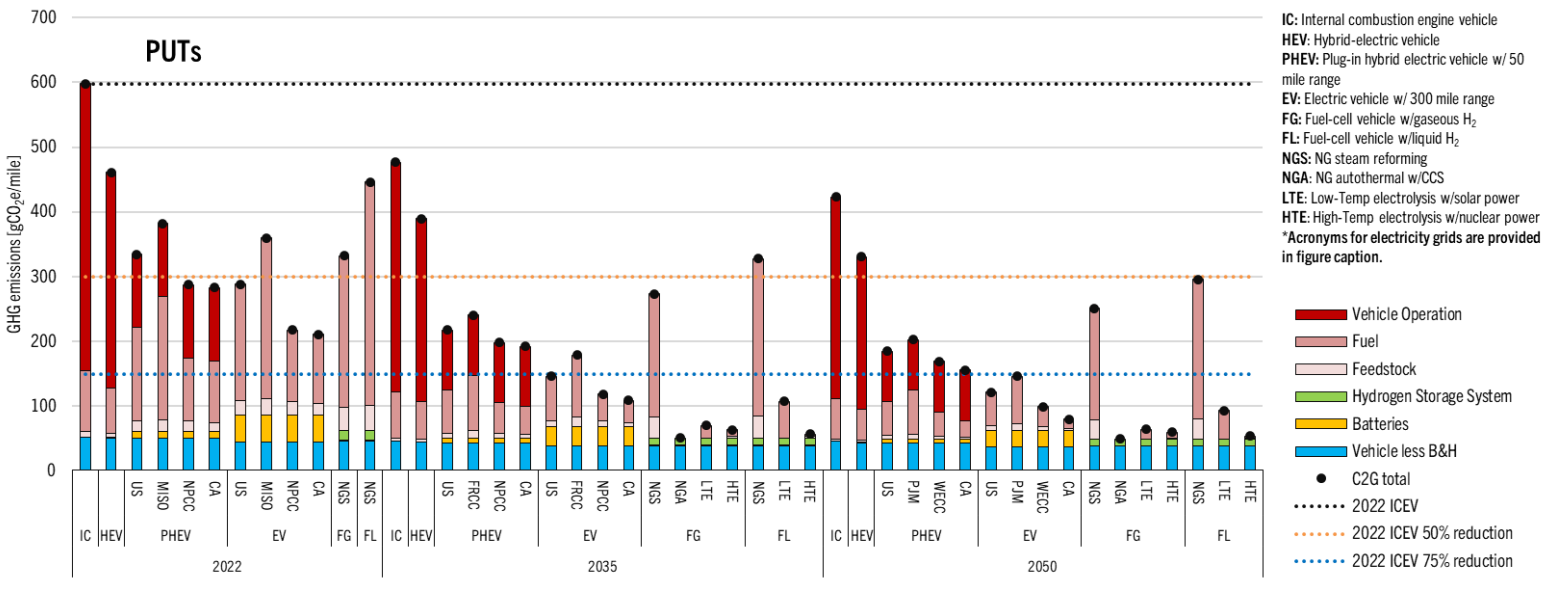
- All four powertrain options are projected to have improved future fuel economies

LCA: Results – Small SUV

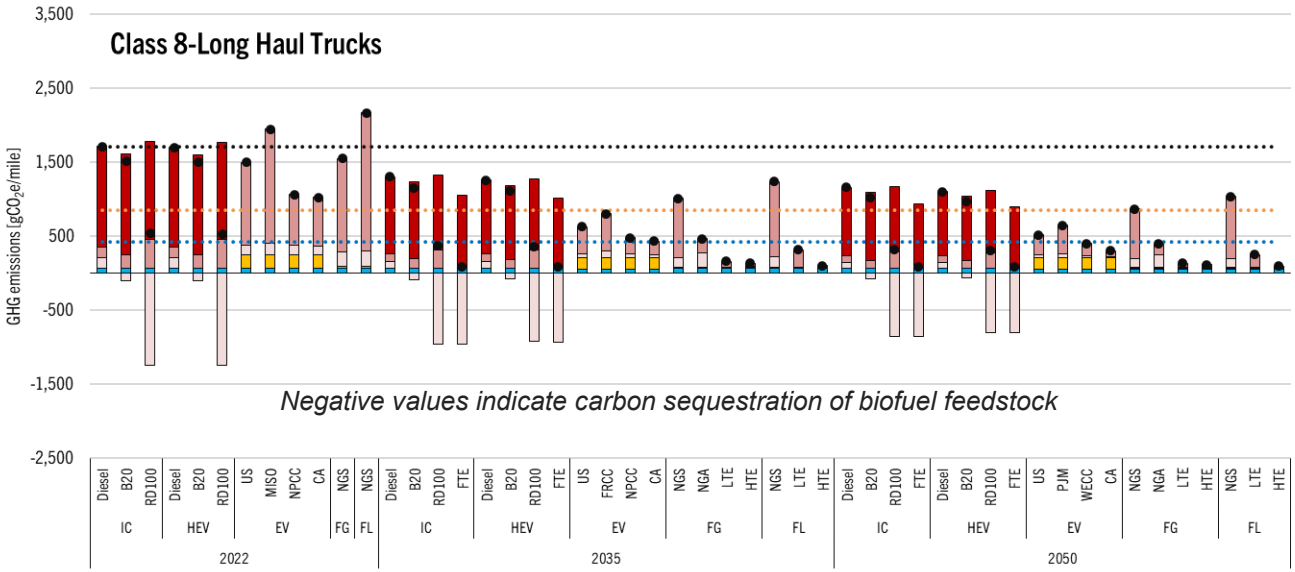


- **For 2022** simulation, **EV** is the only powertrain option achieving more than **50% reduction** with baseline fuel production pathway
  - ✓ FCVs and PHEVs also achieve significant GHG emissions reduction, but not more than 50%
- **For future** simulations, **EV** is still the least carbon-intensive option **(>75%** reduction) with baseline grid option.
  - ✓ However, **cleaner hydrogen production** pathways (NGA, LTE, and HTE) **can outperform EV's** carbon intensity in future thanks to less GHG burdens from battery and fuel production.

LCA: RESULTS – PICKUP TRUCK



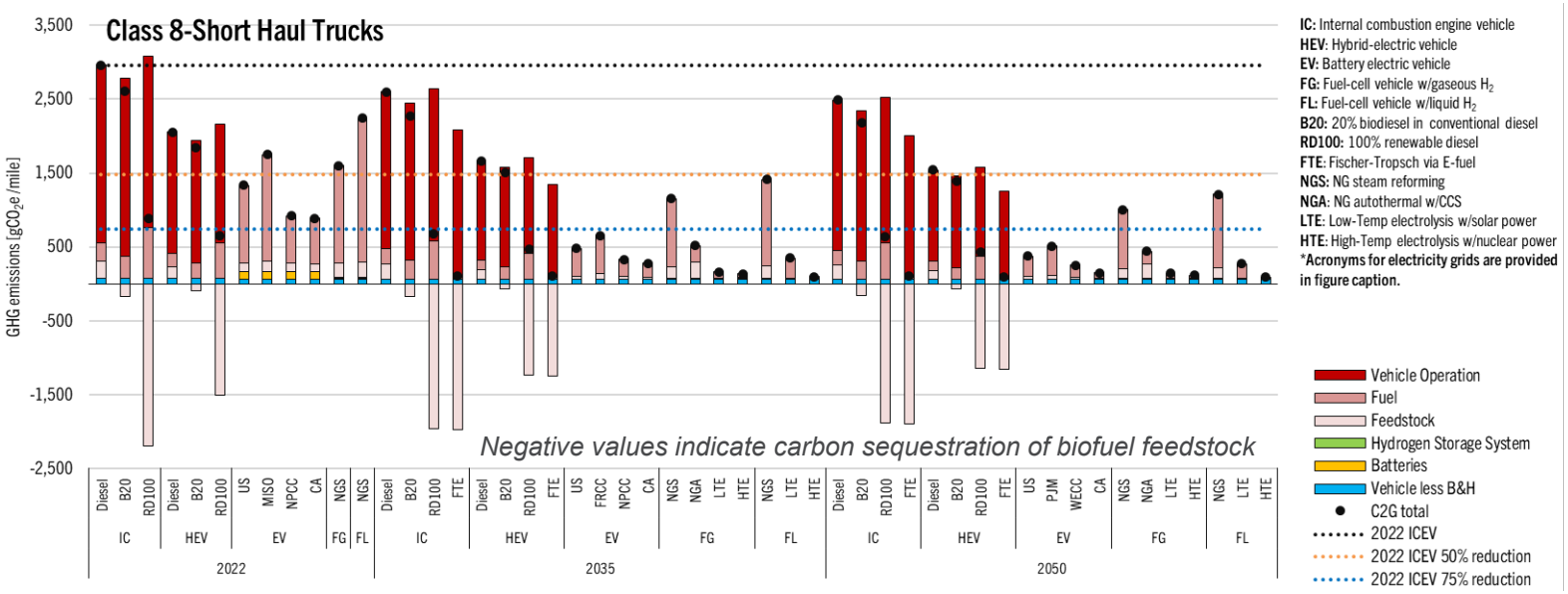
LCA: Results – Class 8 Long-Haul Trucks



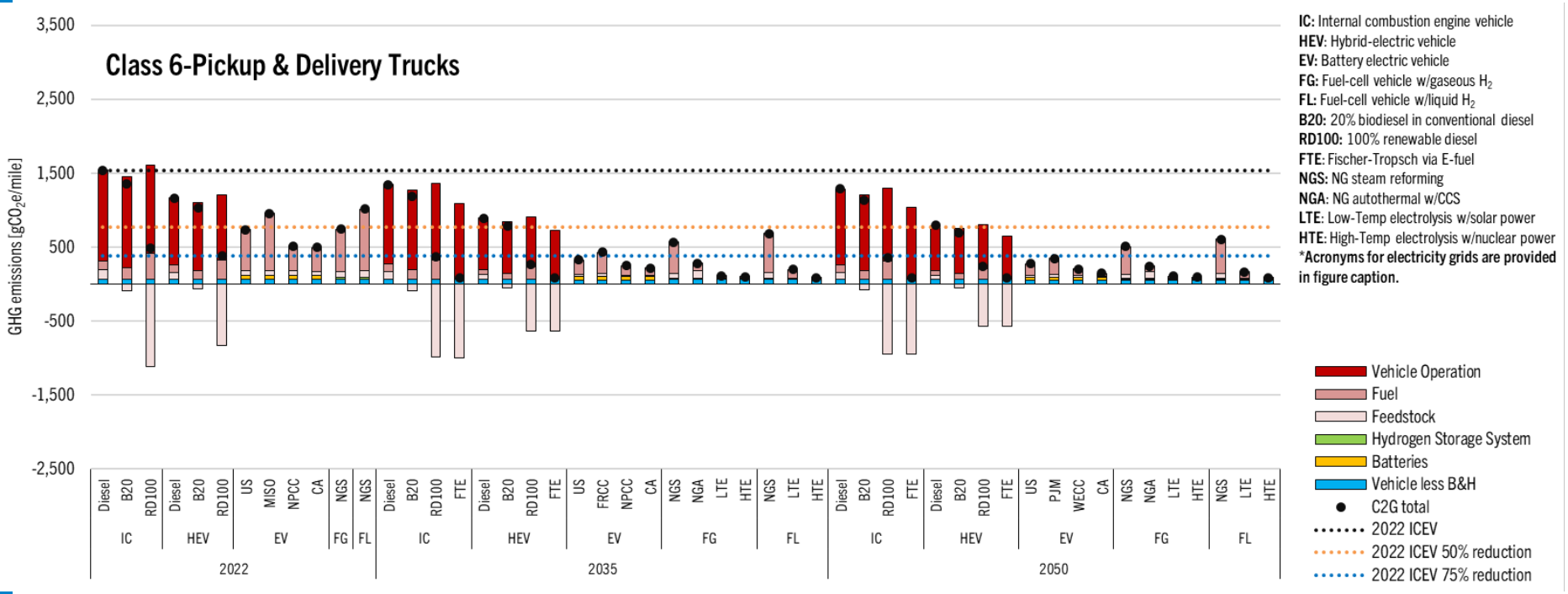
IC: Internal combustion engine vehicle
HEV: Hybrid-electric vehicle
EV: Battery electric vehicle
FG: Fuel-cell vehicle w/gaseous H_2
FL: Fuel-cell vehicle w/liquid H_2
B20: 20% biodiesel in conventional diesel
RD100: 100% renewable diesel
FTE: Fischer-Tropsch via E-fuel
NGS: NG steam reforming
NGA: NG autothermal w/CCS
LTE: Low-Temp electrolysis w/solar power
HTE: High-Temp electrolysis w/nuclear power
***Acronyms for electricity grids are provided in figure caption.**

Vehicle Operation
Fuel
Feedstock
Hydrogen Storage System
Batteries
Vehicle less B&H
C2G total
2022 ICEV
2022 ICEV 50% reduction
2022 ICEV 75% reduction

LCA: Results – Class 8 Short-Haul Trucks



LCA: RESULTS – CLASS 6 PICKUP & DELIVERY TRUCKS



Questions?

Michael Wang (mwang@anl.gov)

Visit https://greet.anl.gov/