

March 3, 2025

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# Introducing ICEVs, HEVs, PHEVs, EVs, and FCVs in R&D GREET<sup>®</sup>

2:00-3:00 p.m. CT

## **Instructors**

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*Jarod Kelly, Taemin Kim*



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# On-Road Vehicles in R&D GREET



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# Light-duty vehicles (LDVs) in R&D GREET

## Types of LDV Technologies in R&D GREET

Internal combustion engine vehicle (ICEV)

Conventional spark-ignition (SI)

Spark-ignition direct-injection (SIDI)

Compression-ignition direct-injection (CIDI)

Hybrid electric vehicle (HEV)

Plug-in hybrid electric vehicle (PHEV)

Battery electric vehicle (BEV)

Fuel-cell electric vehicle (FCV)



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# Types of powertrains in R&D GREET

## ICEV

Internal combustion engine vehicle

## HEV (Hybrid Electric Vehicle)

A vehicle with an internal combustion engine and a battery; this vehicle cannot run on battery power alone

## PHEV (Plug-in Hybrid Electric Vehicle)

A vehicle with an internal combustion engine and a battery; this vehicle can run on battery power alone

## BEV (Battery Electric Vehicle)

A vehicle that runs solely on battery power

## FCV (Fuel Cell Vehicle)

A vehicle that uses a fuel cell to power its electric motor; this vehicle runs on oxygen (from air) and compressed hydrogen



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# LDVs' fuel economy and emission factors in R&D GREET

## Argonne's Autonomie Model

A detailed vehicle simulation model used to estimate energy-consumption using key parametric assumptions including vehicle weights by components

## EPA MOVES Model

A model used to calculate criteria air pollutant (CAP) emission factors in R&D GREET except for CO<sub>2</sub> (VOC, CO, NO<sub>x</sub>, SO<sub>x</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub>)

## CO<sub>2</sub> Emissions in R&D GREET: Carbon Balance

CO<sub>2</sub> emissions are calculated using the carbon content of fuel and carbon containing emissions (e.g., VOC and CO)



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# Light-duty vehicles (LDVs) in R&D GREET



## Types of LDVs in R&D GREET

Passenger cars, sports utility vehicles (LDT1), and pickup trucks (LDT2)

## Types of Fuels for LDVs in R&D GREET

Gasoline (E10), diesel, biofuels, different forms of natural gas (NG), electricity, and hydrogen

## Time-series Data for Each LDV

LDV fuel economies can be modified in the “Car\_TS,” “LDT1\_TS,” and “LDT2\_TS” tabs

## WTP and WTW Results for LDVs in R&D GREET

Summary results can be found in the “Results” tab in R&D GREET 1



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# Medium and heavy-duty vehicles (MHDVs) in R&D GREET

## Types of MHDVs in R&D GREET

Combination trucks (long-haul and short-haul), different classes of vocational vehicles, heavy-duty pickup trucks and vans, refuse trucks, and different types of buses

## Types of MHDV Technologies in R&D GREET

Spark-ignition engine vehicles, CIDI engine vehicles, HEVs, BEVs, and FCVs

## Types of Fuels for MHDVs in R&D GREET

Diesel, biofuels, CNG, LNG, electricity, and hydrogen

## Results for MHDVs in R&D GREET

Results will be located on the “HDV\_WTW” and “HDV\_TS” tabs



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# Types of medium and heavy-duty vehicles (MHDVs)

## Combination Long-haul Trucks

A truck tractor with one or more trailers, drives more than 200 miles per day, and has a sleeper cab  
*Class 8b: > 60,000 lb gross vehicle weight rating (GVWR)*

## Combination Short-haul Trucks

A truck tractor with one or more trailers, drives 200 miles or less per day, and does not have a sleeper cab  
*Class 8b: > 60,000 lb GVWR*

## Heavy Heavy-duty Vocational Vehicles

A commercial vehicle typically used in construction  
*Class 8: > 33,000 lb GVWR*

## Medium Heavy-duty Vocational Vehicles

A commercial vehicle typically used for regional deliveries  
*Class 6-7: 19,500-33,000 lb GVWR*

## Light Heavy-duty Vocational Vehicles

A commercial vehicle typically used for regional deliveries  
*Class 2b-5: 8,500-19,500 lb GVWR*

## Heavy-duty Pickup Trucks and Vans

Trucks and vans designed for commercial use  
*Class 2b-3: 8,500-14,000 lb GVWR*

## Refuse Trucks

A truck designed to collect garbage  
*Class 8a: 33,000-60,000 lb GVWR*

## School/transit buses/inter-city Buses

A bus designed to transport individuals to school, within a city, and between a city respectively



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# LCA of On-Road Vehicles in R&D GREET

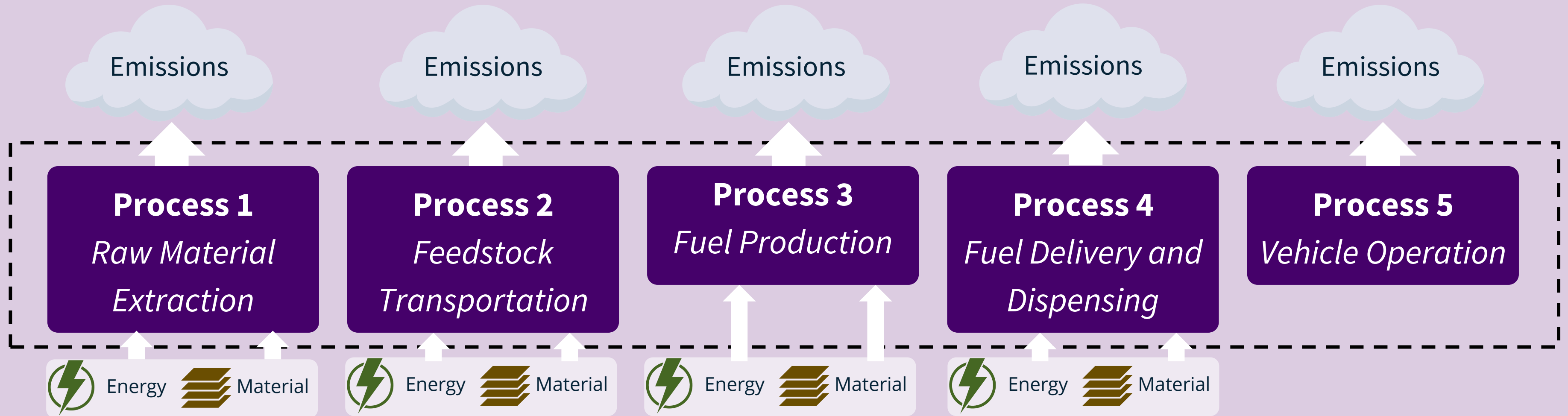


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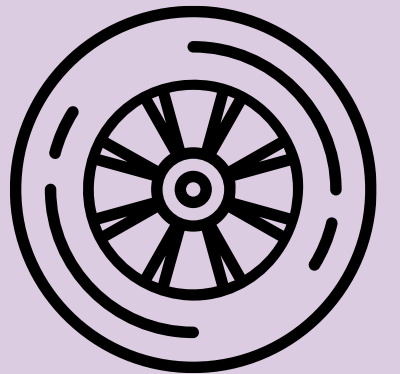
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# Fuel cycle in R&D GREET: *well-to-wheels analysis*

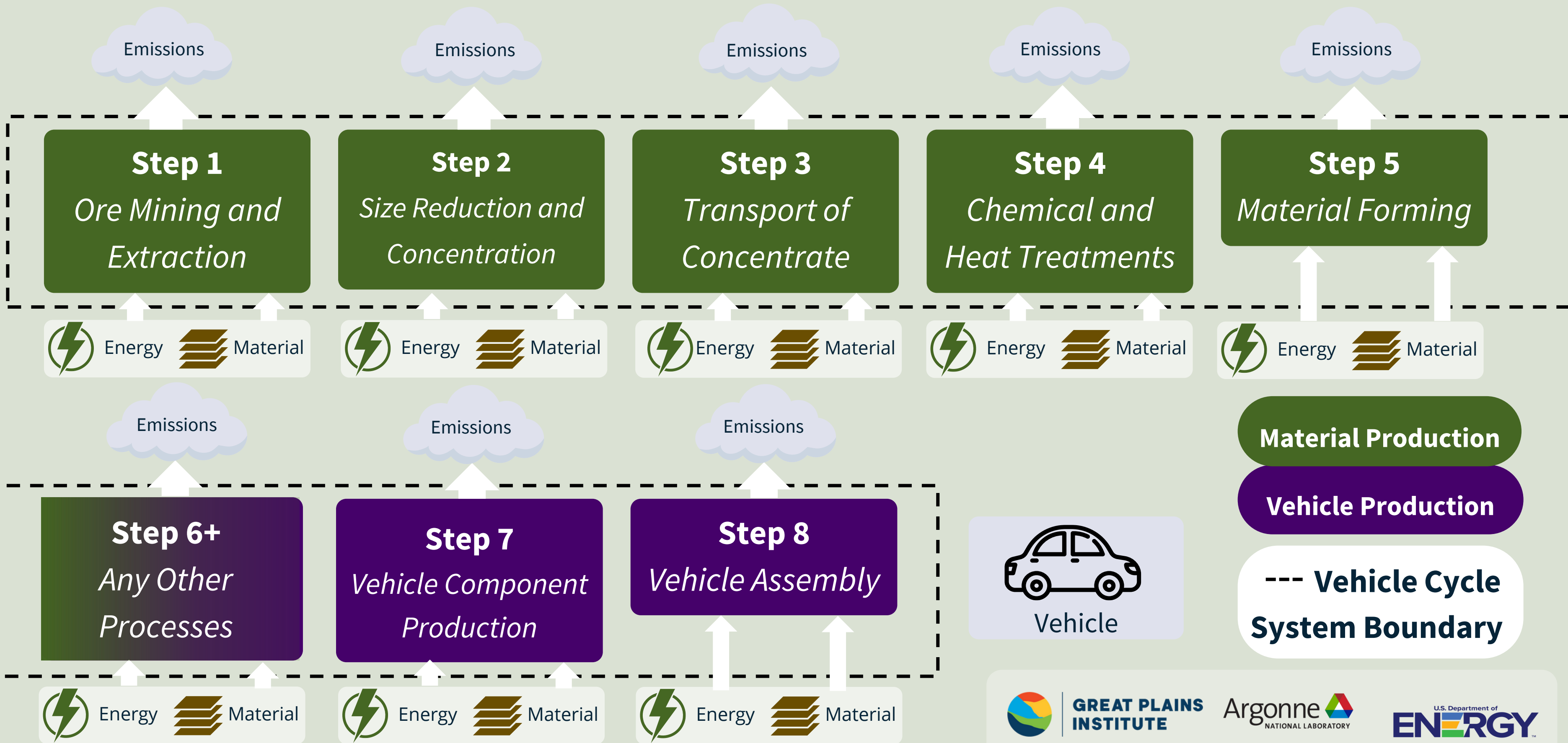


**LDVs and MHDVs**  
Fuel Economy: *Argonne's Autonomie*  
CAP Emissions: *EPA Moves*

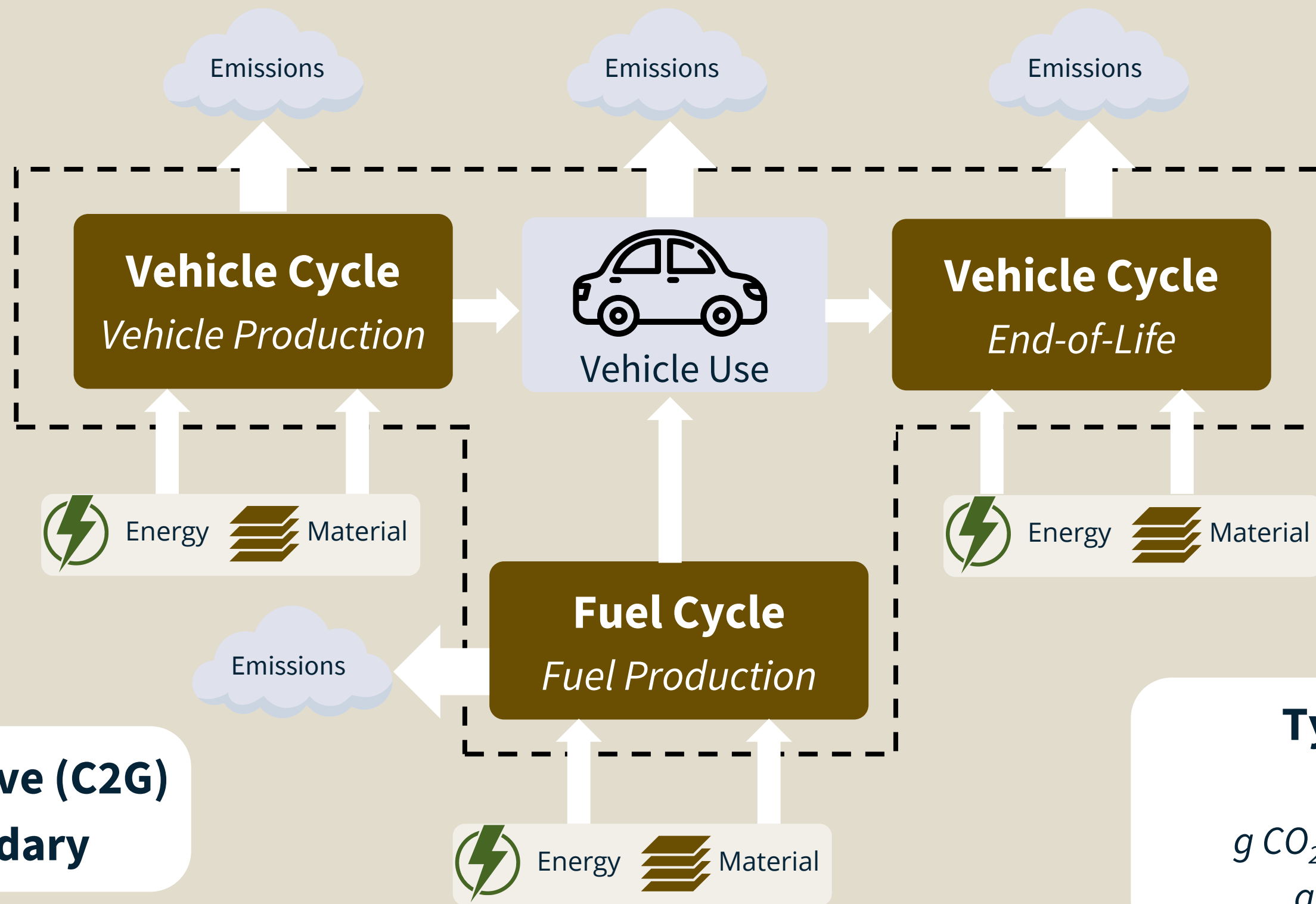
----- **Well-to-Wheels (WTW) System Boundary**



# Vehicle cycle in R&D GREET: *material and vehicle production*



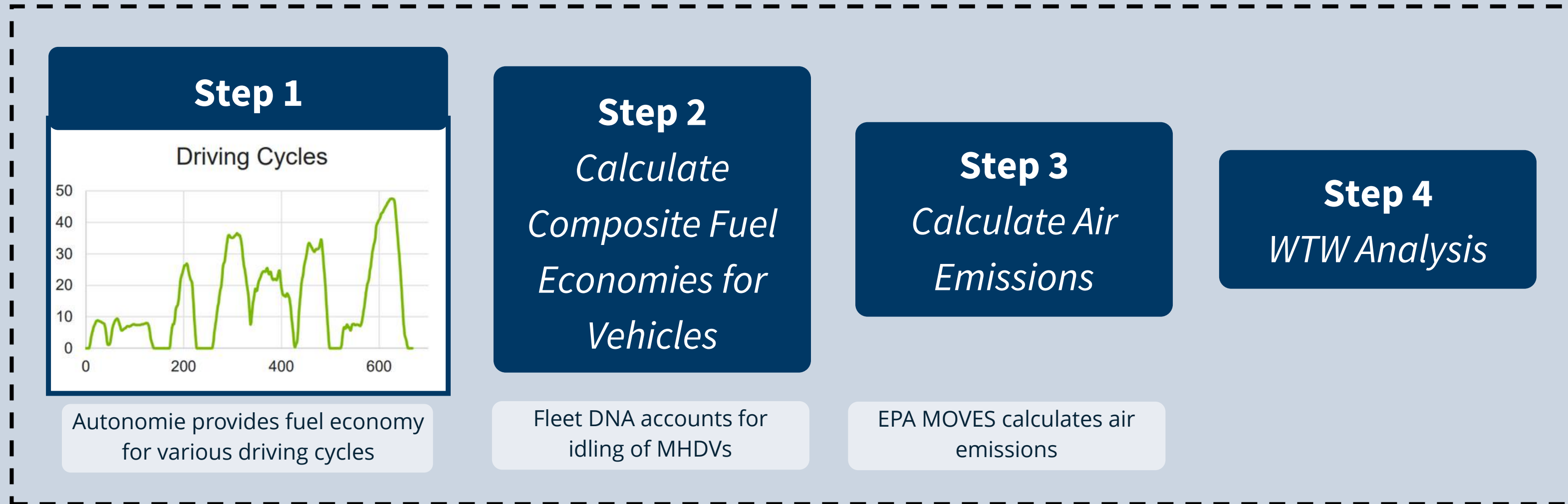
# C2G life cycle in R&D GREET: *cradle-to-grave analysis*



--- Cradle-to-Grave (C2G)  
System Boundary

**Typical Units**  
*g CO<sub>2</sub>e/mile*  
*g CO<sub>2</sub>e/passenger-mile*  
*gCO<sub>2</sub>e/ton-mile*

# Life cycle of on-road vehicles in R&D GREET



[- Argonne Autonomie Model](#)



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# Fuel Modeling for On-Road Vehicles in R&D GREET

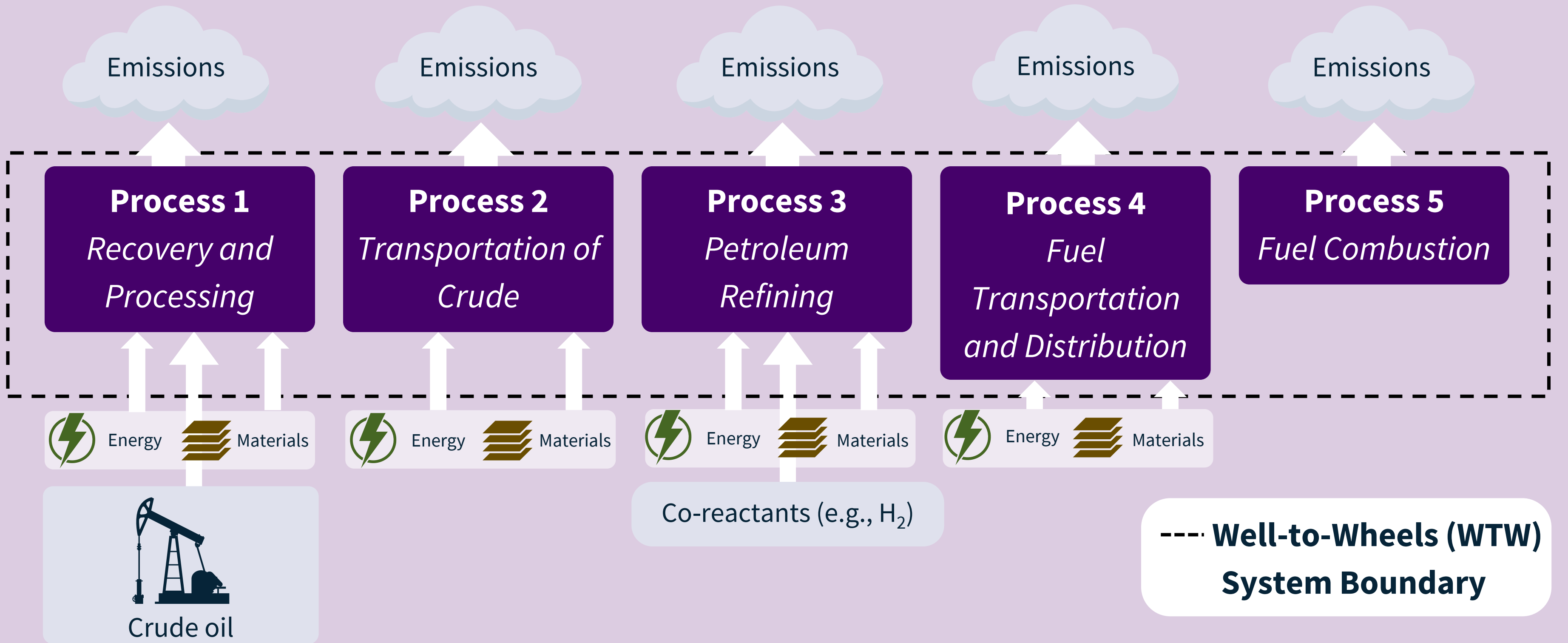


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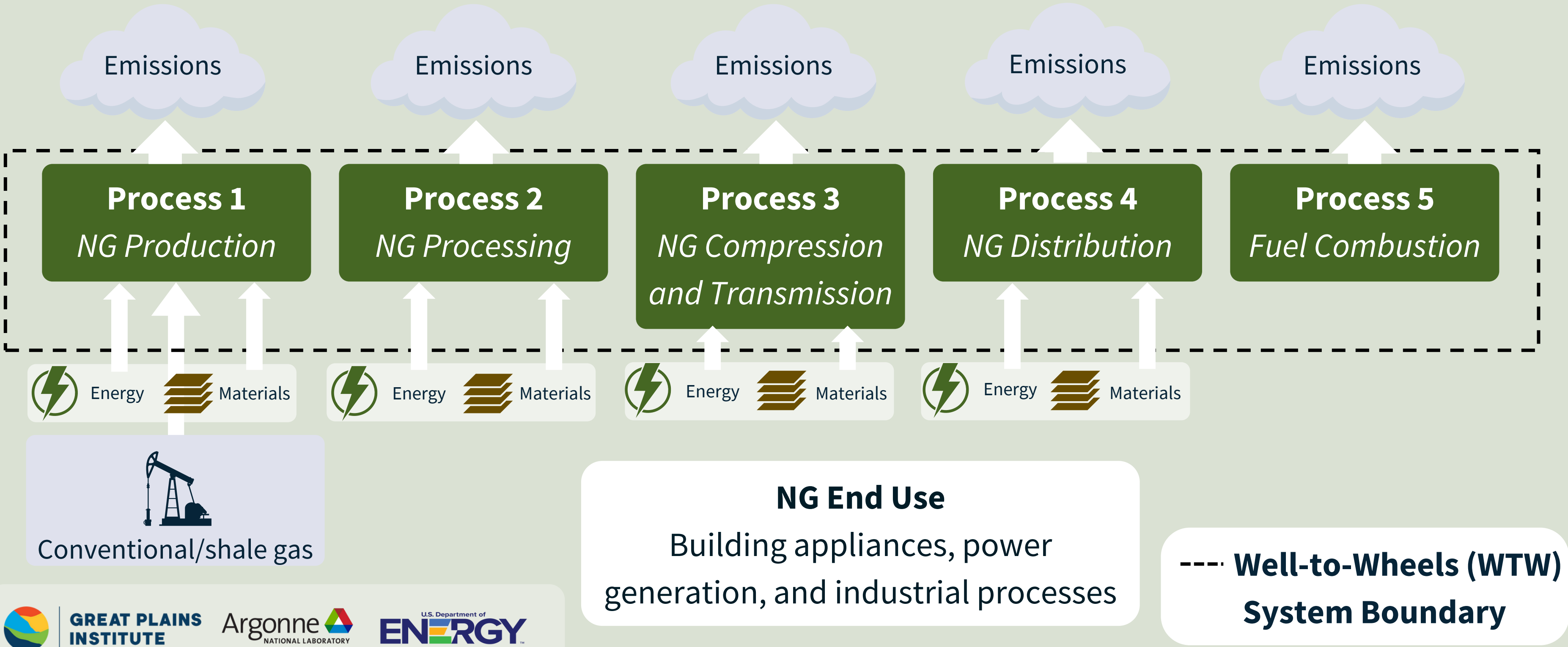
# Life cycle of fuels from petroleum in R&D GREET



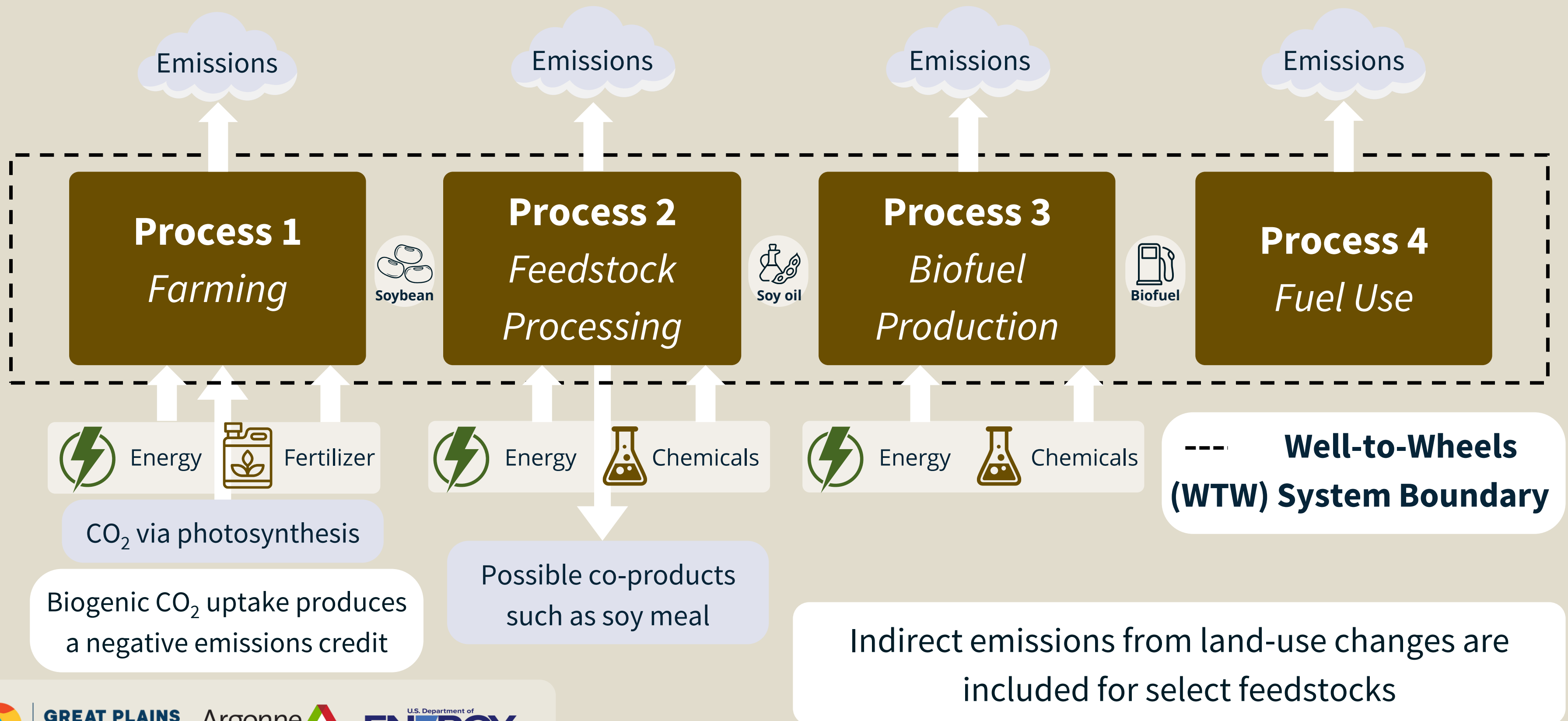
All direct and upstream activities are included

# Life cycle of natural gas in R&D GREET

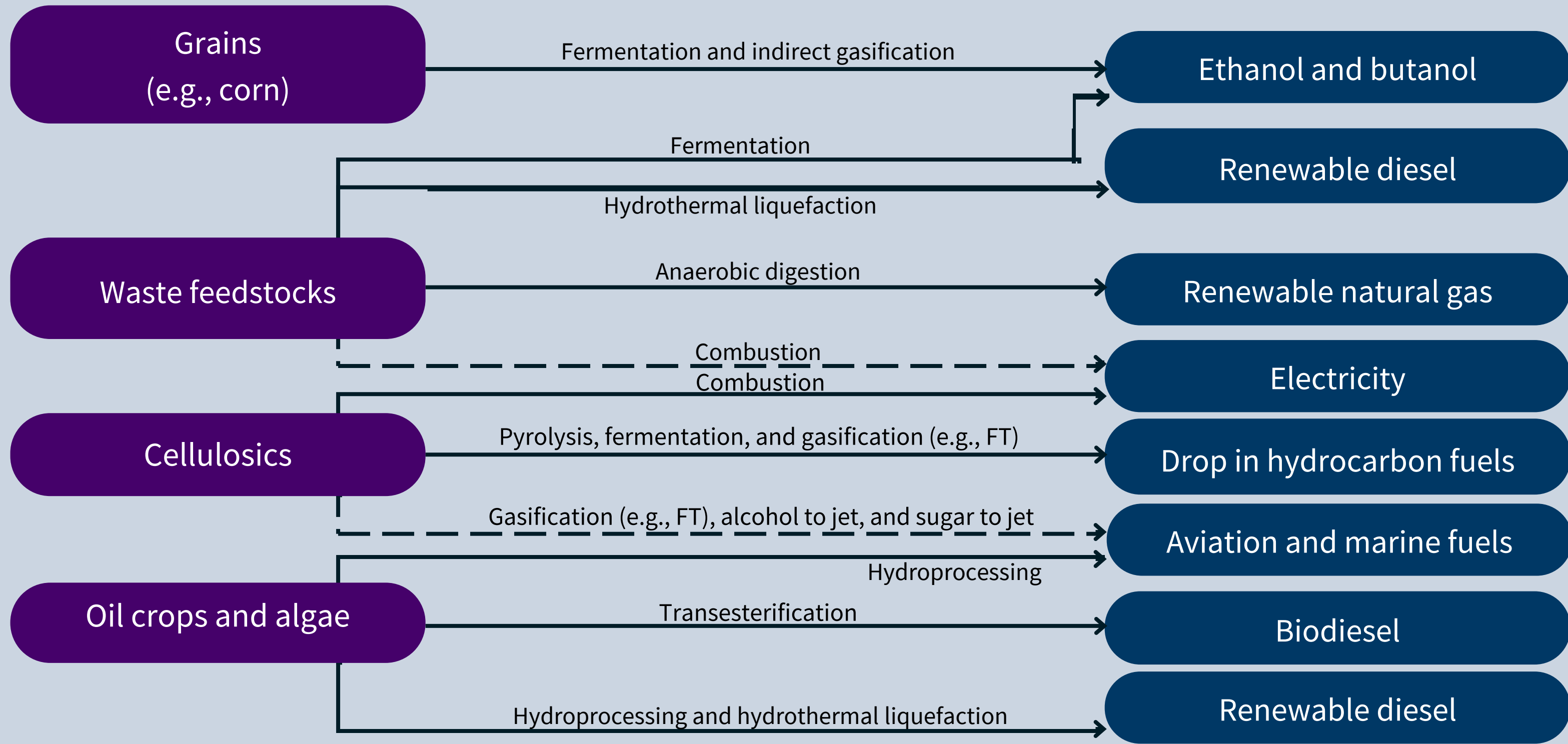
R&D GREET addresses the natural gas supply chain and various end uses



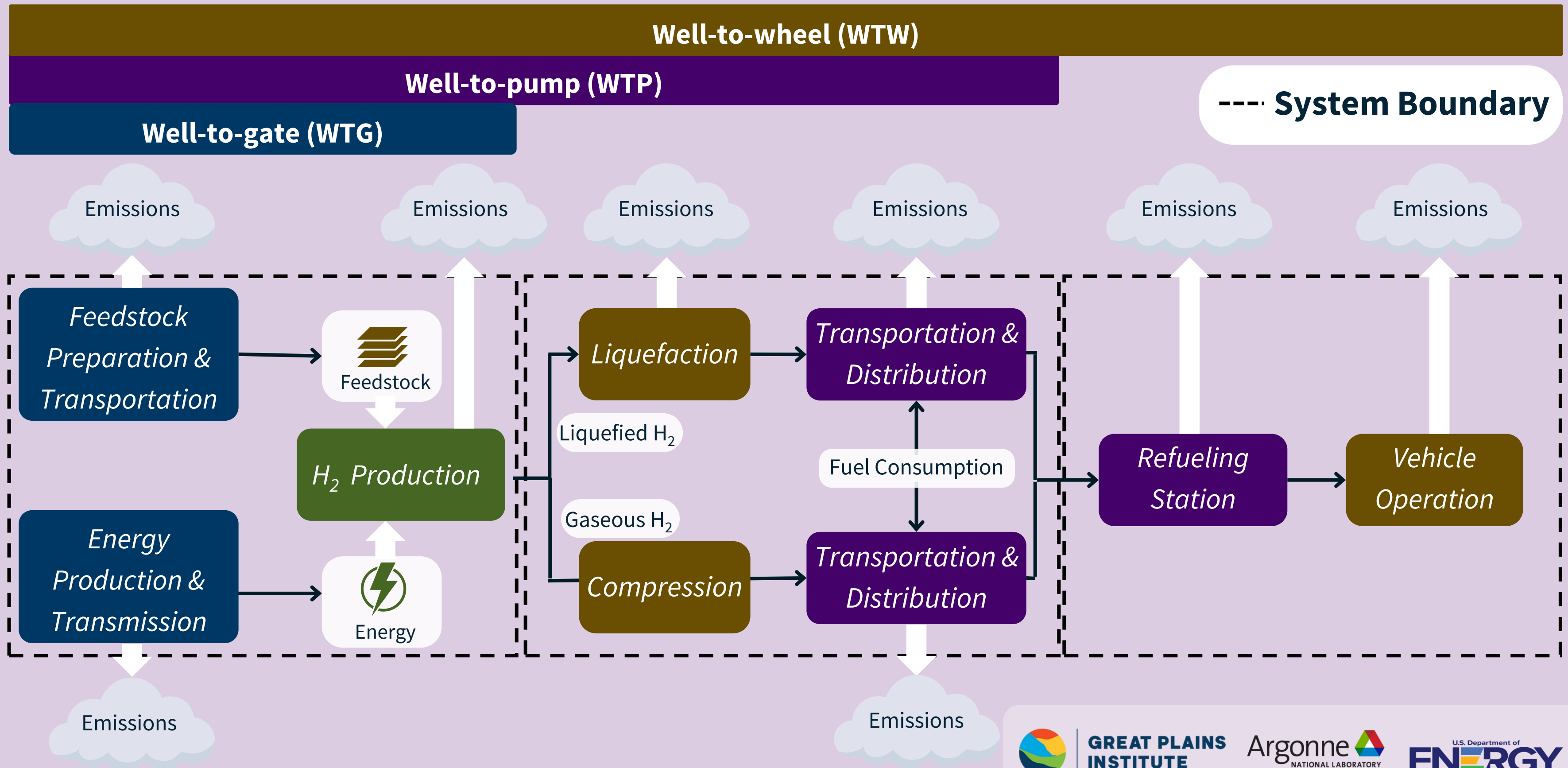
# Life cycle of biofuels in R&D GREET: *example from soybeans*



# Example biofuels pathways in R&D GREET



# System boundaries for hydrogen production in R&D GREET



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# Available hydrogen production pathways in R&D GREET

## Electrolysis

- Low temperature electrolysis: proton exchange membrane (PEM)
  - U.S. Mix, Regional Mix, Wind, Solar PV, Hydroelectric, and Nuclear LWR
- High temperature electrolysis: solid oxide electrolyzer cell (SOEC)
  - Nuclear LWR

## Natural Gas Reforming

- Steam methane reforming (SMR)
  - Natural Gas and Renewable Natural Gas
  - CCS available
- Autothermal reforming
  - Natural Gas and Renewable Natural Gas
  - CCS available

## Gasification

- Biomass
  - Poplar, Willow, Switchgrass, Corn Stover, Forest Residue, and Miscanthus
- Coal
  - CCS available
- Pet coke
  - CCS available
- Coke oven gas

## Co-Product

- Chlor-alkali
- Steam cracker

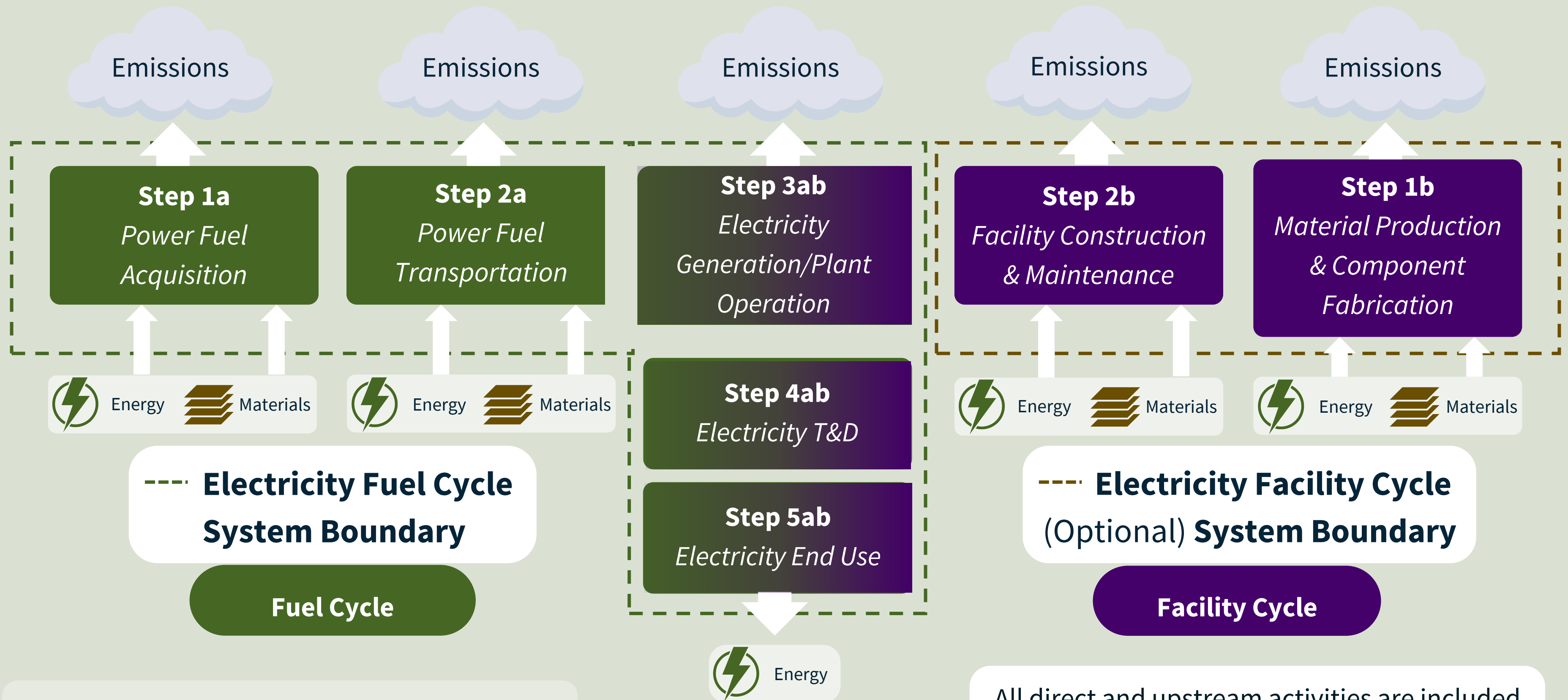
## Biological

- Fermentation

And More



# Life cycle of electricity in R&D GREET



All direct and upstream activities are included

# Electricity generation technologies: *fossil*

**R&D GREET covers electricity generation from various sources and more than 30 generation technologies**

## **Coal**

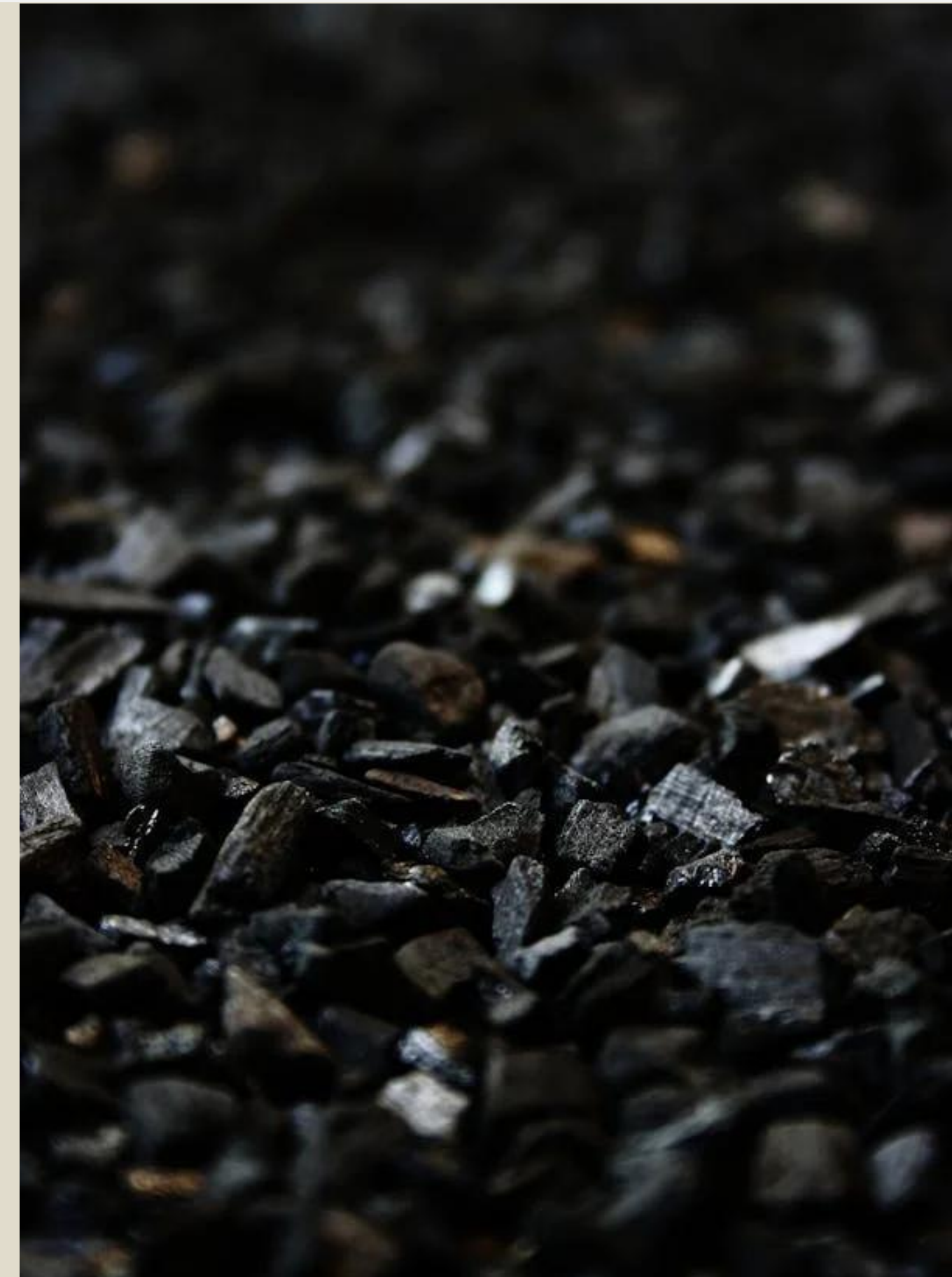
Steam boiler (with or without carbon capture and sequestration (CCS)), *combined heat and power (CHP)*; integrated gasification combined cycle (IGCC)

## **Natural Gas**

Combined cycle turbine (with or without CCS), *CHP*; simple cycle turbine, *CHP*; steam boiler, *CHP*; reciprocating combustion engine

## **Oil**

Steam boiler; gas turbine; reciprocating combustion engine



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# Electricity generation technologies: *nuclear*

**R&D GREET covers electricity generation from various sources and more than 30 generation technologies**

## **Nuclear**

- Light water reactor (LWR)
  - Pressurized water reactor (PWR)
  - Boiling water reactor (BWR)
- High-temperature gas reactor (HTGR)

## **Other Generation III and Generation IV Reactors**

Generation IV reactors contain technological advancements for enhanced sustainability



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[- Generation IV Goals, Technologies and GIF R&D Roadmap | GIF Portal](#)

# Electricity generation technologies: *renewables*

## **Biomass**

Steam boiler; IGCC; feedstock of forest residue, switchgrass, poplar, willow, miscanthus and more

## **Wind Turbine**

On-shore and off-shore

## **Solar**

Single-cSiPV and multi-cSiPV

## **Geothermal**

Hydrothermal flash; hydrothermal binary; enhanced geothermal systems

## **Hydropower**

Concrete gravity dam and embankment dam



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# Data sources for R&D GREET electricity LCA

## Thermal Efficiencies

Unit-level performance data (EIA 923 and 860)

## GHG Emission Factors

CH<sub>4</sub> and N<sub>2</sub>O emissions are estimated by multiplying the fuel specific heat input in mmBtu by the appropriate EFs from Table C-2 of EPA's Final Mandatory Reporting of GHG Rule (EPA 2009)  
CO<sub>2</sub> emissions are calculated from fuel carbon content and fuel consumption

## CAP and Water Consumption

Criteria air pollutants (EPA NEI 2017, EIA, e-GRID)  
Water consumption (EIA and USGS)

## Electricity Generation Mixes

Regional and national mixes (EIA's annual energy outlook)



# Vehicle Modeling for On-Road Vehicles in R&D GREET



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# From materials to vehicles

Each vehicle is a collection of components, which in turn, are a collection of materials

**Materials Modeling**

Material 1

Material 2

Material 3

Material 4

...

Material N

Materials are combined to model components

**Component Modeling**

Component 1

Component 2

Battery

...

Component N

Components are combined to model the vehicle cycle

**Vehicle Modeling**

Vehicles

Usage

2nd Life

EOL



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# Example: Battery Modeling for On-Road Vehicles in R&D GREET



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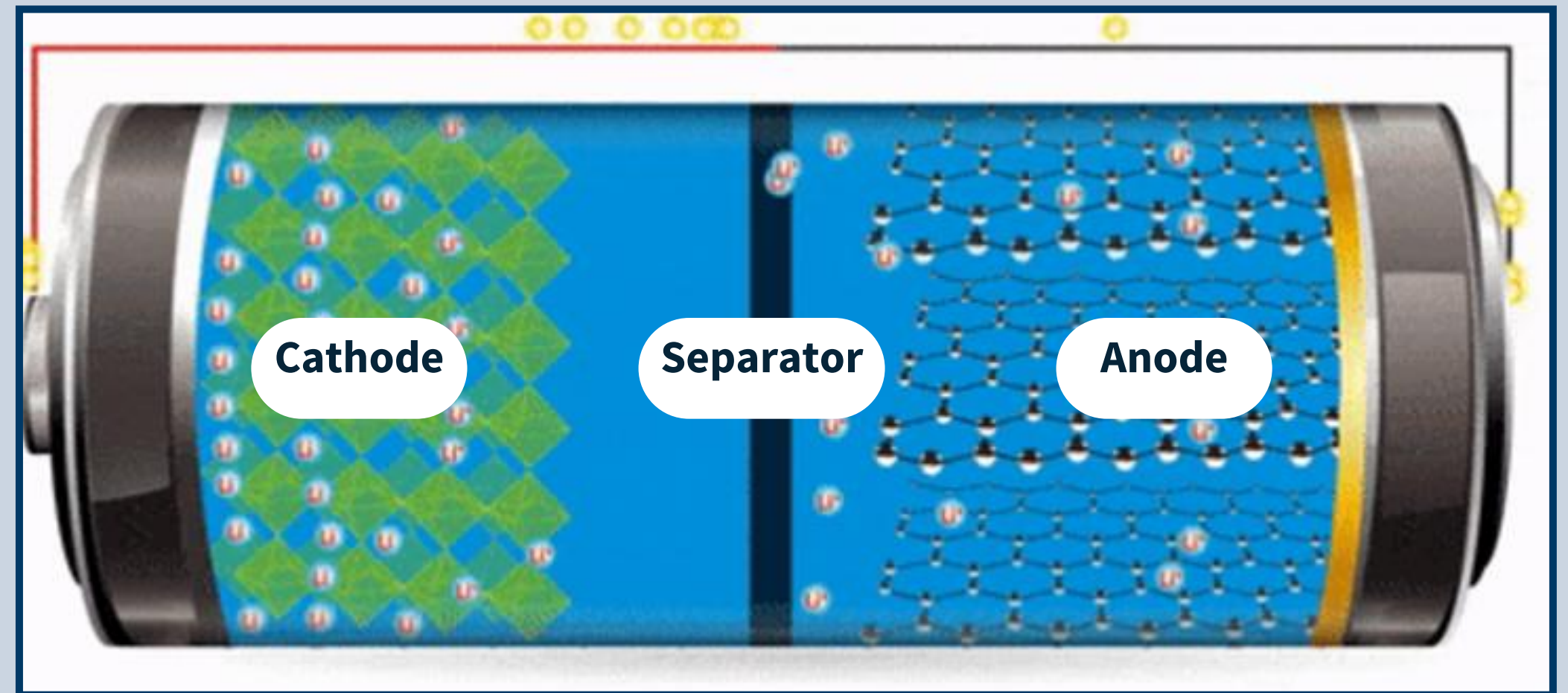
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# Battery electric vehicle mineral use

**Electric vehicles (BEVs) use many materials in lithium-ion batteries**

Nickel, lithium, manganese,  
cobalt, lithium  
hexafluorophosphate, ethylene  
carbonate, dimethyl carbonate,  
phosphorous, polyvinylidene  
fluoride, N-methyl-2-  
pyrrolidone, graphite, silicon,  
lithium metal, and more



[- DOE Explains...Batteries | Department of Energy](#)



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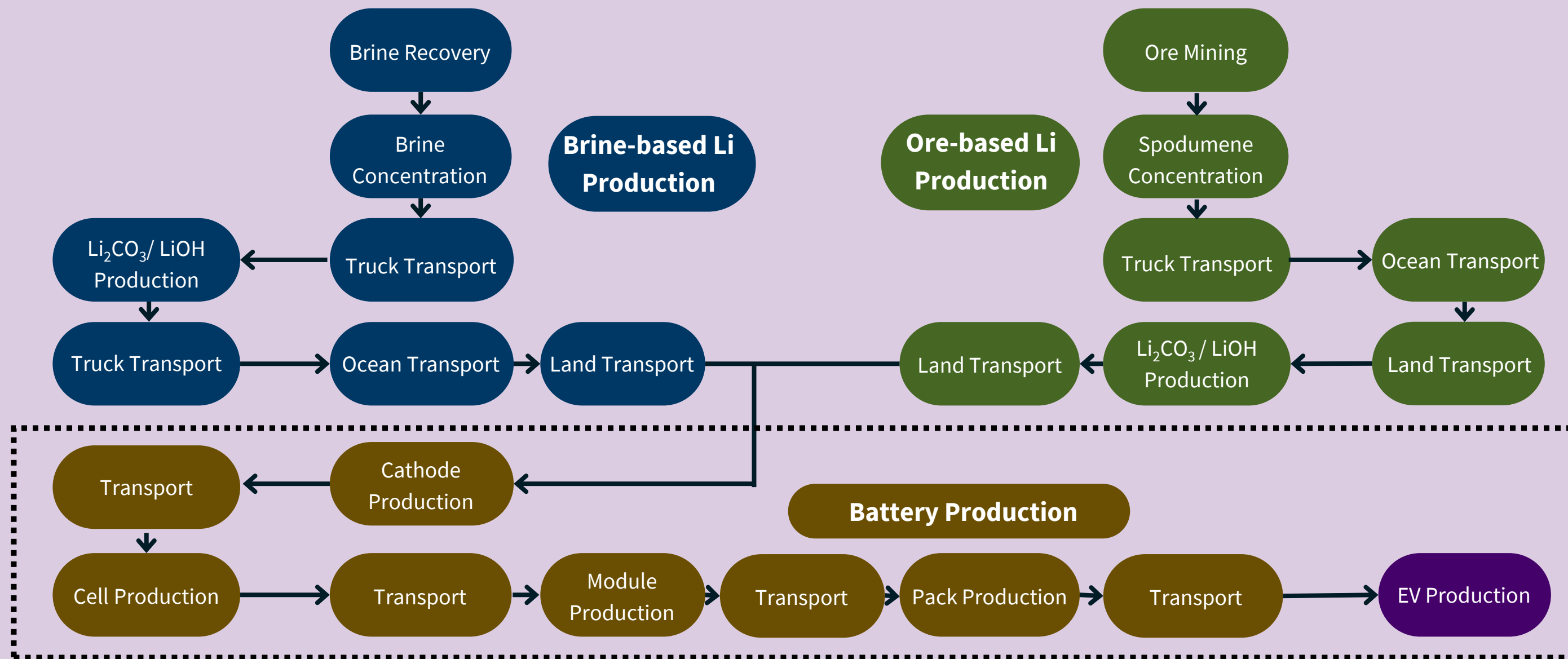


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# Battery modeling

From the materials, ANL extends to batteries and leverages Argonne's BatPaC model for the bill of materials (BOM): *the "recipe" of the battery*



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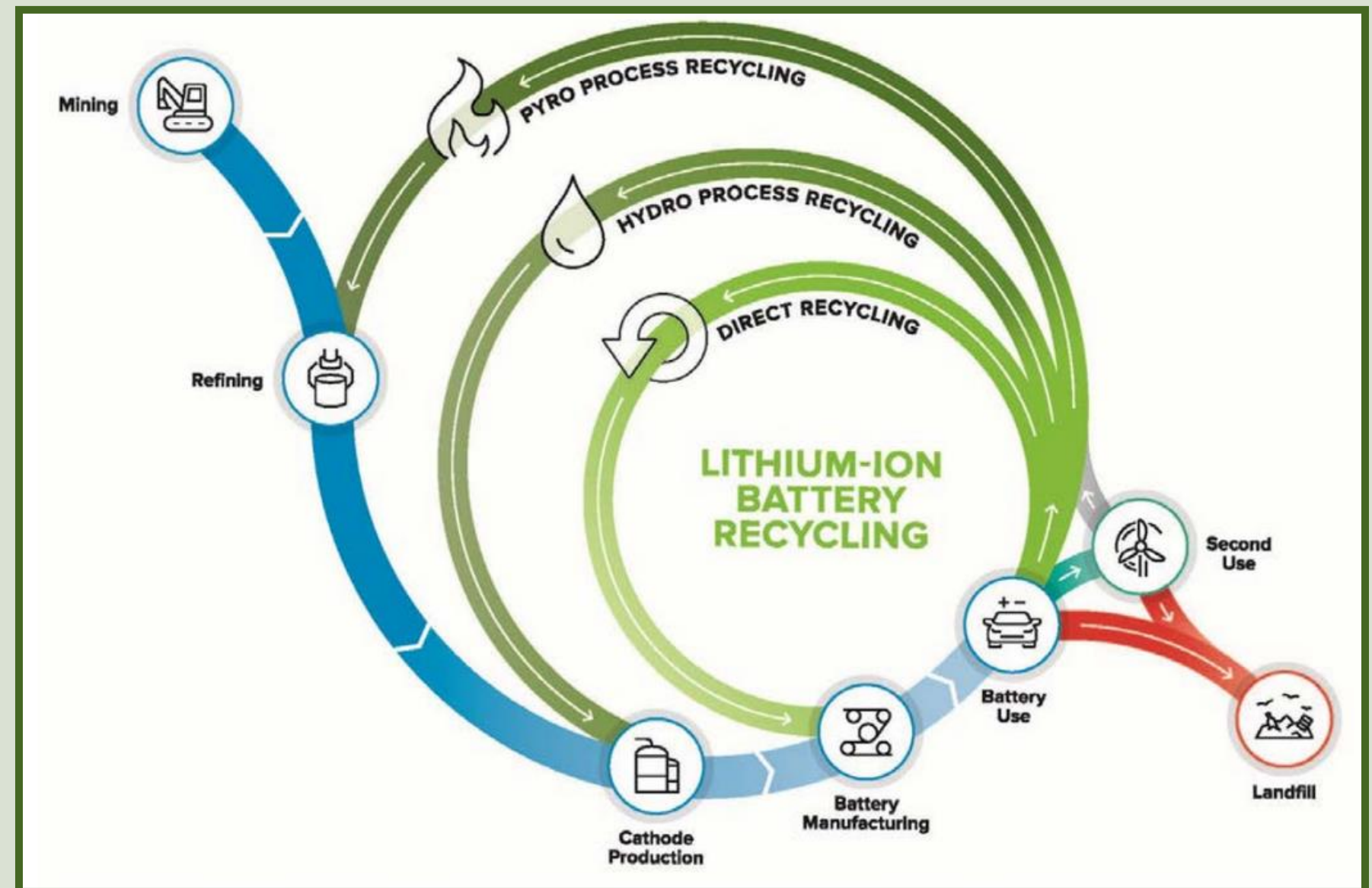
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# Battery recycling model

## Modeling framework of Argonne's EverBatt Recycling Model

Recycling is benchmarked against virgin production to provide a holistic picture of the benefits and trade-offs of battery recycling

**GREET incorporates the energy and material balance from EverBatt to model the emissions, energy use, and water consumption of battery recycling**



[- Novel Processing and Design Technologies will Make Battery Recycling Profitable | Recell Advanced Battery Recycling](#)



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# LCA Results for On-Road Vehicles in R&D GREET



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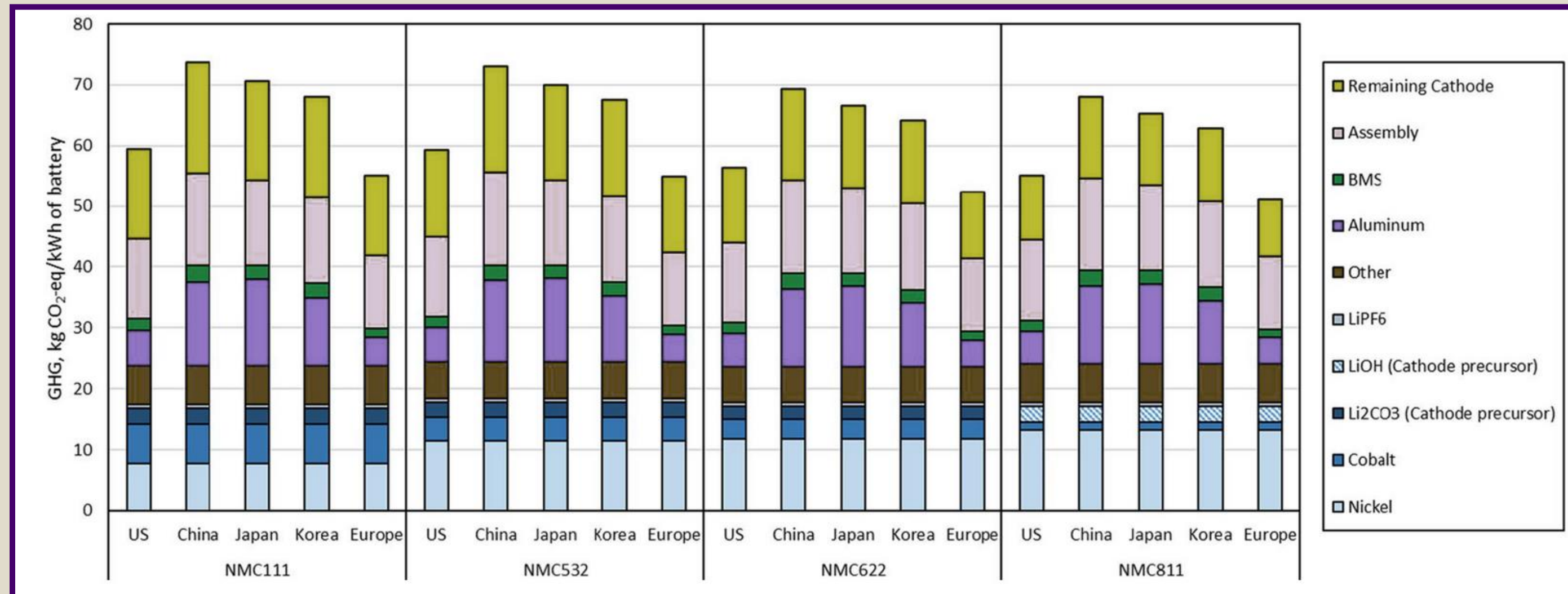
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# Life cycle GHG emissions in R&D GREET

## Global supply chains of current battery production impact LCA results

### Argonne LCA of Global Regional Supply Chains Along with NMCxyz Variance



NMCxyz  
variance:  
cathode  
composition  
(i.e., NMC811)

- [Winjobi et al., 2022, Sustainable Materials and Technologies](#)



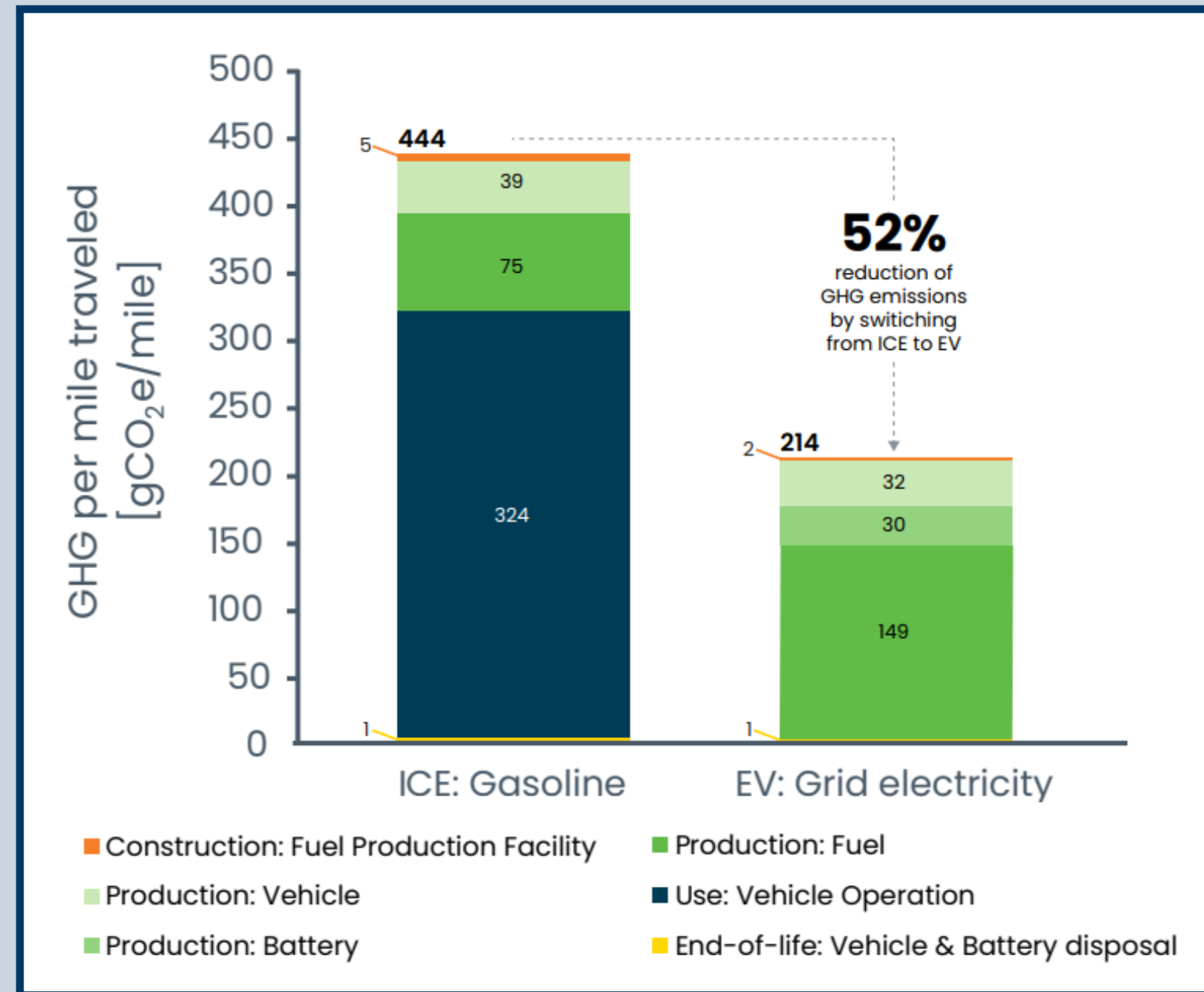
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# Life cycle GHG emissions in R&D GREET

## Compare Gasoline ICEV to EV for Small SUVs



- [R&D GREET LDV Fact Sheet, 2024,](#)  
[Department of Energy](#)



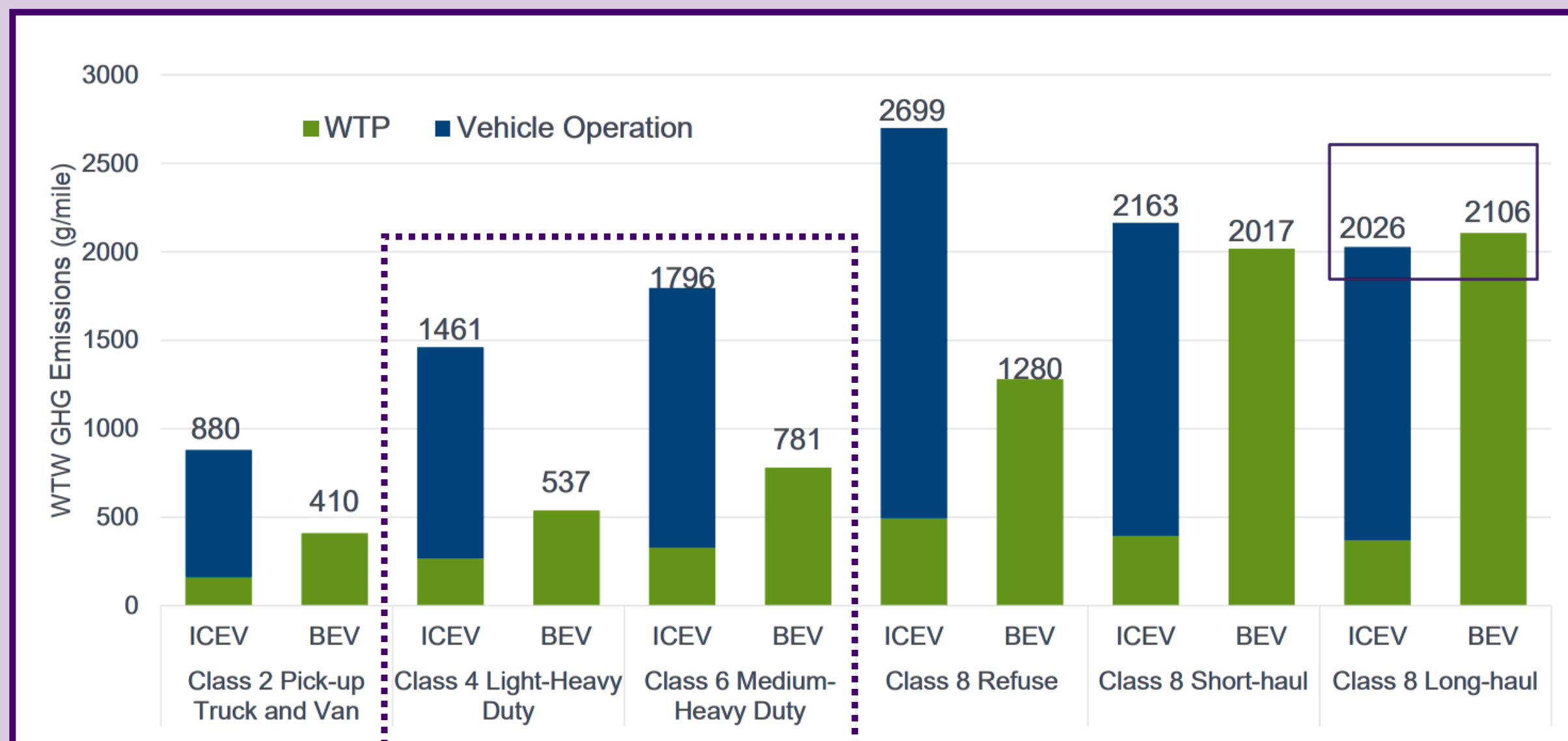
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# Well-to-wheels GHG emissions of BEV MHDVs: 2019 U.S. Mix

For BEVs, the fuel consumption, and thus, GHG emissions, increase with **increasing weight class**

For vocational vehicles, shifting to BEV from ICEV can reduce WTW GHG emissions by **49-63%**



- R&D GREET

**Note:** this figure was generated for illustrative purposes. As R&D GREET is updated, the values could change

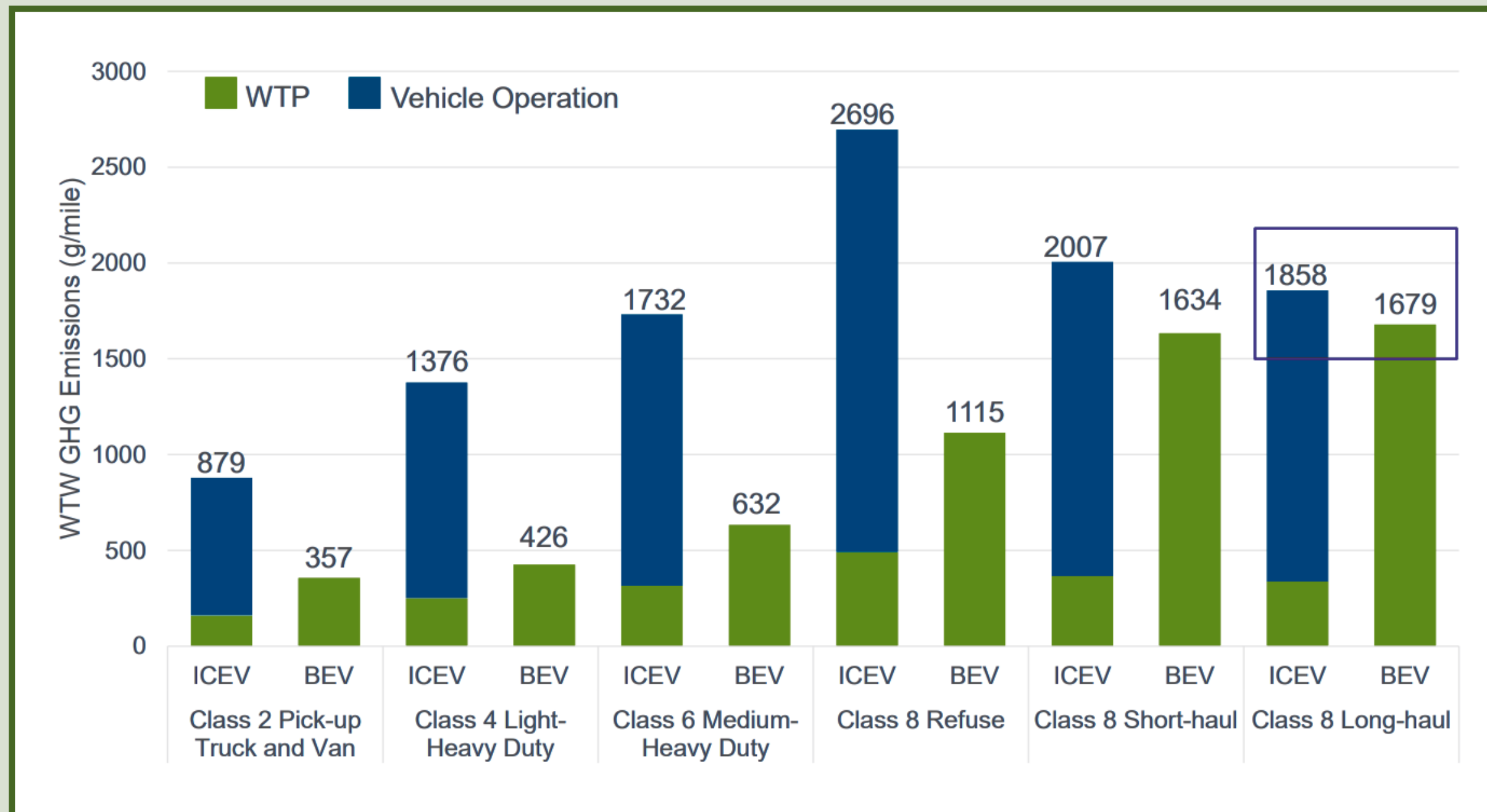


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# Well-to-wheels GHG emissions of BEV MHDVs: 2030 U.S. Mix

For class 8 long-haul vehicles, the WTW GHG emissions for BEVs are estimated to be less than the emissions associated with diesel ICEVs **in 2030**



- [R&D GREET](#)

**Note:** this figure was generated for illustrative purposes. As R&D GREET is updated, the values could change



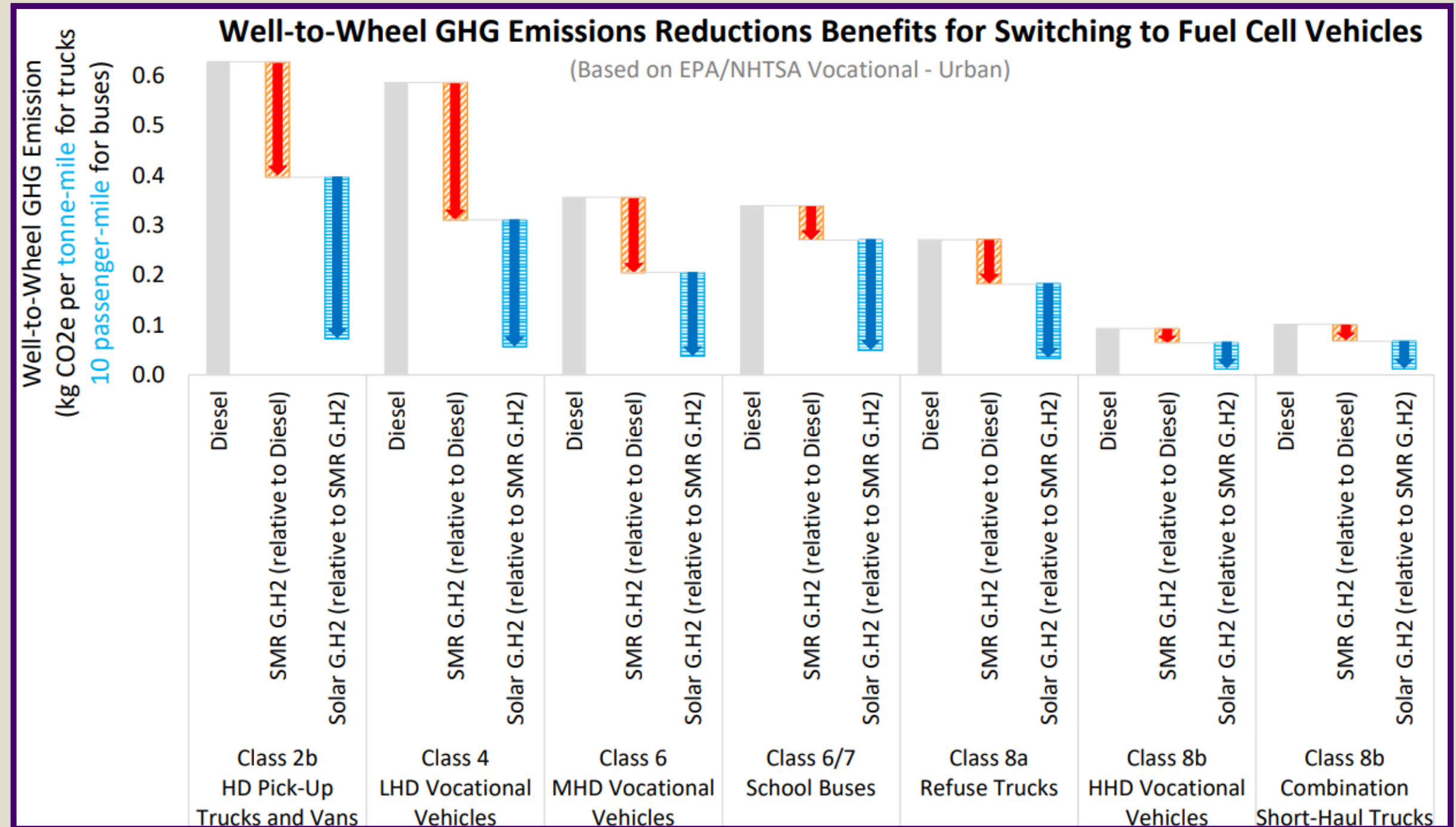
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# Well-to-wheels GHG emissions of FCV MHDVs

FCVs have a **greater fuel economy** than ICEVs and exhibit **lower GHG emissions** when using hydrogen produced using **renewable energy**



Compared to diesel counterparts, MHD hydrogen FCVs create less GHG emissions across classes



- [R&D GREET](#)

**Note:** this figure was generated for illustrative purposes. As R&D GREET is updated, the values could change

# GREET capabilities for on-road vehicles

	Light-duty Vehicles (LDVs): “Results” tab	Medium and Heavy-duty Vehicles (MHDVs): “HDV_WTW” tab
Vehicle Options	<p>3 Types of LDVs</p> <p>Sedans   SUVs   Pickup Trucks</p> 	<p>10 Types of MHDVs Covering the Following</p> <p>Sleeper/Day Cabs, Vocational Vehicles, HD Vans, Buses, and Refuse Trucks</p> 
Powertrain Options	<p>5 Types of Powertrains</p> <p>ICEV, HEV, PHEV, BEV, FCV</p>	<p>4 Types of Powertrains</p> <p>ICEV, HEV, BEV, FCV</p>
Fuel Pathway Options	<p>Numerous Fuel Options and Pathway Details Can be Selected</p> <p>ICEV: gasoline, diesel, CNG, LPG, biofuels, etc. HEV/PHEV: similar suite of fuel options as ICEV</p> <p>BEV: electricity with different grid choices FCV: hydrogen with different production pathways</p>	



# On-road vehicle tabs in R&D GREET

## Primary

Vehicles

Car\_TS

LDT1\_TS

LDT2\_TS

MHDV\_TS

in R&D GREET 1

## Some Secondary

Results

MHDV\_WTW

in R&D GREET 1

## Some Secondary

All tabs

in R&D GREET 2

Some tabs are on material impacts that feed into vehicle-cycle impact calculations, while other tabs are about vehicles or vehicle-cycle impact calculations



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## Questions?

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Visit <https://greet.anl.gov/>

## Contributors

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# THANK YOU



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