

February 3, 2025

# Introducing R&D GREET<sup>®</sup> 2: Vehicle/Material Cycle Analysis

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

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5. R&D GREET 2 Capabilities



# What Makes Up R&D GREET?



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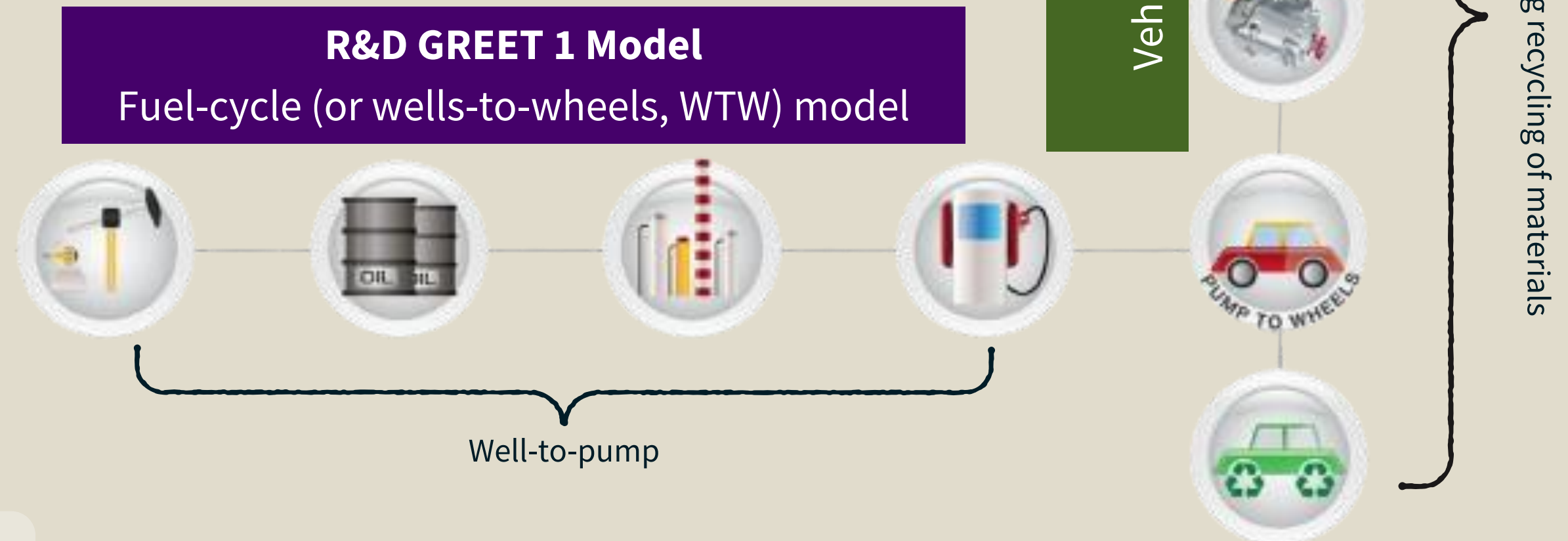
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# The R&D GREET model framework

## R&D GREET 2: Vehicle/materials Cycle

- Includes the entire supply chain of material production and the incorporation of these materials into vehicle components and the final vehicle
- [Well-to-wheels] + [vehicle cycle] = [cradle-to-grave]

Interacts with  
R&D GREET 1 for  
fuel cycle  
results



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# R&D GREET 2: Vehicle/materials Cycle



Vehicle cycle, including recycling of materials

**Raw Material Recovery**

**Material Processing and Fabrication**

**Vehicle Component Production**

**Vehicle Operation**

**Vehicle Assembly, Disposal, and Recycling  
(ADR)**



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# Materials in R&D GREET 2



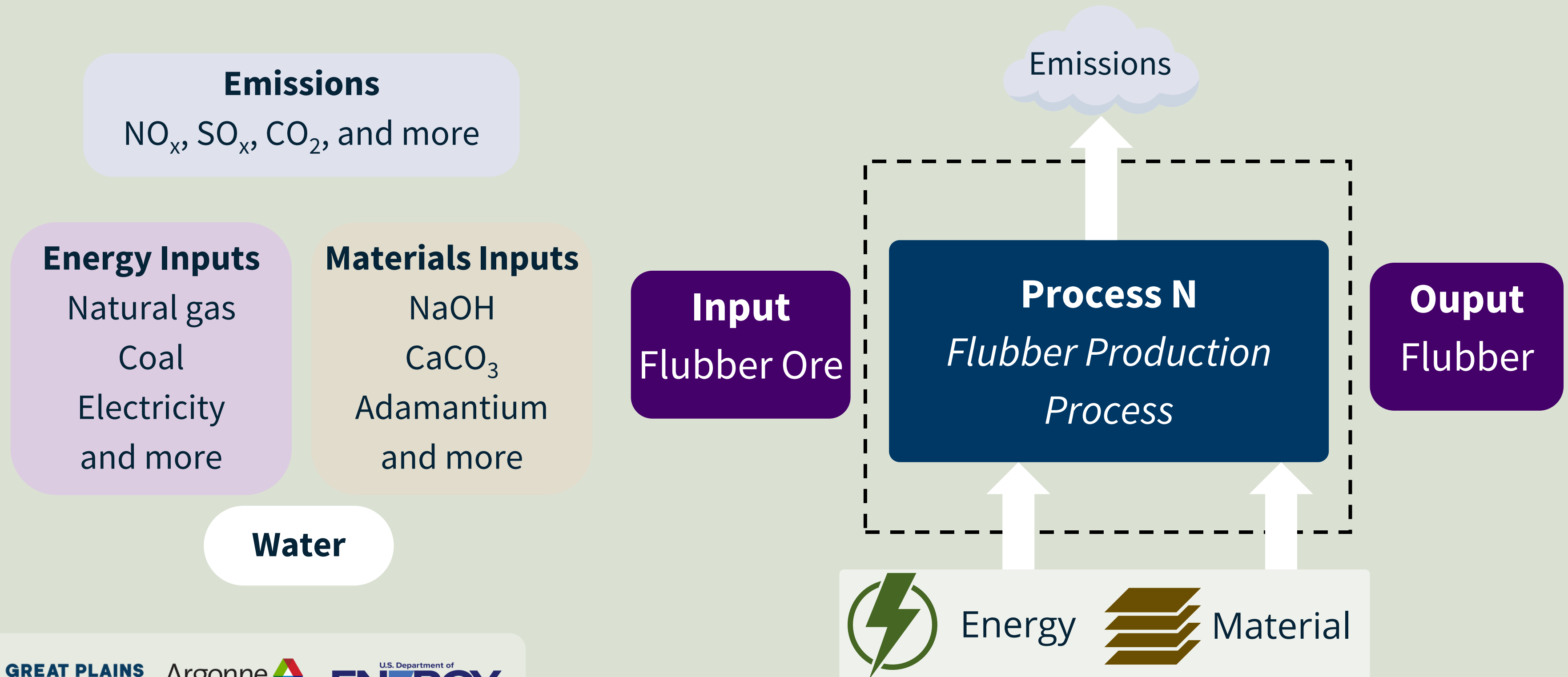
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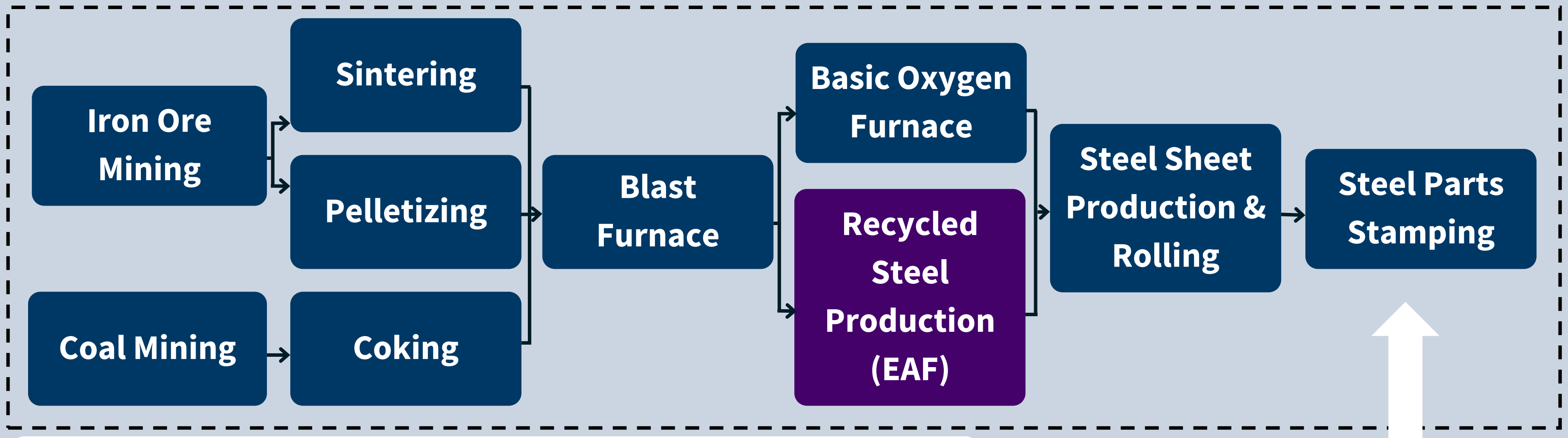
# A simplified material production example:

## *flubber production*



# A simplified material-to-vehicle pathway example: *steel production*

Materials are modeled step-by-step from ore mining to part production



**Many materials can be, and are, produced in multiple ways**

Steel is produced by basic oxygen furnace (BOF) (*virgin/primary steel*) or electric arc furnace (EAF) (*secondary steel*)

**Steel Auto Parts**



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# Materials in R&D GREET 2: *recovery, processing and fabrication*

## R&D GREET captures the life cycle emissions of material production

- Impacts of **production processes** employed for raw material recovery, material processing, and fabrication
- Embodied impacts of **input materials** and **energy sources** used for different production processes
- **Transportation** of inputs associated with each production process and of the supply of final product to consumer (subject to data availability)

## Major expansions/updates over time for battery materials

Lithium, nickel, and cobalt

Material Type	Examples
Ferrous Metals	Steel, stainless steel, iron
Non-Ferrous Metals	Aluminum, copper, nickel, cobalt, magnesium, and manganese
Plastics	Polypropylene, nylon, carbon fiber-reinforced plastic, ABS, EPDM, epoxy, LDPE, HDPE, and more
Vehicle Fluids	Engine oil and windshield fluid
Others	Glass, graphite, silicon, cement, and lithium



# Components and Vehicles



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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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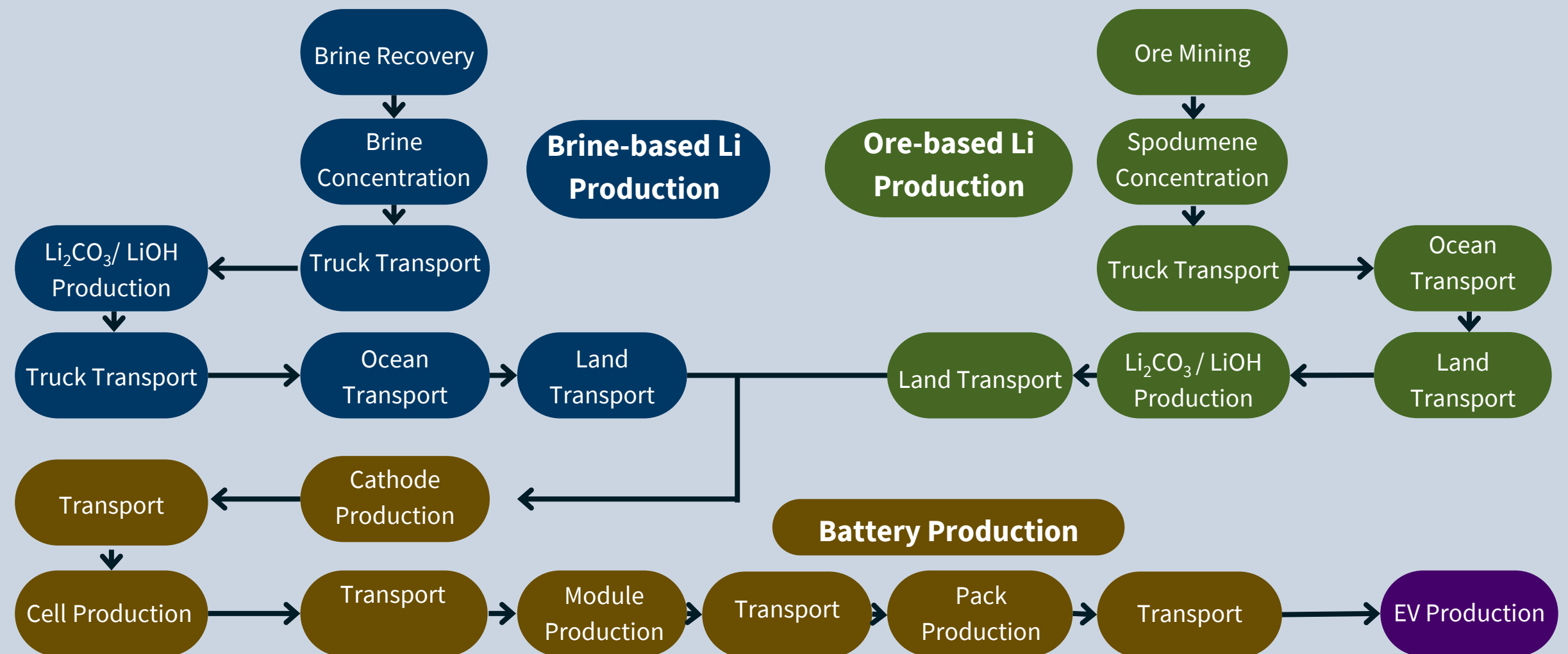
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# Example: *battery production*

## Battery electric vehicles (BEVs) use a number of critical materials in lithium-ion batteries

Lithium chemicals, which are produced from both Chile Salar brines and Australia-based spodumene ores processed in China

Nickel sulfate, which is produced from high-purity nickel metal and mixed hydroxide precipitate via processing of laterite/oxide nickel ores, whether the metal is obtained from varying grades of ore



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# Example: *battery production*

**R&D GREET 2 contains these variations and evaluates the effect of these supply chain parameters on the impacts of material production**

These impacts influence the embodied impacts of batteries and, subsequently, the vehicle cycle impacts of BEVs

Inventory of these materials, and details about the manufacturing, inform the battery inventory that enables an accurate characterization of impacts of electric-related powertrains

## **Supply Chain Parameters**

Ore type  
Ore grade  
Source of ore



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# Recycled Content



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# Recycled content



**Automobiles use a wide range of materials, both in primary and secondary (recycled forms)**

Recycled content has a significant effect on vehicle cycle and life cycle impacts of vehicles, depending on the approach used for life cycle analysis

R&D GREET 2 has the capacity to model both of the common approaches (recycled content method and end of life recycling method) to determine the end of life impacts of materials based on their recyclability



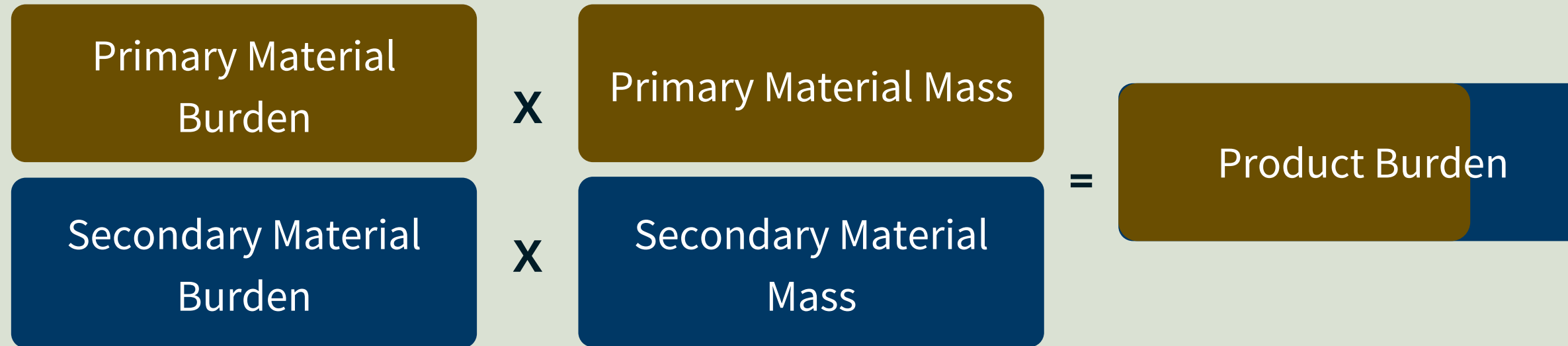
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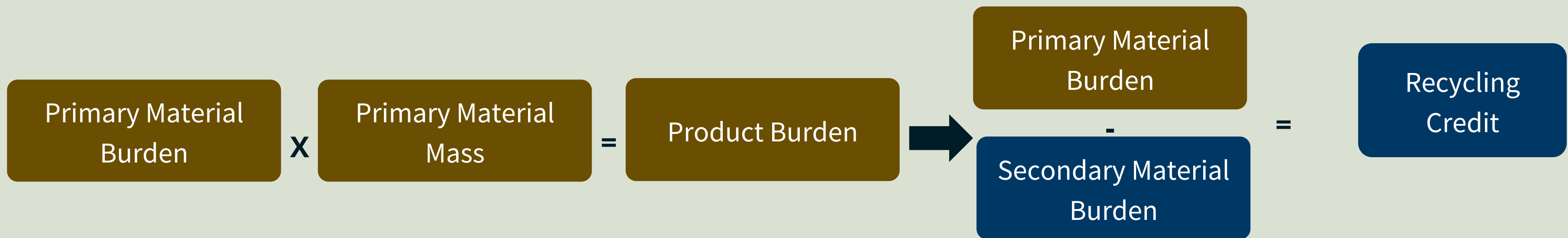
# Recycled content

## Recycled Content Method



**R&D GREET uses the recycled content method as default**

## End of Life Recycling Method



# Vehicle Specifics in R&D GREET 2



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# Vehicle types covered in R&D GREET 2

## Light-duty Vehicles (LDVs)

Car

Sports utility vehicle (SUV)

Pick-up truck (PUT)

## Medium and Heavy-duty Vehicles (MHDVs)

Class 6 pickup-and-delivery (PnD) truck

Class 8 regional day-cab truck

Class 8 long-haul sleeper-cab truck



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# Vehicle powertrains covered in R&D GREET 2

## Light-duty Vehicles (LDVs)

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)

## Medium and Heavy-duty Vehicles (MHDVs)

Class 6 PnD truck: ICEV, HEV, BEV, and FCV

Class 8 trucks: ICEV, BEV, and FCV

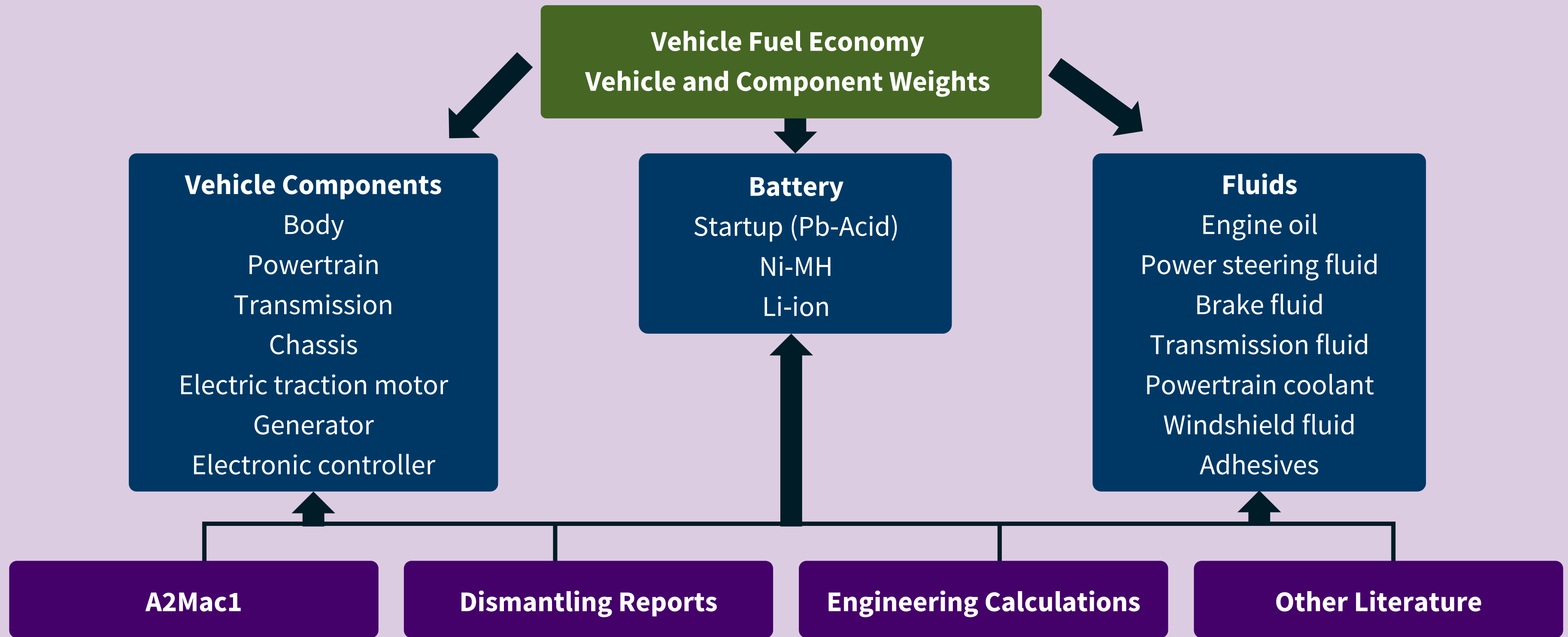


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# Material inventory development



# Material inventory development: *component weight*



## Weight Sizing

Most vehicle components in R&D GREET 2 are sized based on data from Autonomie - an Argonne-based detailed vehicle simulation model

[- Islam et al., 2021, Argonne National Laboratory](#)

- Autonomie uses **iterative process** to size vehicle components such that these meet technical specifications like acceleration, grade, and maximum speed
- **Major outputs** from Autonomie include component sizing, energy consumption by cycle, and component weights
- R&D GREET reads the **relevant parameters** for different simulation years in Autonomie, including fuel economy, component mass, and battery sizing (power or energy)



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# Material inventory development: *batteries*



## **Batteries**

One major exception to the approach for weight and material composition data is for batteries

Battery sizing from Autonomie is inputted into Argonne's BatPaC (Battery Performance and Cost Estimation) model to determine the battery bill-of-materials and overall weight (for lithium-ion batteries)

## **BatPaC**

Provides the optimal battery design and cost outputs for lithium-ion batteries with different cathode chemistries, based on specific inputs (like battery pack design and output power/energy)



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# All Tabs in R&D GREET 2



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# Tabs in R&D GREET 2

**Scenario Control Variables and Input Assumptions Related to Passenger Car and its Components**

**1. Specification of Total Vehicle Weight, pounds**

	ICEV: Conventional Material	ICEV: Lightweight Material	HEV: Conventional Material	HEV: Lightweight Material	PHEV: Conventional Material	PHEV: Lightweight Material	EV: Conventional Material	EV: Lightweight Material	FCV: Conventional Material	FCV: Lightweight Material	PHEV35: Conventional Material	PHEV35: Lightweight Material
Passenger Car 1	3,183	2,692	3,429	2,839	3,713	3,007	4,026	3,193	3,644	2,930	3,336	2,760
Passenger Car 2	3,170	2,476	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A		
Selected Passenger Car	3,183	2,692	3,429	2,839	3,713	3,007	4,026	3,193	3,644	2,930		

**2. Vehicle Battery and Fluids Weight**

**2.1) Battery Weight**

**Cast and Forged Iron**

1) Key Input Parameters (from the *Mat\_Inputs* sheet)

1.1) Shares of Iron Types in a Vehicle for Average Iron Calculation, % by wt

	Cast Iron	Forged Iron
	85.0%	15.0%

**2) Shares of Combustion Process**

Resi. oil industrial boiler  
NG industrial boiler  
Coal industrial boiler

**Platinum-Group Metals (PGMs)**

1) Key Input Parameters (from the *Mat\_Inputs* sheet): Selection of Method for Estimating Energy Use for PGMs

1 -- South African mine  
2 -- North American mine

1 -- Weight based energy allocation  
2 -- Market value based energy allocation

**3) Calculations of Energy Consumption**

Water consumption (gal/ton of material)

**Cement / Concrete**

1) Key Input Parameters

1.1. Materials shares

Selection: U.S. National Average

	Material Shares in Cement			Material Shares in Concrete			
	Clinker (limestone)	Gypsum	Clay	Cement	Aggregate	Sand	Water
Selected	94%	5%	1%	9%	49%	35%	7%
U.S. National Average	94%	5%	1%	9%	49%	35%	7%

**2.2) Fluids Weight**

Energy inputs: mmBtu per ton of material  
product, except as noted

Urban emission share

Shares of process fuels

Overview

R&D GREET Excel is run on Microsoft Excel, which allows calculations to be run on several interconnected "Tabs"



# Categories of tabs in R&D GREET 2

## Inputs Tabs

Users can customize their LCA calculation

- **Vehi\_Inputs:** connects to the R&D GREET 1 model and specifications for lifetime, replacement frequency, and weight for the vehicle, battery, and vehicle assembly process for LDVs
- **Mat\_Inputs:** material composition for vehicle and battery components and specifications for recycling rates broken down by material type
- **MHDV\_Inputs:** inputs for medium-heavy-duty vehicles
- **MHDV\_Mat\_Parameters:** material composition for vehicle and battery components for MHDVs
- **Battery\_Assembly:** inputs for the chemicals and mechanism used to assemble batteries



# Categories of tabs in R&D GREET 2

## Vehicle-specific Tabs

Users can further customize their specific vehicle and provide detailed information and results for a specific vehicle

**Examples:** “Car,” “SUV,” “Class 6 PnD Trucks,” “Class 8 Day-cab Trucks,” and “Class 8 Sleeper-cab Trucks”

## Material-specific Tabs

Users can further customize their specific material and provide detailed information and results for a specific material

**Examples:** “Steel,” “Zinc,” and “Lead”

## Technology-specific Tabs

Users can further customize their specific chosen technology used to generate power in these pathways

**Examples:** “Wind\_Turbine,” “Solar\_PV,” and “Hydropower”



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# Categories of tabs in R&D GREET 2

## Calculations-specific Tabs

Users can further customize a specific scenario and understand the emissions along the pathway

**Examples:** “*Mat\_Sum,*” “*Vehi\_ADR,*” “*Vehi\_Comp\_Sum,*” and “*MHDV\_Fluids*”

## Results Tabs

Results for the LCA calculation

- **TEC\_Results:** *Vehicle cycle and light-duty vehicle C2G results*
- **MHDV\_TEC\_Results:** *Vehicle cycle and medium- and heavy-duty vehicle C2G results*



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# R&D GREET 2 Capabilities



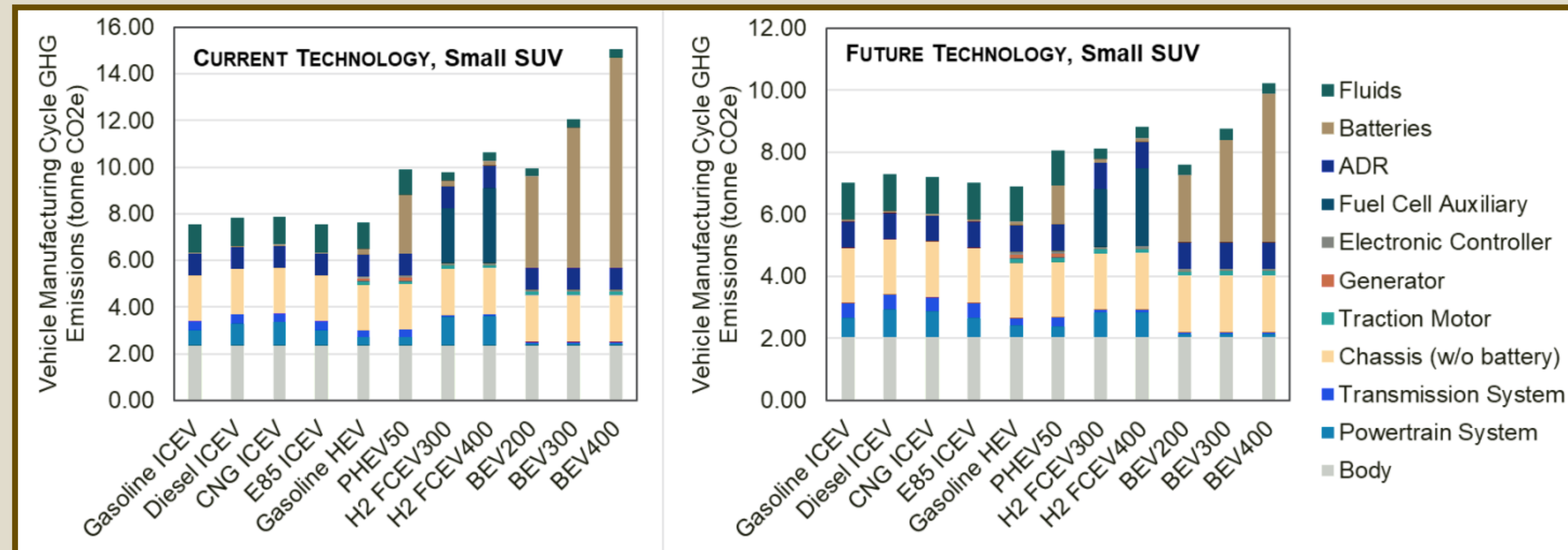
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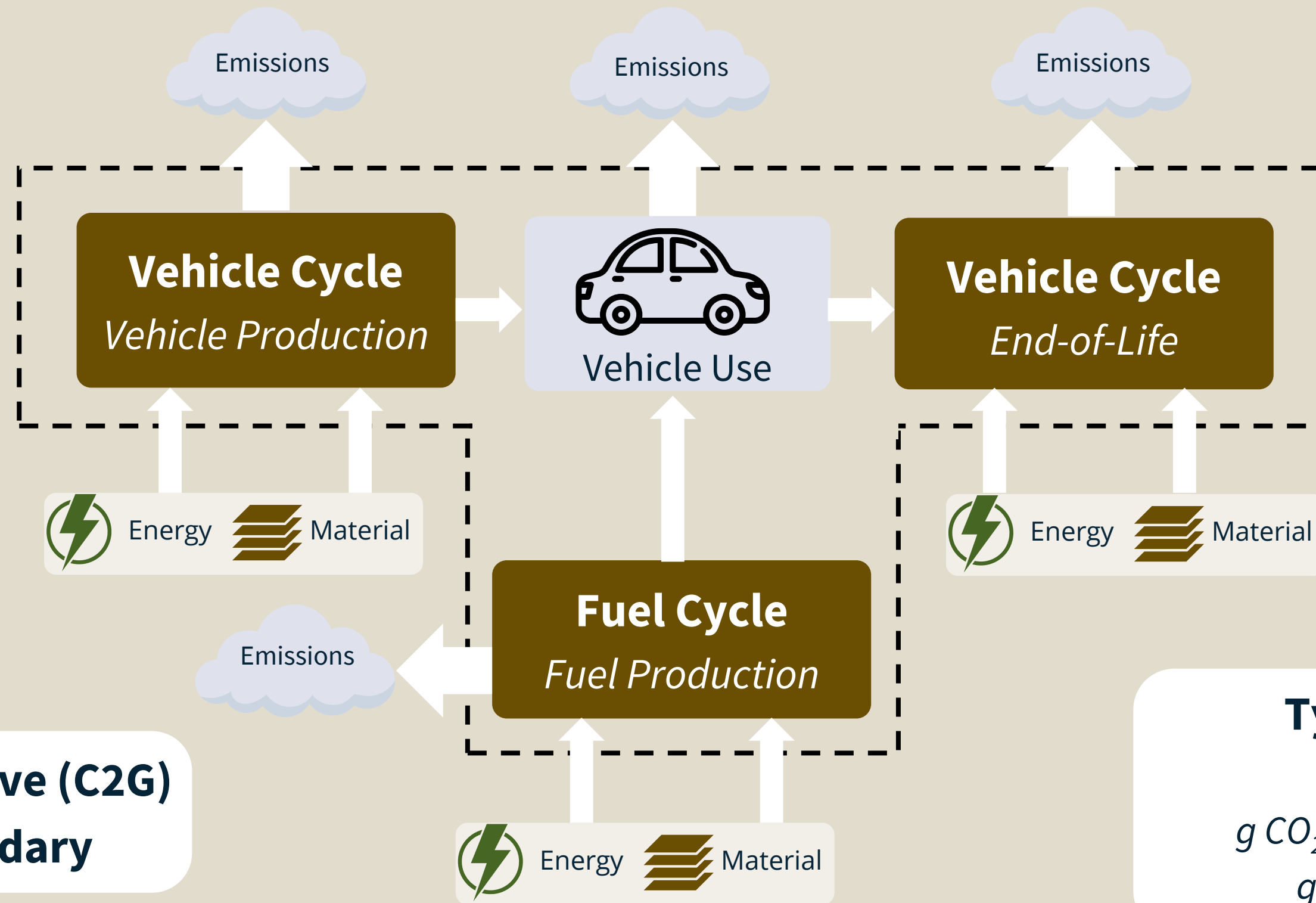
# Evaluate vehicle cycle GHG emissions

Understand how the transition from conventional internal combustion engine-based powertrains to alternative powertrains will impact the vehicle cycle

Understand how battery size impacts the vehicle cycle



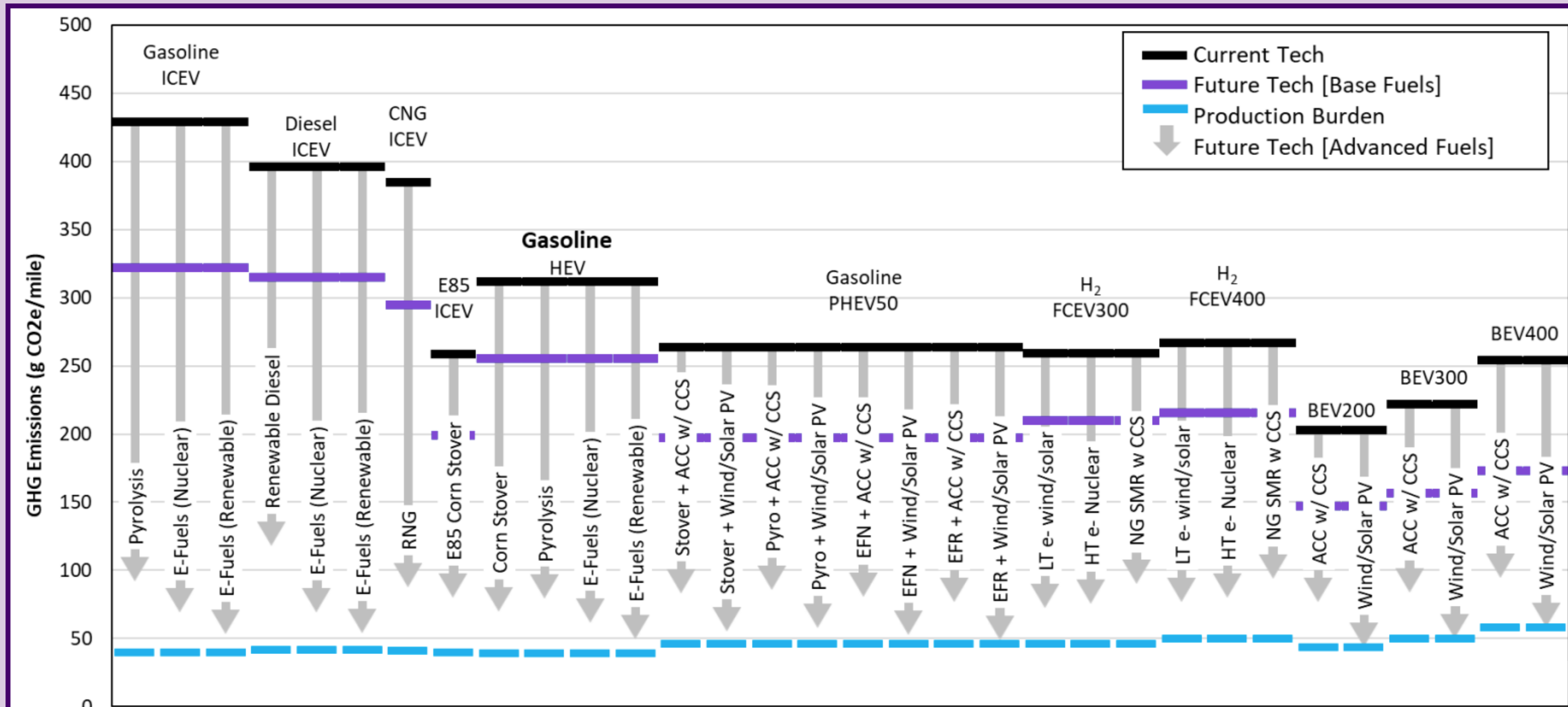
# C2G life cycle in R&D GREET: *cradle-to-grave analysis*



--- 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*

# Cradle-to-grave (C2G) impacts



- Kelly et al., 2022, Argonne National Laboratory

# Questions that can be answered about C2G impacts

How can technology improvements in powertrains reduce GHG emissions?

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

How can we decarbonize through different energy pathways?



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## Questions?

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## Contributors

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