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Webinar for Clean Cities and Communities
(Virtual)

Electric Vehicles and their Batteries: A Life Cycle Perspective on Environmental Impacts

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The GREET effort at Argonne National Laboratory is supported by the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy and Carbon Management, the Office of Technology Transition, 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.

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TOPICS FOR DISCUSSION

- Argonne National Laboratory
- What is life cycle analysis (LCA)?
- What is Argonne's GREET® model?
- What trends have we observed in battery LCA?

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Argonne by the numbers: World-leading research at scale in suburban Chicago

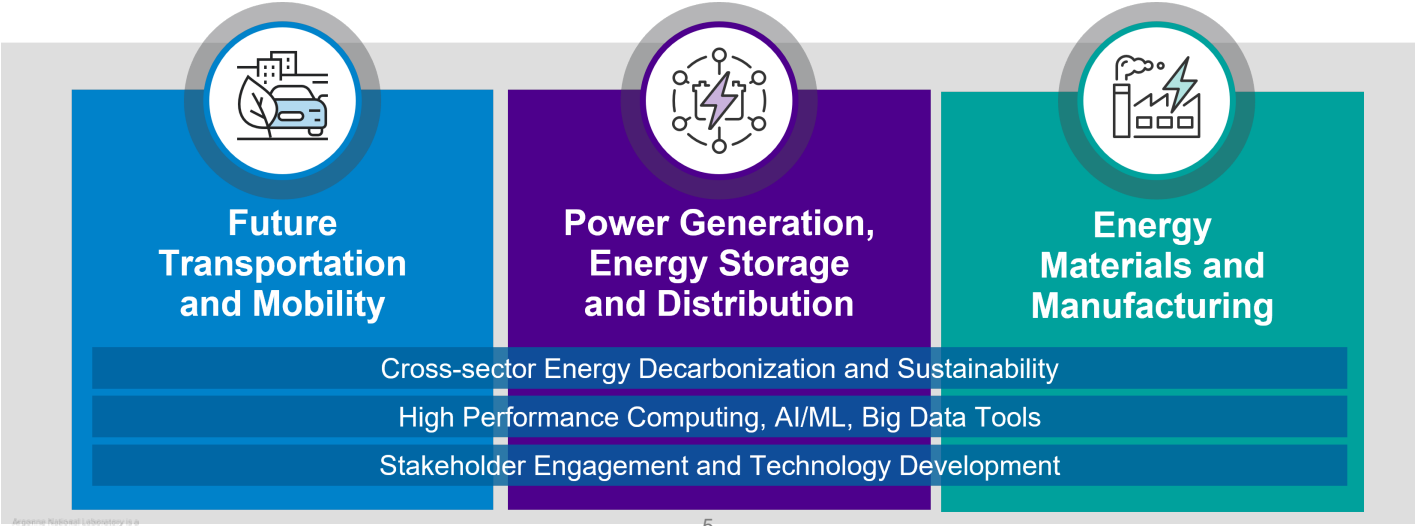
$1.15	billion-dollar budget
3,500	employees, including 1,800 researchers and 500 students
6,000	researchers supported by 6 DOE-SC and DOE-NE user facilities
5	national research centers led by Argonne
3	locations: Chicago suburbs, City of Chicago, and Washington, D.C.

Argonne is organized in six areas

- Advanced Energy Technologies
- Computing, Environment and Life Science
- Nuclear Technologies and National Security
- Photon Sciences
- Physical Sciences and Engineering
- S&T Partnerships and Outreach

Advanced Energy Technologies

- **Vision:** Enable a sustainable, secure, equitable, and prosperous energy future
- **Mission:** Solve the most pressing energy, mobility, materials, and manufacturing challenges through world-class scientific and engineering expertise and facilities.



Life Cycle Analysis (LCA)

- **LCA estimates the environmental effects of a product or process based on that product/process's input energy and materials**

- LCA is an important step to holistically evaluate the sustainability of technologies and policies
  - From singular stages to the complete supply chain; shifts in environmental burdens from one stage to another are not missed
  - LCA thinking has helped changes in corporate and consumer behaviors

What are the elements of an LCA?

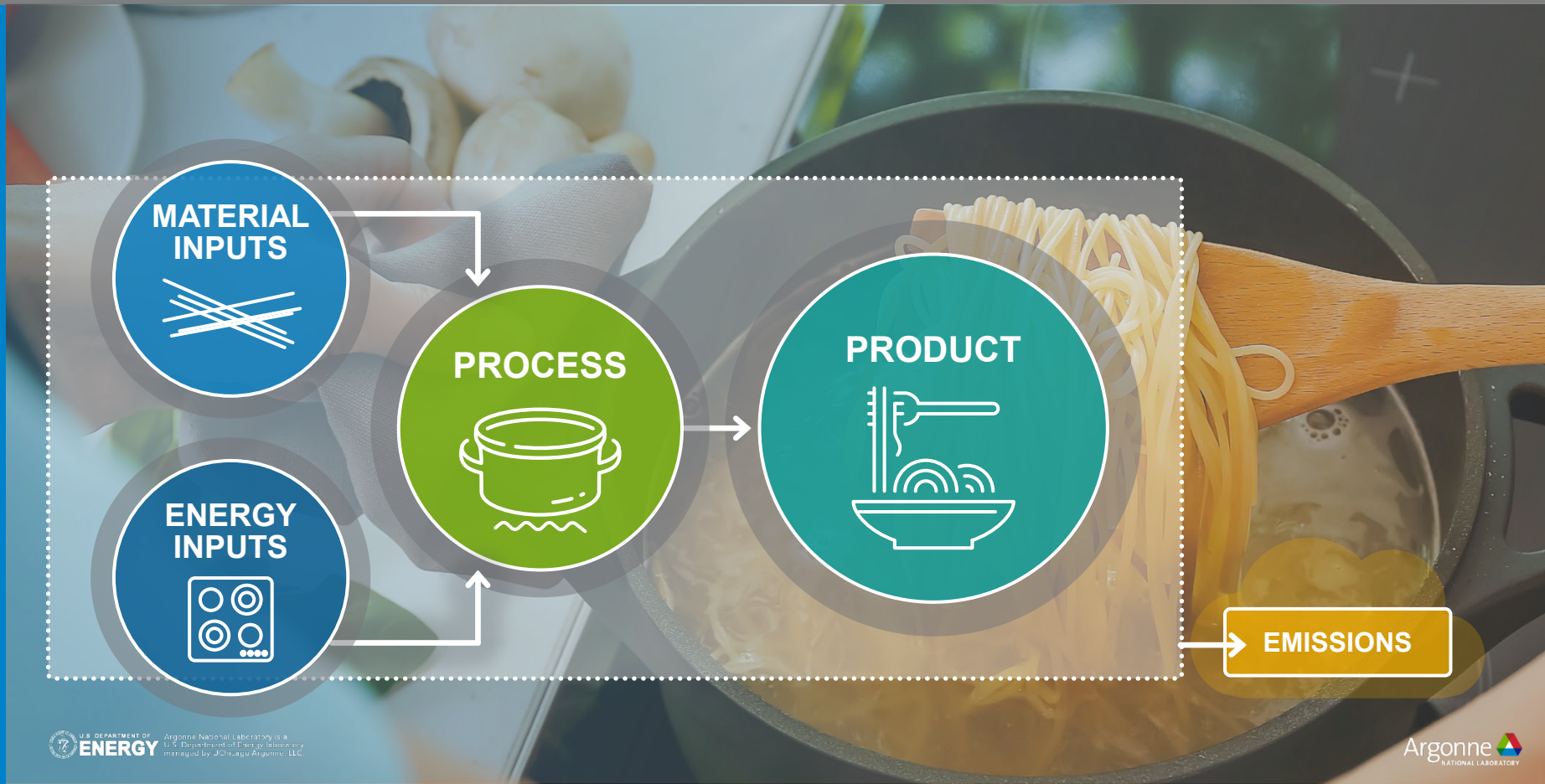
1. Define the Goal and Scope
    1. Define the functional unit
    2. Define the system (what's in and what's out)

2. Life Cycle Inventory
    1. Inputs and output identification (*measure everything flowing in and out of system)*
    2. Background data sets

3. Life Cycle Impact Assessment
    1. Impact categories (global warming potential, acidification, etc.)
    2. What's an equivalent?

4. Interpret Results
    1. Place findings in context
    2. Consider scenarios

WHAT IS LIFE CYCLE ANALYSIS?



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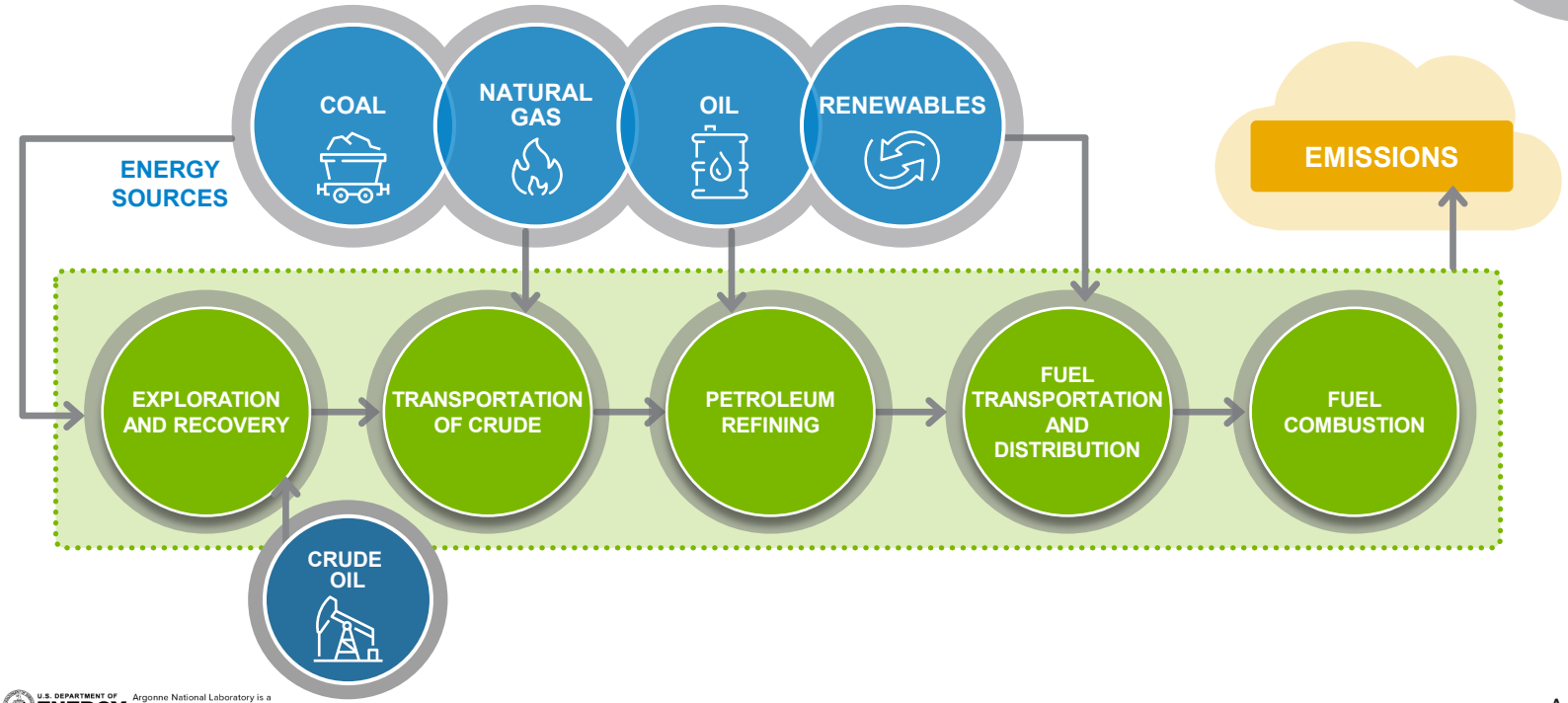
PRODUCING PETROLEUM FUELS



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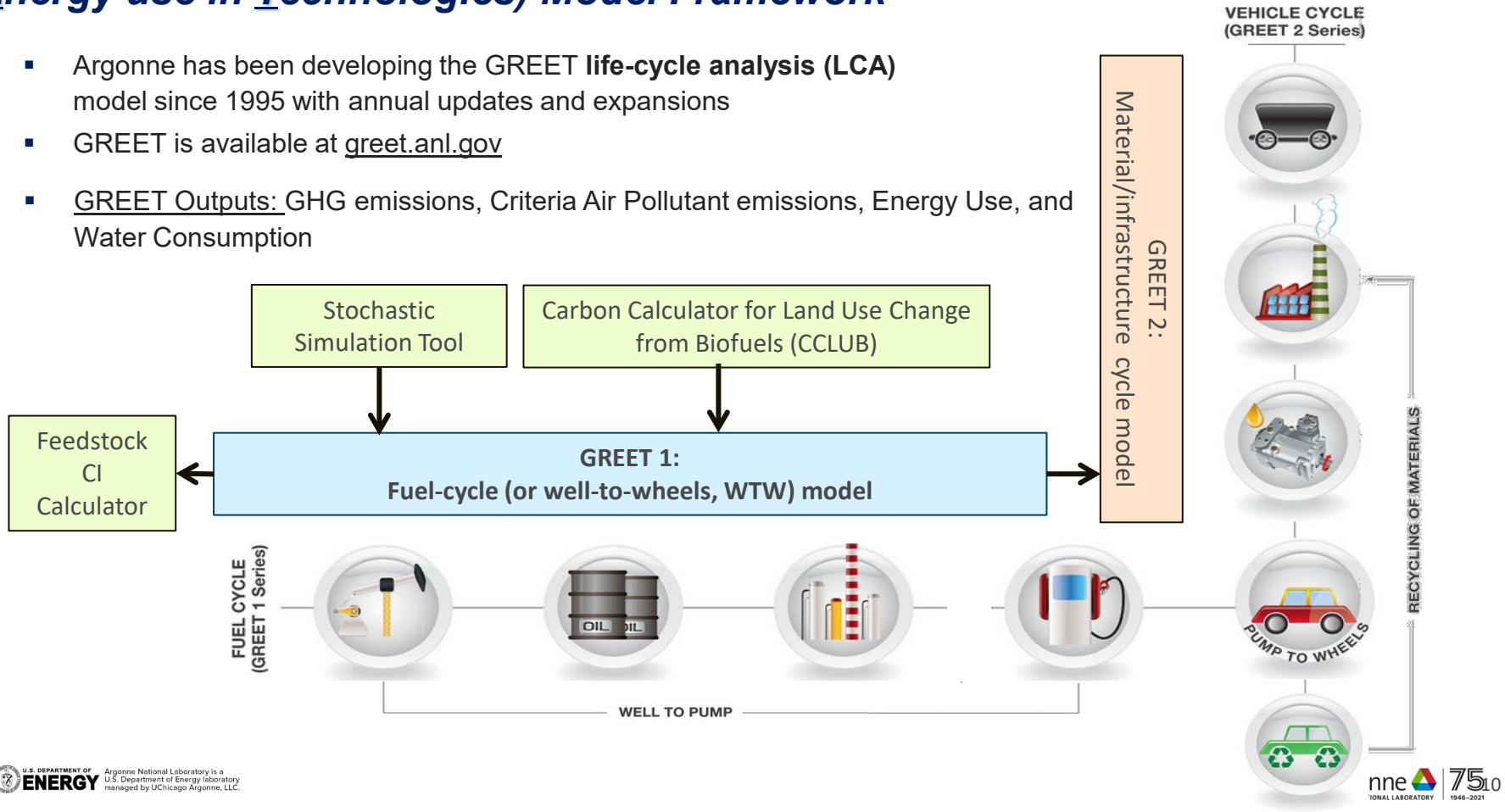
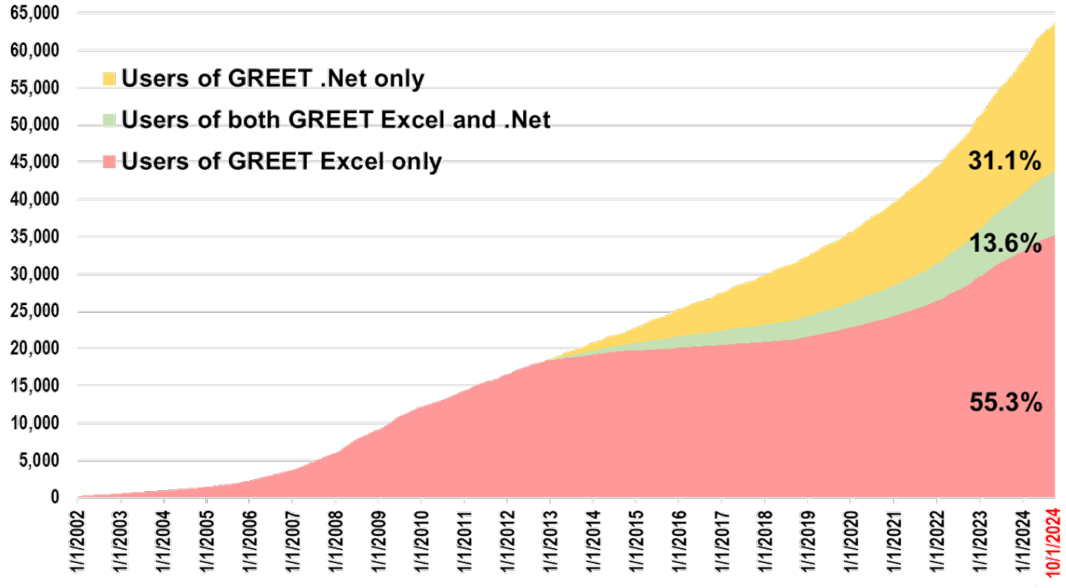
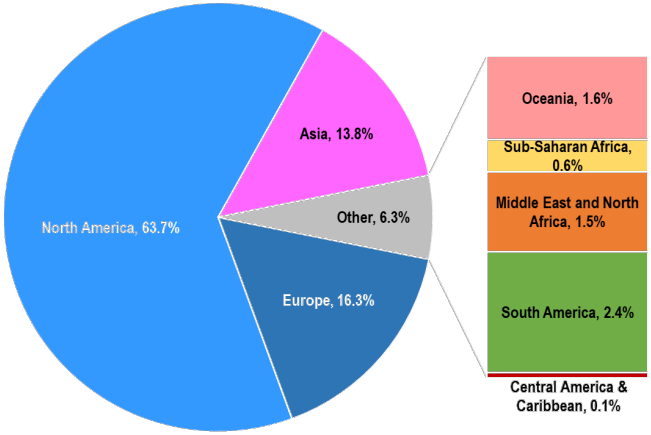
The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) Model Framework

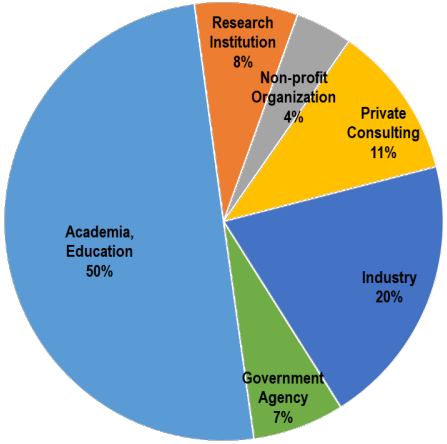
- Argonne has been developing the GREET **life-cycle analysis (LCA)** model since 1995 with annual updates and expansions
- GREET is available at greet.anl.gov
- GREET Outputs: GHG emissions, Criteria Air Pollutant emissions, Energy Use, and Water Consumption



There are >63,000 registered GREET users globally







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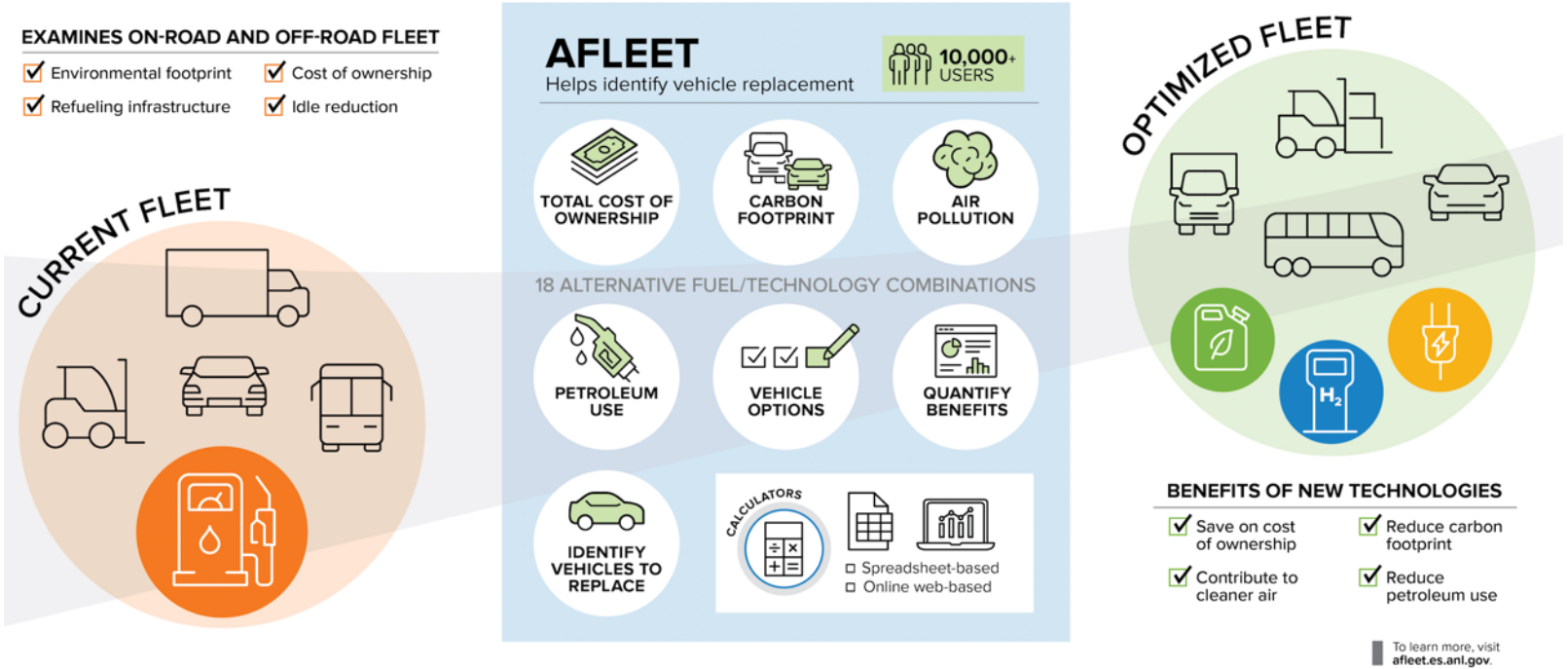
AFLEET

Alternative Fuel Life-Cycle Environmental and Economic Transportation Tool



AFLEET's suite of tools

AFLEET Tool (xlsx)

The AFLEET spreadsheet provides detailed energy, emission, and cost data for light-duty, heavy-duty, and off-road AFVs. It has the following 5 calculators depending on the user's goals:

- Simple payback
- Total cost of ownership
- Fleet footprint
- Idle reduction
- Electric vehicle charging

AFLEET Online

AFLEET Online replicates the spreadsheet's Simple Payback Calculator with a user-friendly interface and analyzes the following metrics:

- Petroleum use
- Greenhouse gas emissions
- Air pollutant emissions
- Simple payback

HDVEC

The Heavy Duty Vehicle Emissions Calculator (HDVEC) is an AFLEET-based online tool that compares NOx, PM, GHGs and funding cost-effectiveness of environmental mitigation projects for the following fuel types:

- Diesel
- Electric
- Natural gas
- Propane

ATRAVEL

The ATRAVEL Tool was developed to estimate costs, travel time, and emissions of private vehicle ownership and other travel modes based on your location and travel patterns, while also providing related travel metrics at both local and regional levels. The travel modes currently included are:

- Private vehicle
- Transit
- Ridehail

AFLEET CFI

The AFLEET Charging and Fueling Infrastructure (CFI) Emissions Tool estimates GHG and air pollutant emissions for proposals to the FHWA's CFI Discretionary Grant Program for the following fuel types:

- Electric
- Hydrogen
- Natural gas
- Propane

https://afleet.es.anl.gov/home/

Covers 18 fuel/vehicle technologies

- Conventional
- Hybrids
- Plug-in electrics
- Alternative fuels: CNG, LNG, LPG, H_2, ethanol, biodiesel, renewable diesel

Recent Enhancements

- **Charging & Fueling Infrastructure (CFI) tool**
- **EV Charger TCO (total cost of ownership) calculator**
- **EV utility electricity rate calculator**
- **AFLEET Online: Payback On- & Off-Road, TCO**
- **Coming in 2025: Ports off-road equipment calculator, Marine and Rail Payback calculators**

Examines light-, medium-, heavy-duty, and off-road vehicles:

- Petroleum use
- GHGs
- Air pollutants
- Cost of ownership

AFLEET 2023 Update webinar available on YouTube
https://www.youtube.com/watch?v=1088VsUjY5Y&t=2s

GREET SCOPE - ALL TRANSPORTATION SECTORS

Under pressure to GHG and criteria air pollutant emissions. GREET includes
- Ocean and inland water transportation
- Baseline diesel and alternative marine fuels

Marine

3% (11%)

Air

11% (13%)

Fast-growing sector with GHG reduction pressure. GREET includes
- Passenger and freight transportation
- Various sustainable aviation fuels and petroleum jet fuels

GREET

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

Road

72% (75%)

Rail

2% (1%)

Rail transportation in GREET includes
- Diesel
- Electricity
- CNG/LNG

* Share of transportation GHG emissions in the US (and globally in 2019), remaining 12% for US is from pipelines and offroad (EIA, IEA). GREET also includes LCA of industry sectors, buildings, and plastics.

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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

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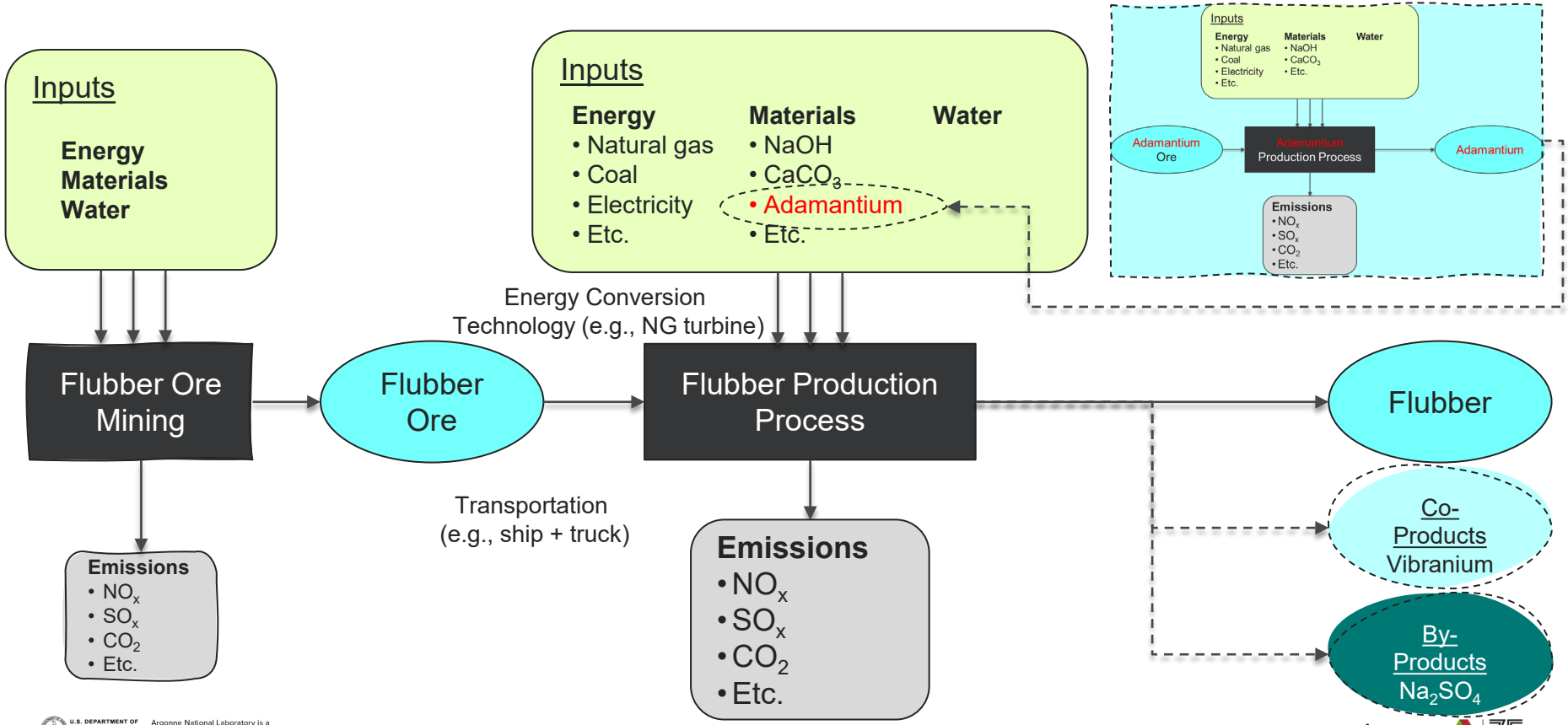
Plug-in Hybrid Electric Vehicles (PHEVs)
- Spark-ignition engines:
- Compression-ignition engines

Battery-Powered Electric Vehicles
- Various electricity generation sources

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

R&D GREET LCA for a given material



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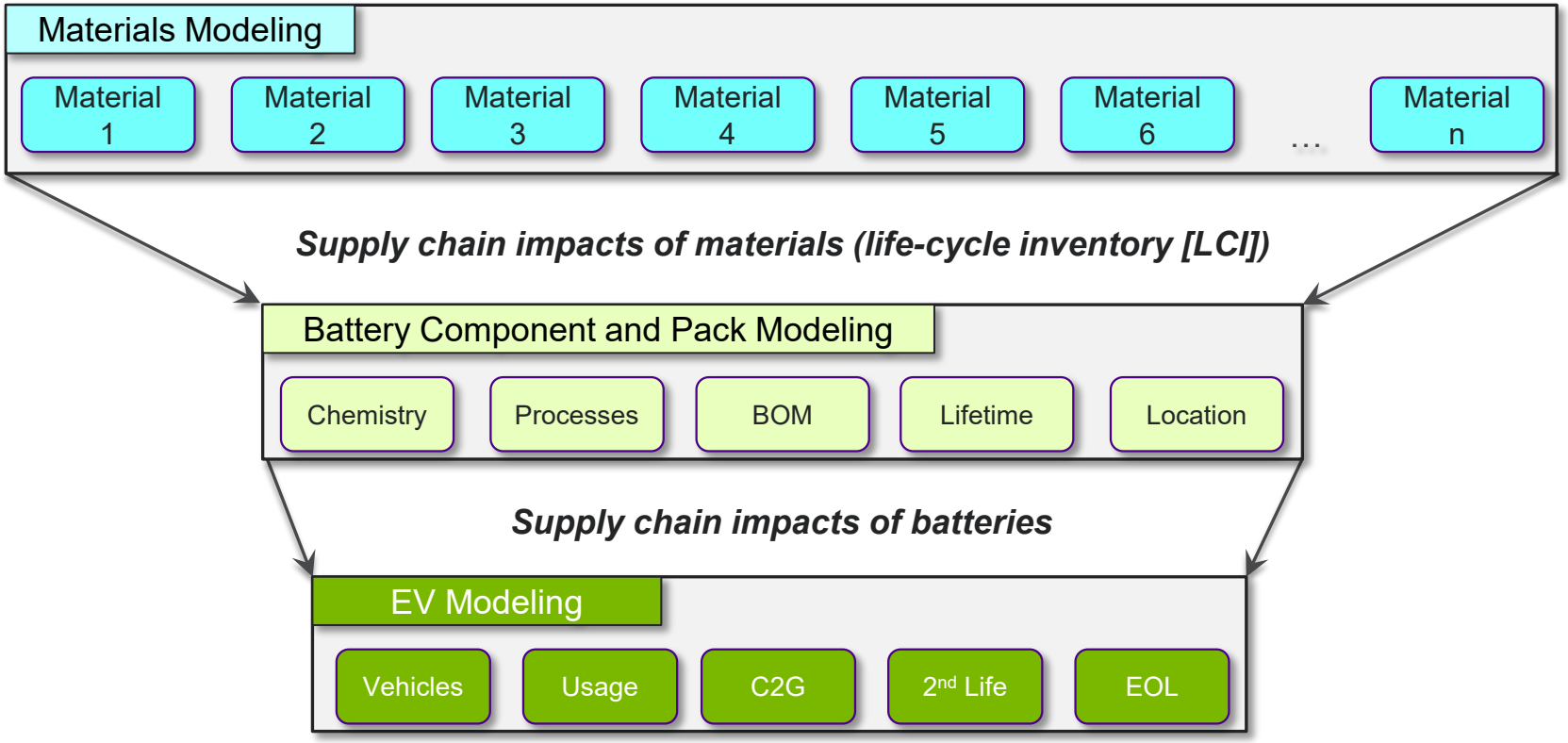
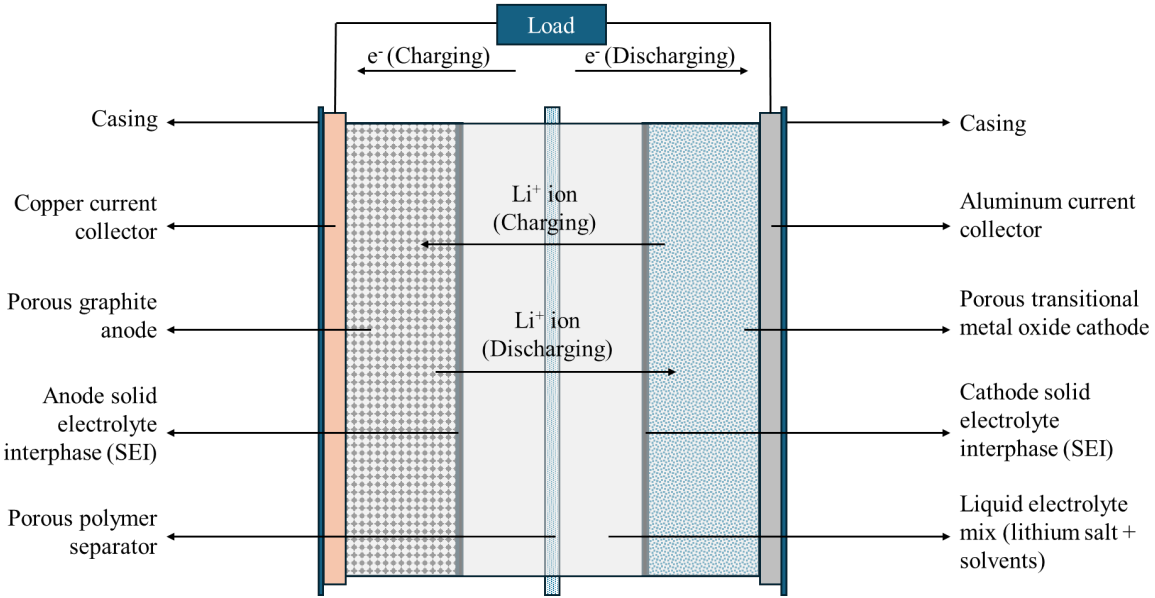
Framework of vehicle cycle analysis: example of EVs – from materials, to batteries, and to EVs



BEVs contain many critical materials both within batteries and other EV components; GREET has extensive coverage and ongoing improvement efforts

Critical materials in a lithium-ion cell



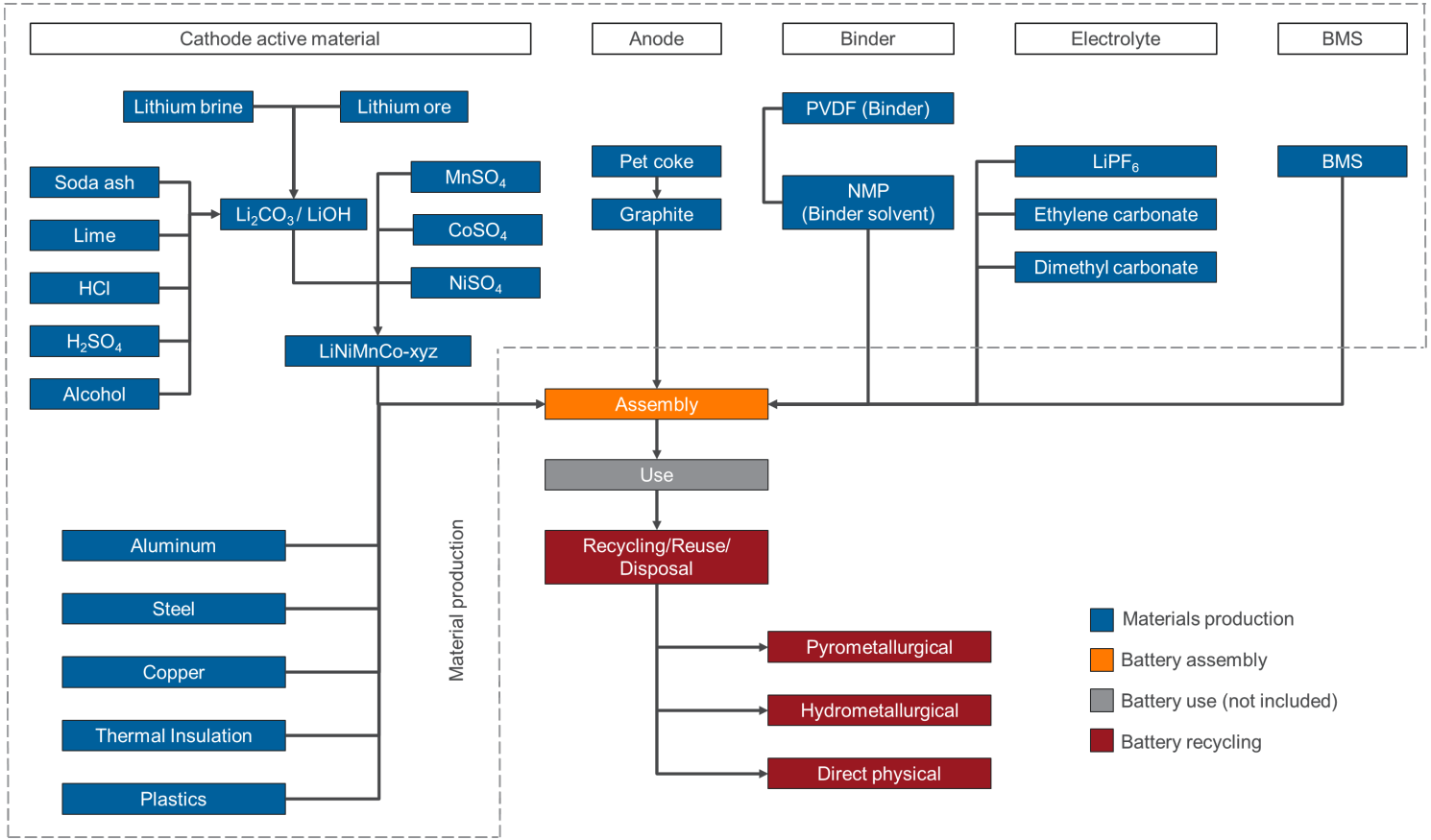
Materials Extraction and Refining

- From ore to chemical form
- Supply chain details
- Lithium, nickel, aluminum, etc.

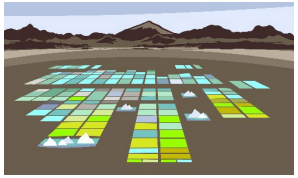
Batt. Components and Assembly

- Cathode and cathode precursors
- Anodes
- Electrolytes
- Separators
- Pack components
- Assembly operations

Battery LCA coverage in GREET



Detailed supply chain for lithium LCA



Brine recovery

Brine concentration

Brine-based Li Production

Ore-based Li Production

Ore mining

Spodumene concentration

Li_2CO_3 / LiOH production

Truck transport

Truck transport

Ocean transport

Truck transport

Ocean transport

Land 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

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Image by Shutterstock, 13167342 (ore operation photo).
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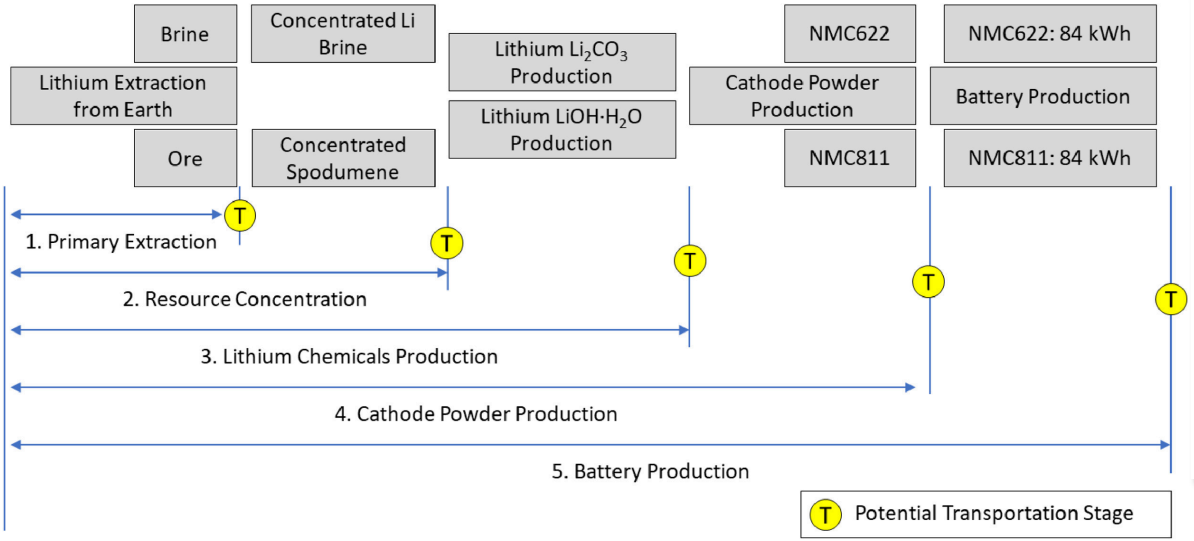
GREET investigates battery material supply chain flows

- Argonne's GREET has evaluated the impact of battery material production location on battery production burdens
- Argonne determined the impacts of lithium sourcing based on location and resource type

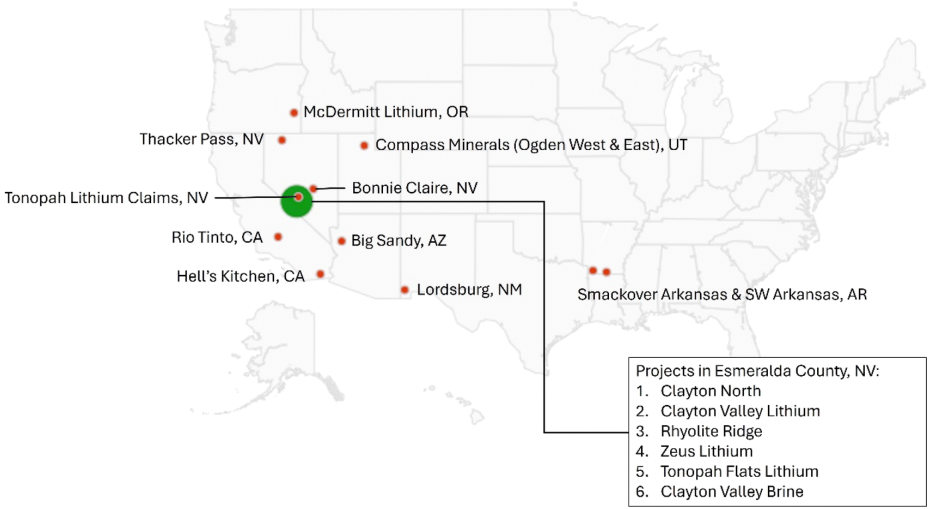


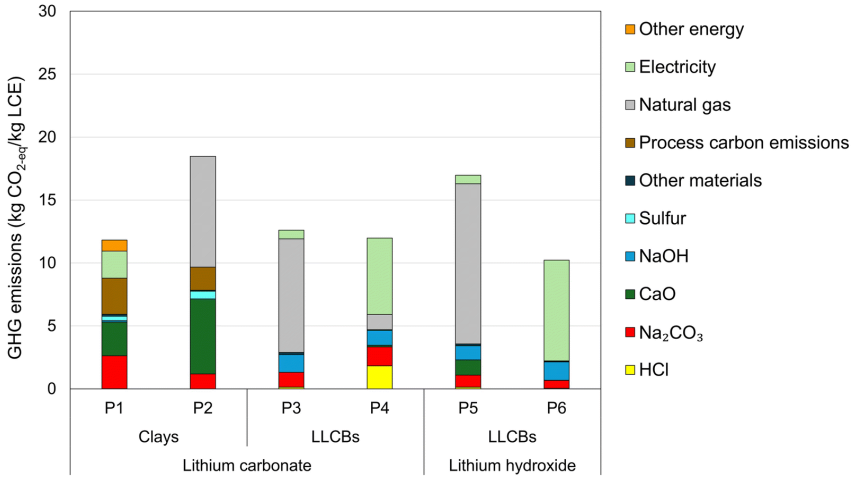
Kelly, Wang, Dai, and Winjobi (2021) (https://doi.org/10.1016/j.resconrec.2021.105762)
Winjobi, Kelly, and Dai (2022) (https://doi.org/10.1016/j.susmat.2022.e00415)
Kelly, Dai, and Wang (2019) (https://link.springer.com/article/10.1007/s11027-019-09869-2)

Consistency in LCA methodology ensures comparable and reliable evaluation of technologies, especially emerging and nascent technologies

GREET has identified material and energy hot-spots for US domestic Li-chemical production (and similarly, for other battery materials)

- Domestic Li analysis based on feasibility studies published by operating companies
- Method of bottom-up, process-level analysis allows detailed insights into main drivers





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Iyer and Kelly, 2024. https://doi.org/10.1039/D4SU00446A

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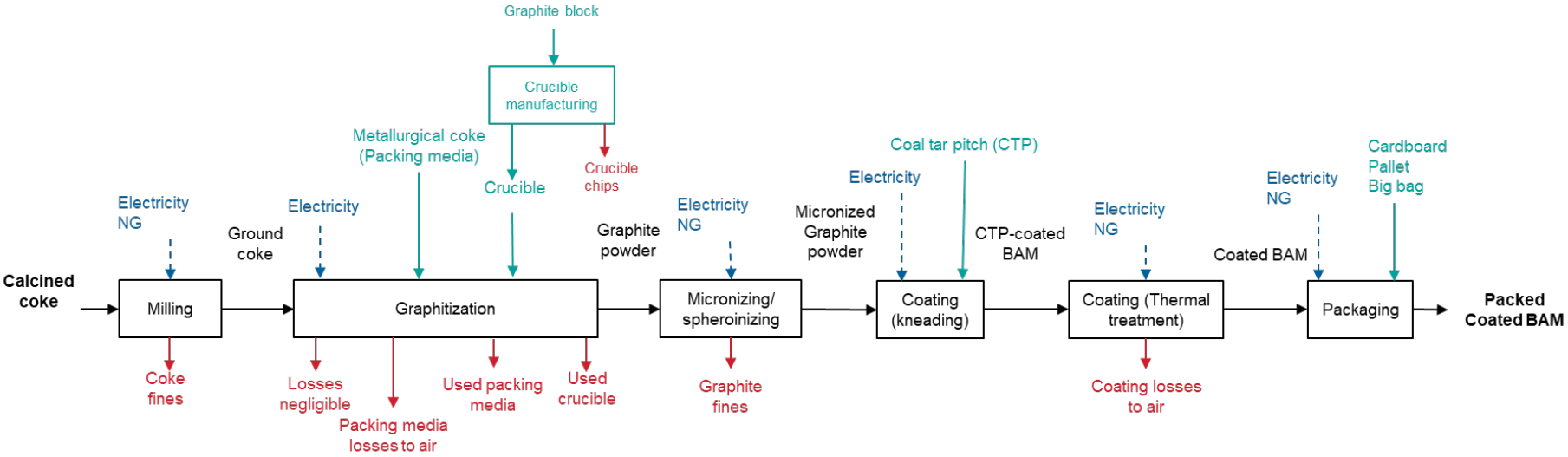
Example of GREET LCA for CMMs: Graphite

GREET considers graphite's entire production route



Production of graphite anode via Acheson powder route for lithium-ion batteries

- Detailed process modeling to account for material and energy **inputs** and **outputs** (emissions) and processing parameters for synthetic graphite production
  - *Technology route employed*: Acheson powder route
  - *Major processing parameters of concern*: Crucible lifetime; Micronizing yield

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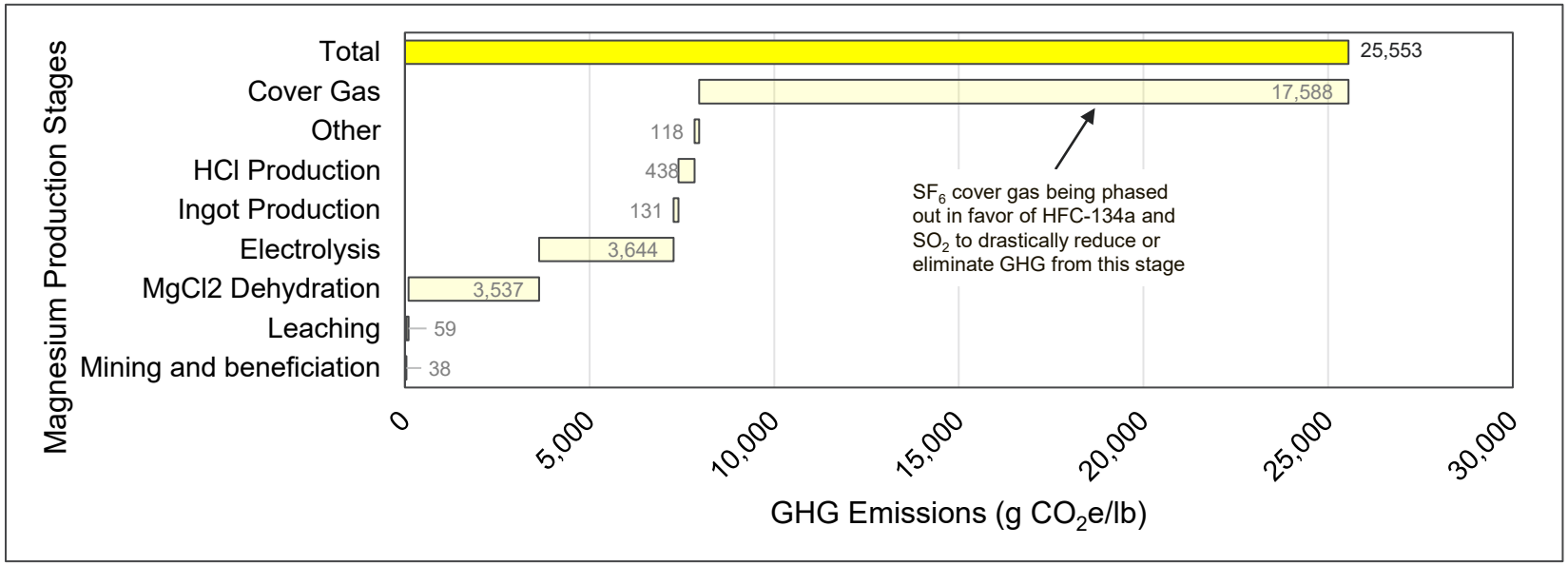
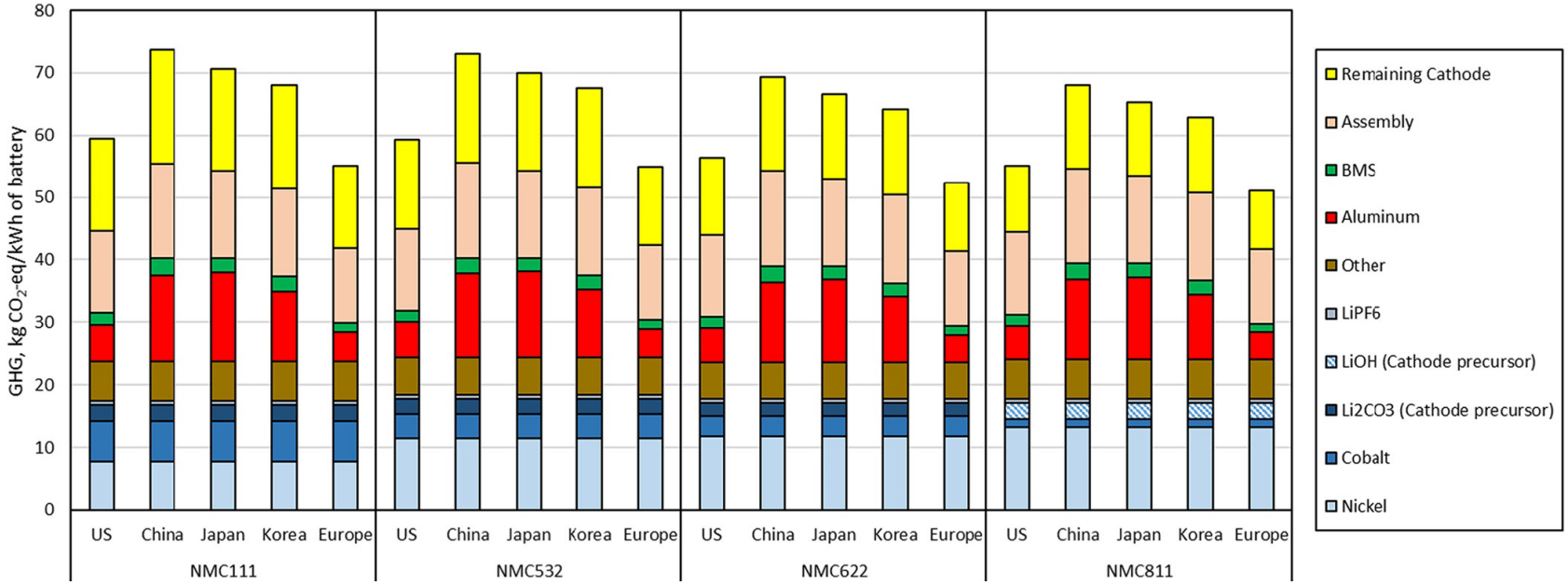
GREET's process-level data allow deep investigation

Stage-by-stage analysis of GHG intensity of electrolytic magnesium production (hot-spot identification)

- ✓ GREET 2 facilitates such identification for critical materials, as well as vehicle, building, and construction materials across their supply chains



Global supply chains of current battery production impact LCA results



LIB life-cycle GHG emissions by chemistries and production regions

Winjobi, Kelly, and Dai (2022) (https://doi.org/10.1016/j.susmat.2022.e00415)

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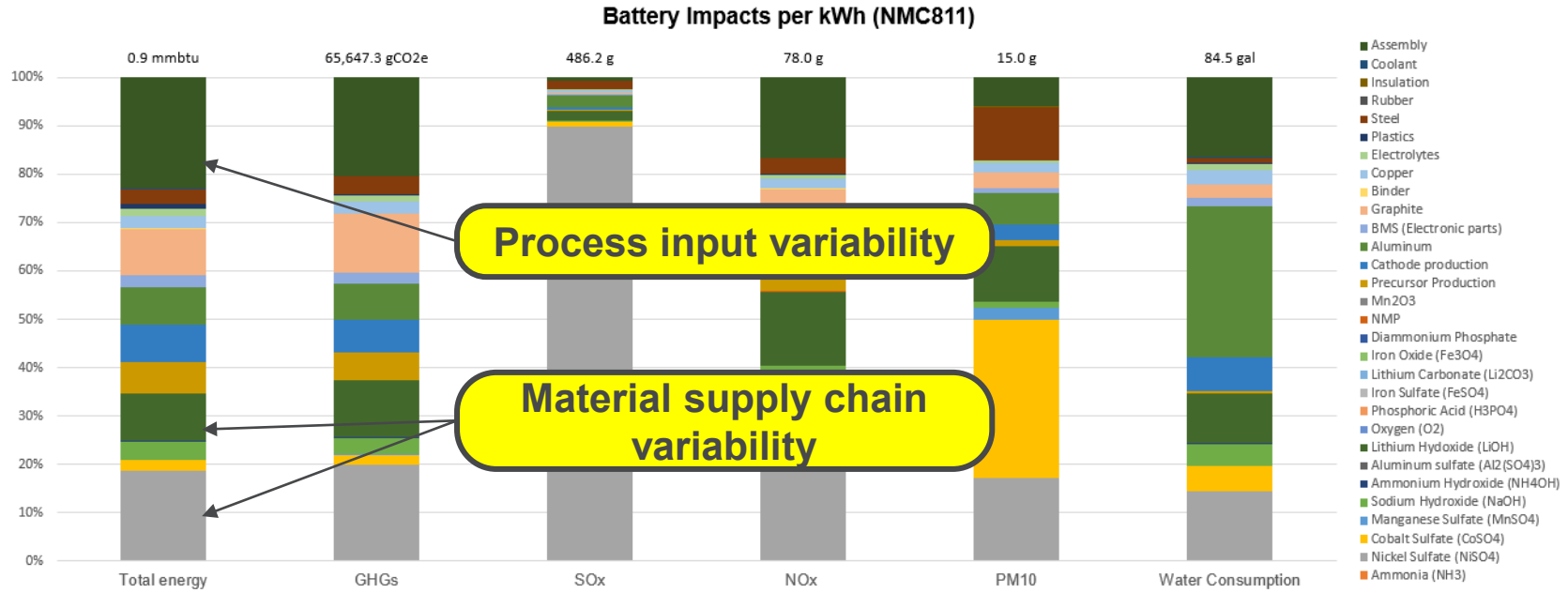
R&D GREET Battery Module

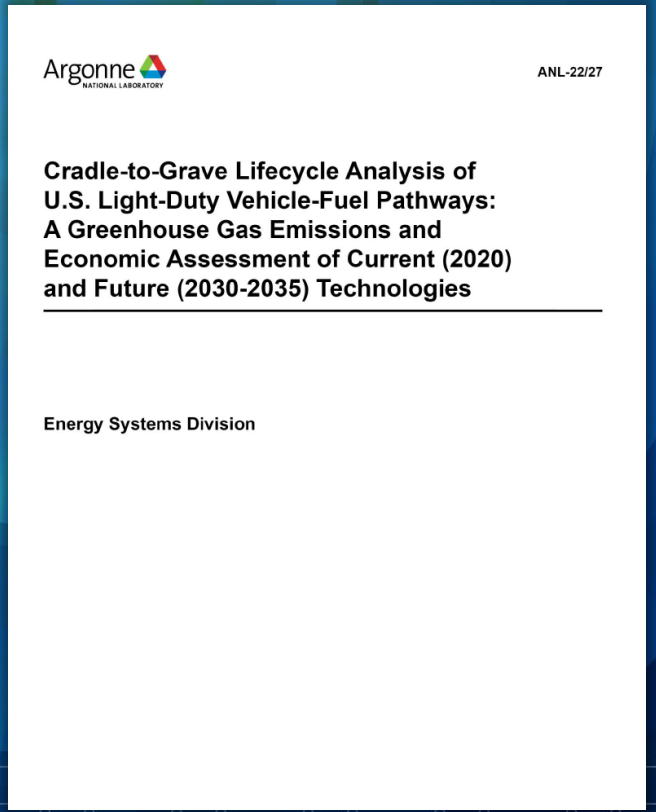
Developed with feedback from industry and university stakeholders

- User-friendly tool to support rapid battery LCA studies
- Parametric variability facilitates deep insights



Cradle-to-Grave (C2G) LCA of light-duty vehicles by considering potential future vehicle/fuel improvements:

a joint effort between DOE and industries including EPRI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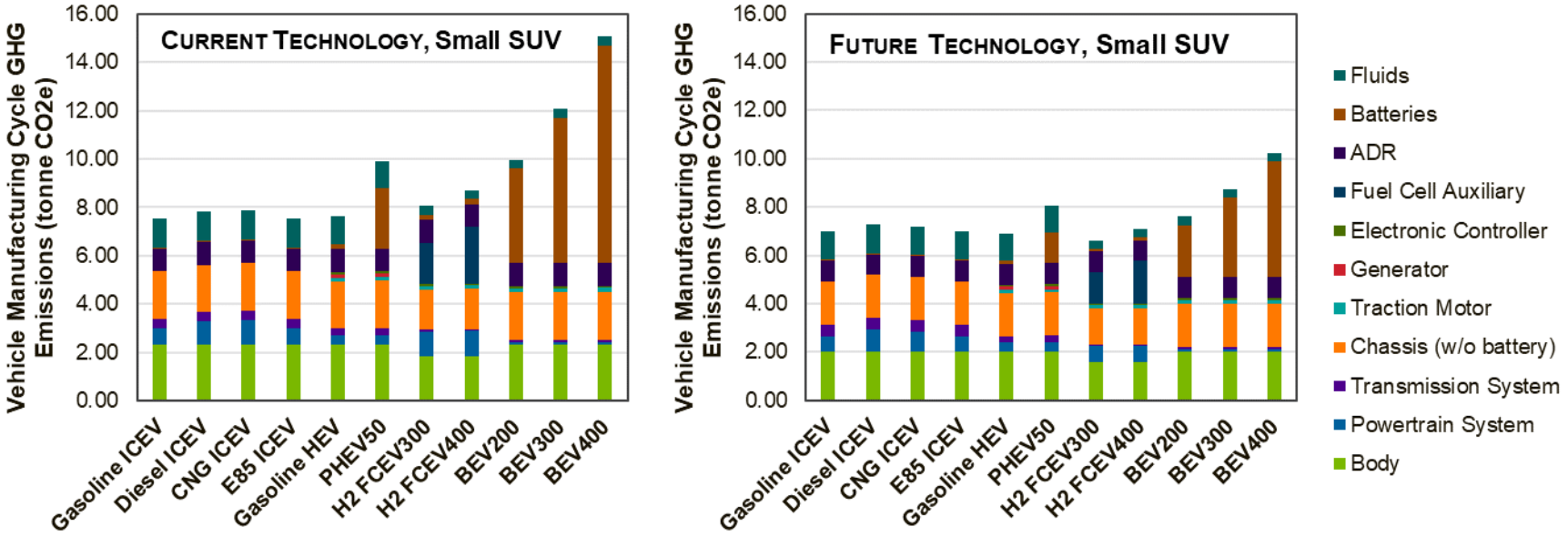
ANL-22/27

Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2020) and Future (2030-2035) Technologies

Energy Systems Division

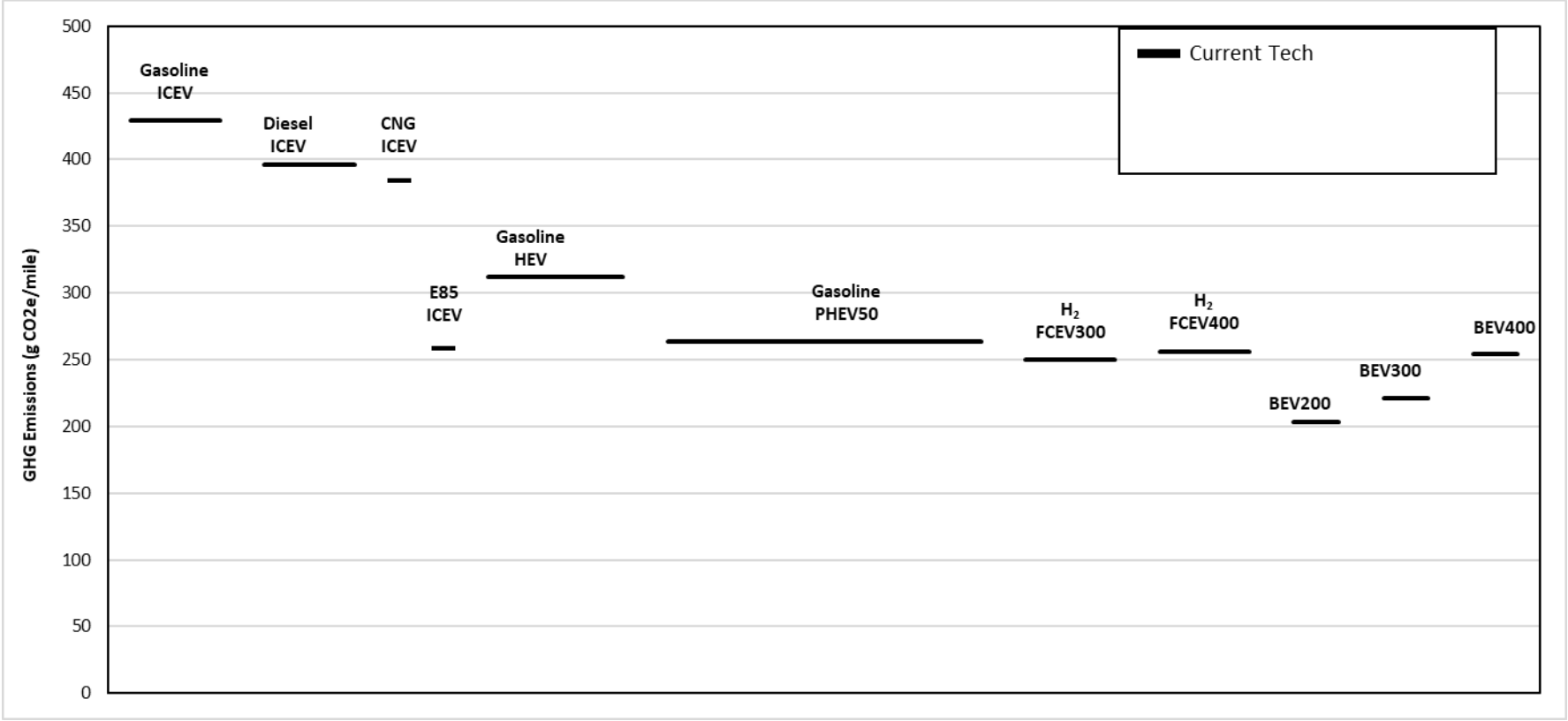
Zooming in on the Vehicle Cycle

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



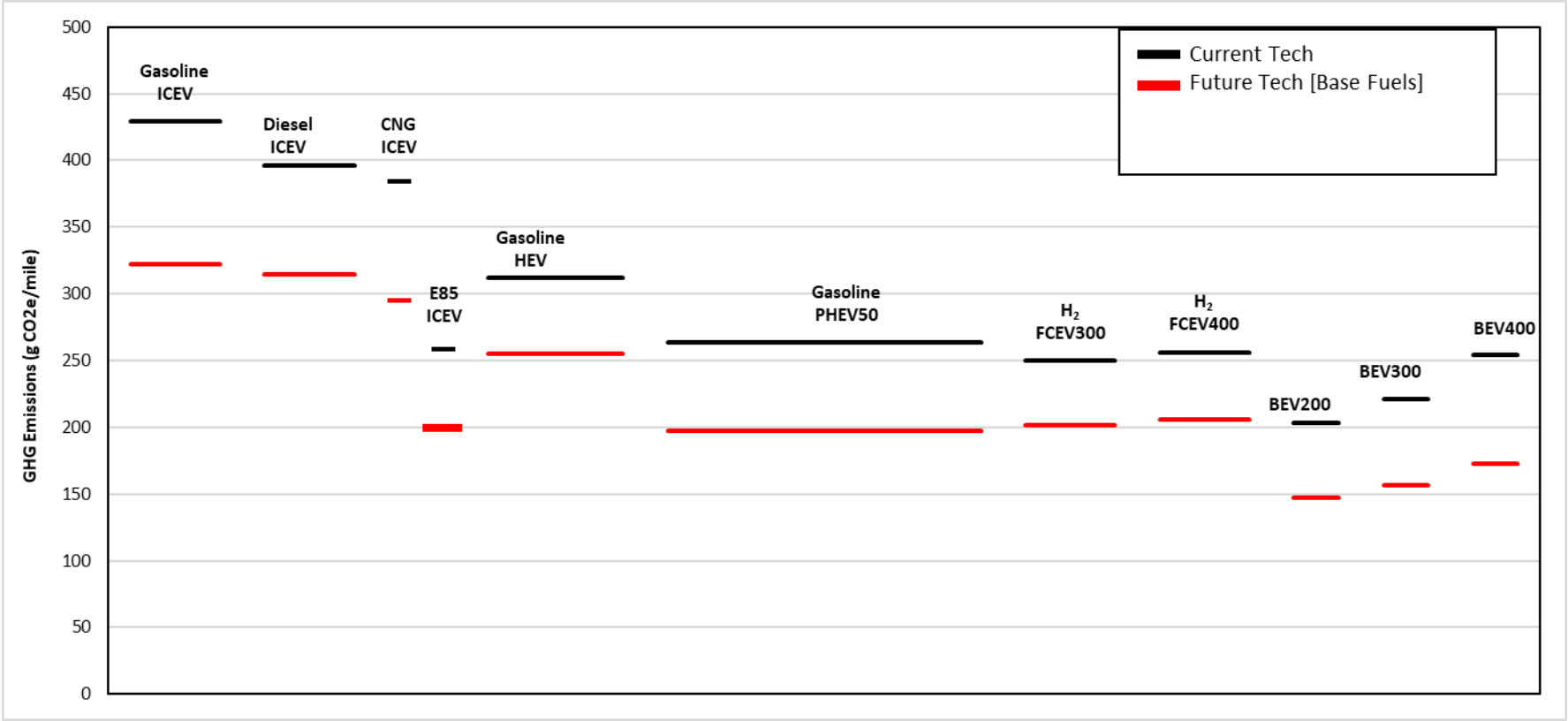
Results: GHG emissions

What is the current picture for this analysis?



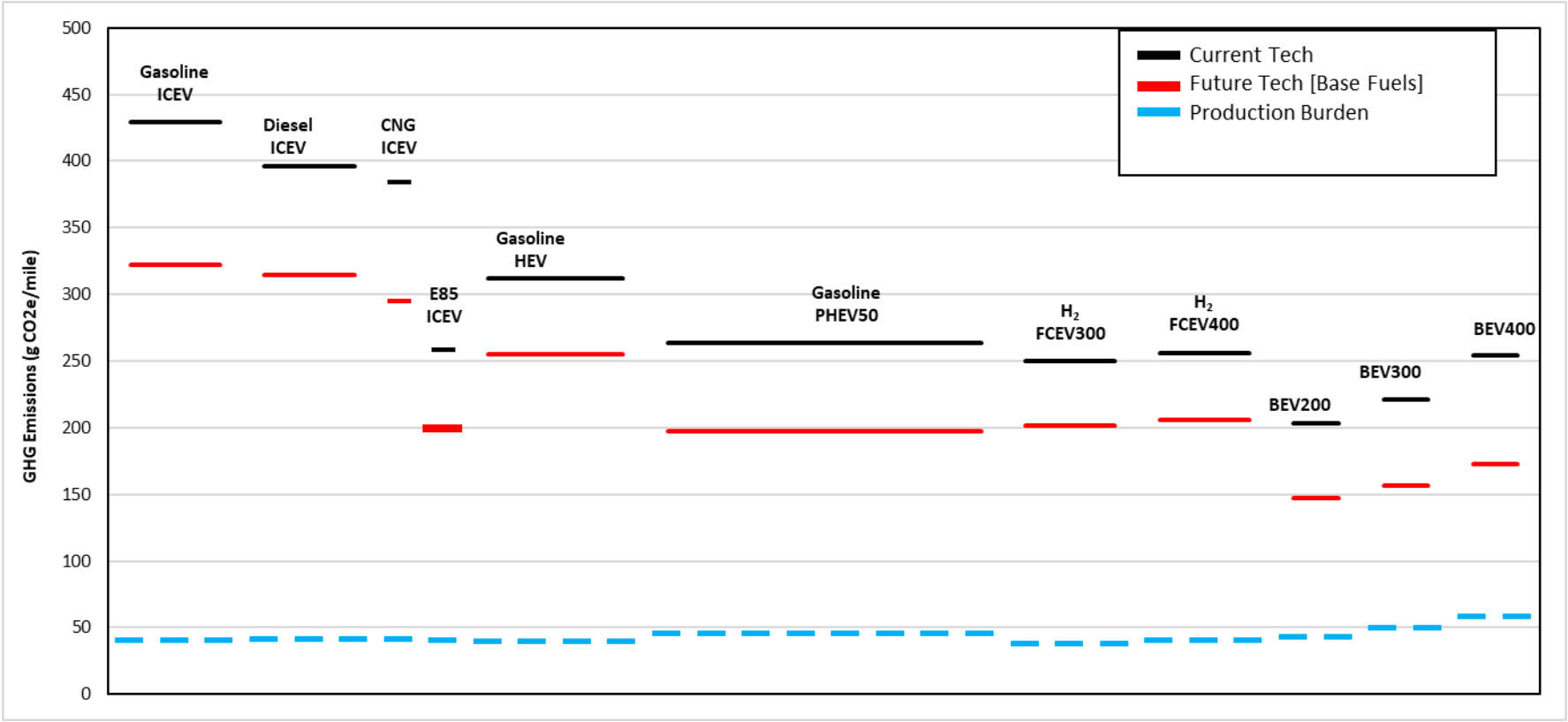
Results: GHG emissions

How can technology improvements in powertrains reduce GHG emissions?



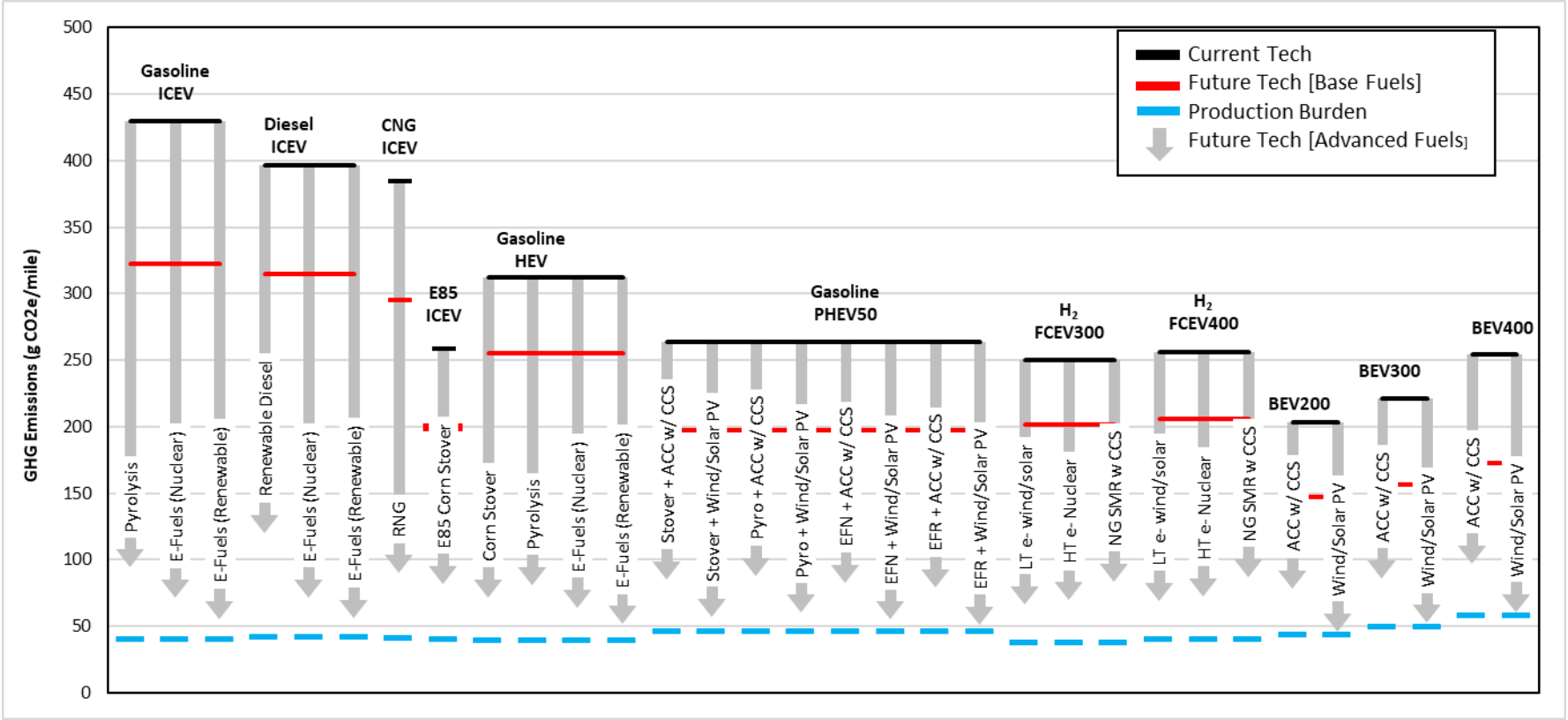
Results: GHG emissions

What component of those future emissions are associated with the vehicle cycle?



Results: GHG emissions

Finally, how can we decarbonize through different energy pathways?



Questions?

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