

NOVEMBER 7, 2022
GREET TRAINING WORKSHOP



GREET 2 MODEL: VEHICLE & MATERIAL CYCLE ANALYSIS

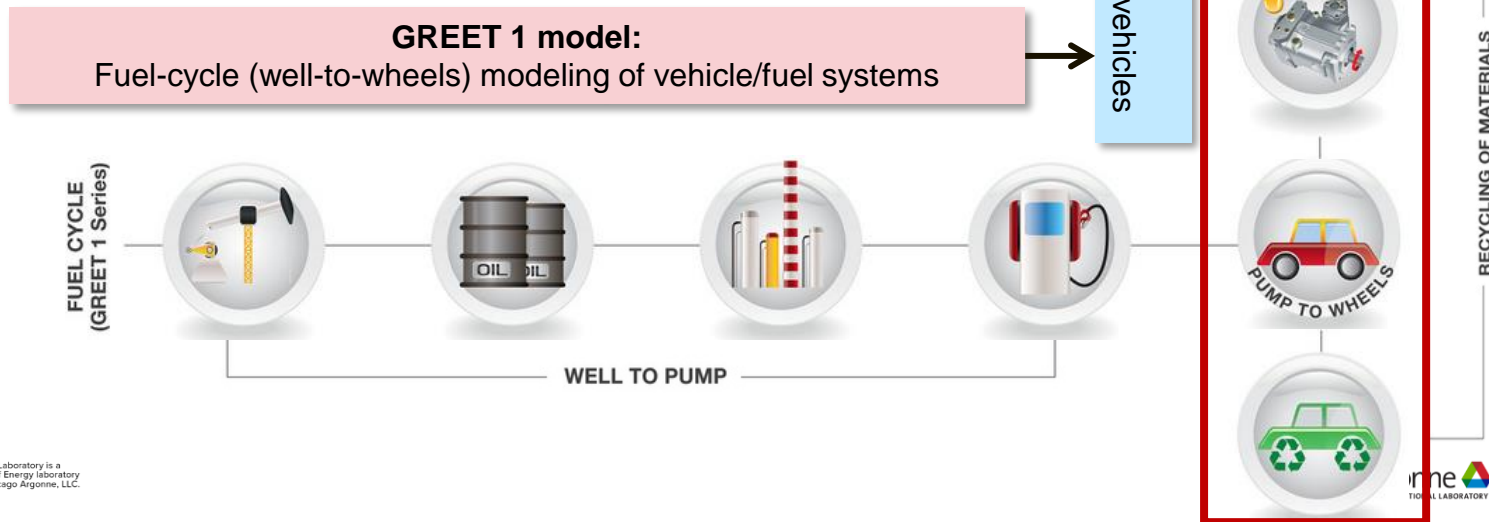
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The GREET model framework

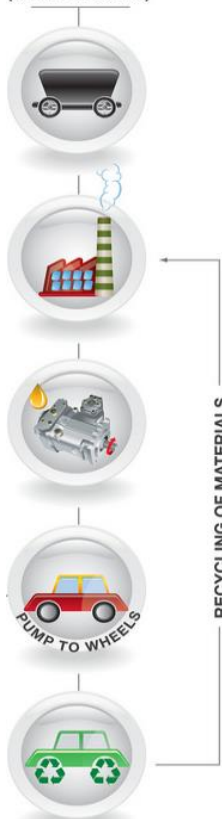
- **GREET2: Vehicle cycle**

- Includes the entire supply chain of material production
- [Well-to-wheels] + [Vehicle Cycle] = [Cradle-to-Grave]
- Interacts with GREET1



GREET 2 simulates vehicle cycle from material recovery to vehicle disposal

VEHICLE CYCLE
(GREET 2 Series)



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

Life cycles of 60+ materials are included in GREET 2

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

- ☐ Several important lightweighting materials included in GREET 2
 - Aluminum, magnesium, carbon fiber reinforced plastics, and high strength steel (comparable to steel)
- ☐ Major expansion in battery materials
 - ☐ Updated lithium, nickel, cobalt, and other important chemicals
- ☐ Capture embodied emissions of production inclusive of processes, transportation, and input materials

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

Detailed supply chains are configured for critical materials in GREET LCA model

Fuel cycle + vehicle cycle = cradle-to-grave (C2G) (GREET1 + GREET2 models)

Fuel production cycle (WTP) + vehicle operation (PTW) =
well to wheels fuel cycle (WTW) (GREET1)

Fuel Production Cycle
(Well-to-Pump, WTP)

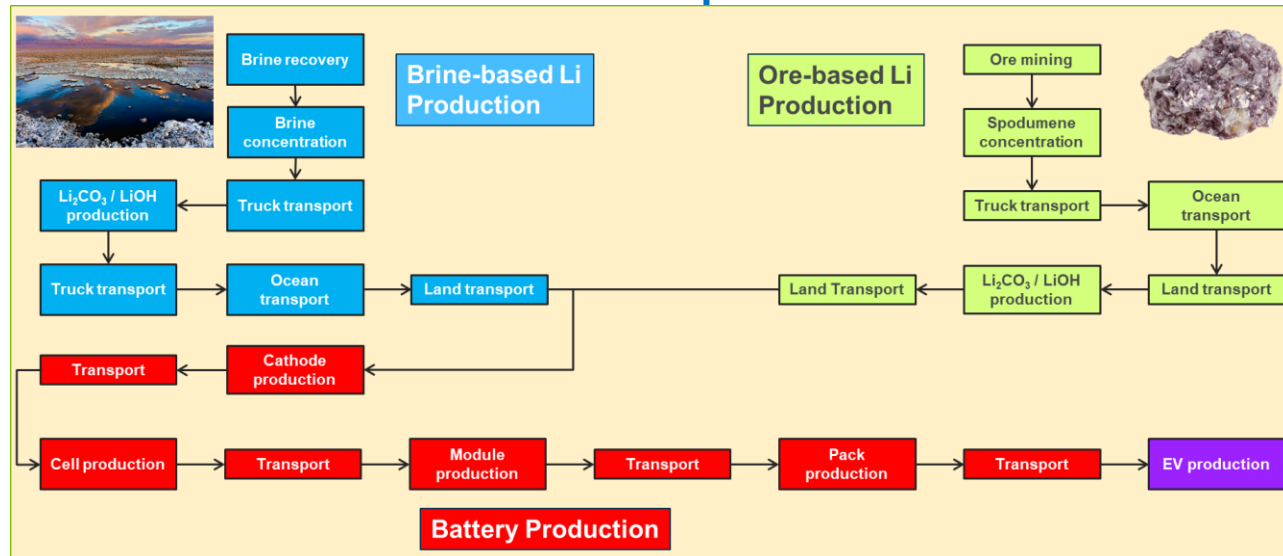
Vehicle Operation:
Pump-to-Wheels (PTW)

Vehicle manufacturing cycle + vehicle end of life =
vehicle cycle (GREET2)

Vehicle Manufacturing
Cycle (VMC)

Battery
Manufacturing Cycle

Vehicle End of
Life (EOL)



GREET LCA Methodology: Vehicle Cycle

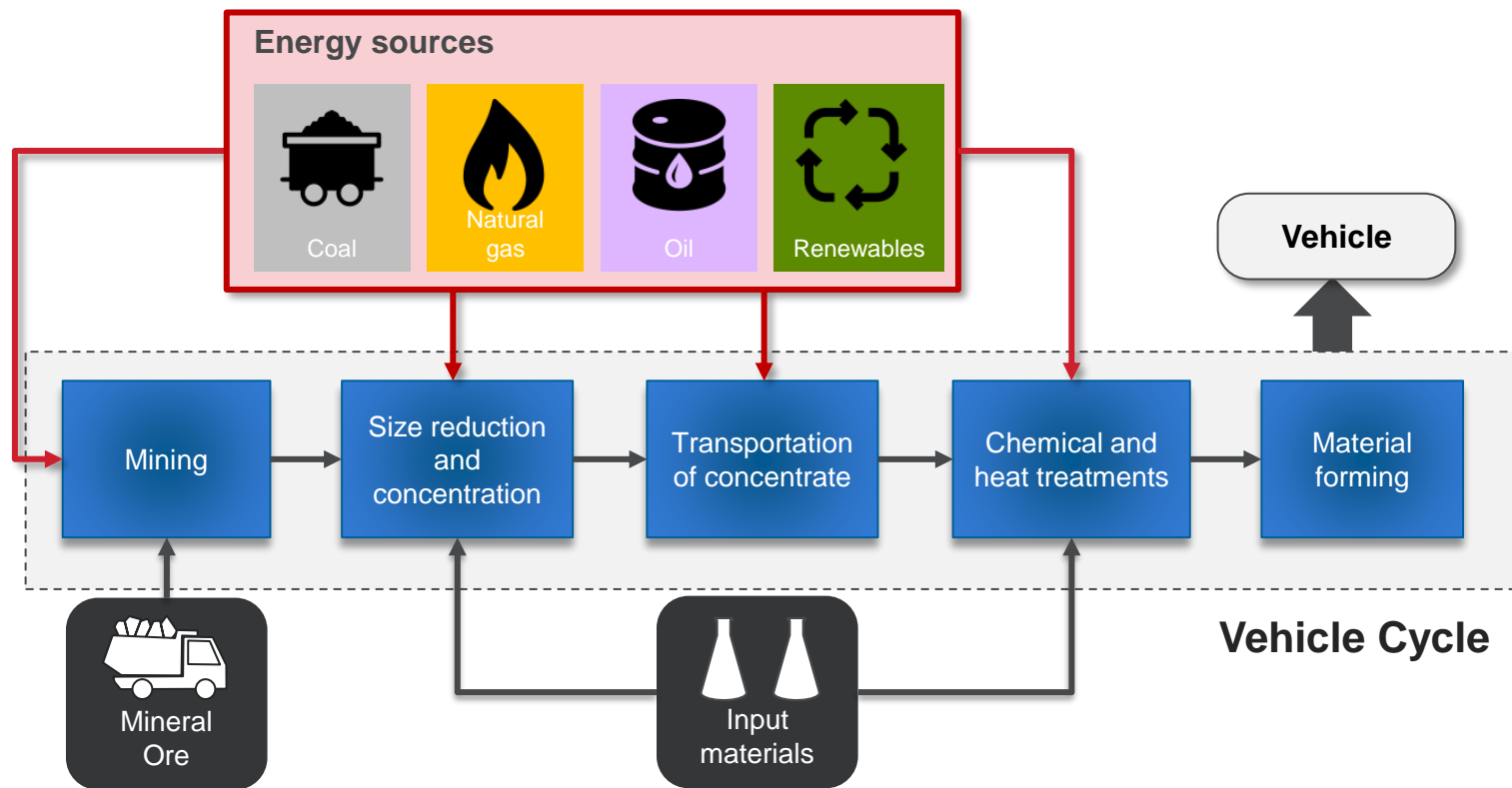


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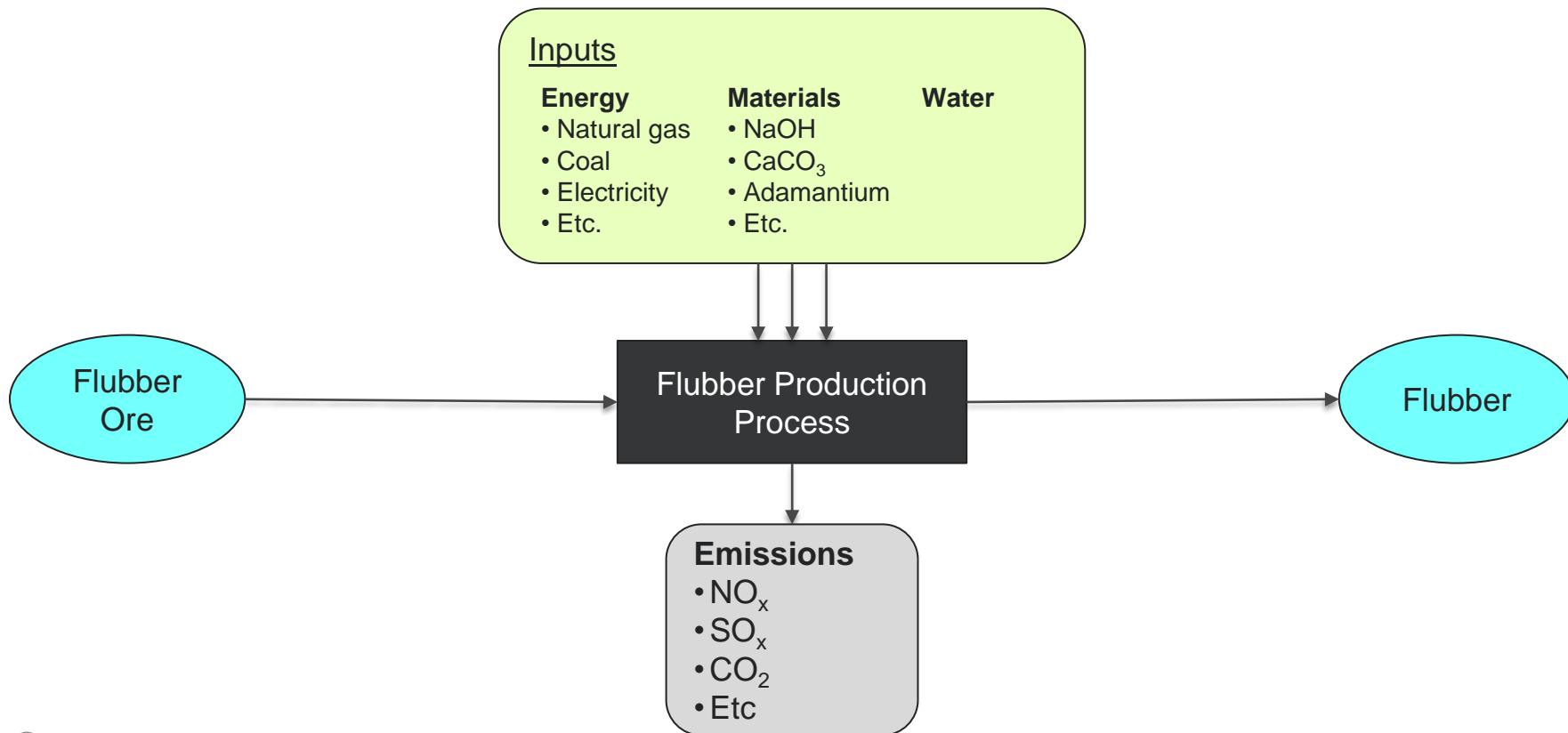


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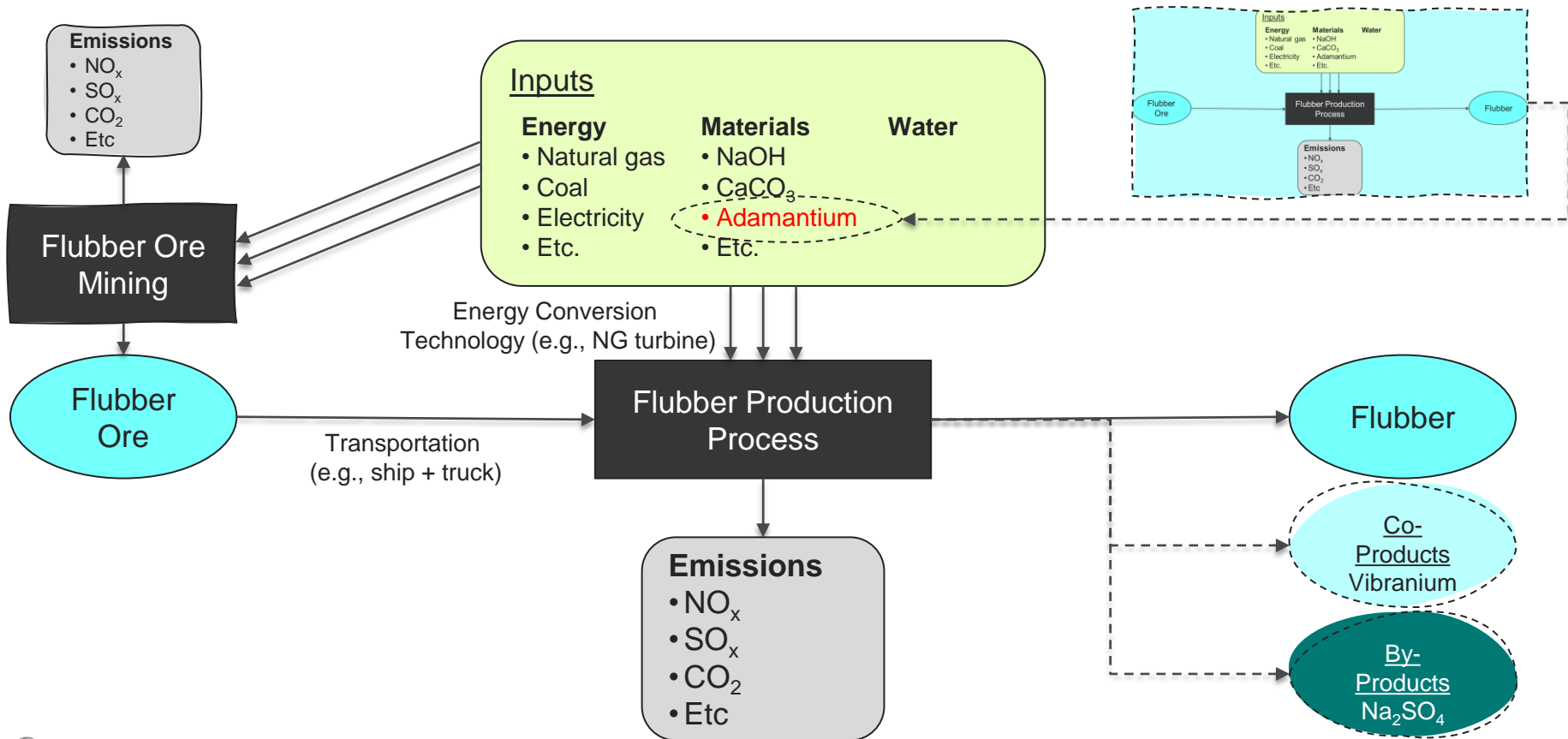
Material pathways: A general structure



Basic “How To” for an example material

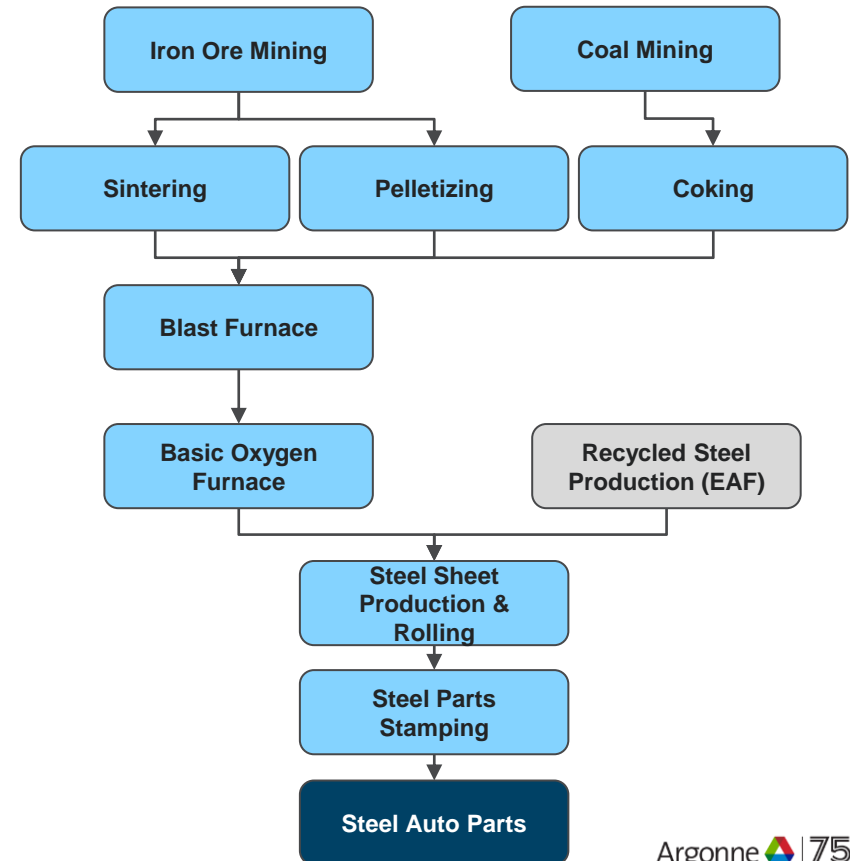


More detailed “How To” for an example material



Key parameters for material production: Steel

- Materials are modeled step-by-step from ore mining to part production
- Many materials can be, and are, produced in multiple ways
 - Blend of known production approaches when data are available
- Most steel is produced via either a Basic Oxygen Furnace (BOF) or an Electric Arc Furnace (EAF)
 - BOF steel is generally primary
 - EAF steel is generally secondary



REET outputs include energy use, criteria pollutants, greenhouse gases, and water consumption

Energy use

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

Air pollutants

- VOC, CO, NO_x, PM₁₀, PM_{2.5}, and SO_x
- Estimated separately for total and urban (a subset of the total) emissions

Greenhouse gases (GHG)

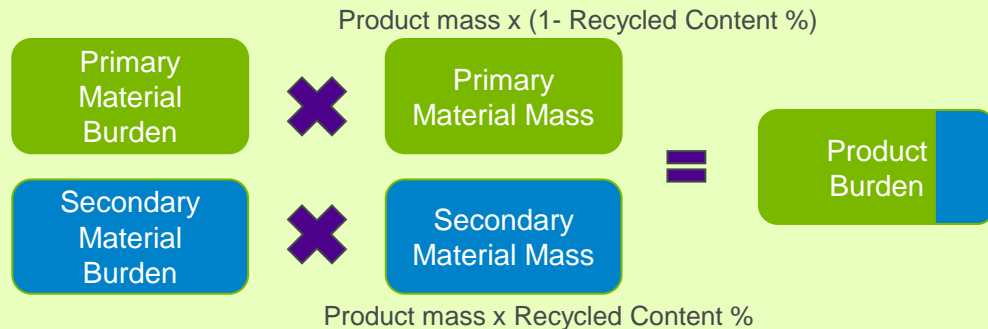
- CO₂, CH₄, N₂O, black carbon, and surface albedo
- CO_{2e} of the five (combined with their global warming potentials)

Water consumption

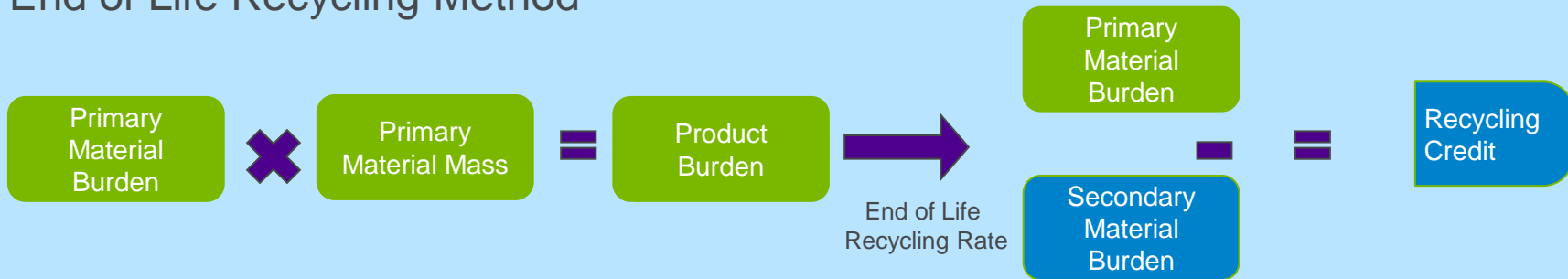
- Freshwater consumption
- Water stress, considering water supply and demand (energy-water nexus)

Treatment of recycled materials

Recycled Content Method

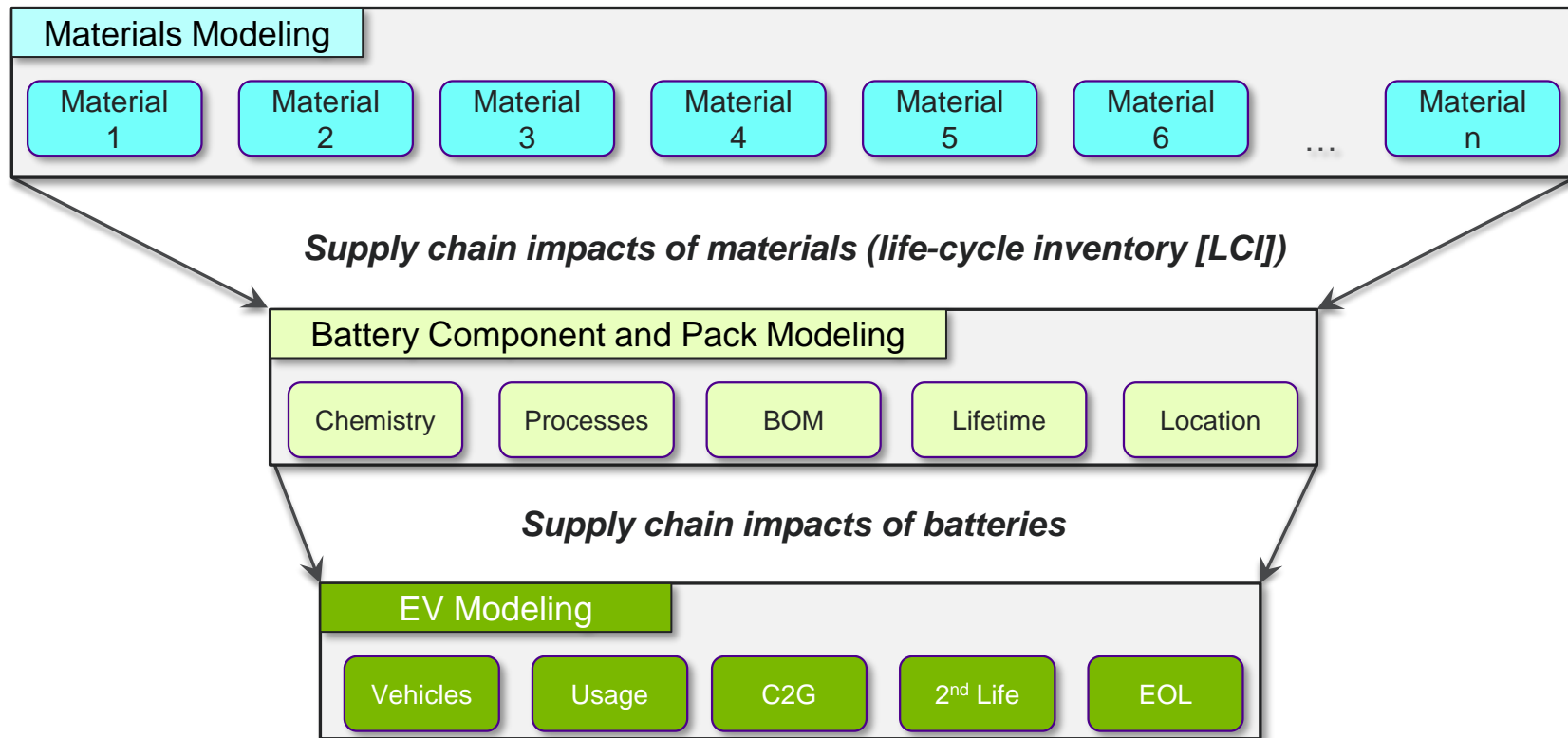


End of Life Recycling Method



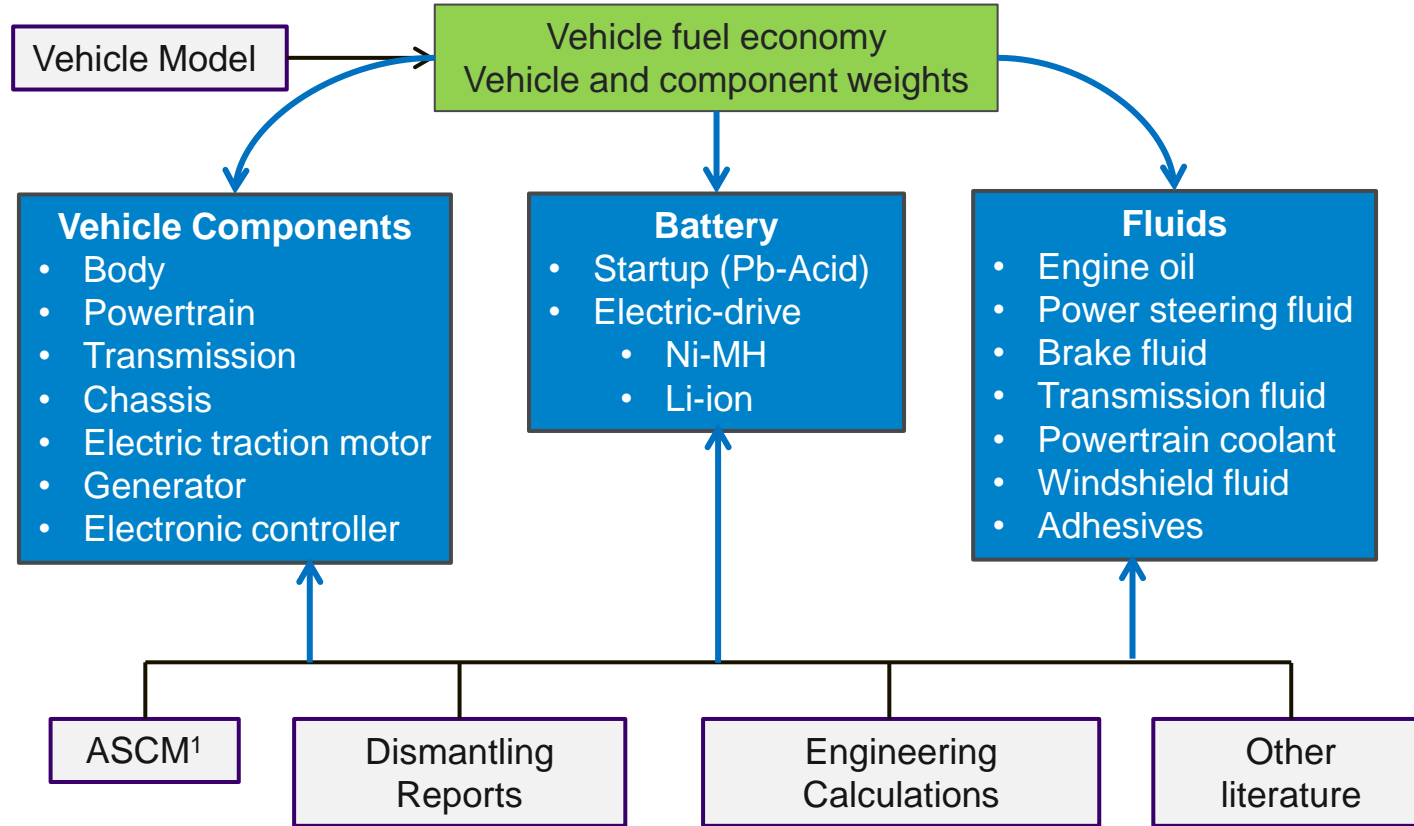
Materials and material processing create supply chains

Every vehicle is a collection of components which are a collection of materials



Impacts of EV production, use, and EOL

Approach to developing a materials inventory (bill of materials) for vehicles in GREET 2



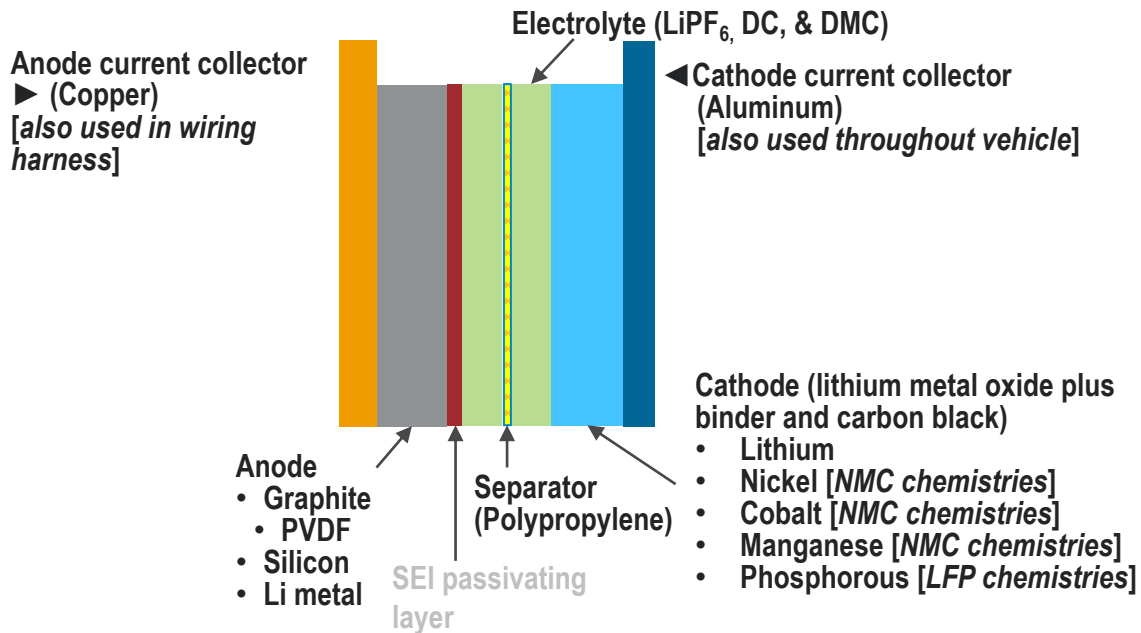
BEVs contain many critical materials both within batteries and other EV components; GREET has extensive coverage and ongoing improvement efforts

- ANL has modeled these battery components, their materials; cathode is a major driver

Battery

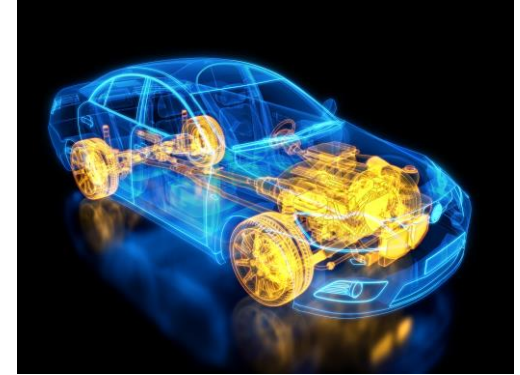
- Nickel
- Lithium
- Manganese
- Cobalt
- LiPF_6
- Ethylene carbonate
- Dimethyl carbonate
- Phosphorous
- PVDF
- NMP
- Graphite
- Silicon
- Li metal

Critical materials in a lithium-ion cell



Available vehicle powertrains and classes in GREET

- Car, SUV, and Pickup Truck
 - Internal combustion engine vehicle (ICEV)
 - Hybrid electric vehicle (HEV)
 - Plug-in hybrid electric vehicle (PHEV)
 - Battery electric vehicle (BEV)
 - Fuel cell vehicle (FCV)
- Class 6 (pick-up and delivery), Class 8 (regional haul, and long haul)
 - Internal combustion engine vehicle (ICEV)
 - Hybrid electric vehicle (HEV)
 - Battery electric vehicle (BEV)
 - Fuel cell vehicle (FCV)



Parametric vehicle details from Argonne's Autonomie

- Autonomie is a detailed vehicle simulation model (*Islam et al. 2021, ANL/ESD-21/10*)
 - Vehicle components sized through iterative process to meet technical specifications:
 - Acceleration,
 - Grade,
 - Maximum speed

Vehicle specification outputs

- Component sizing
- Energy consumption by cycle
- Weights
- Etc.

<https://publications.anl.gov/anlpubs/2021/10/171713.pdf>

Baseline vehicle total vehicle weight: (sans fluids)

	ICEV:	HEV:	FCV:	PHEV20:	PHEV50:	EV200:	EV300:	EV400:	EV500:
	Conventional Material	Conventional Material	Conventional Material	Conventional Material	Conventional Material	Conventional Material	Conventional Material	Conventional Material	Conventional Material
Model Year									
MY 2015	3,183	3,380	3,587	3,706	3,982	4,268	4,268	4,268	4,268
MY 2020	3,093	3,234	3,387	3,417	3,635	3,303	3,620	4,039	4,559
MY 2025	2,934	3,042	3,096	3,166	3,316	3,084	3,380	3,765	4,253
MY 2030	2,899	2,987	3,043	3,082	3,239	2,895	3,091	3,366	3,697
MY 2035	2,917	2,985	3,037	3,069	3,208	2,864	3,102	3,307	3,547
MY 2050	2,829	2,983	3,032	3,053	3,177	2,787	2,974	3,131	3,307

Battery Storage (kWh), for PHEV and EV

	PHEV20:	PHEV50:	EV200:	EV300:	EV400:	EV500:
	Conventional Material	Conventional Material	Conventional Material	Conventional Material	Conventional Material	Conventional Material
Model Year						
MY 2015	8	15	84	84	84	84
MY 2020	8	19	47	74	110	154
MY 2025	8	17	44	69	102	144
MY 2030	7	16	43	66	98	136
MY 2035	7	15	40	67	91	119
MY 2050	6	13	36	61	82	106

- Depending on the selected simulation year, GREET reads the relevant parameters for the simulation year, such as Fuel Economy, Vehicle Mass, Battery Sizes, etc.

What can we do with GREET?



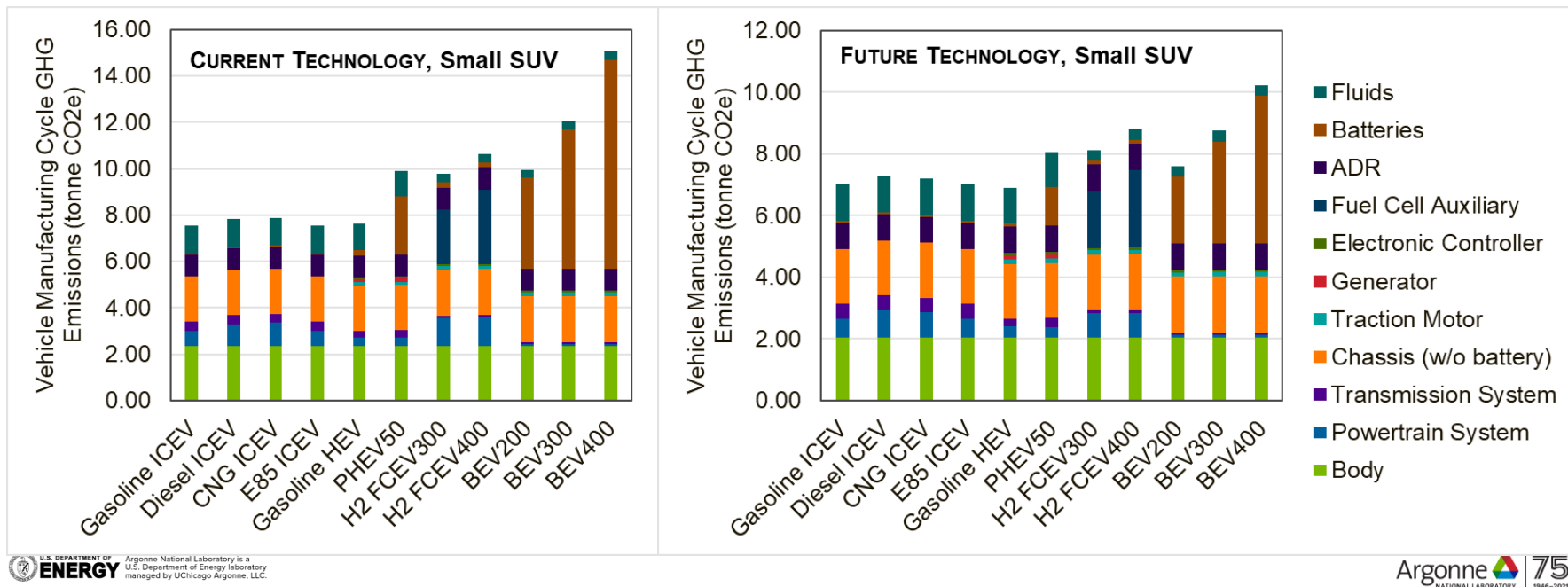
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Evaluate vehicle cycle greenhouse gas emissions

- How will a transition to alternative powertrains impact the vehicle cycle?
- CURRENT TECHNOLOGY shows greater GHG impact from alternative powertrains than FUTURE
- GREET provides a breakdown of impacts by vehicle system
- Battery size clearly impacts total embodied GHG emissions

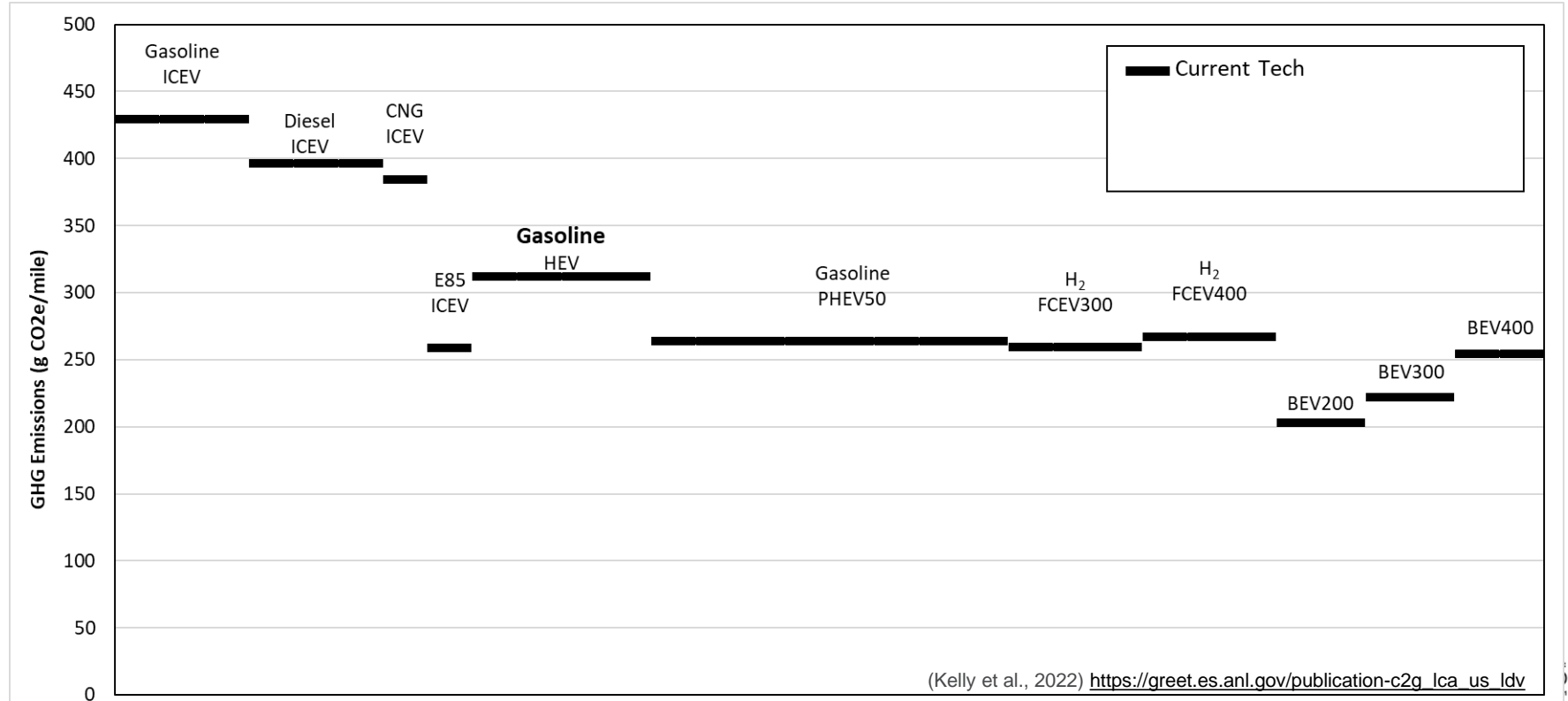


Coupling the detailed WTW analysis with the Vehicle Cycle can provide us with C2G impacts

	CURRENT TECHNOLOGY cases	FUTURE TECHNOLOGY Cases
Gasoline (E10)	U.S. average crude mix (blended with 10% corn ethanol)	Bio-renewable gasoline (pyrolysis)
		E-fuels (Nuclear electricity + CO2)
		E-fuels (Renewable electricity + CO2)
Diesel	U.S. average crude mix	Bio-renewable diesel (pyrolysis)
		Hydroprocessed renewable diesel (HRD) from soybeans
		20% Fatty Acid Methyl Ester (FAME) drop-in bio-based diesel (B20) from soybeans
		Gas-to-liquid Fischer-Tropsch Diesel (GTL FTD)
		E-fuels (Nuclear electricity + CO2)
		E-fuels (Renewable electricity + CO2)
CNG	U.S. average of conventional and shale gas mix	Renewable natural gas (NG) (from landfill gas)
Ethanol (E85)	85% corn ethanol (blended with 15% petroleum gasoline blendstock)	85% Cellulosic from corn stover (blended with 15% petroleum gasoline blendstock)
Hydrogen	Centralized production from Steam Methane Reforming (SMR)	Low temperature electrolysis from wind/solar
		High-temperature electrolysis using nuclear energy
		Natural gas SMR with Carbon Capture and Storage (CCS)
Electricity	EIA-AEO U.S. average electricity generation mix in 2020	Natural gas Advanced Combined Cycle (ACC)
		Natural gas ACC with CCS
		Wind
		Solar photovoltaic (PV)

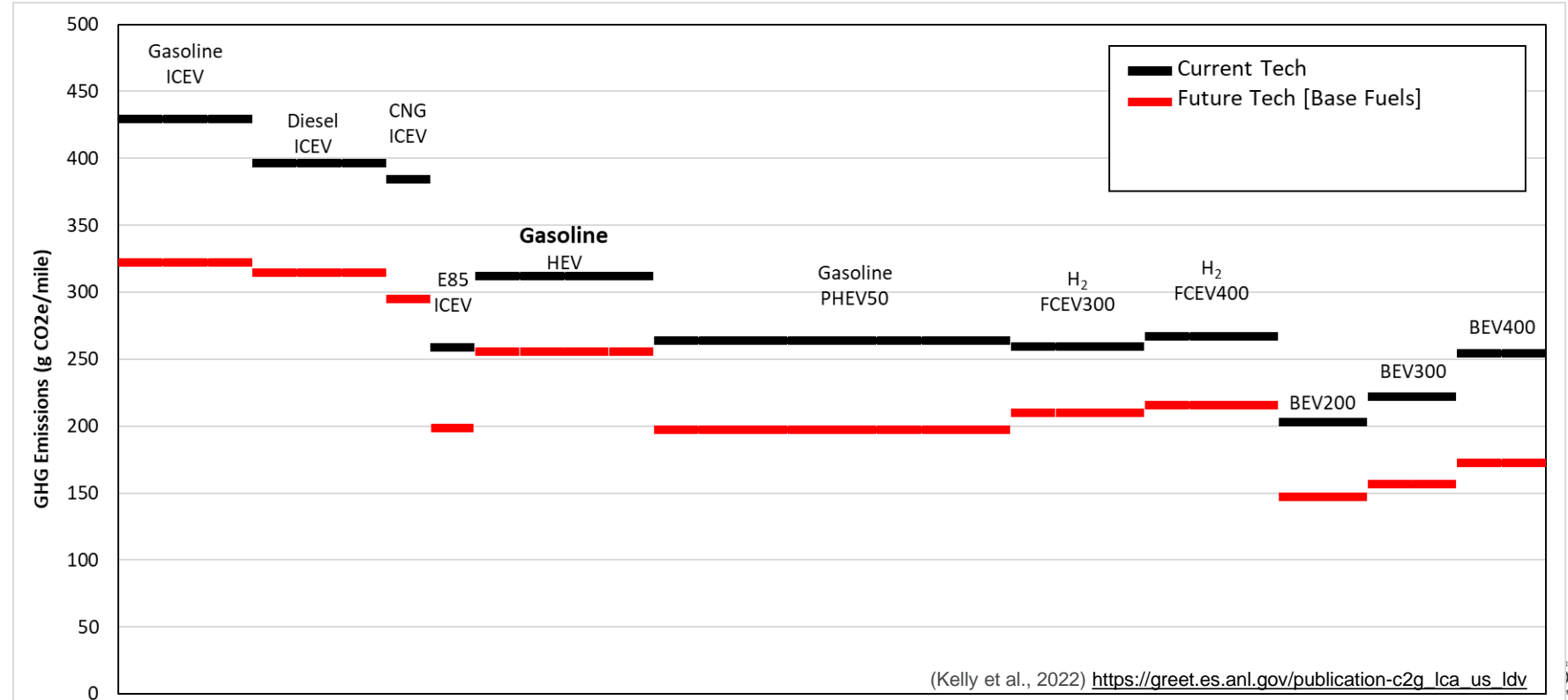
Cradle to grave Small SUV GHG emissions

What is the current picture for this analysis?



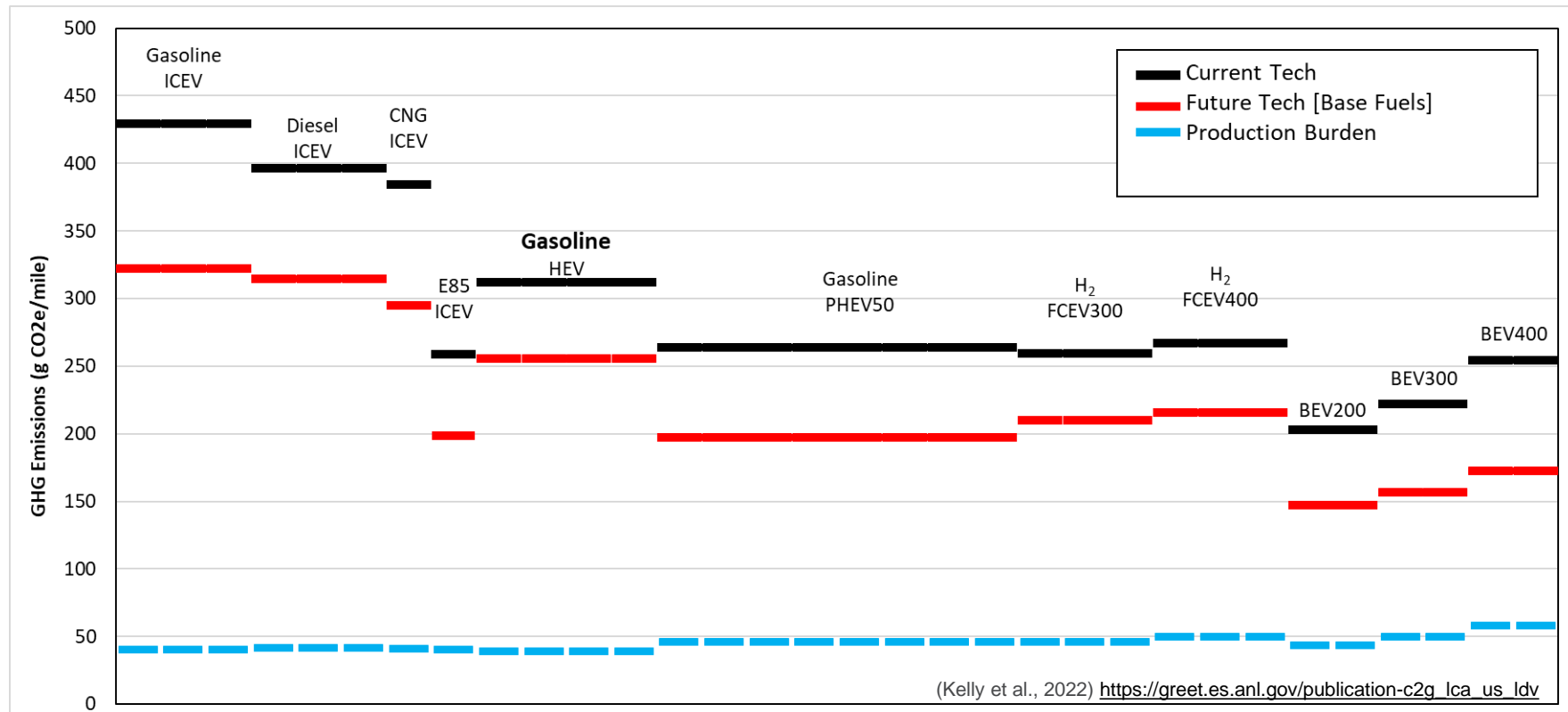
Cradle to grave Small SUV GHG emissions

How can technology improvements in powertrains reduce GHG emissions?



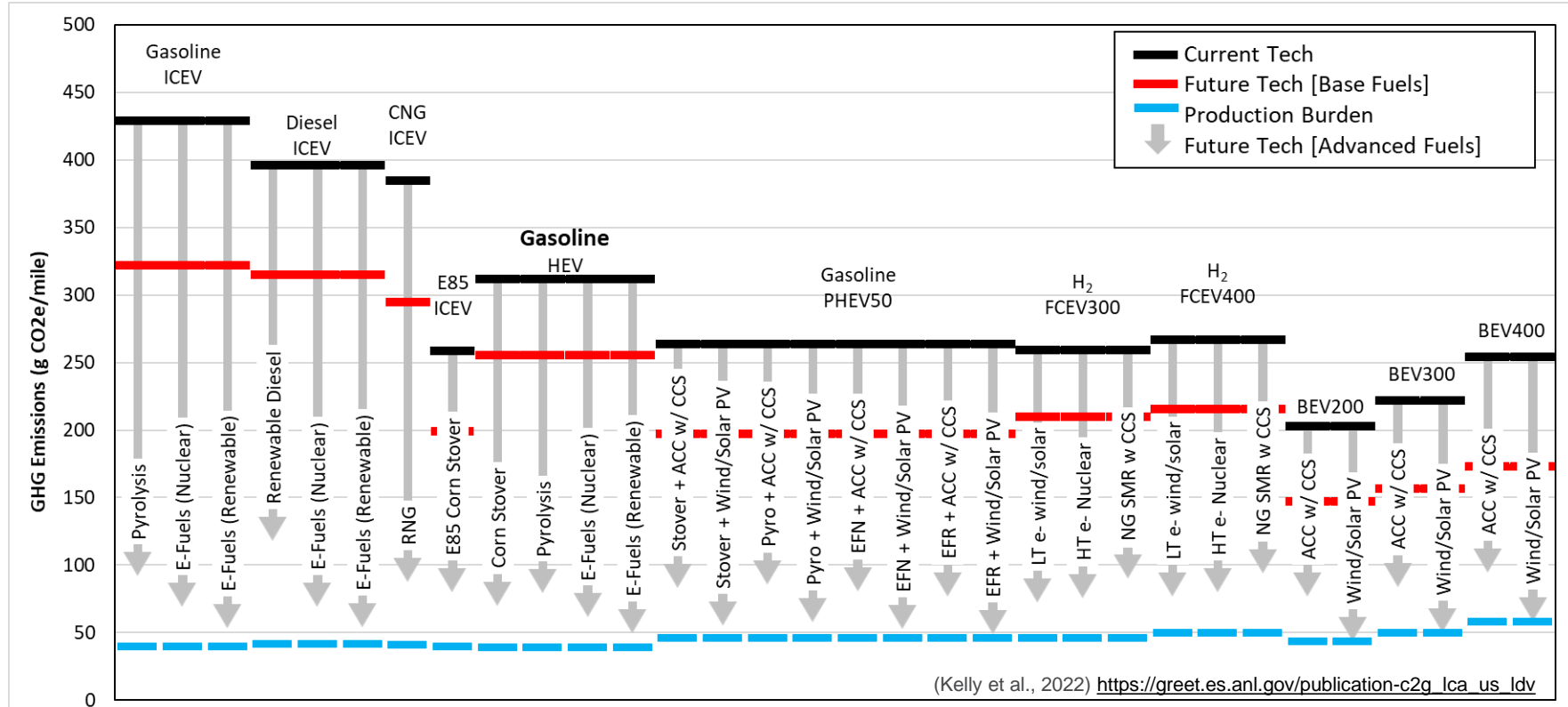
Cradle to grave Small SUV GHG emissions

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



Cradle to grave Small SUV GHG emissions

Finally, how can we decarbonize through different energy pathways?



Acknowledgements

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Questions?

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