ANL VTO Analysis Modeling Program

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June 21, 2022

2022 DOE VTO AMR

Project ID: van017

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Project Overview

Timeline	Barriers Addressed
• Project start date: 10/01/2019 • Project end date: 09/30/2022 • Percent complete: 90%	• Indicators and methodology for evaluating environmental sustainability • Evaluating energy and emissions benefits of vehicle/fuel systems • Overcoming inconsistent data, assumptions, and guidelines
Budget	**Partners**
• Total Project Funding: $1.5 M • Funding for FY22: $500 K	• Industries: OEMs and energy companies via US DRIVE • Other National Labs: NREL, ORNL, LBNL • Other org.: Univ. of Michigan, UC Davis • Aluminum Association and American Iron and Steel Institute

Project Overall Objectives

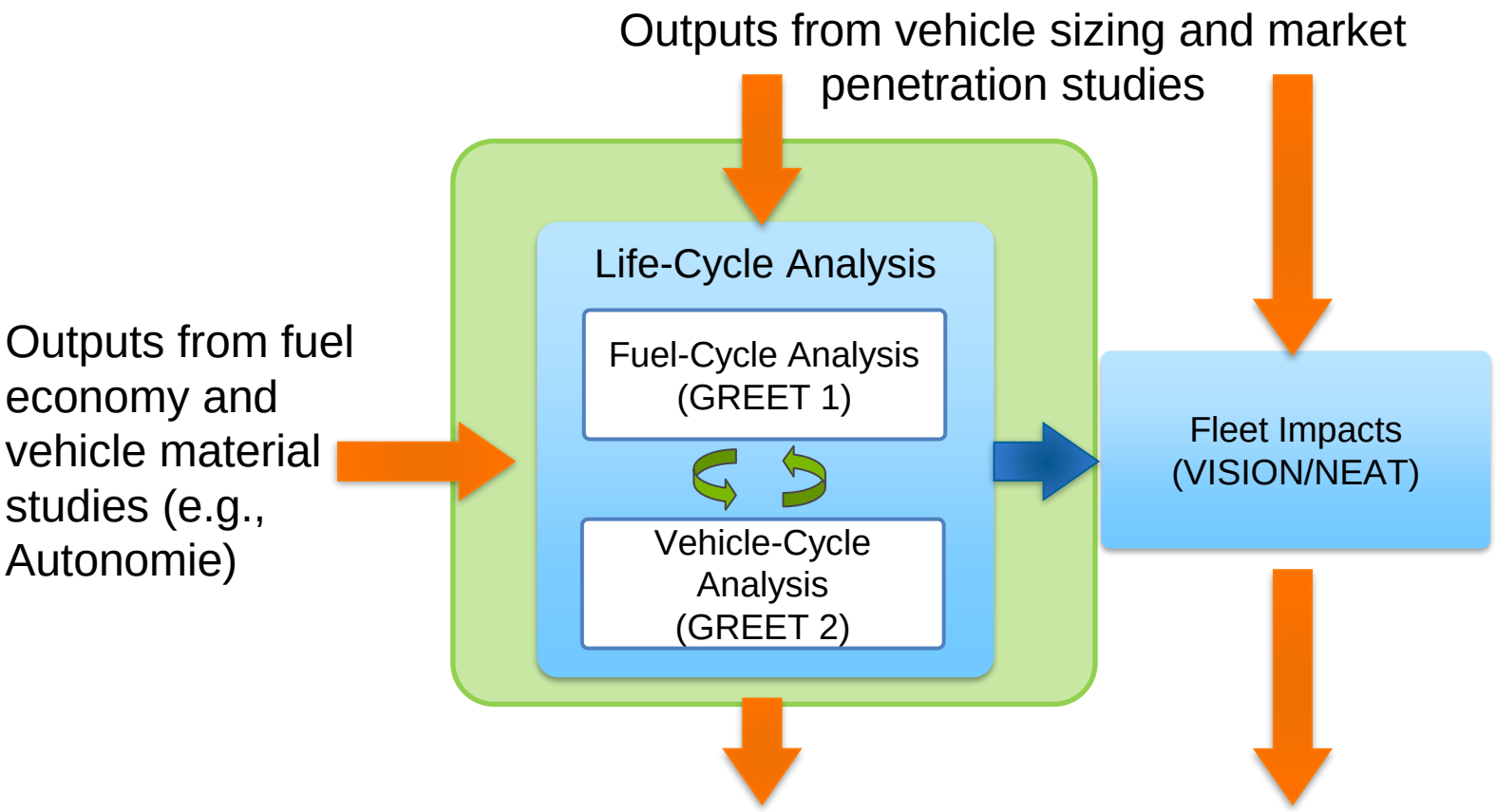
- Overcome inconsistent data, assumptions, and guidelines by developing transparent models:
  - The **GREET** life-cycle analysis (LCA) models holistically evaluate the energy and environmental impacts of vehicle/fuel systems with both a fuel cycle and a vehicle cycle, and address emerging technologies and mobility options.

- To develop indicators and methodology for energy and environmental sustainability, and to evaluate the energy and environmental benefits of vehicle/fuel systems, both models include:
  - Energy use, especially related to petroleum reductions from advanced vehicle technologies and alternative transportation fuels
  - Greenhouse gas (GHG) emissions impacts of vehicle/fuel systems
  - Air pollutant emissions impacts (NOx, PM10, SOx, VOC, etc.)
  - Water consumption of different transportation fuels

Task-Specific Objectives

- ***Task 1:*** Expand modeling GREET to include select medium- and heavy-duty vehicles (MHDVs) for vehicle cycle analysis
- ***Task 2:*** Develop regional GHG and criteria air pollutant emissions for power plants and refineries and assess the well-to-wheels (WTW) environmental impacts of MHD Battery Electric Vehicles (BEVs) at the regional level
- ***Task 3:*** Perform integrated system assessment of vehicle/fuel systems to develop cradle-to-grave (C2G) GHG emissions and costs for small SUVs and midsize sedans
- ***Task 4:*** Release of GREET model annually and publication of WTW record

Internal Linkage Within GREET and Interaction with Other VTO Analysis Projects and Models



- Outputs to VTO Program Benefits Analysis
- Analysis informing industry through US DRIVE partnership

FY22 Milestones and Accomplishments

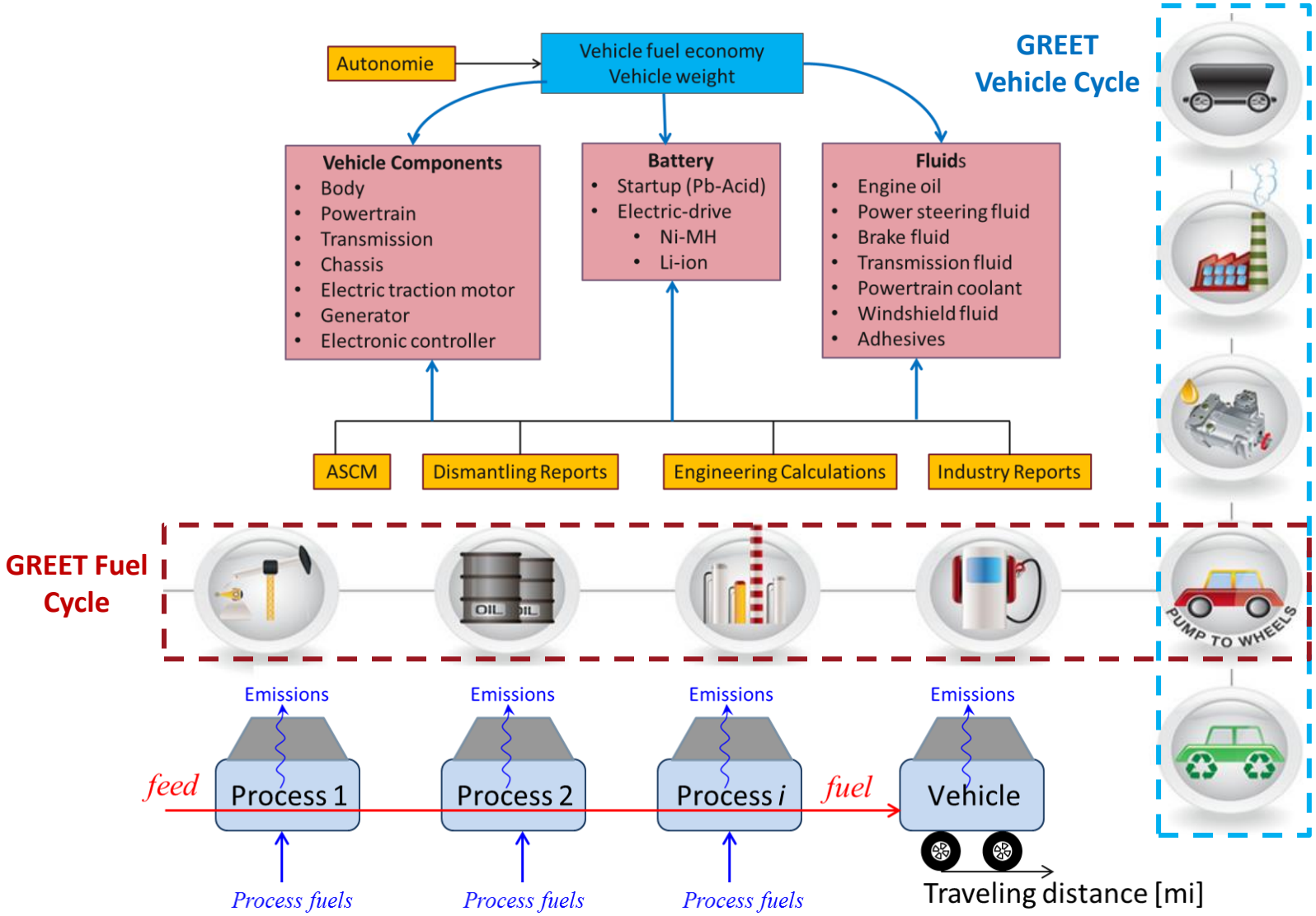
- Collect and analyze vehicle fuels and materials supply chain data

- Develop models and analyze issues related to vehicle operation and manufacturing

- Conduct LCA of various vehicle/fuel systems
- Publish GREET model and results

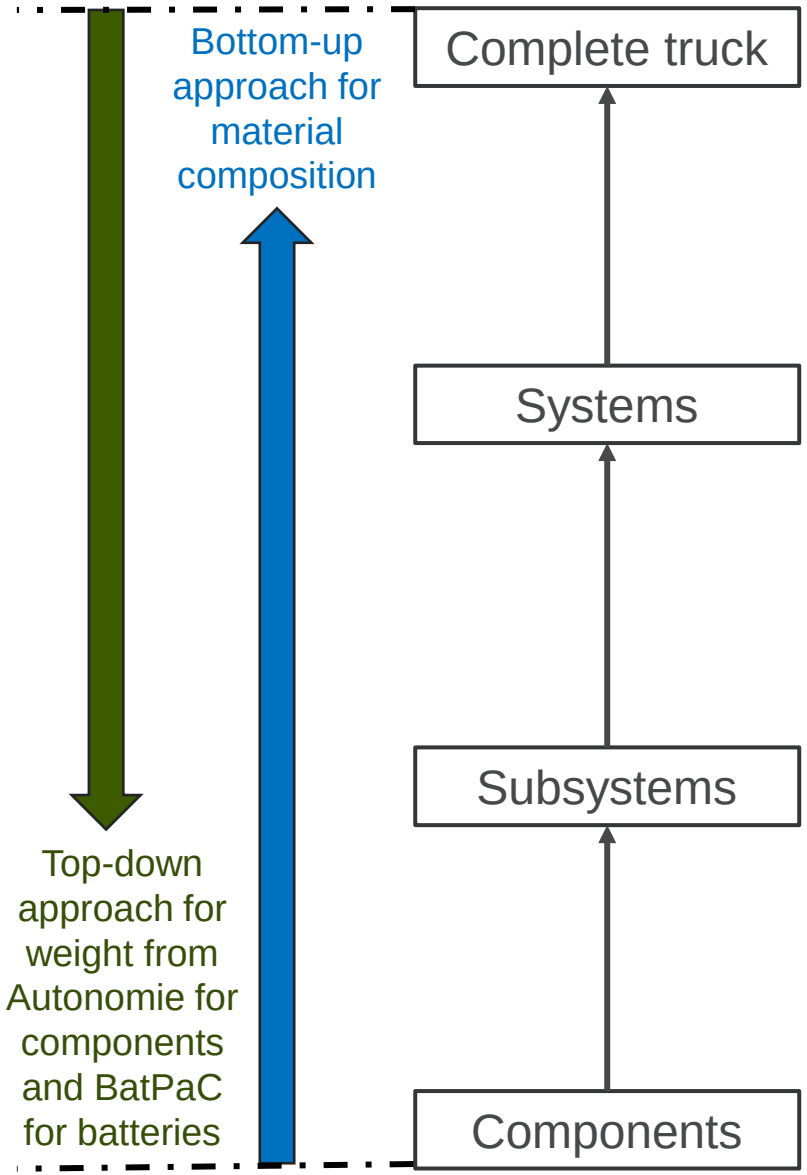
Milestone	Milestone Name / Description	Milestone Type	Milestone Status
Q1	Collect data for life cycle inventory analysis of key critical materials	Quarterly	Completed
Q2	Data collection for transportation-related Criteria Air Pollutant (CAP) emissions	Quarterly	Completed
Q3	Document LCA results for ISATT	Quarterly	Completed
Q4	Annual update and release of GREET models	Annual	On track

GREET® Life Cycle Analysis – Approach



Life-cycle analysis of MHDVs

Inventory analysis approach for medium- and heavy-duty vehicles (MHDVs)



Class 6 pickup-and-delivery (PnD) truck

Class 8 regional day-cab and long-haul sleeper-cab trucks

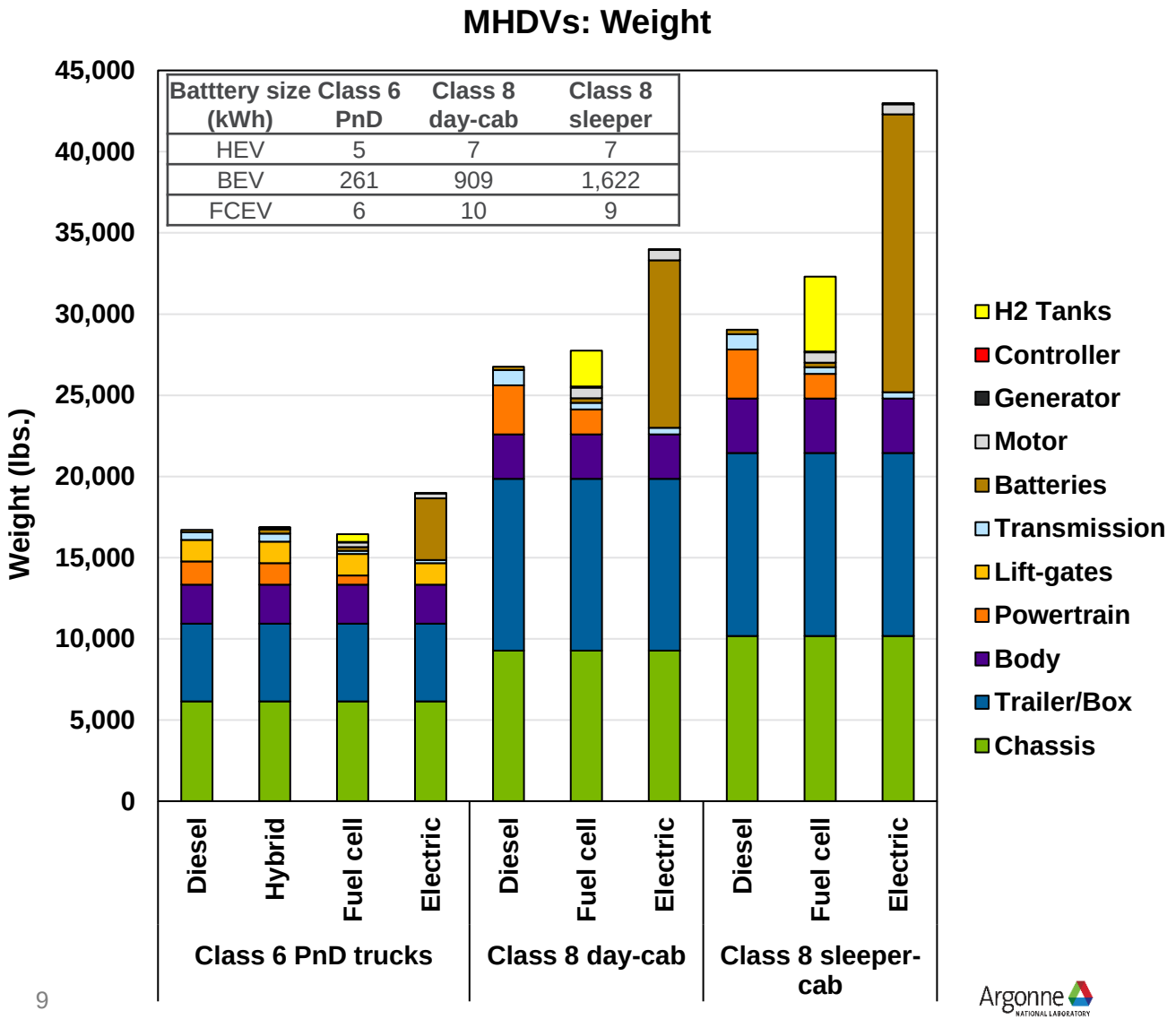
Powertrain	Chassis	Transmission	Electric drive
Truck body	Trailer/Box	Batteries	Others

Chassis: Axles (steer/drive), suspensions, brakes, cross-members, frame
Powertrain: Engines (with fuel tanks and cooling), fuel-cell stacks
Truck body: Cab-in-white, sleeper unit, fairings, hood, windows, interior
Electric drive: Traction motor, electronic controller
Trailer/Box: Body, trailer chassis (axle/wheel/tire/suspension/brake)
Others: H_2 tanks, auxiliary systems

Examples include engine block, fifth wheel, gearbox, instrument panel, etc.

MHDV weight composition shows that advanced powertrains weigh more than conventional diesel

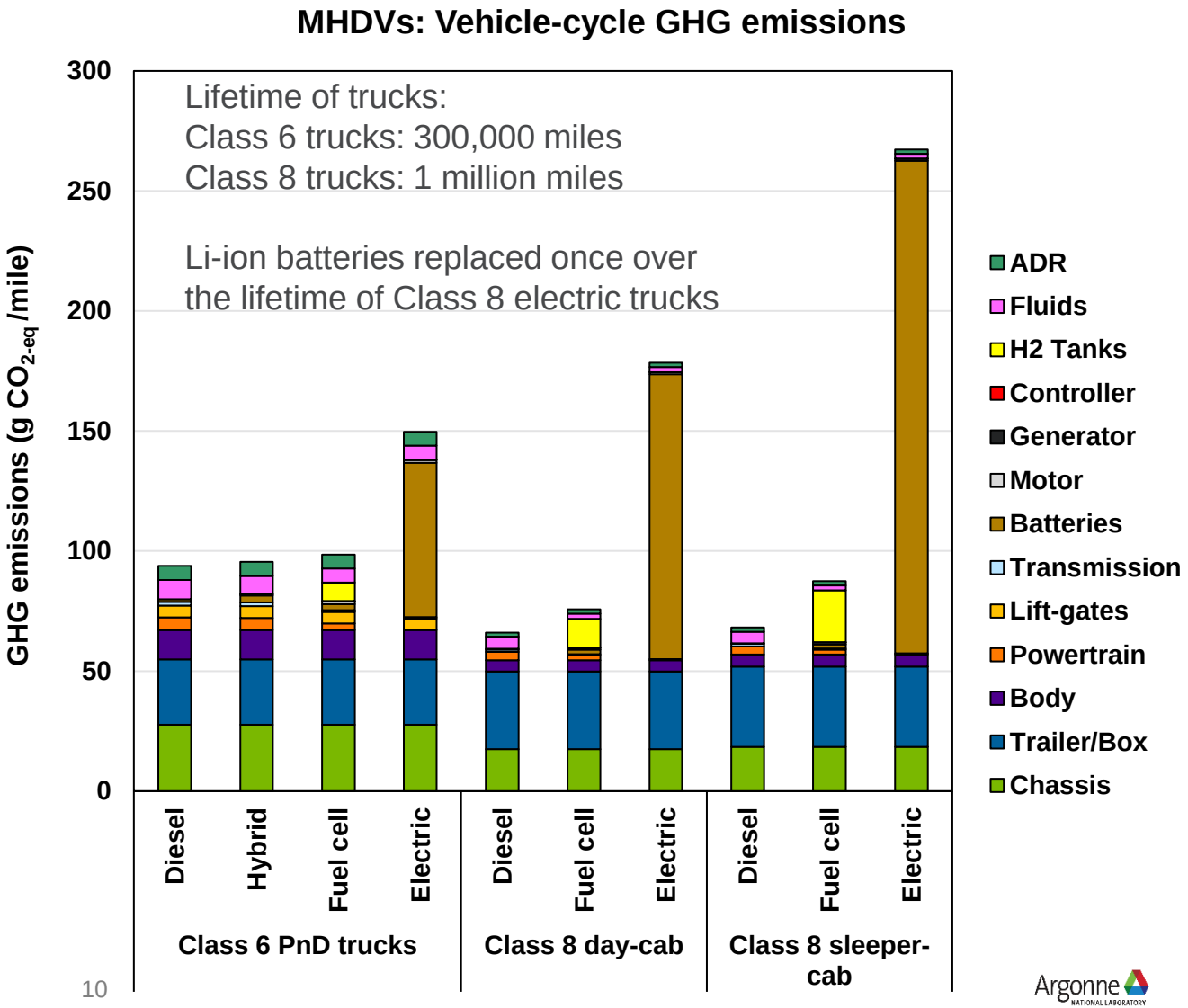
- **Major contributors:**
  - Chassis, trailer/box, body, and lift-gates constitute the bulk (~60-90%) of MHDV weight
  - Propulsion-specific systems account for 8-40% of mass:
    - Diesel & Hybrid trucks: Powertrain
    - Electric trucks: Batteries
    - Fuel cell trucks: H_2 tanks (Class 8)
  - Contributions stem from:
    - Use of steel in all components
    - Aluminum use in trailer/box, body, powertrain (diesel) and lithium-ion batteries (electric)
    - Mass of lithium-ion batteries (cathodes, anodes, and copper current collector)
    - Carbon fiber-reinforced plastic (CFRP) and stainless steel in H_2 tanks (fuel cell trucks)



Batttery size (kWh)	Class 6 PnD	Class 8 day-cab	Class 8 sleeper
HEV	5	7	7
BEV	261	909	1,622
FCEV	6	10	9

Vehicle-cycle GHG emissions follow the general trend of vehicle weight

- **Major contributors:**
  - Common systems (along with ADR* and fluids) constitute the majority (~60-90%) of vehicle-cycle emissions:
    - Exceptions: Class 8 electric trucks
  - Effect of propulsion-specific systems on vehicle-cycle emissions ranges widely:
    - Diesel & Hybrid trucks: Powertrain (~5%)
    - Electric trucks: Batteries (45-75%)
    - Hybrid trucks: FC systems (15-30%)
  - Outsized influence of components for alternative powertrains is a result of their constituent materials/aspects:
    - Batteries (Li-ion): Cathode, anode, battery assembly, battery replacement (Class 8)
    - H_2 tanks: CFRP

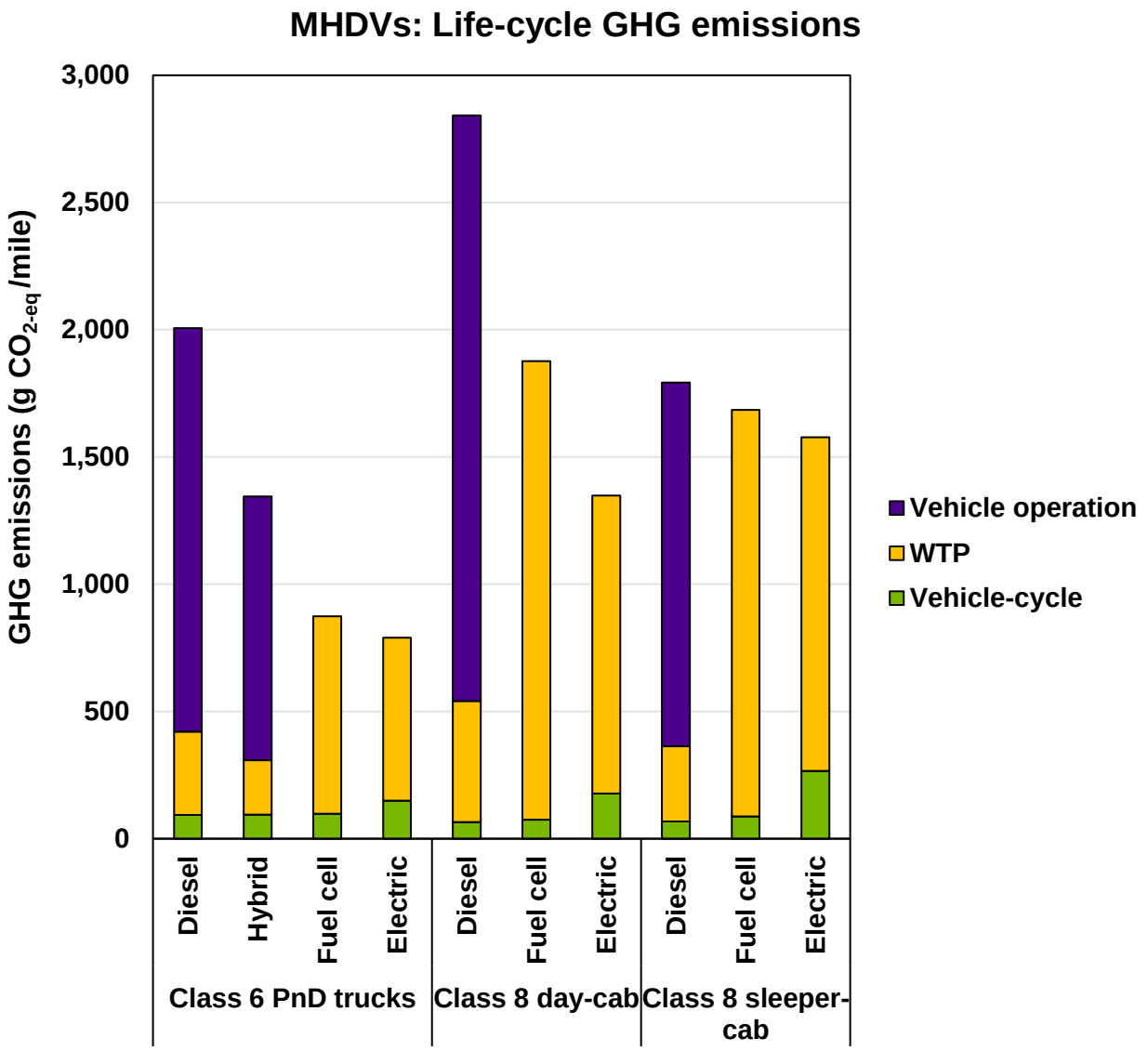


*ADR-Assembly, disposal, and recycling

Life-cycle GHG emissions are dominated by the use phase regardless of the powertrain

- **Order of life-cycle GHG emissions for all MHDVs:**
  - BEV less than FCEV less than ICEV
    - The **opposite of vehicle-cycle effects**!
  - Benefit of alternative powertrains vary by application:
    - Highest for Class 6 trucks (~60%)
    - Lowest for Class 8 sleeper-cab trucks (~8-12%)
- **Energy efficiency ratios**
  - The efficiency of advanced powertrains varies by application

Powertrain	Energy Efficiency Ratios		
	Class 6 PnD	Class 8 day-cab	Class 8 sleeper-cab
Diesel	100%	100%	100%
Hybrid	153%	-	-
Fuel cell	252%	118%	110%
Electric	403%	233%	178%



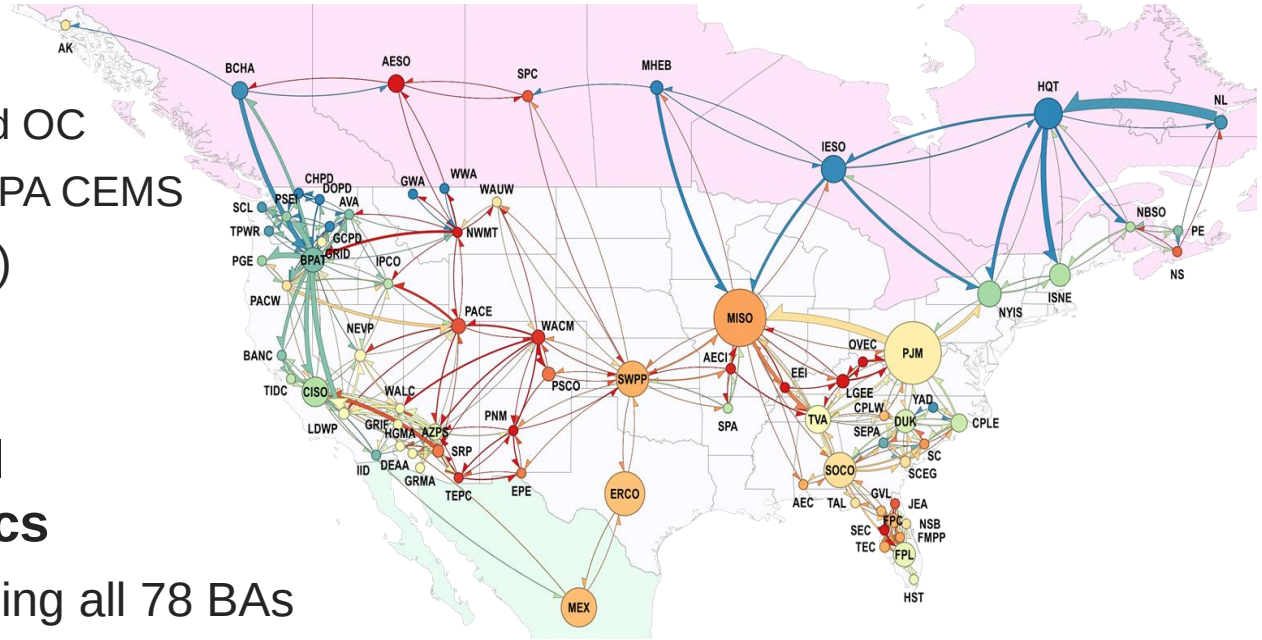
* R.K. Iyer, J.C. Kelly, and A. Elgowainy, *Vehicle-cycle & Life-cycle analysis of Medium & Heavy-Duty Trucks* (forthcoming)

Regional GHG and CAP Emissions for Power Plants and Refineries

- **Facility-level data sources for power plants and refineries**
  - GHG, including CO_2, CH_4, and N_2O
    - EPA GHGRP, EIA Electric Power Data
  - Criteria air pollutants (CAP)
    - including VOC, CO, NO_x, SO_2, PM_{10}, $PM_{2.5}$, BC, and OC
    - EPA NEI2014, NEI2017, EIA Electric Power Data, EPA CEMS
  - Activity data (for estimation of missing emissions)
    - EIA Form-923, EIA Refinery Capacity Report, etc.

US electricity network is operated by balancing authorities (BA)

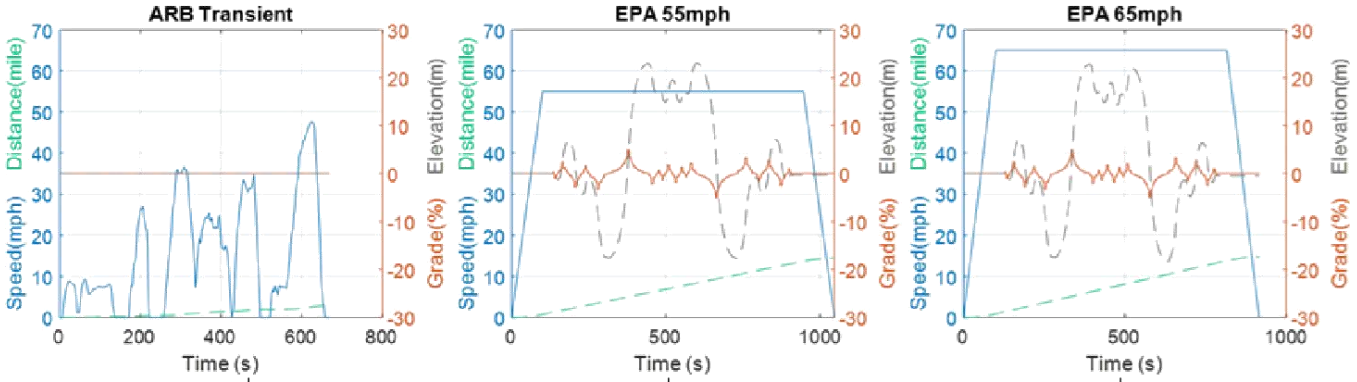
Electricity flows among BAs and the corresponding GHG intensities

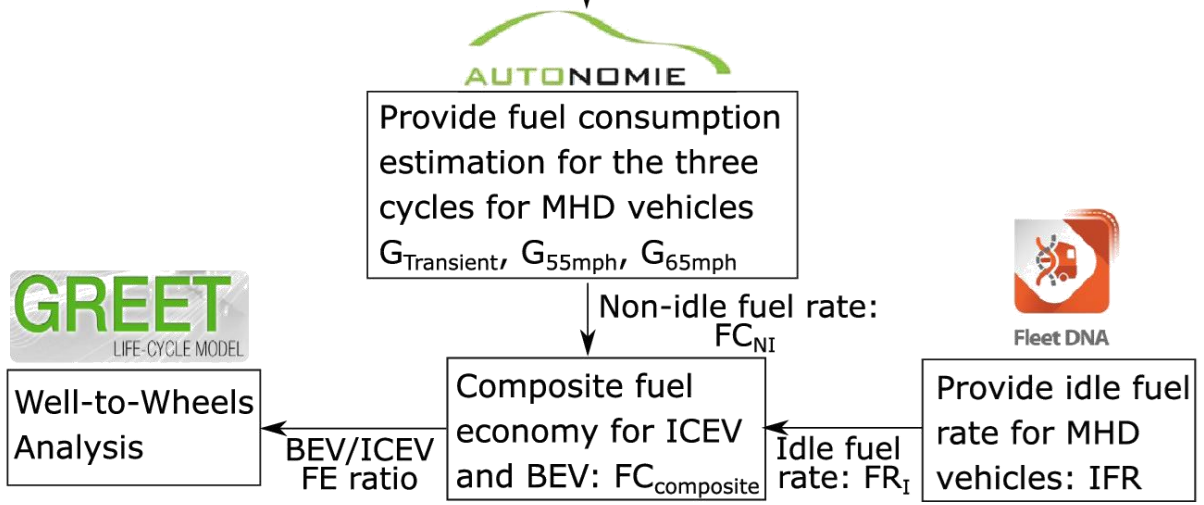


- **Seasonal and sectoral variations of regional consumption-based electricity characteristics**
  - Use a network-based modeling framework including all 78 BAs in the North American electrical grid
  - Collect and process fuel consumption, electricity generation, interchange, sales by sector, and emissions of GHGs and CAPs at the monthly and BA levels
  - Use Argonne's GREET.Net software to implement the framework and derive consumption-based electricity results

WTW comparison of ICEV and BEV for MHD trucks at the state level

- **Based on Argonne's recent national WTW analysis of MHD BEV trucks**
  - Liu et al., EST, 55, 538–546, 2021
- **Expand to the state level with consumption-based regional electricity characteristics**
- **Consider 6 types of MHD trucks**
  - Class 8 long-haul combination
  - Class 8 short-haul combination
  - Class 8 refuse
  - Class 6 medium heavy-duty vocational
  - Class 4 light heavy-duty vocational
  - Class 2 pickup trucks and vans
- **Use Argonne's Autonomie model to estimate the fuel economy of individual truck technologies**
- **Use Argonne's GREET model for WTW analysis of both GHGs and CAPs**



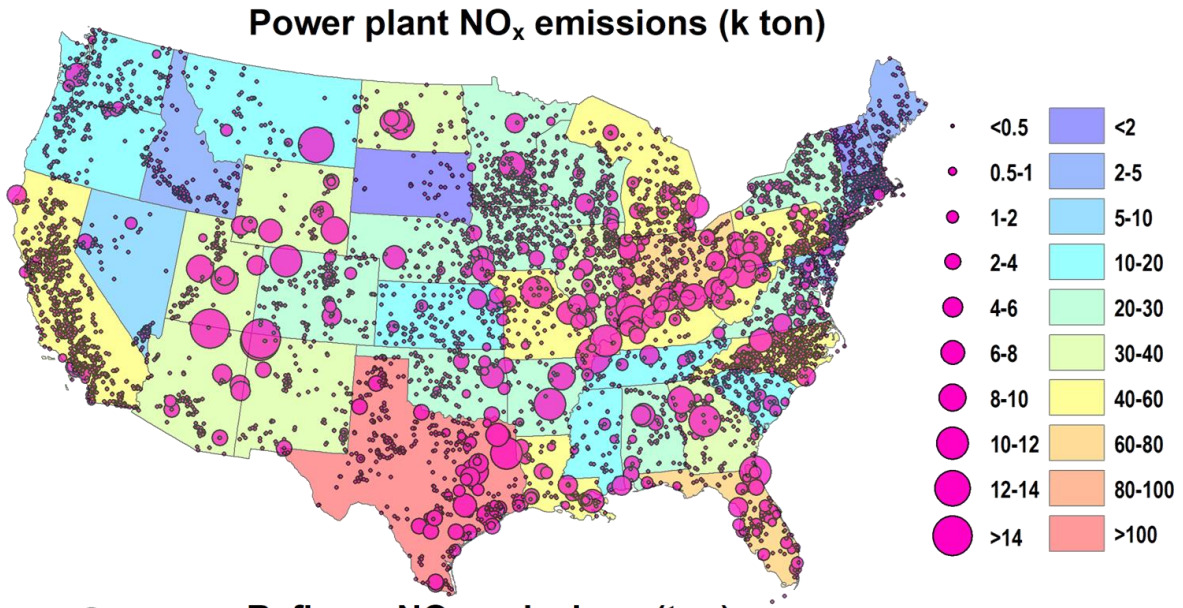


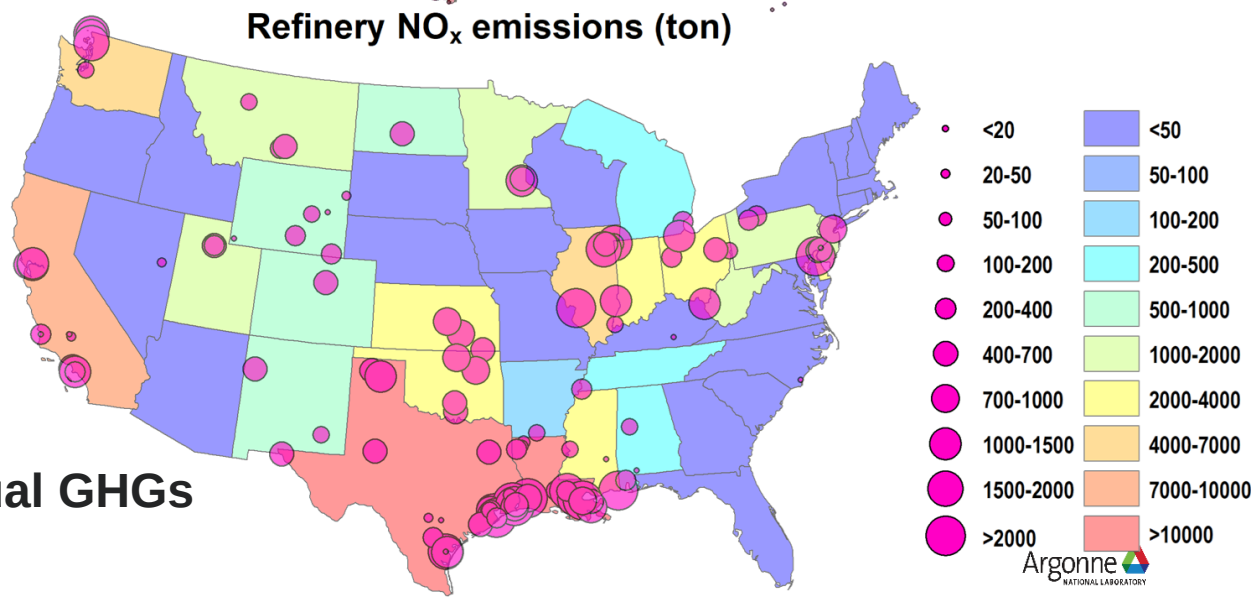
GHG and CAP Emissions for Individual Power Plants and Refineries

National summary

	Power plants	Refineries
No. of facilities	8700+	130+
Base year	2017	2019
CO_2 (M ton)	1961	216
CH_4 (k ton)	156	11.3
N_2O (k ton)	26.2	1.82
VOC (k ton)	33.3	17.8
CO (k ton)	604	47.9
NO_x (k ton)	1415	87.0
SO_x (k ton)	1424	27.6
PM_{10} (k ton)	148	23.0
$PM_{2.5}$ (k ton)	117	20.0
BC (k ton)	5.96	2.43
OC (k ton)	19.4	3.03

Example: NO_x

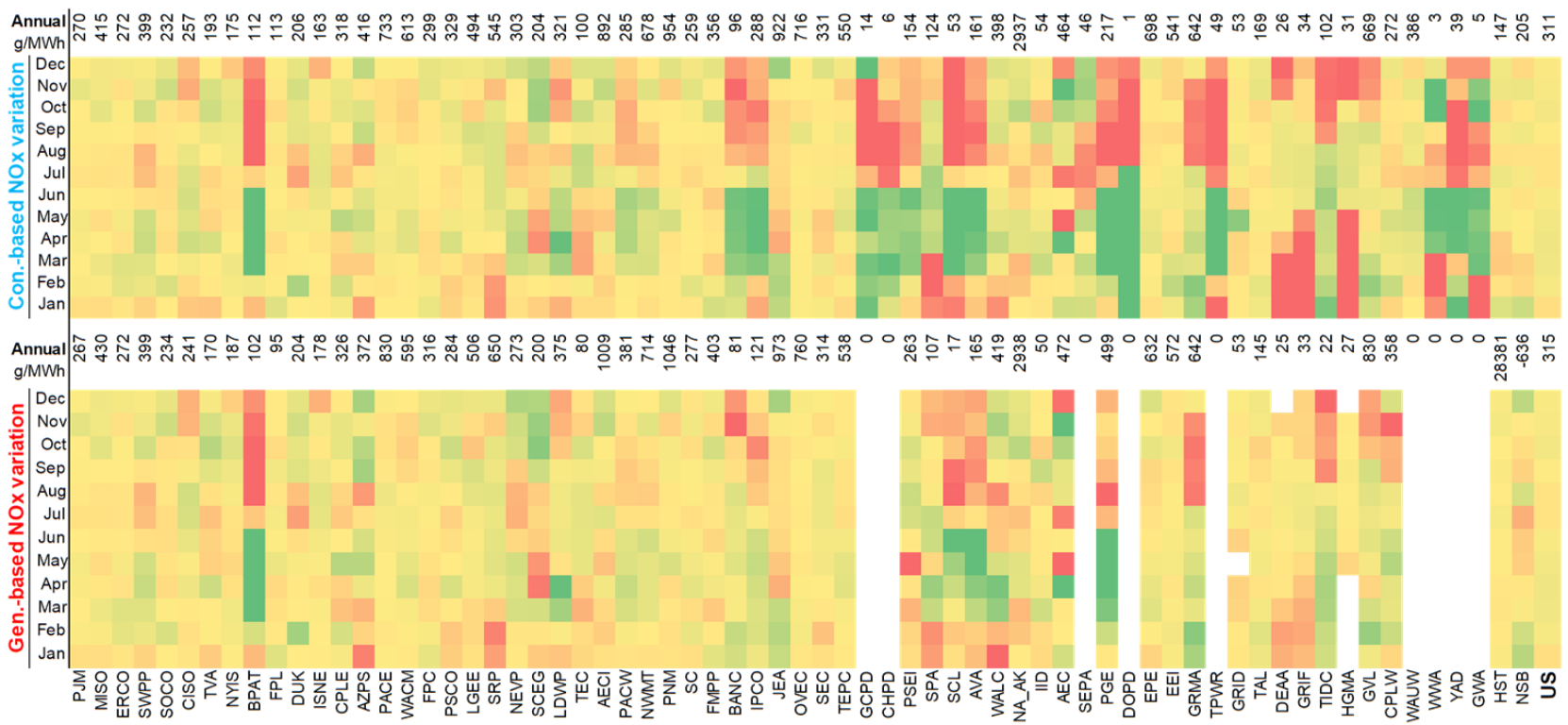




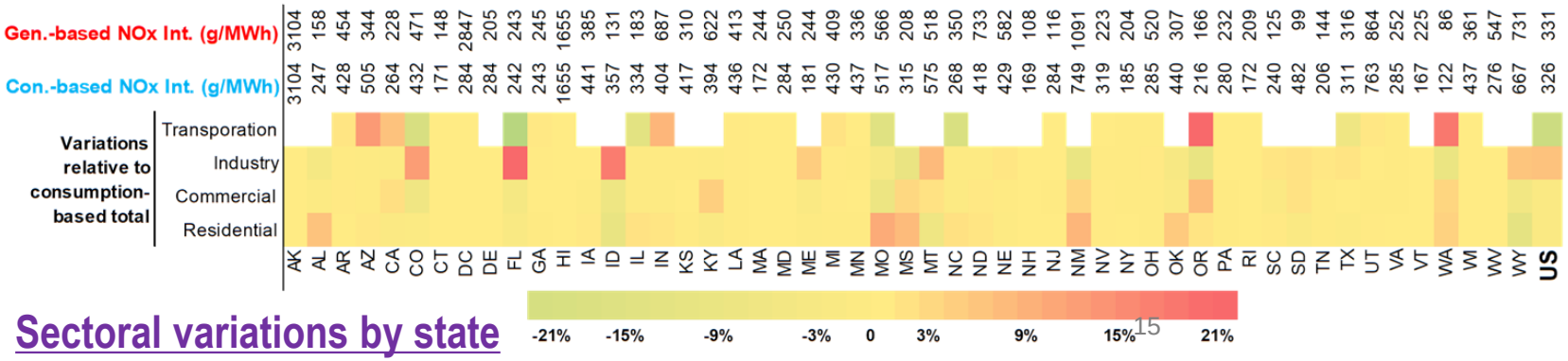
- **Results are available for other CAPs and individual GHGs**
- **ANL is working on updating estimates to 2020**

Beyond GHGs, Seasonal and Sectoral Regional Electricity CAP Emissions Added in FY22

NO_x as an example



Monthly variations by BA



Sectoral variations by state

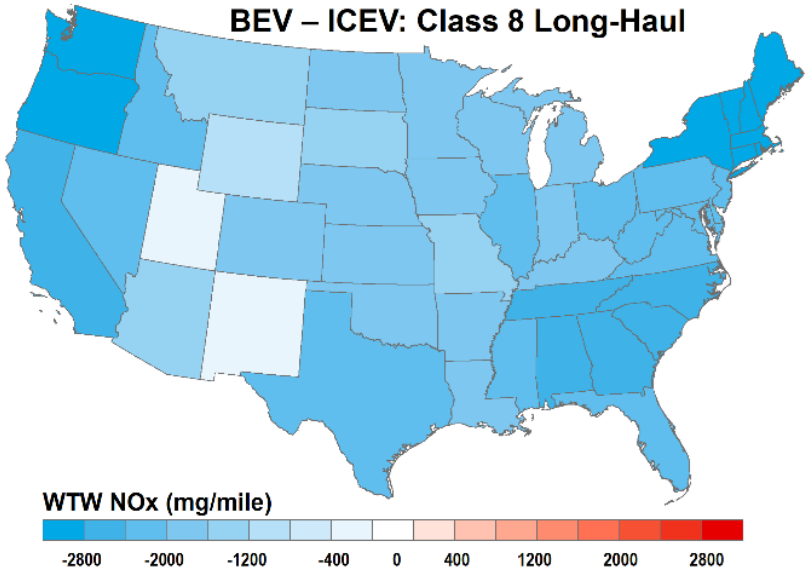
- **Consumption-based electricity characteristics differ from generation-based ones, particularly for small regions**
- **Electricity characteristics (CAP, GHG, and mixes) show highly spatial and temporal variations**
- **Electricity used in different sectors are not the same**
  - Nationally, electricity used in the industry sector is more GHG and CAP-intensive than that used in other sectors

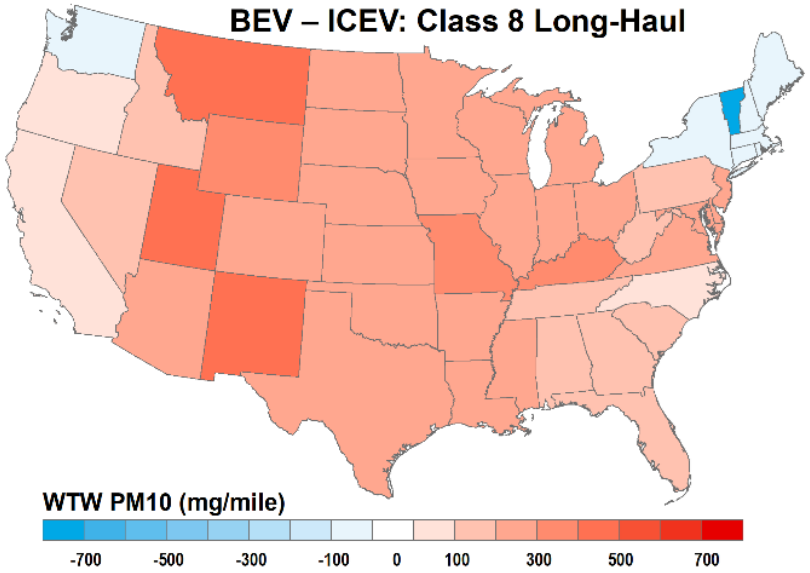
  e.g., 6.0% for GHG,13.5% for SO_2, 6.4% for NO_x

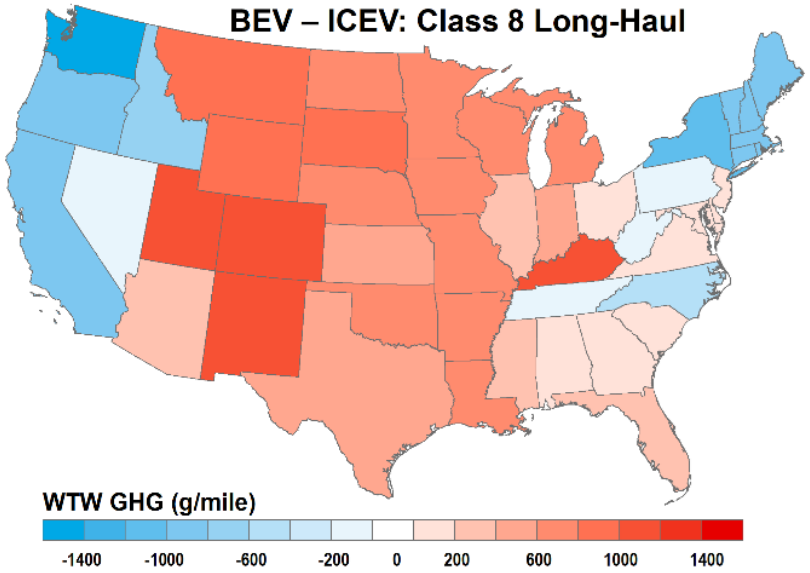
  Transportation sector only includes the electricity used in power railroads and railways
- **Seasonal and sectoral variations of electricity characteristics could change the life-cycle comparison of related technologies significantly**
- **Results are available for other CAPs, GHGs, energy use, and mixes**

WTW Comparison of Diesel ICEV and BEV for MHD Trucks

Example: Class 8 long-haul combination for NO_x, PM_{10}, and GHG







- **Consumption-based electricity characteristics are used for BEVs evaluation**
- **Environmental impacts of MHDV electrification are mixed at the regional level. Class 8 long-haul BEVs have…**
  - **Less WTW NO_x emissions** than their ICEV counterparts in all continental U.S. states
  - Generally **higher WTW PM_{10} emissions** across the U.S. except for the Northwest and the Northeast, with their cleaner grids
  - **Mixed WTW GHG comparison** results relative to their ICEV counterparts

  * Results may vary by MHDV class
- **Results are available for individual GHGs and other CAPs and for other 5 types of MHD trucks**

Cradle-to-Grave (C2G) Life Cycle Analysis (LCA) of light-duty vehicles considering lifetime cost and GHGs

- Model and analyze current and future C2G GHG emissions and costs of midsize sedans and small SUVs for US DRIVE ISATT
  - Years: Current – 2020, Future – 2030-2035
  - Utilize Argonne's Autonomie simulation outputs (VAN023) for vehicle characteristics and costs using DOE parameters and OEM insights
  - Apply GREET to develop C2G GHG emissions for vehicle/fuel systems
  - Use DOE models and open literature to identify energy costs
  - Joint funding with HFTO

Vehicle Technologies and Fuel Types

Vehicle Technology	Gasoline*	Diesel	CNG	E-fuels	E85	H_2	Elec.
ICEV	X	X	X	X	X		
HEV	X						
H_2 FCEV (300, 400 mi)						X	
BEV (200, 300, 400 mi)							X
PHEV50 ¥	30%						70%

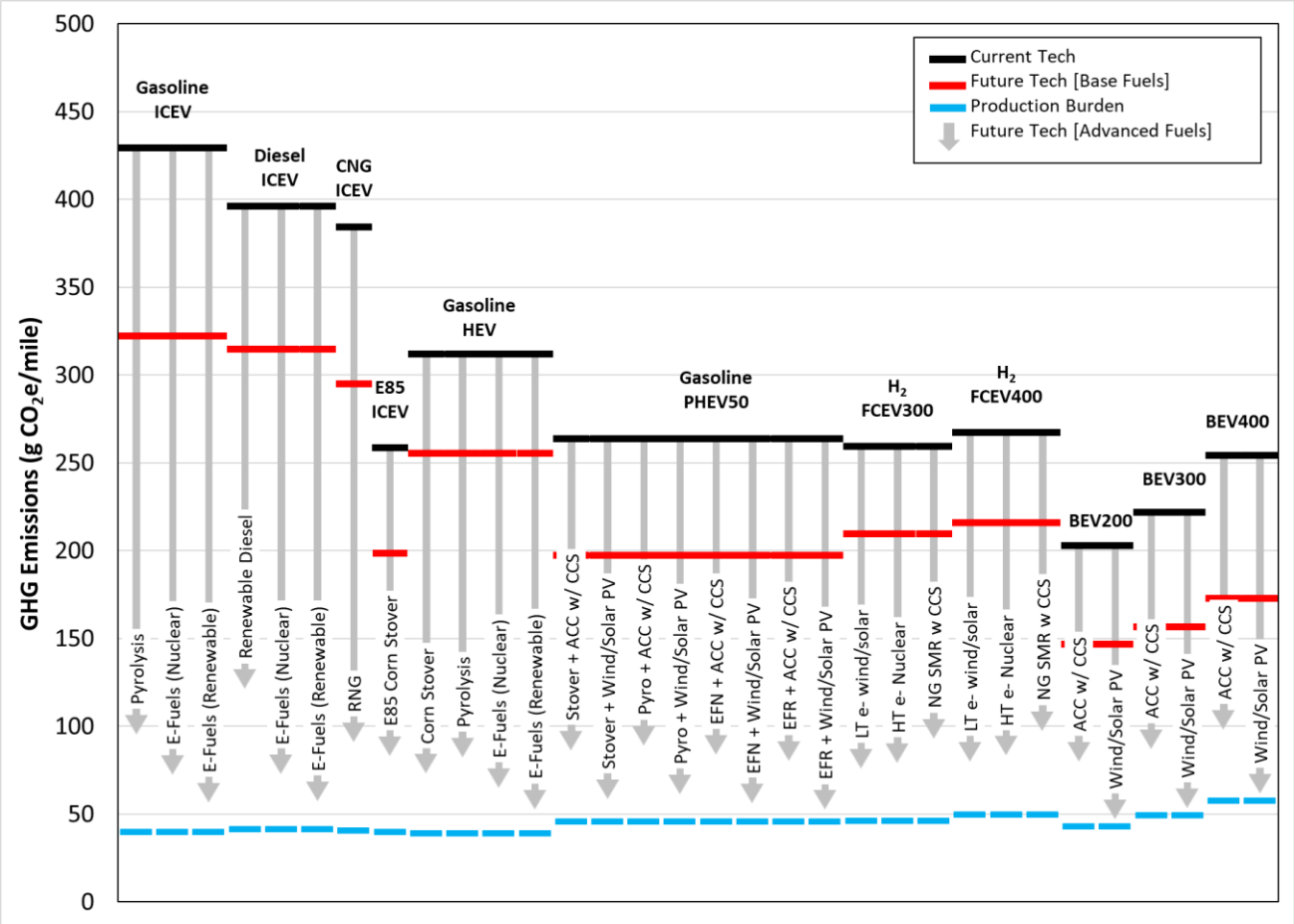
** Gasoline (E10) assumed to contain 10% corn ethanol by volume.*
¥ PHEV gasoline and electricity energy usage mix assumed per SAE J2841.

Consider Current and Future Fueling Pathways

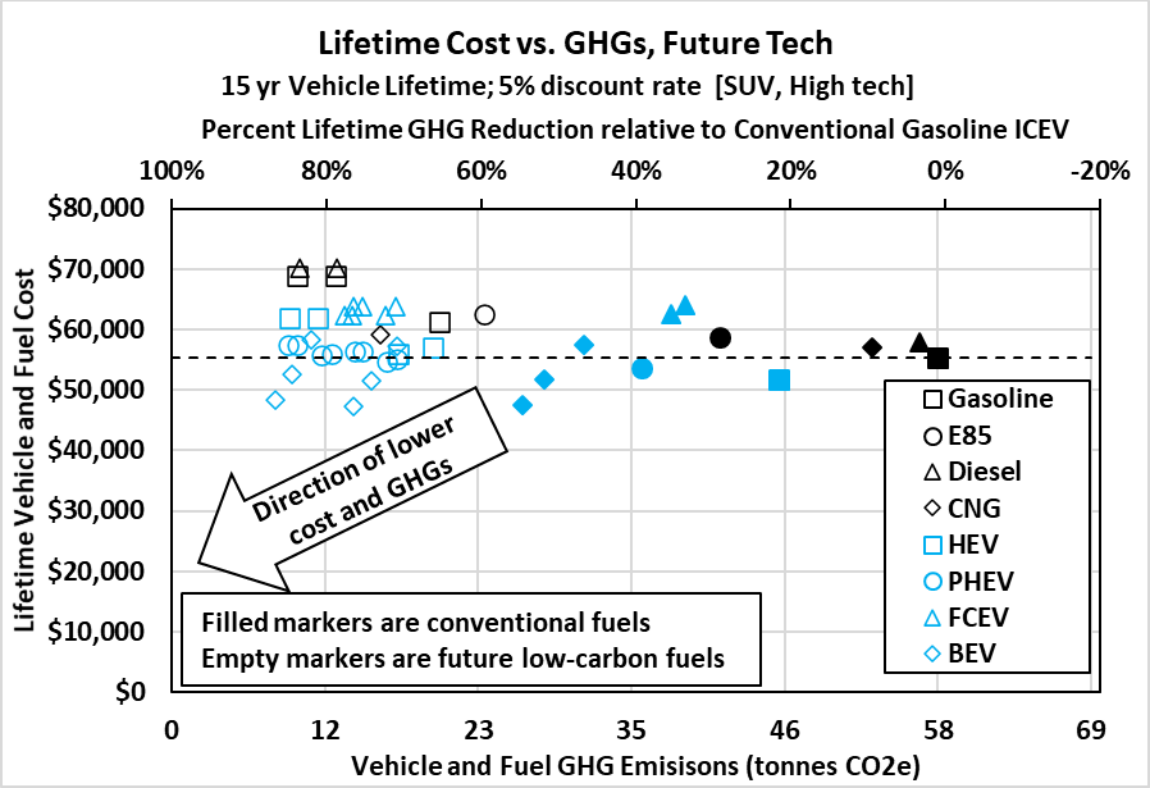
	CURRENT TECHNOLOGY	FUTURE TECHNOLOGY
Gasoline (E10)	U.S. average crude mix (w/ 10% corn ethanol)	Bio-renewable gasoline (pyrolysis)
		E-fuels (Nuclear electricity + CO2)
		E-fuels (Renewable electricity + CO2)
Diesel	U.S. average crude mix	Bio-renewable diesel (pyrolysis)
		20% fatty acid methyl ester (soybeans)
		E-fuels (Nuclear electricity + CO2)
		E-fuels (Renewable electricity + CO2)
CNG	U.S. average (conv./shale mix)	Renewable natural gas (NG) from landfill gas
Ethanol (E85)	85% corn ethanol (w/ 15% petroleum gasoline)	85% cellulosic from corn stover (w/ 15% petroleum gasoline)
Hydrogen	Centralized production from NG Steam Methane Reforming (SMR)	Low temp. electrolysis from wind/solar
		High temp. electrolysis from nuclear
		NG SMR with Carbon Capture and Storage (CCS)
Electricity	EIA-AEO U.S. average electricity generation mix in 2020	NG Advanced Combined Cycle (ACC) with CCS
		Wind power
		Solar photovoltaic (PV)

C2G LCA for LDVs shows opportunities to reduce both GHGs and costs, with deep carbonization for select pathways

- Integration of cost analysis with GHG analysis yields insight into both the cost and decarbonization potential of advanced vehicle and advanced fueling technologies



Life cycle GHG for current and future small SUVs considering different vehicle-fuel pathways

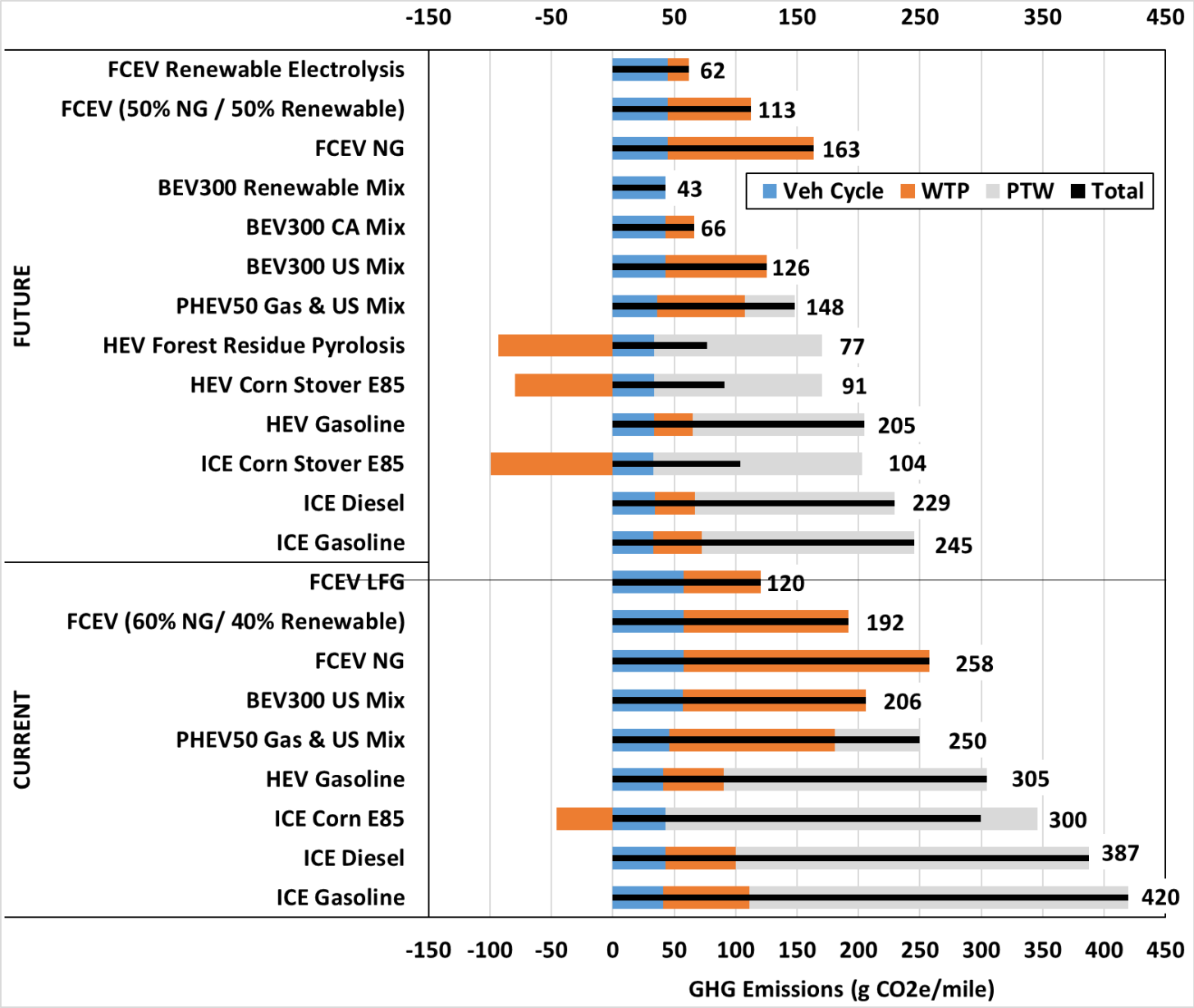


Lifetime cost and GHG emissions for current and future SUVs considering different vehicle-fuel pathways

Published tools (GREET model) and reports inform decision-makers of current and future LCA trends

- **GREET model public release**
  - Annual release builds upon the foundation of prior GREET research and expands coverage in vehicle production and energy pathways
  - Continuously document supporting data and findings in journal articles and technical reports

- **EERE Record (# 21003)**
  - Used latest conventional and advanced vehicle fueling pathways (GREET) along with vehicle simulation data (Autonomie) to evaluate current and future C2G GHG emissions
  - Published findings inform decision-makers and policy experts



Life Cycle GHG Emissions (g CO 2e/mi) for Selected Current (2020) and Future (2050) Fuels and Vehicle Technologies for Small SUVs

Responses to Previous Year Reviewers' Comments

- No reviewer comments from last year

External collaboration

- U.S. DRIVE for C2G of light duty vehicles
  - Inputs on vehicle technology options and fuel pathway choices
  - Verification of key parameters by member companies
- Other national labs
  - NREL: Input via ISATT
  - ORNL: Interact with S. Davis on transportation energy statistics
  - LBNL: Marginal grid studies
- Research organizations and industry associations
  - University of Michigan: vehicle materials supply chain and characteristics of automated vehicles
  - Consultation with, and contributions from, the Aluminum Association and American Iron and Steel Institute

Remaining challenges and barriers

- Data availability and quality, and consistency across organizations: challenges for all the models
  - CAP emission update relies on EPA's NEI which is released every three years (the most recent is NEI2017)
  - Projections of electricity interchanges among regions
  - Modeling and simulations to produce required inputs
- Modeling methodologies
  - GREET: How to consistently address vehicle end-of-life treatment, recycled content vs. credit approaches
  - High regional resolution emissions inventory to inform mid- and end-point impacts
- Technology/market dynamics over time
  - Need to address technology improvements and market changes as time progresses so that their effects can be reflected in GREET benefits assessment
  - Need to address emerging technologies and new mobility options
  - Need to keep up with rapidly evolving advancements in electrification technologies
- Metrics of modeling results
  - Energy, emissions, water
  - Provides only a subset of results needed to evaluate vehicle technologies/systems
- Objective and consistent LCA results for technologies
  - Dissemination of information to government agencies and industry stake-holders
- Trade-offs between environmental performance and cost
  - Techno-economic analysis together with LCA

Planned/proposed future work

- Annual release of GREET expansion updates plus documentation
- Extend C2G studies by developing MHDV life cycle and cost analyses
- Consider linking the developed emissions by source to midpoint impact assessment tools such as EPA's TRACI. Extend the environmental impact analysis to metrics such as smog formation, acidification, human health, etc. Provide valuable information to community-level environmental justice related analysis
- Update background data and LCA formulation associated with copper to consider changes to ore grade
- Update vehicle material compositions for select electric vehicle components
- Continue to develop high spatial resolution emission inventories of GHGs and CAPs for transportation-related energy sectors and material manufacturing sectors of interest

Any proposed future work is subject to change based on funding levels

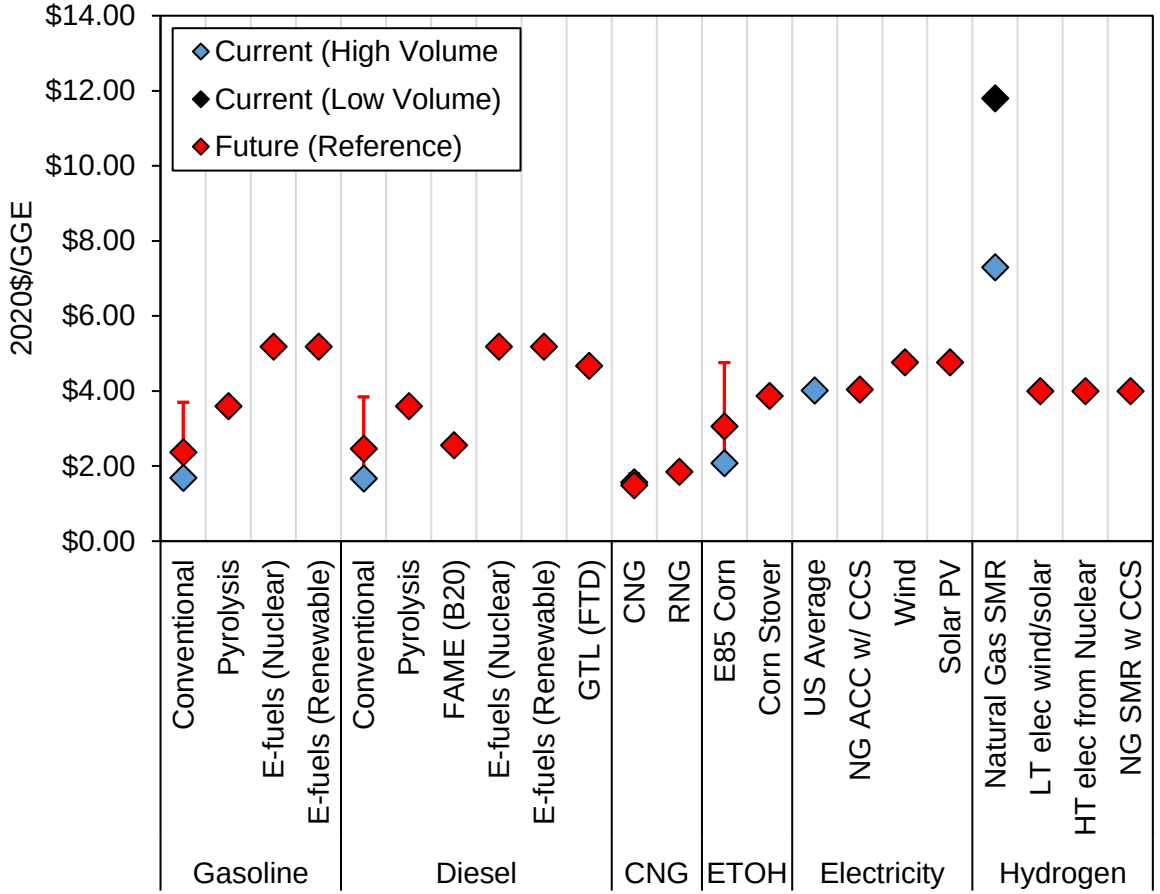
Summary

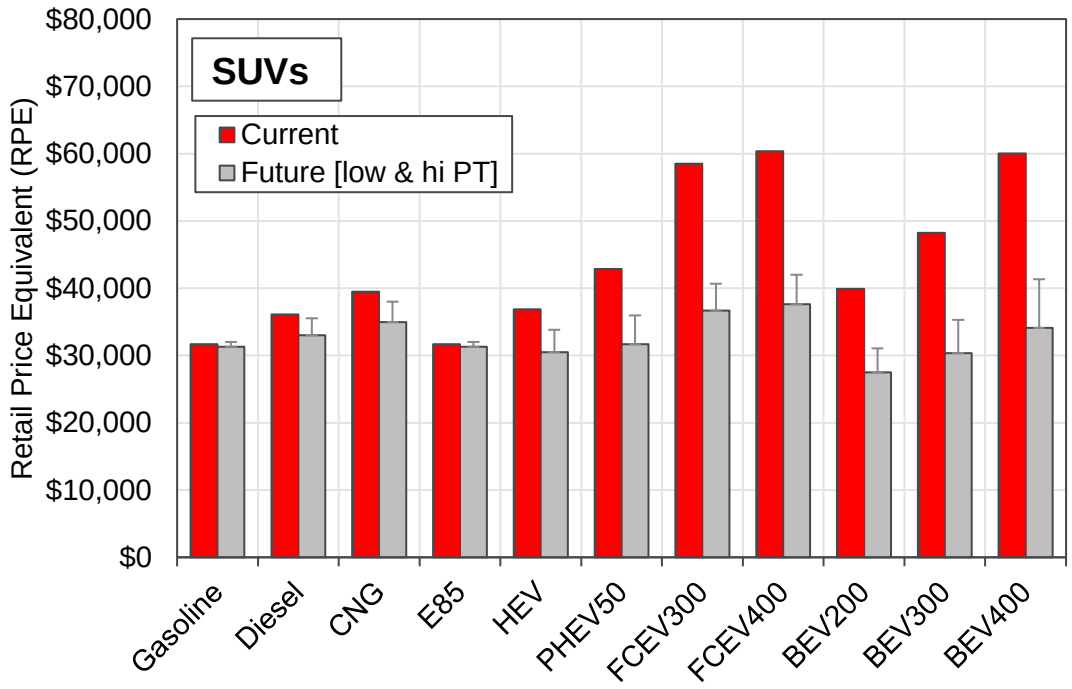
- **Relevance**: Develop indicators and LCA methodology for energy and environmental sustainability for evaluating vehicle/fuel systems
- **Approach**: Expand and update GREET (with >50,000 registered users) to improve evaluation of fuel and vehicle cycles for technology pathways of interest
- **Collaborations**: Collaborated with U.S. DRIVE members (OEMs and energy companies), national Labs (NREL, ORNL, LBNL), University of Michigan, UC-Davis, Aluminum Association, and American Iron and Steel Institute.
- **Technical accomplishments and progress in the past year**
  - Developed detailed vehicle material composition model for MHDVs and integrated into GREET
    - Vehicle-cycle GHG emissions follow the general trend of vehicle weight
    - Life-cycle GHG emissions are dominated by the use phase regardless of the powertrain
  - Added seasonal and sectoral regional electricity CAP emissions
    - Electricity characteristics (CAP, GHG, and mixes) show highly spatial and temporal variations
    - Seasonal and sectoral variations of electricity characteristics could change the life-cycle comparison of related technologies significantly
  - Evaluated C2G GHG of LDVs
    - LDVs show opportunities to reduce both GHGs and costs, with deep carbonization for select pathways
- **Future Research**:
  - Annual release of GREET expansion updates plus documentation
  - Extend C2G studies by developing MHDV life cycle and cost analyses
  - Consider linking the developed emissions by source to midpoint impact assessment tools such as EPA's TRACI
  - Update vehicle material compositions for select electric vehicle components
  - Continue to develop high spatial resolution emission inventories of GHGs and CAPs for transportation-related energy sectors and material manufacturing sectors of interest

Technical Backup

Combine vehicle cost (RPE) data along with operational data, discount rates, and usage to determine lifetime vehicle cost

- Fuel costs vary widely between fueling pathways on a gasoline gallon equivalent (GGE) basis
- Upfront retail price equivalent (RPE) of the small SUVs are significantly higher for FCEV and BEVs for the Current scenario but reduce substantially in the Future scenario
- Electric vehicle charging equipment included for BEV and PHEV scenarios





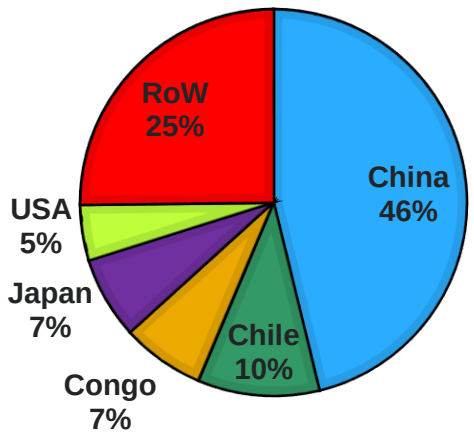
- *Low refers to a case of low technology progress incorporated into the vehicle*
- *Hi PT refers to a scenario with high powertrain technology progress*
- *PHEV50 has an Adjusted Test Cycle range of 50 miles resulting in a utility factor of 0.697*
- *Current = MY2020, and Future = MY2030-2035*

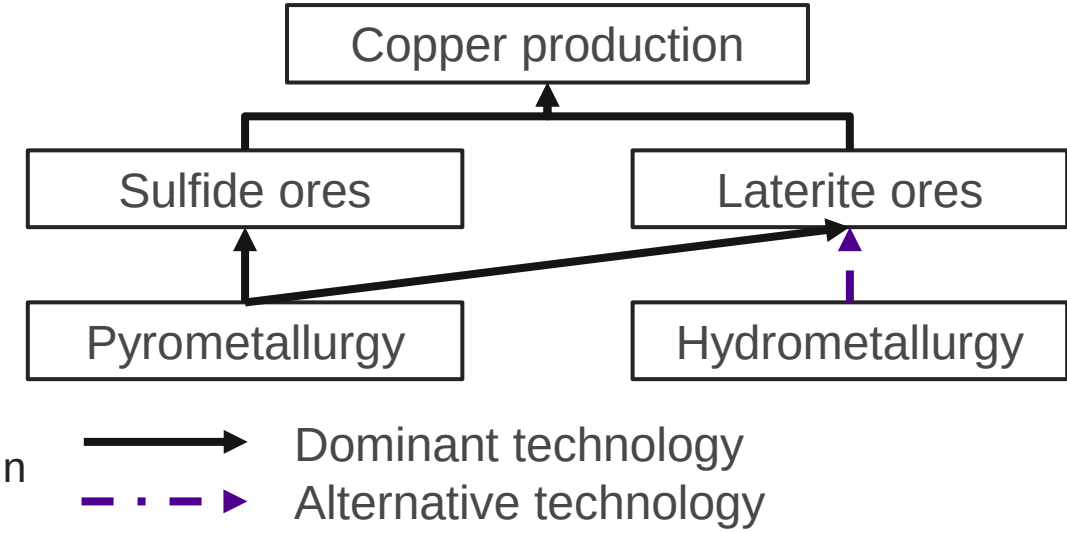
Argonne NATIONAL LABORATORY

Copper: Life-cycle assessment

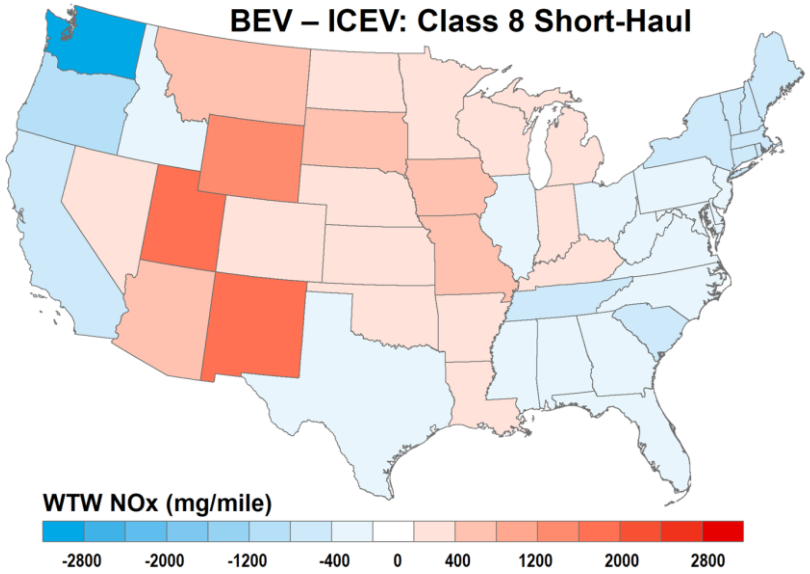
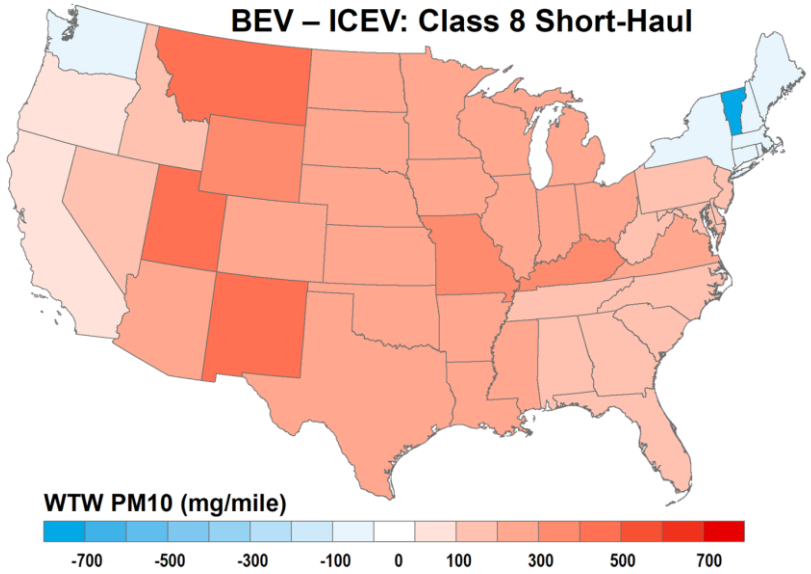
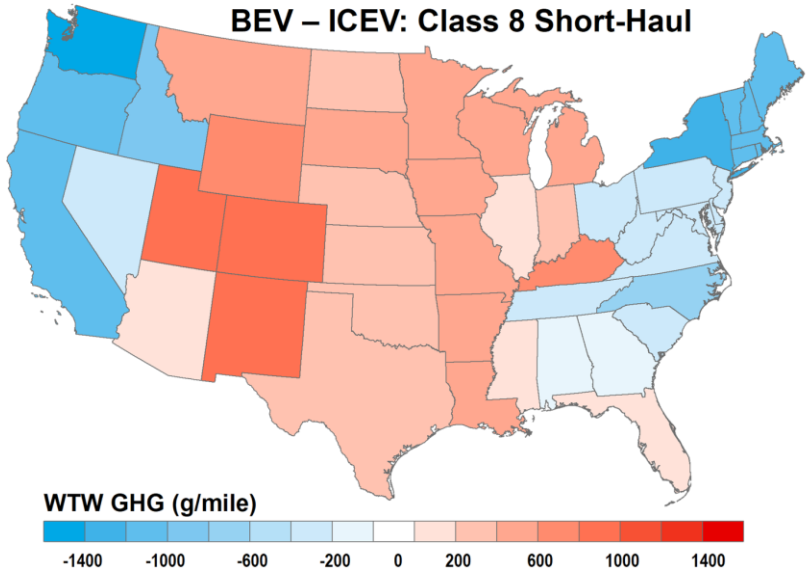
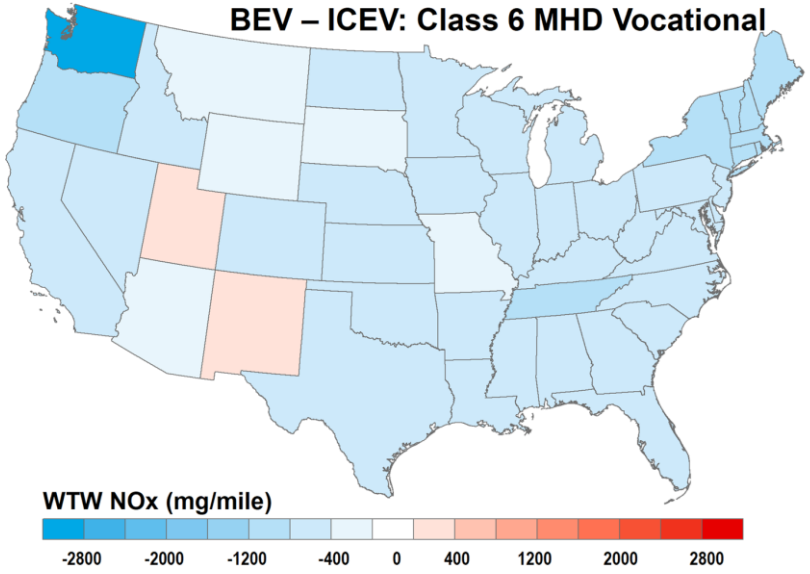
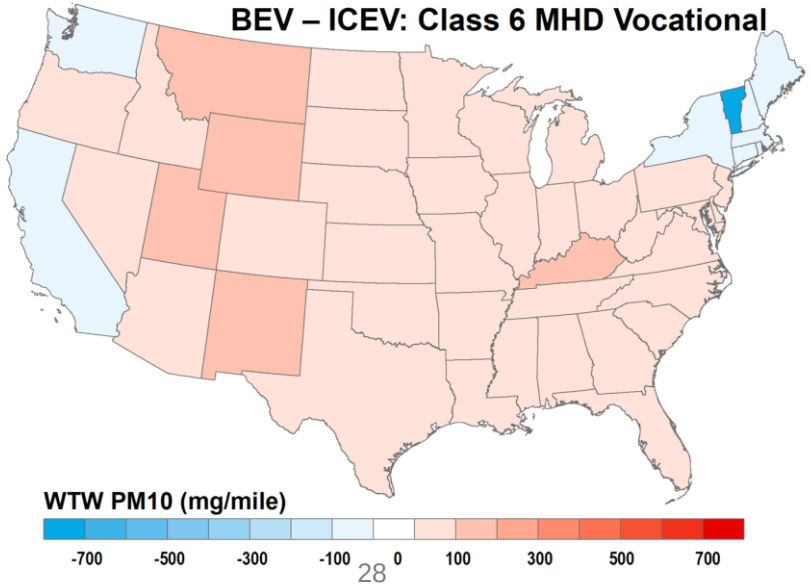
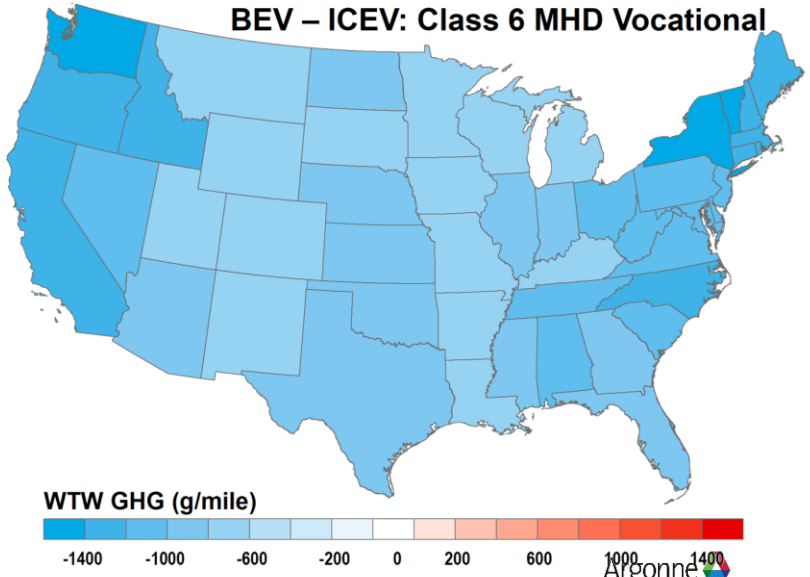
- **Copper is critical to the US due to:**
  - Current and future demand (including Li-ion batteries)
  - Temporal decline in ore grade (% Cu content)
  - Environmental impacts of Cu production depend on:
    - Ore type (sulfide/laterite)
    - Ore location (region-specific inputs and electric grid mix)
    - Ore grade (increasing energy needs with declining Cu content)
- **Updating GREET Cu LCA to analyze region-specific impacts of Cu production**
- **Current work:**
  - Pyrometallurgy (sulfide ores): $E = 15.63G^{-0.53}$
    - Gross energy use (E) for Cu mining and beneficiation varies with ore grade (G), with little change by grade for other steps
    - Literature review in progress accounting for regional variation in Cu inventory and resultant impact on emissions

GLOBAL COPPER PRODUCTION





Sulfide ores: 80% Cu production
Laterite ores: 20% Cu production

WTW Comparison of Diesel ICEV and BEV for MHD Trucks (Cont'd)

Class 8 short-haul combination and Class 6 MHD vocational for NO_x, PM_{10}, and GHG