Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis

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Executive Summary

- With continued improvements in vehicle and fuel technologies (in line with U.S. Department of Energy targets and vetted with industry), **zero-emission vehicles (ZEVs) can reach total-cost-of-driving parity with conventional diesel vehicles by 2035** for all medium- and heavy-duty (MD/HD) vehicle classes (without incentives).
- Assuming economics drive adoption, **ZEV sales could reach 42% of all MD/HD trucks by 2030**, reflecting lower combined vehicle purchase and operating costs (using real-world payback periods).
- In this scenario, ZEV sales reach >99% by 2045, and **80% of the MD/HD stock transitions to ZEVs by 2050, reducing CO_2 emissions by 69% from 2019.**
- **Two technological solutions**—battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs)—are viable in multiple market segments, offering **alternative pathways for decarbonization**.
  - **BEVs tend to become cost-competitive** for smaller trucks before 2030 and for short-haul (<500-mile) heavy trucks before 2035.
  - **Hydrogen FCEVs** tend to become cost-competitive for long-haul (>500-mile) heavy trucks by 2035.

Executive Summary (cont.)

- This study looks at three different vehicle classes and eight different use cases/driving distances. **ZEV adoption is more rapid in lighter and shorter-distance vehicles**, which also tend to be centrally fueled, reducing infrastructure risk.
  - Based on external studies, **buses are assumed to fully transition to ZEV by 2030** (100% sales).
- Since economics are more likely to drive adoption in business applications, especially in larger companies, it is possible that **demand for ZEVs could rise rapidly in MD/HD trucks once cost parity is reached**. Manufacturing capacity and charging/refueling infrastructure will need to increase commensurately to support vehicle adoption.
- Operating cost savings are a critical factor, especially for heavy long-haul trucks, so **results are highly sensitive to assumed fuel prices** (both for new technologies and for existing diesel fuels). Energy management techniques, proactive utility and clean fuel investment planning, and associated policies are needed to lower final energy costs.
- Results are also very sensitive to **technology improvement trajectories, adoption decision-making, and uncertain assumptions about future freight demand, logistics, and vehicle use**.

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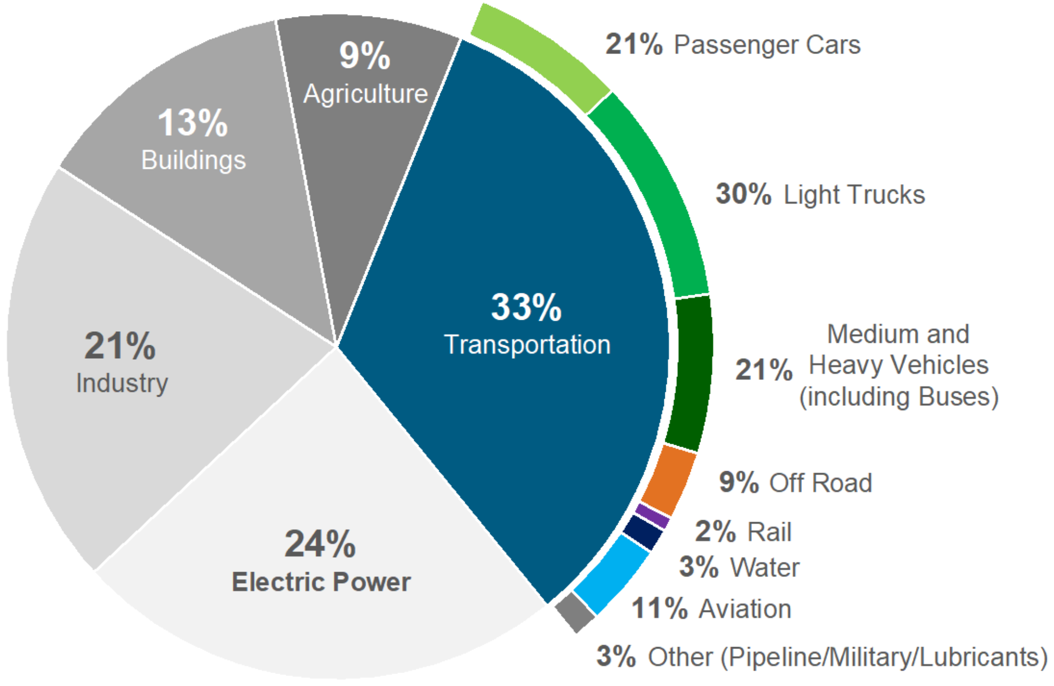
INTRO & SCOPE

Intro and Scope

- Achieving a **net-zero emission economy by 2050** requires aggressive curbing of transportation emissions.
- **Medium- and heavy-duty vehicles** (MHDVs) are the second largest contributor to transportation emissions (21%).
  - Major source of **local air pollution** disproportionally affecting disadvantaged communities.
  - We consider **all on-road vehicles >10,000 lbs.** (freight and non-freight trucks, buses).
- **Scope:** model **potential ZEV adoption based on economics (cost of driving) to inform feasible decarbonization pathways.**

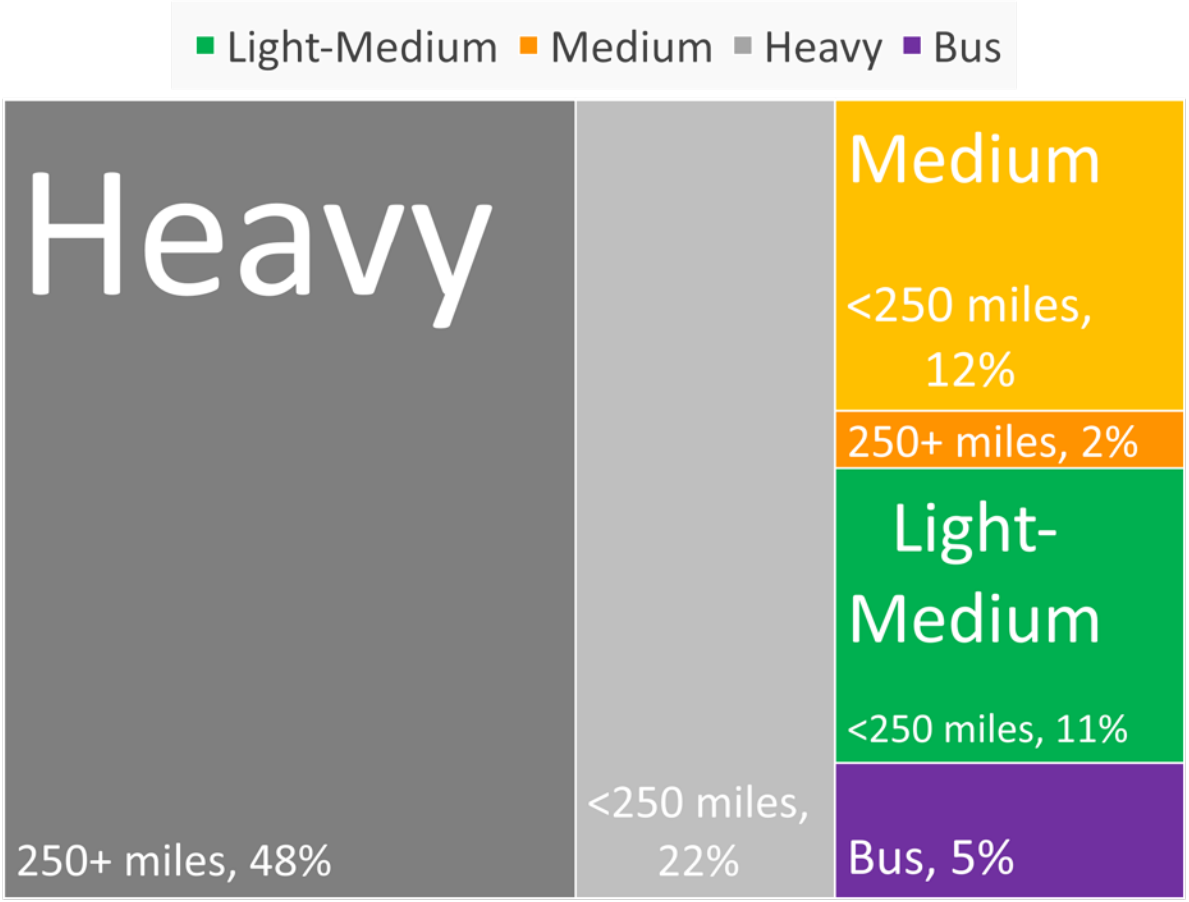
2019 U.S. GHG Emissions



MHDV Segmentation

- **MHDVs include multiple applications and use cases**, both in terms of vehicle size class and use (vehicle miles traveled [VMT] and range requirements).
  - Heavy trucks use 70% of energy (41% of stock).
- **Not all trucks are the same**: different size classes and use cases lead to different vehicle requirement and costs, determining opportunity for ZEV adoption.
- **Zero-emission vehicles (BEVs and FCEVs)** offer a viable decarbonization pathway.
  - While commercial deployment is still limited, there are growing opportunities as technology is advancing rapidly.
- **Low-carbon liquid fuels** can also help reduce emissions from legacy vehicles.

2019 MHDV Emissions (445 MM ton CO_2)



Goal of this Analysis

Goal: Economic analysis of the MD/HD transportation sector that identifies cost-effective adoption opportunities for zero-emission vehicles based on total cost of driving.

Approach: Model potential ZEV adoption based on economics (cost of driving):

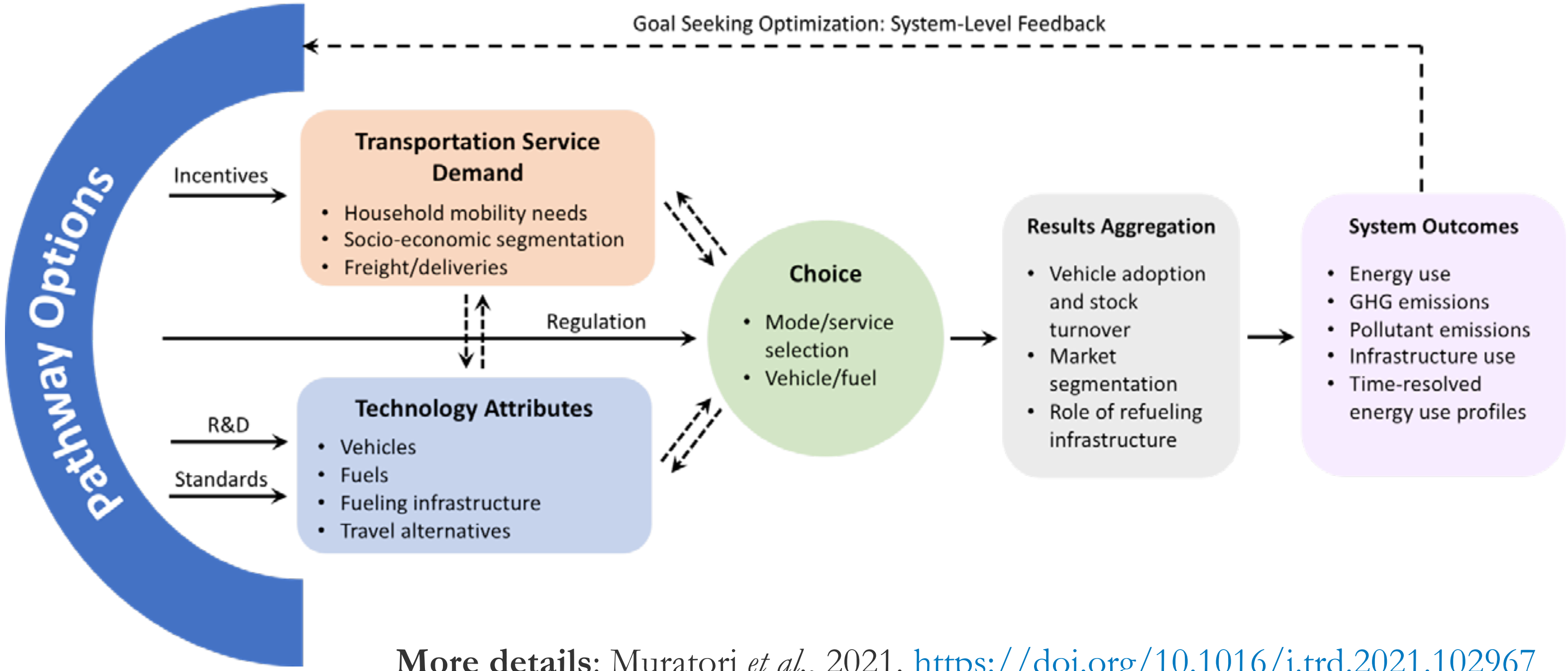
- Leverage extensive work on **component-level and vehicle technology** evolution over time estimating future vehicle costs and characteristics (used an inputs in this analysis).
- Leverage and **expand previous analyses** that focus on single vehicles and hypothetical use cases (e.g., fixed VMT for a given vehicle type) and use the Transportation Energy & Mobility Pathway Options (TEMPO) model freight demand segmentation to look at **system-level adoption opportunities and emissions implications:**
    - Represent **heterogenous vehicle applications** by class (vehicle size) and use (VMT).
    - Perform a **cost parity analysis** based on diverse vehicle uses to inform on real-world market opportunities for different vehicle classes and use cases.
    - Estimate **energy use and emissions over time for the entire MHDV stock.**

APPROACH & KEY ASSUMPTIONS

What is TEMPO?

TEMPO

The Transportation Energy & Mobility Pathway Options ([TEMPO]TM) model is a **comprehensive transportation demand macro model to explore long-term scenarios** of energy use across all transportation segments and to integrate with large, multisectoral studies.



More details: Muratori *et al.*, 2021. https://doi.org/10.1016/j.trd.2021.102967

TEMPO models **all domestic passenger and freight travel demand** across all travel modes and projects their evolution over time to generate possible transformation scenarios.

- Population and economic growth drive increased demand for mobility over time.
- **55% growth in total MD/HD truck VMT** between 2019 and 2050 (aligned with Annual Energy Outlook [AEO][1]).

[1] U.S. Energy Information Administration. 2019. Annual Energy Outlook 2019. https://www.eia.gov/outlooks/aeo/.

MD/HD Representation

TEMPO

Three Vehicle Classes

Light-Medium (Class 3)
10,000–14,000 lbs.

Medium (Class 4–6)
14,000–26,000 lbs.

Heavy (Class 7–8)
26,000+ lbs.

Six technologies in each vehicle class (ICEV, HEV, FCEV, and three BEV ranges). Freight demand (VMT) by class from AEO.

Up to Eight Shipment Distance Bins

0–99 miles	100–249 miles
250–499 miles	500–749 miles
750–999 miles	1,000–1,499 miles
1,500–1,999 miles	2,000+ miles

Shipment distance bins from FAF and VIUS data represent different applications and vehicle use (e.g., short-haul and long-haul).

Multiple Vehicle Applications

Freight trucks (activity based on FAF)	61% stock; 74% VMT
Non-freight trucks (follow activity in 0–249-mile bins)	39% stock; 26% VMT

Freight and non-freight stock and activity based on analysis of VIUS, FAF, and AEO.

FAF: Freight Analysis Framework
HEV: hybrid electric vehicle
ICEV: internal combustion engine vehicle
VIUS: Vehicle Inventory and Use Survey

Buses are also included and described here.

AEO: U.S. Energy Information Administration. 2019. Annual Energy Outlook 2019. https://www.eia.gov/outlooks/aeo/.
FAF: Federal Highway Administration (FHWA), 2019. Freight Analysis Framework - 2017. https://ops.fhwa.dot.gov/freight/freight_analysis/faf/.
VIUS: U.S. Census Bureau (US CB), 2004. Vehicle Inventory and Use Survey (VIUS). Retrieved from https://www.census.gov/library/publications/2002/econ/census/vehicle-inventory-and-use-survey.html.

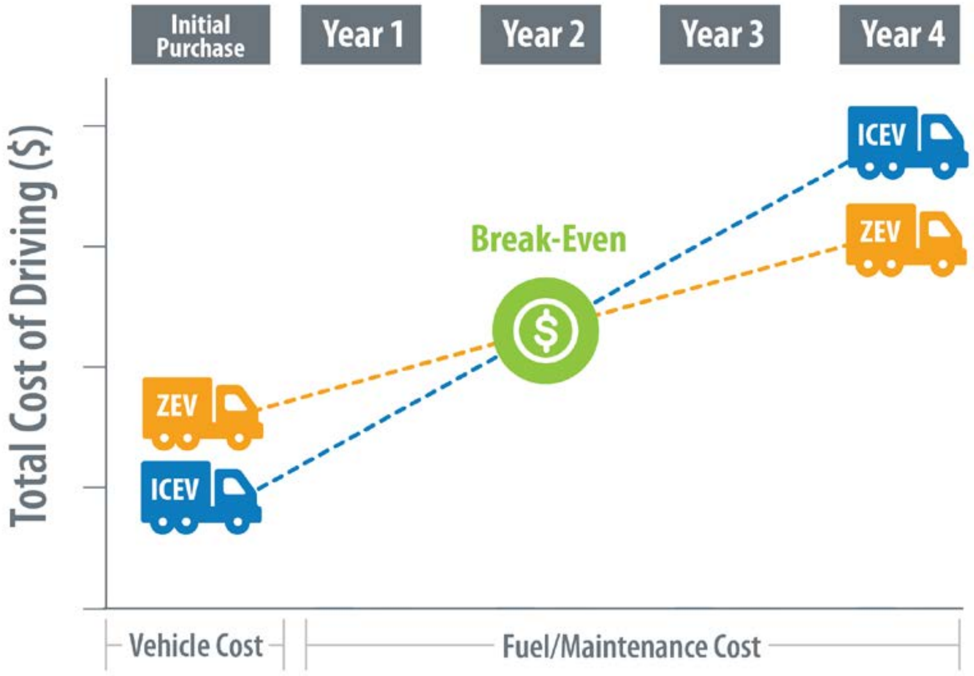
Drivers of Vehicle Adoption

TEMPO

Vehicle adoption in TEMPO is determined by total cost of driving (TCD):

- Upfront **vehicle cost** (manufacturer's suggested retail price [MSRP])
- **Fuel costs** (vehicle fuel economy and fuel price)
- **Maintenance** costs
- **Vehicle usage** (VMT)
- **Financial horizon** considered (or discount rate)
- Monetized **charging time cost** for BEVs (charging availability and speed)
- **Logit formulation** – captures heterogeneities. Lowest TCD captures greatest market share.

Nonfinancial factors like availability of make/models, driver preferences, manufacturing or infrastructure constraints, and other external drivers of adoption are not considered. Resale value is not considered.



Example of a ZEV reaching cost parity with ICEV

Cost parity = ZEV reaches breakeven within assumed financial horizon (despite higher vehicle cost, thanks to lower operational costs)

Key Assumptions

- **Zero-emission vehicle** technologies (BEV, FCEV): MSRP and fuel economy improving over time, in line with DOE projections and vetted with industry:
  - **Batteries**: $80/kWh (pack level) in 2035 and $50/kWh in 2050 (see battery and fuel cell assumptions)
  - **Fuel Cells**: $80/kW in 2035 and $60/kW in 2050 (see battery and fuel cell assumptions)
  - **Conventional ICEV fuel economy** is assumed to improve by 32%–37% across vehicle classes by 2050 (see details).

- **Zero-emission infrastructure and fuels** (see fuel price trajectories):
  - **BEV** charging is assumed to become progressively available as BEVs are adopted
  - BEV average charging price reaches **$0.18/kWh by 2030** and is held constant through 2050
  - **FCEV fueling** is assumed to phase in and be **fully available by 2040**
  - Hydrogen average refueling price reaches **$4/kg by 2035** and is held constant through 2050
  - Results for **alternative fuel price assumptions** available in sensitivity scenarios here.

- Beyond technology advancements, how we think about the investments and the **financial horizon** considered when adopting transportation technologies can have a substantial impact on cost of driving:
  - **3–5 years financial horizon** considered when determining cost parity for ZEVs (see details). Additional savings can be accrued over over vehicle lifetime but are assumed to not impact adoption decisions.

Key Uncertainties

The following parameters are **highly uncertain and significantly affect model outcomes and trade-offs between different technologies** (see sensitivities):

- **Fuel cost** evolution (diesel, electricity, and especially hydrogen) and infrastructure utilization.
- **Vehicle costs and fuel economy**.
- **Financial horizon** – years of incremental cost savings considered by fleet owners when making purchase decisions; may be different for different use cases.
- Vehicle **adoption decisions** – the assumption that fleets will make decisions based on tangible economic considerations, versus other harder-to-quantify factors like decarbonization pledges.
- Future **freight demand growth**, stock turnover, and **freight logistics** including truck operations and trip distance distributions.
    - Charging speed and value of charging time for BEVs are also uncertain.
- **Limited data for non-freight uses** (26% of VMT, here assumed to reach cost parity in line with short-distance freight trucks).

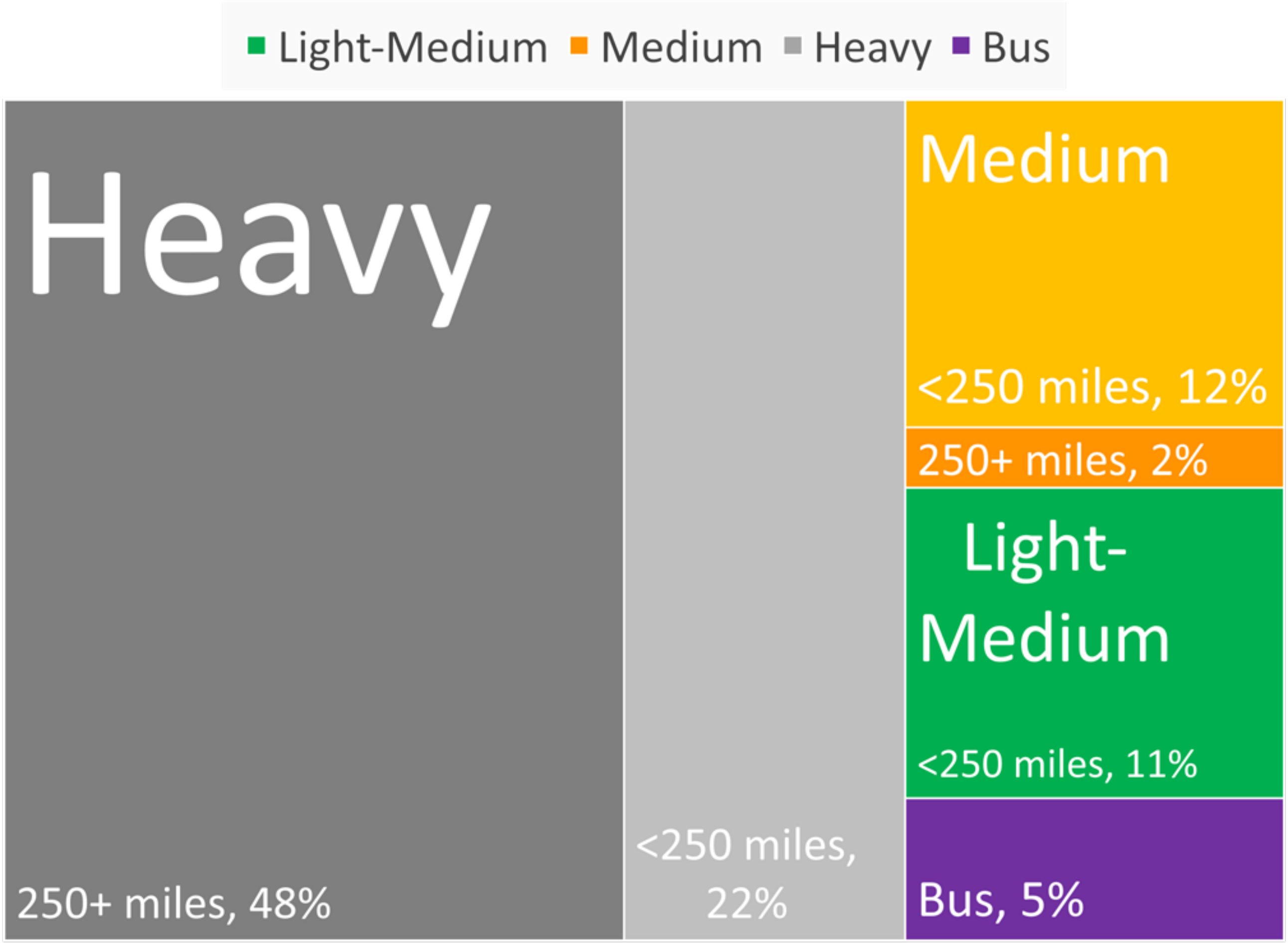
SYSTEM-LEVEL PERSPECTIVE: MARKET SEGMENTATION

2019 MHDV Emissions

TEMPO MHDV market segmentation:

- **Freight demand** (ton-miles in 2017) from FAF, segmented by shipment distance bin.
- Freight **demand growth** over time from AEO (+55% by 2050).
- Total **VMT by vehicle size class** from AEO.
- **Load factors** by vehicle class from VIUS.
- **Vehicle use by distance bin** derived from FAF-VIUS synthesis.
- Total **vehicle stock** based on AEO and separated into shipment distances using FAF and VIUS.
- **Vehicle sales**: estimated endogenously in TEMPO with tech mix based on TCD.
- **Vehicle fuel economy** from AEO (2017) and future projections vary by scenario.

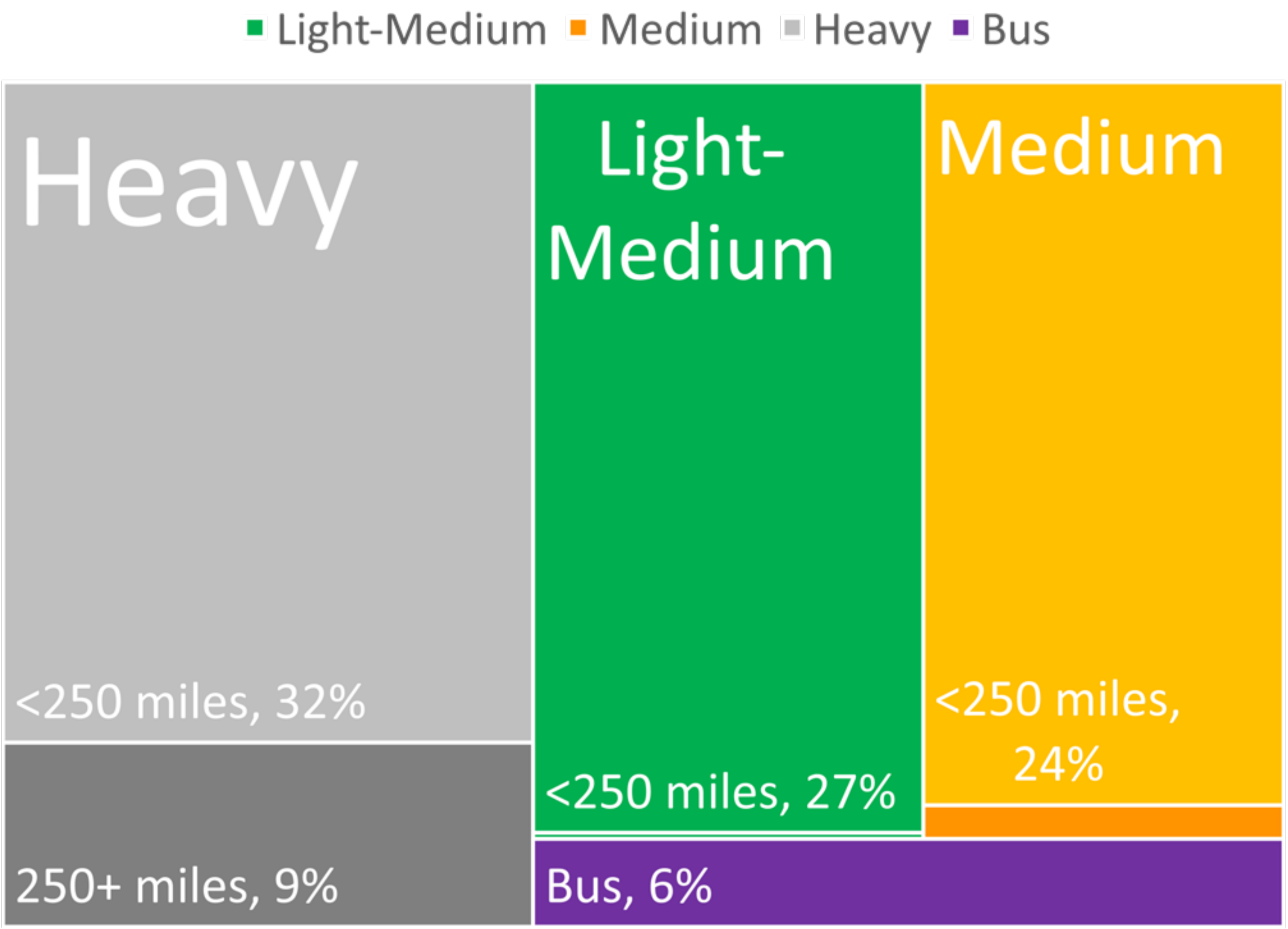
2019 MHDV Emissions (445 MM ton CO_2)



2019 MHDV Stock

- Stock and sales shares are not necessarily proportional to contributions to emissions, due to wide disparities in VMT and fuel economy.
- Heavy trucks are ~40% of total vehicle stock but are responsible for about 70% of emissions due to lower fuel economy and greater VMT.
- For trucks, 2019 total stock is based on AEO and separated into shipment distances using FAF and VIUS.
- Bus stock is estimated from AEO passenger-miles traveled (PMT).

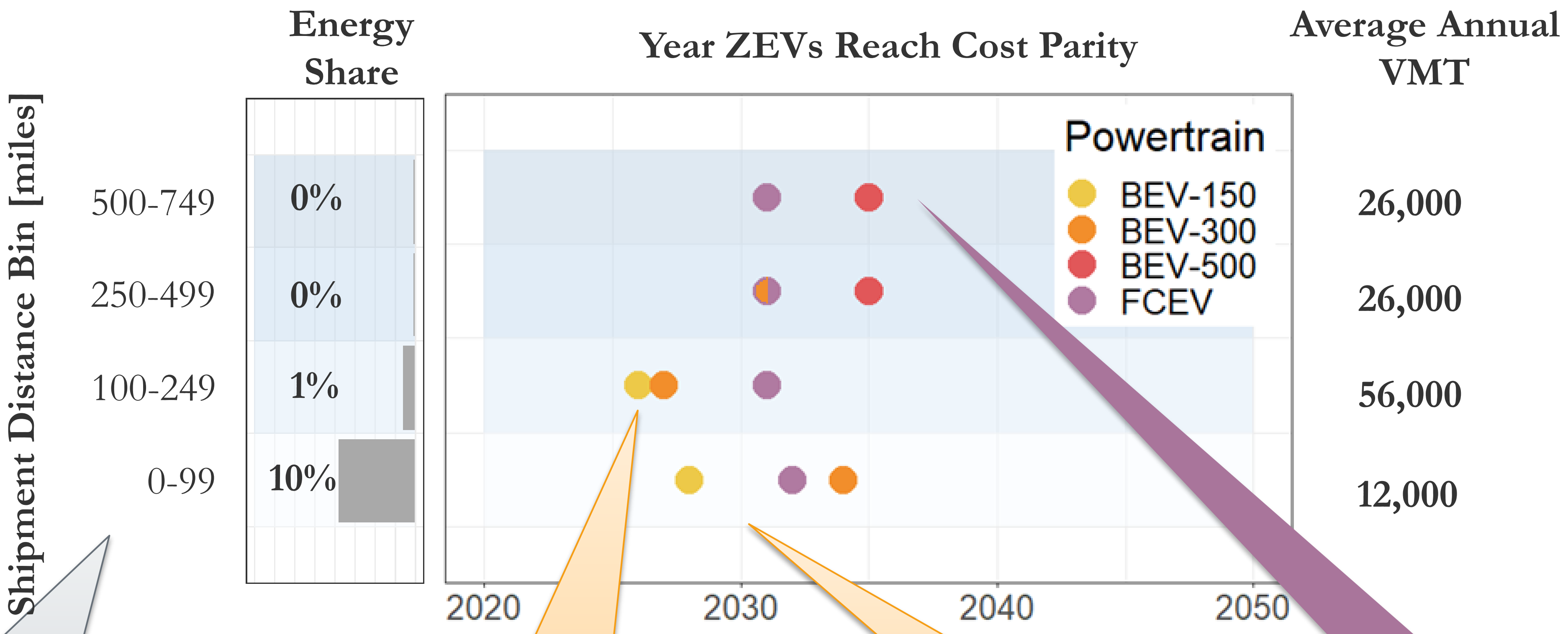
2019 MHDV Stock (13 M vehicles)



COST PARITY ANALYSIS

Cost Parity by Distance Bin
Light-Medium Trucks

Vehicle Sales	Energy Share
35%	11%



Different freight distance bins impact vehicle VMT and TCD, in turn affecting when ZEVs reach cost parity

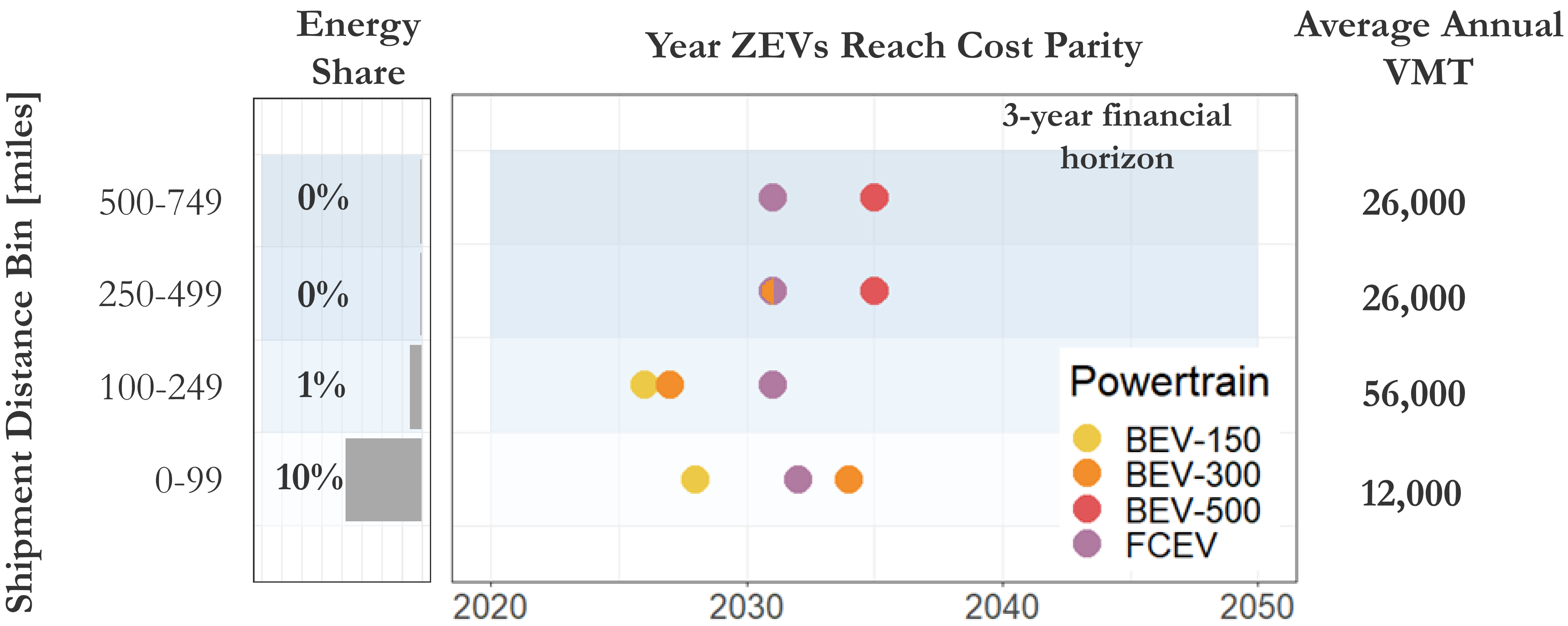
BEV-150 reach cost parity for 100–249-mile uses in 2026

BEV-150 reach cost parity for 0–99-mile uses in 2028 (lower VMT)

FCEV reach cost parity in 2032, BEV-500 in 2035 (high charging costs)

Cost Parity by Distance Bin
Light-Medium Trucks

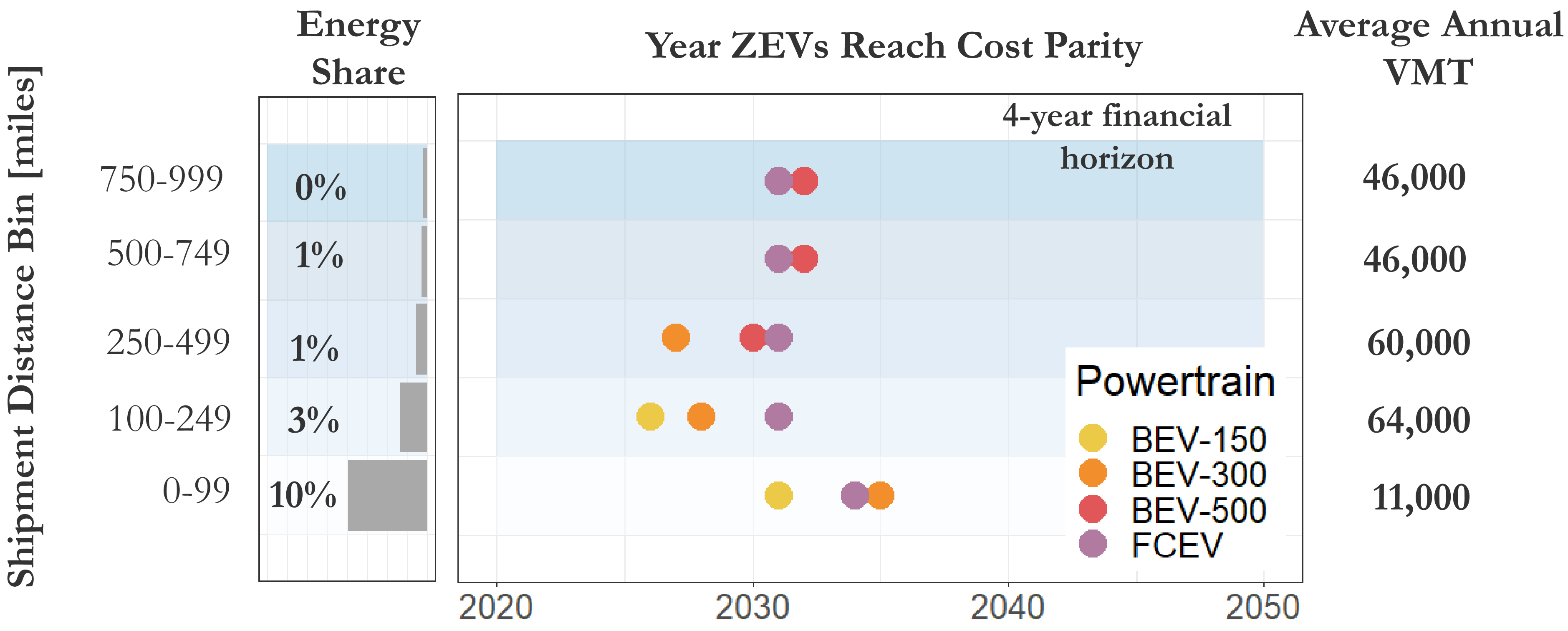
Vehicle Sales	Energy Share
35%	11%



- **Two ZEV tech solutions** and pathways for many applications provide more options and mitigate risks.
  - **BEVs achieve cost parity with ICEVs before 2035** in every distance bin.
- **>99% ZEV sales by 2035 or earlier**
  - **2050 stock**: 75% BEV, 11% FCEV, 14% ICEV (**2050 sales**: 88% BEV; 12% FCEV).

Cost Parity by Distance Bin
Medium Trucks

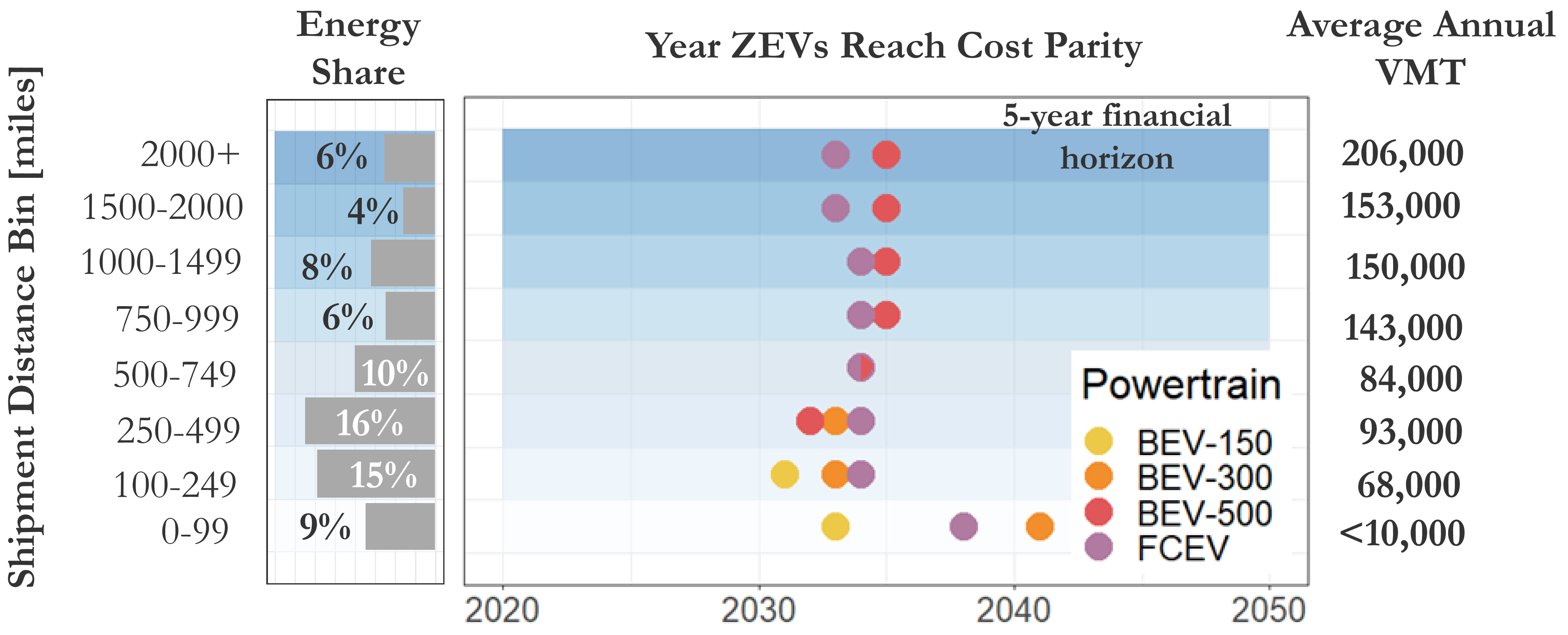
Vehicle Sales	Energy Share
25%	15%



- **ZEVs achieve cost parity with ICEVs before 2035** in every distance bin. Two ZEV tech solutions and pathways for many applications provide more options and mitigate risks.
- **99% ZEV sales by 2046**
  - **2050 stock**: 66% BEV, 16% FCEV, 18% ICEV (**2050 sales**: 82% BEV; 18% FCEV, 0% ICEV).

Cost Parity by Distance Bin
Heavy Trucks

Vehicle Sales	Energy Share
40%	73%

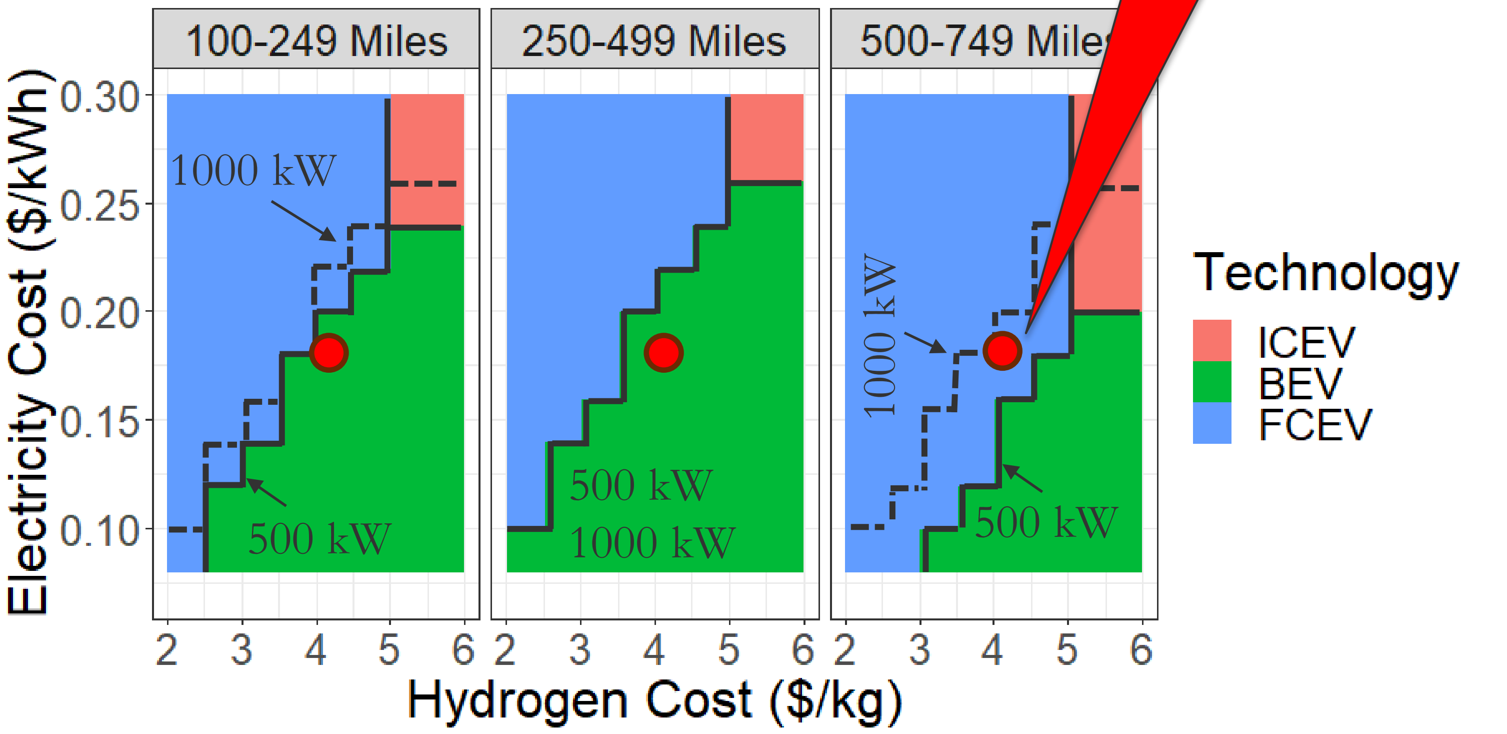


- **ZEVs achieve cost parity with ICEVs by 2035** in every distance bin. Two ZEV tech solutions and pathways for many applications provide more options and mitigate risks.
- **>99% ZEV sales by 2042.** Shorter-distance bins dominated by BEVs; longer bins dominated by FCEVs.
  - **2050 stock**: 56% BEV, 16% FCEV, 28% ICEV (**2050 sales**: 78% BEV; 22% FCEV).
  - 2050 **ton-miles**: 35% BEV; 34% FCEV; 30% ICEV.

Impact of Fuel Prices

- **Fuel prices are highly uncertain** and charging/refueling solutions will have costs that vary by region and over time.
- **Central assumptions are close to separation line**: multiple ZEV pathways. Charging speed is also uncertain and will vary by location (*e.g.*, depot or public) and vehicle.
- Other factors may influence marginal behavior, resulting in less abrupt transitions between technologies.
- BEVs tend to outcompete FCEVs on a TCD basis at lower shipment distances, higher charging speeds, and lower electricity prices.

Lowest Cost Technology, 2035, Heavy Trucks, $4/gal diesel



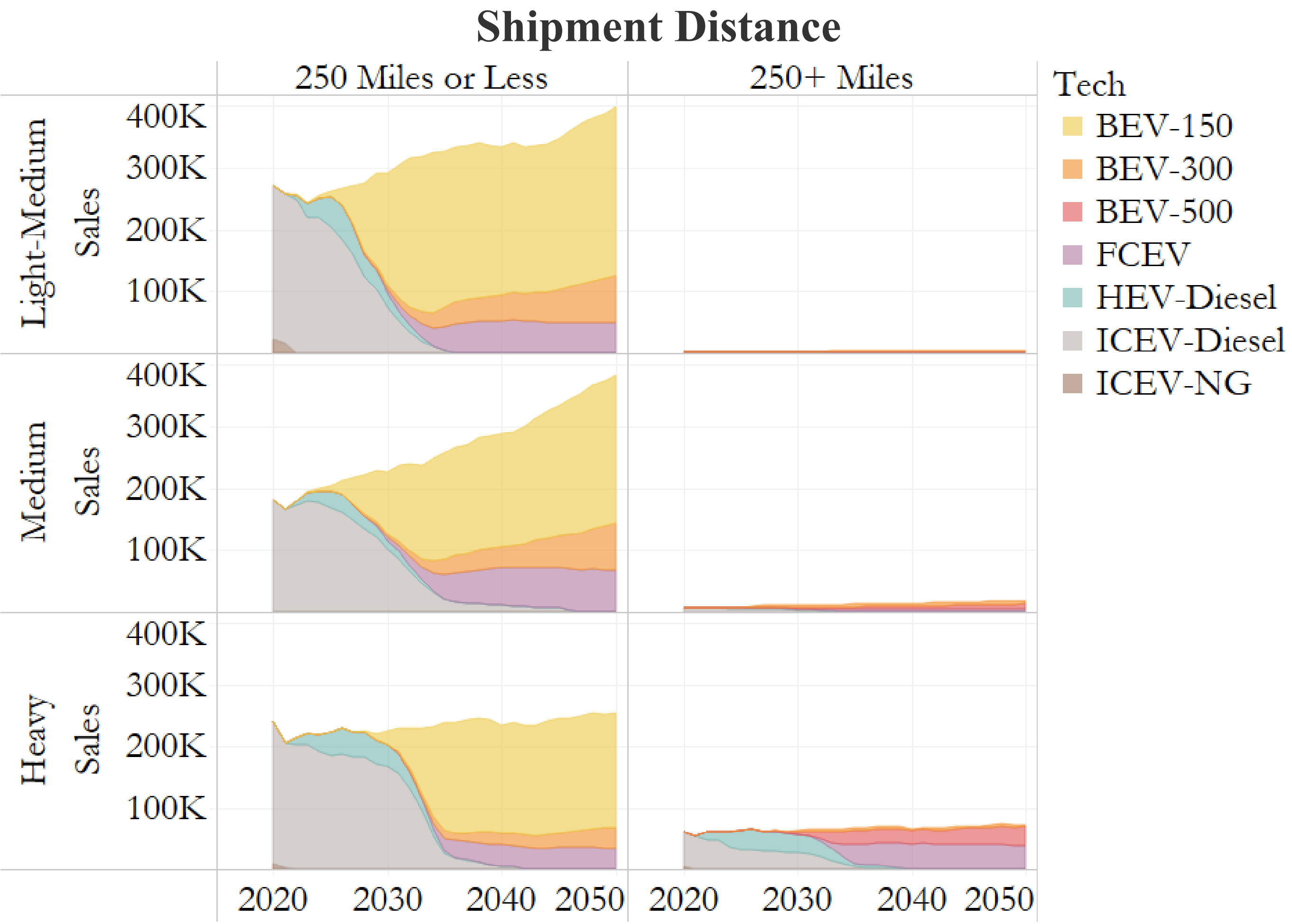
- In long-distance bins, FCEVs dominate even for low electricity prices **if hydrogen prices are below $4–$5/kg and charging <1 MW**. Effect of 1-MW charging varies depending on daily driving distance, the range of BEVs competing in each shipment distance, and assumptions about monetized charging time.

KEY RESULTS

Truck Sales

	Vehicle Sales		Energy Share	
	Short-Haul	Long-Haul	Short-Haul	Long-Haul
Light-Medium	35%	0%	11%	0%
Medium	24%	1%	13%	2%
Heavy	32%	8%	23%	50%

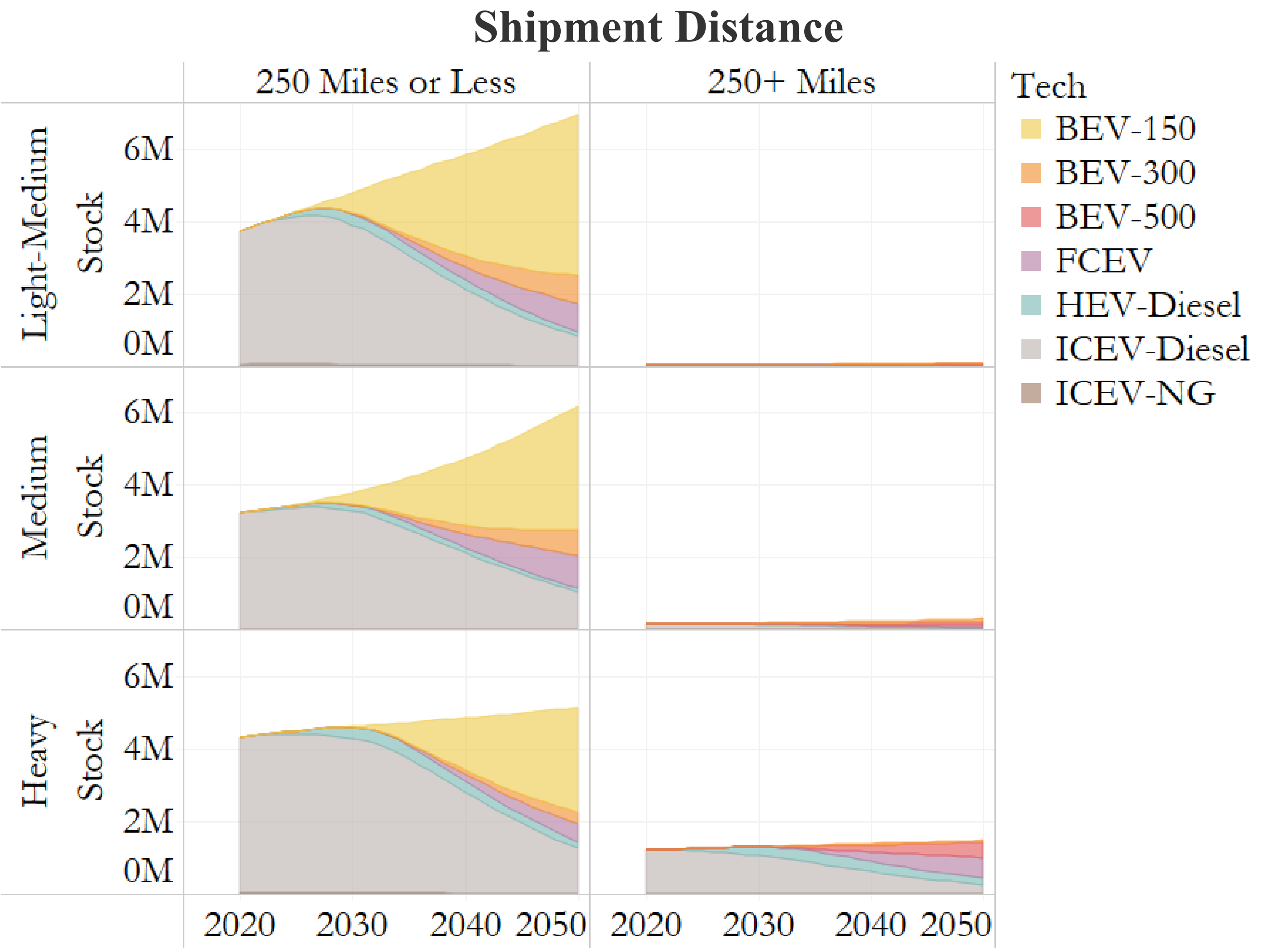
- Total light-medium and medium sales grow substantially from 2020 to 2050 (due to assumed total VMT growth).
- Across all modes (and travel distance bins), **42% ZEV sales are achieved by 2030**, 98% by 2040, and 100% by 2046.
  - **2030 sales** shares: 40% BEV; 2% FCEV.
  - **2050 sales** shares: 83% BEV; 17% FCEV.
- Shorter-distance bins are dominated by short- to mid-range BEVs, while longer-distance bins are dominated by long-range BEVs and FCEVs.
  - See sensitivity for effects of different assumptions: *e.g.*, BEVs can replace FCEVs in longer-distance bins if H_2 price is \$6/kg or electricity price is \$0.12/kWh.



Truck Stock

	Vehicle Stock		Energy Share	
	Short-Haul	Long-Haul	Short-Haul	Long-Haul
Light-Medium	29%	0%	11%	0%
Medium	26%	1%	13%	2%
Heavy	34%	9%	23%	50%

- Vehicle stock turnover hinders emissions reduction potential.
  - Targeted adoption can magnify impact—**9% of the vehicle stock is responsible for 51% of all energy** consumption.
- **ZEV stock reaches 7% of the fleet by 2030, 49% by 2040, and 80% by 2050** (66% BEV; 14% FCEV).
- Despite early growth in emissions due to VMT growth, emissions relative to 2019 decline after 2030, reaching 32% reduction by 2040 and 69% in 2050.

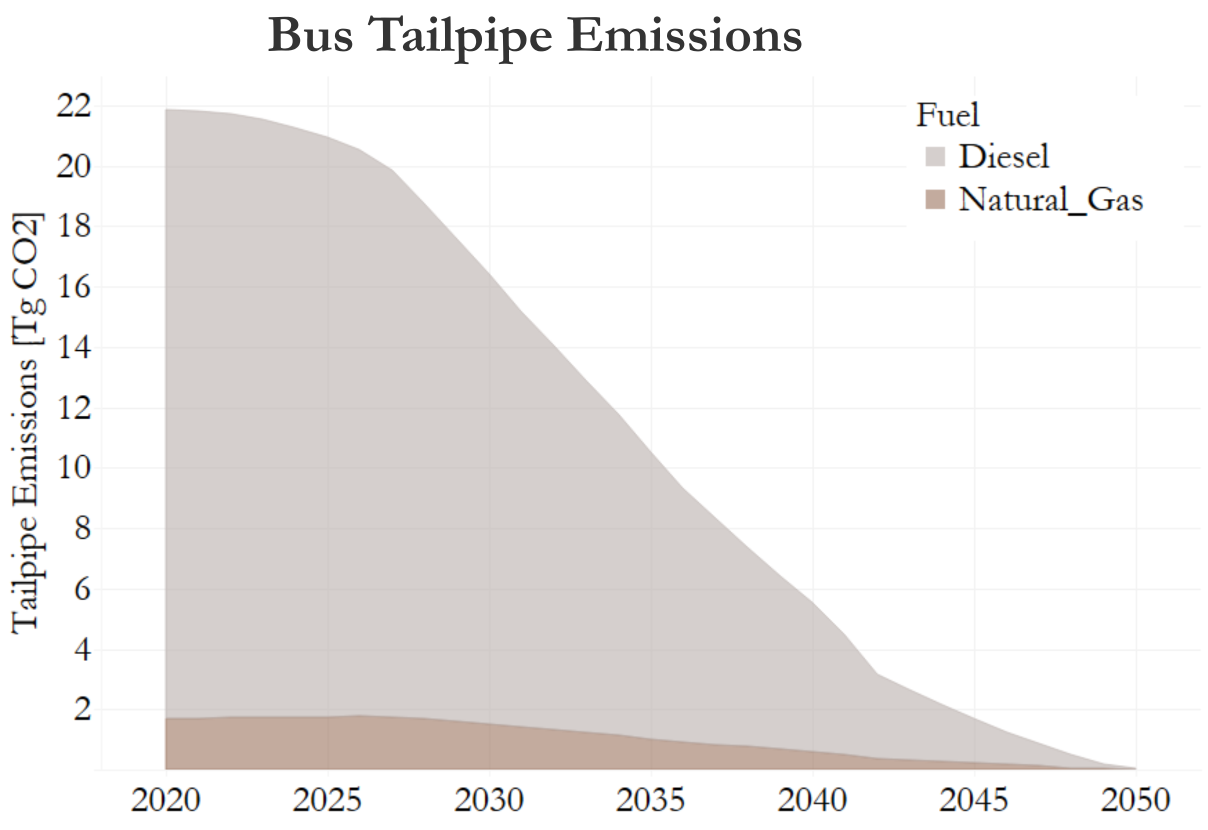


TEMPO

Bus Electrification and Emission Implications

TEMPO

- Buses are **1% of total transportation emissions** in 2019 and 5% of MHDV.
- **Electrifying buses is already cost-competitive** in certain contexts on a TCD basis depending on vehicle and fuel prices and driving requirements (and there is major policy support for rapid bus electrification).
    - BEVs already cost-competitive in some applications and **by 2032 projected to be well below TCO of diesel.**[1]
    - **FCEV buses** may **be competitive with diesel at fuel cell costs below $125/kW and hydrogen prices of $5/kg**, considering a 5-year financial horizon.[2]
- We assume **full transition to ZEV by 2030**, and 20-year life: >99% of bus service (pass-miles) served by ZEVs in 2050, reducing bus emissions by >99% compared to 2019.

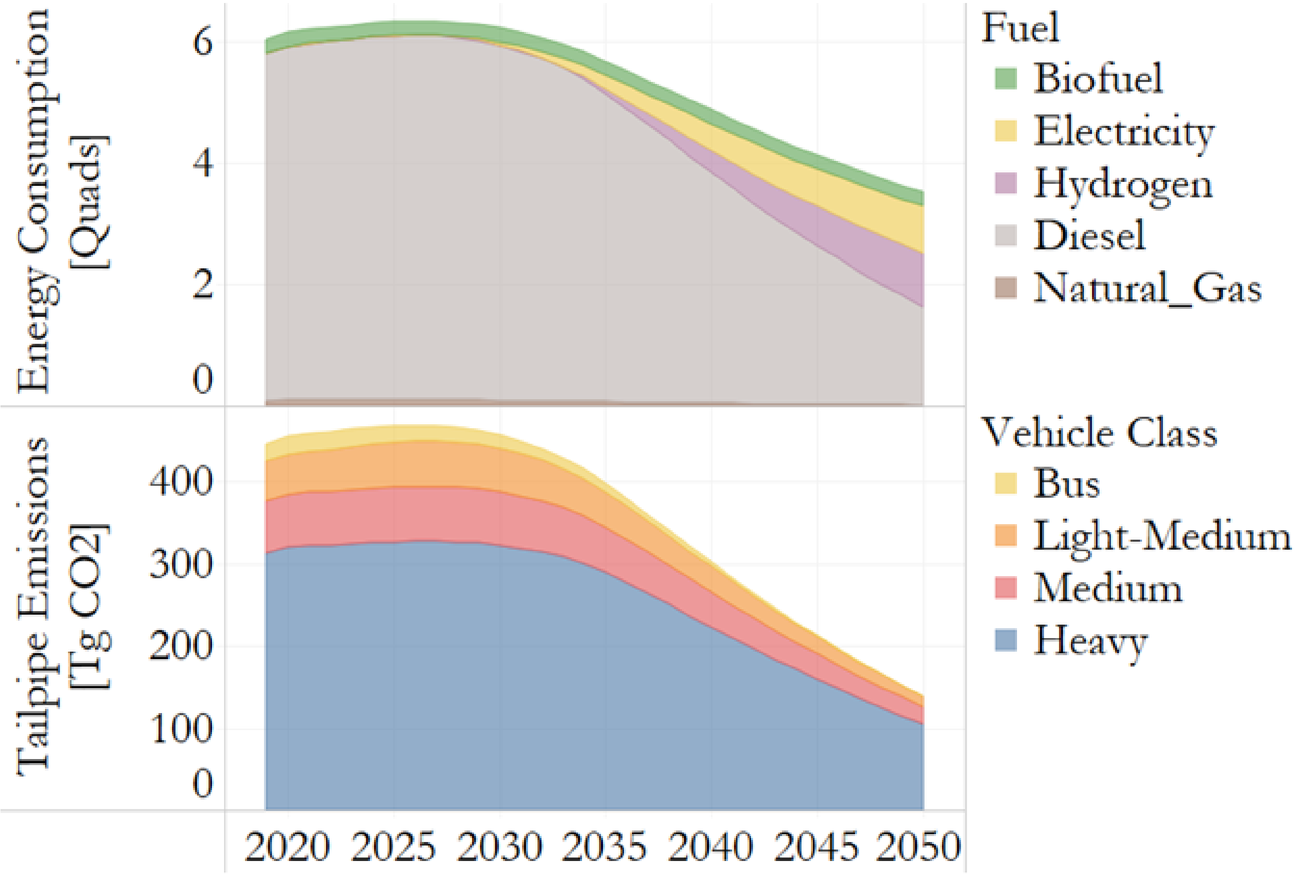


[1] Blynn & Attanucci. 2019. https://doi.org/10.1177/0361198119842117
[2] Burke, A., & Sinha, A. 2020. http://dx.doi.org/10.7922/G2H993FJ

MHDV Energy Consumption and Emissions

- **MD/HD emissions decline by 69% in 2050 relative to 2019, despite 55% freight demand (VMT) growth.**
  - BEV **electricity consumption (including buses)** is 15 TWh in 2030, 127 TWh in 2040, and 227 TWh in 2050.
  - **Hydrogen** demand is 0.1 MMT (2.8 TWh) in 2030, 3.2 MMT (171 TWh) in 2040, and 7.8 MMT (399 TWh) in 2050.[1]
  - **Liquid fuel** demand is 44.1 billion gallons in 2030, 29.3 billion gallons in 2040, and 13.5 billion gallons in 2050 (2019 **biodiesel** consumption of ~2 billion gallons is held constant over time).
- **Low-carbon fuels (not modeled)** can further reduce remaining emissions.

MHDV Tailpipe Emissions and Energy Consumptions

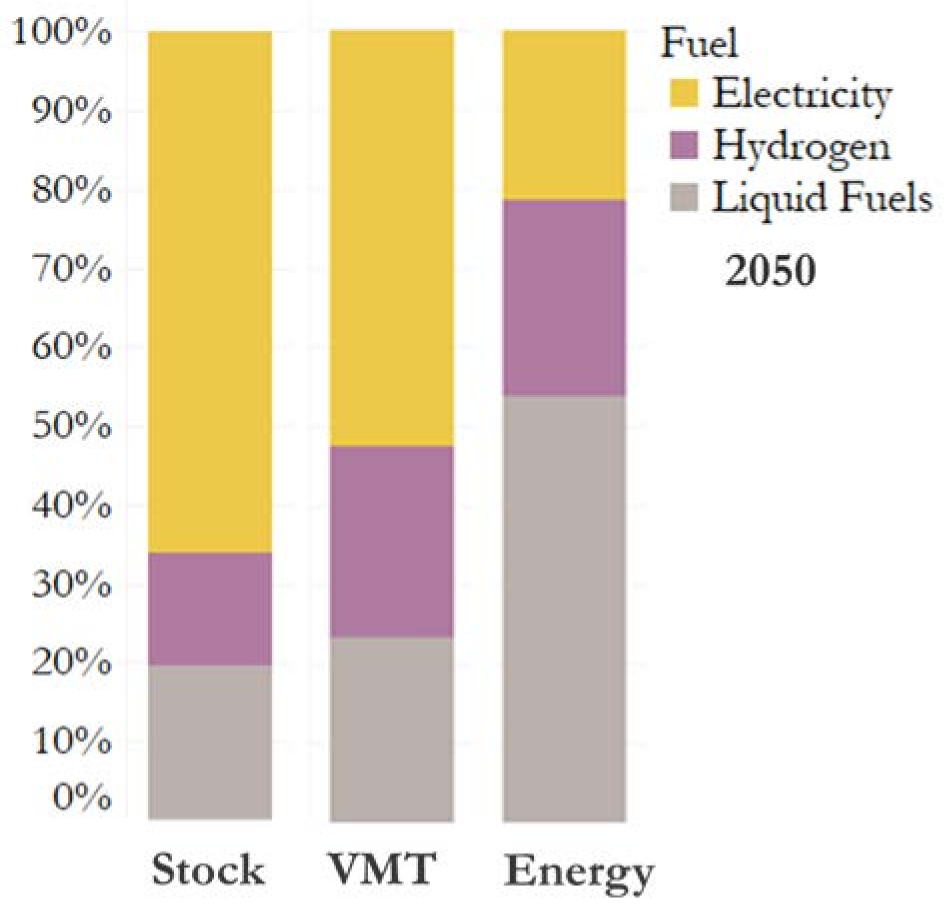


[1] Electrolyzer efficiency from Hunter *et al.*, 2021. https://doi.org/10.1016/j.joule.2021.06.018.

Impact of Segment-Specific Vehicle Adoption

TEMPO

- **Emissions and energy strongly depend on which classes and applications transition to ZEV, on top of the total number of ZEVs:**
  - **Fuel economies vary** greatly across both vehicle classes and powertrains.
  - **Vehicles within a class are driven differently**, depending on their shipment distance bin.
- Most **BEVs** are used in short-haul light-medium and medium applications, which have higher fuel economy.
- **FCEVs** are used substantially in heavy long-haul applications, which have the greatest VMT and lower fuel economy, **increasing their overall energy share relative to their stock**.
- ICEVs are also used substantially in heavy and long-haul applications. ICEVs overall have the lowest fuel economy. Across all classes and applications, **ICEVs represent 20% of stock in 2050 but over half of energy consumption**.



Key Takeaways

- Improvements in zero-emission vehicle technologies (BEV and FCEV) and fuels in line with DOE targets (and vetted with industry) enable **ZEVs to achieve cost parity with diesel by 2035.** Two ZEV tech solutions and pathways for many applications provide more options and mitigate risks:
  - **BEVs tend to become cost-competitive** for almost all light-medium and medium trucks before 2030 and for short-haul (<500-mile) heavy trucks before 2035.
  - **Hydrogen FCEVs tend to become cost-competitive** for long-haul (>500-mile) heavy trucks by 2035.
  - Buses can fully transition to ZEV (100% sales) by 2030.
- Assuming charging/refueling infrastructure is deployed to support ZEV adoption, these enable **ZEV sales to reach 42% by 2030 and >99% of the MHDV market by 2045**, demonstrating the viability of 2030/2035 ZEV targets for MHDVs.
- **Despite 55% growth in projected freight demand (VMT), 2050 CO_2 emissions can be reduced by 69% compared to 2019** and keep dropping in the following decade. However, not all diesel vehicles are replaced by 2050, with the remaining vehicles consuming 13.5 billion gallons of liquid fuels.
  - 80% truck stock are ZEV in 2050 (66% BEV, 14% FCEV). Accelerated stock turnover could help to increase ZEV penetration in 2050. 100% bus stock is BEV by 2050.
  - Low-carbon liquid fuels can help further reduce emissions but are not captured here.

Future Analysis Needs

- Quantify needs and ability for **manufacturing capacity scale-up** and required **upgrades of grid infrastructure** (bulk-power and distribution systems).
- Validate consistent **retail prices for depot and public BEV charging and hydrogen fueling** considering a fully decarbonized power system.
- Broader transportation market effects associated with **supply chain and demand disruptions/shifts including new business models** (*e.g.*, e-commerce) and possible **changes in logistics and vehicle operations** driven by ZEV technologies.
- Incorporate analysis of **co-benefits of ZEV adoption**, including criteria pollutant emissions reductions and health impacts.
- Explore dynamics of ZEV transition, including **co-evolution of vehicle and infrastructure markets.**
- Expand **data collection efforts** to improve assumptions.
- Improve **representation of non-freight applications and vehicle use** (non-freight trucks and buses) and determinants of adoption.
- Incorporate representation of adoption dynamics in the **used vehicle market** and applications for older vehicles.

Thank you!

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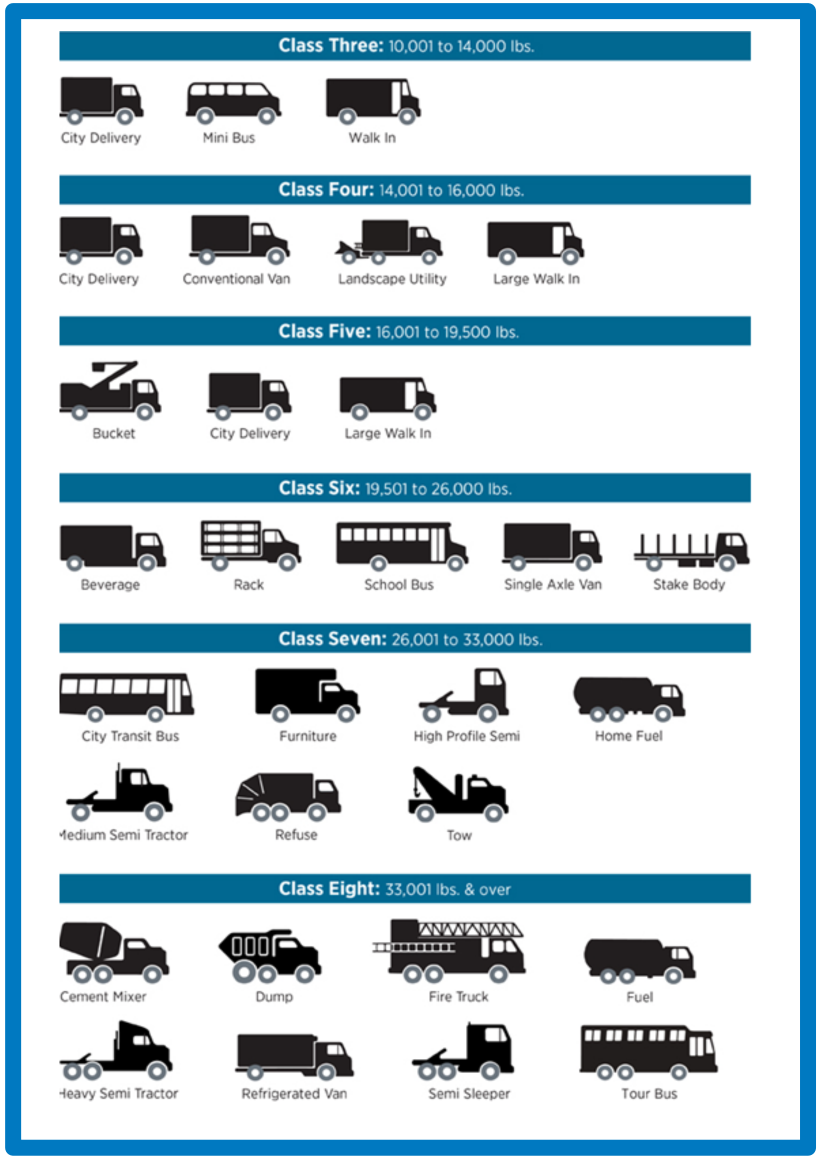
NREL Transforming ENERGY

SUPPLEMENTAL SLIDES

Scope

- TEMPO MD/HD encompasses Class 3–8 freight vehicles and buses (>10,000 lbs. GVWR).
- Freight vehicle applications are modeled in TEMPO. Total VMT by vehicle class is calibrated to AEO 2019, while divisions across shipment distance are based on FAF.
- Non-freight vehicle stock and energy (e.g., garbage trucks, cement mixers) are assumed to transition to ZEV at the same rate as freight, using VMT and stock assumptions based on AEO.
- Non-freight vehicles are disaggregated from AEO using fractions derived from VIUS (39% of stock and 26% of VMT in 2019) and mapped to the 0–250-mile distance bins for each vehicle class.
- Freight stock and VMT shares inform non-freight stock and VMT, implying the same turnover as freight vehicles.



Summary of Vehicle Adoption Approach by Segment

Market Segment	Assumption
Medium- and Heavy-Duty Freight Trucks, All Market Segments	Economically competed based on total cost of driving
Medium- and Heavy-Duty Non-Freight Trucks	Vehicle adoption and use assumed to be identical to short-haul freight (250 miles or less)
Buses	Sales shares assumed to reach 100% ZEV by 2030

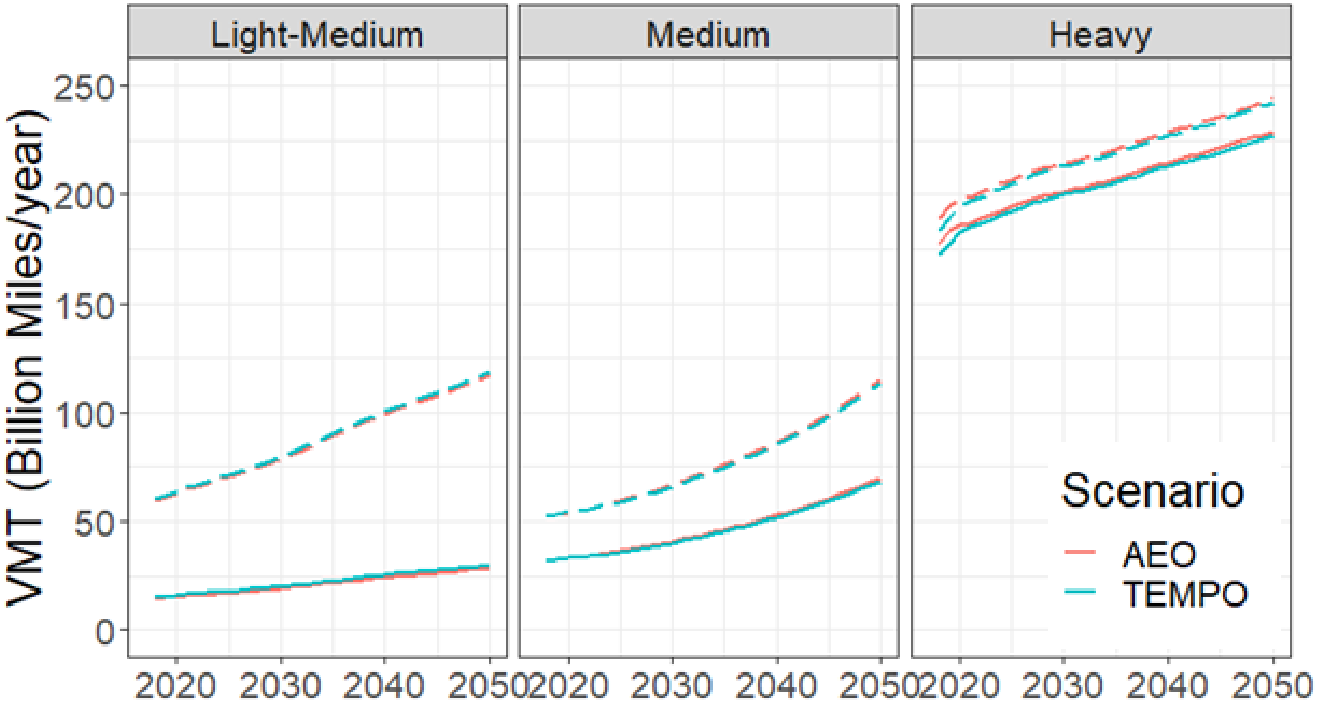
METHODS

Freight Demand Projections: VMT

TEMPO

- Freight demand growth in TEMPO is set exogenously to correspond to AEO freight VMT growth.
- Total VMT grows by 55% between 2019 and 2050. The greatest growth is seen in light-medium and medium (90% and 114% increases, respectively).
- Using load factors from VIUS, we derive VMT from FAF ton-mile demand for freight.
- We compare freight VMT in TEMPO to AEO. AEO is disaggregated into non-freight (e.g., cement mixers/garbage trucks) and freight activity using fractions based on VIUS.
- TEMPO and AEO match closely on freight VMT.

MD/HD Truck VMT, TEMPO and AEO

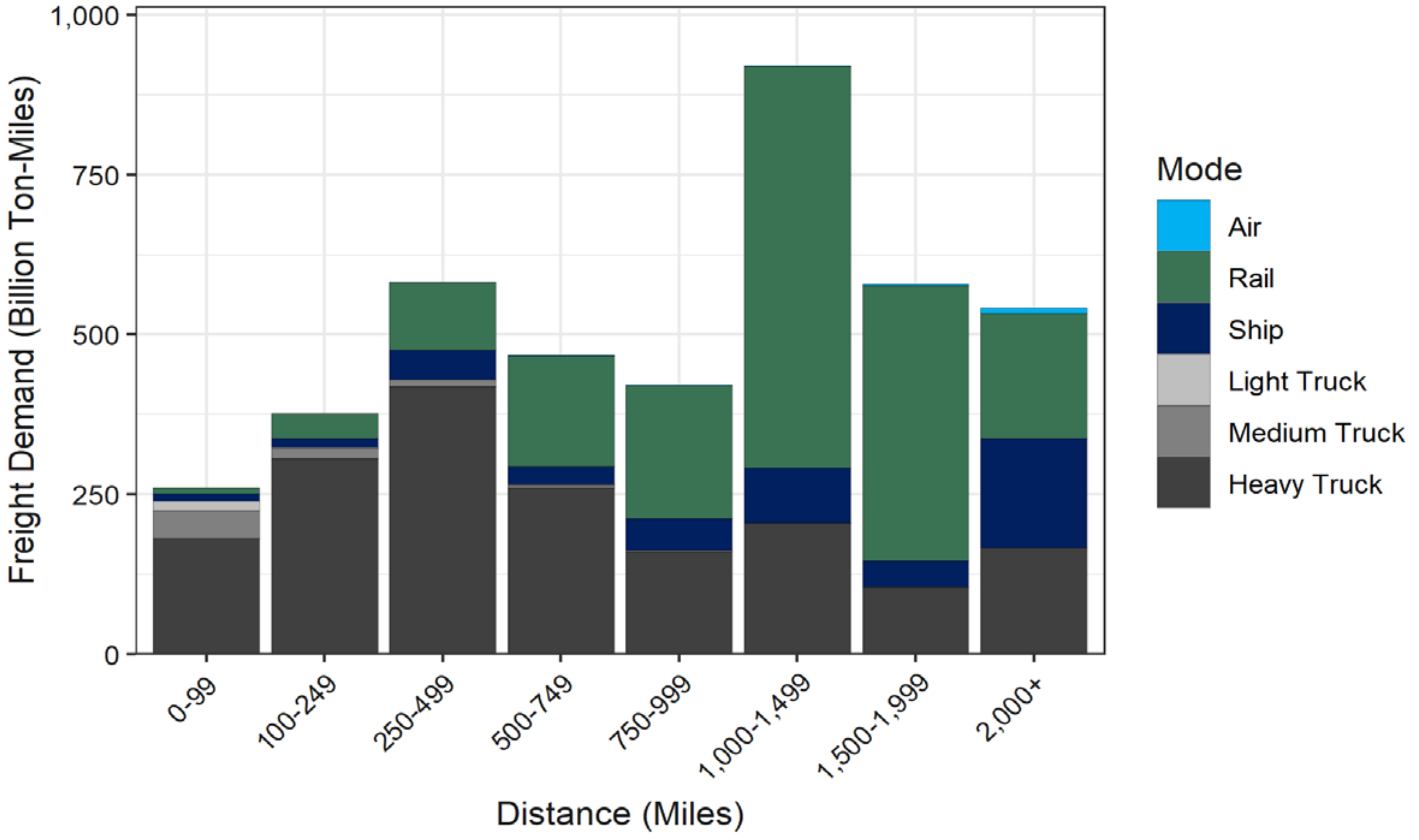


Total VMT (dashed lines; non-freight + freight) and freight VMT (solid lines), AEO and TEMPO MD/HD trucks. Non-freight VMT is assumed to follow the same energy evolution as freight.

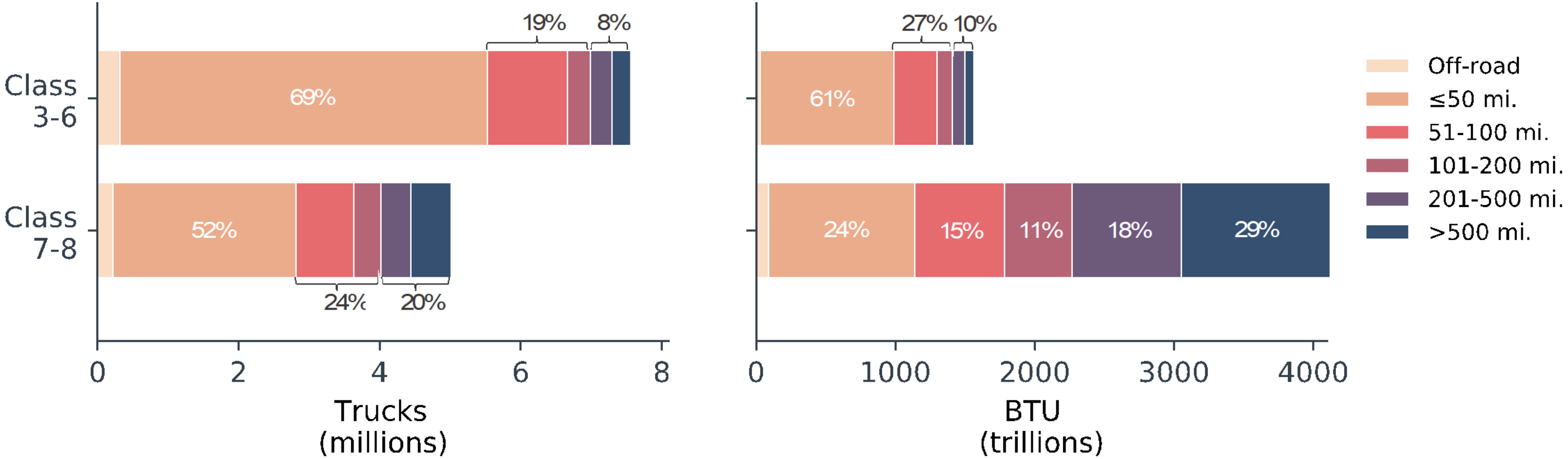
Freight Mode/Tech Choice

TEMPO represents travel choice across freight bins. **Mode and technology choice varies with average shipment distance**.

For medium- and heavy-duty trucks, total demand by distance is informed by FAF, with splits across vehicle class informed by VIUS.



Not all trucks are the same or used the same way



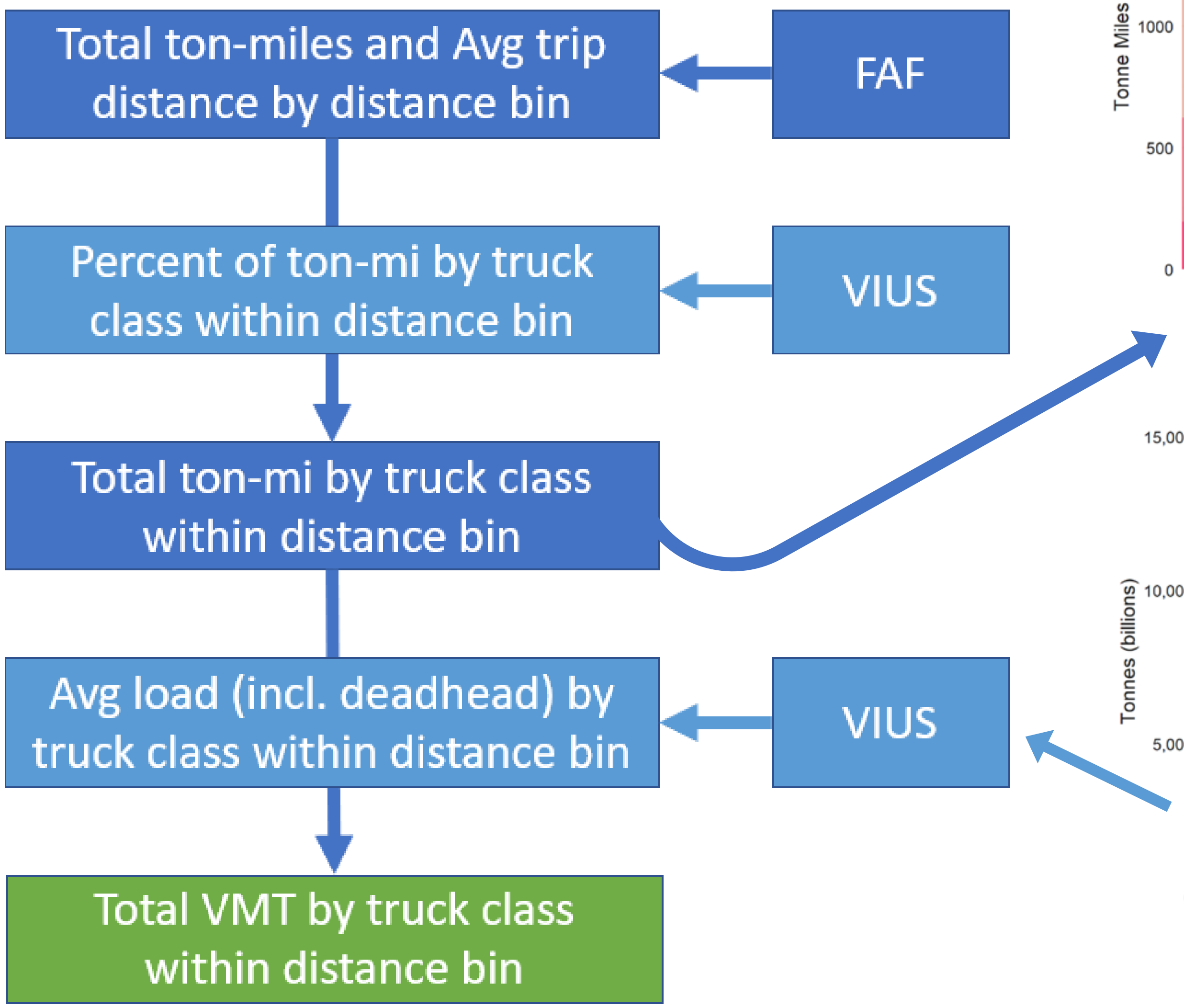
Source: Borlaug et al. 2021. Heavy-duty truck electrification and the impacts of depot charging on electricity distribution systems. Nature Energy.

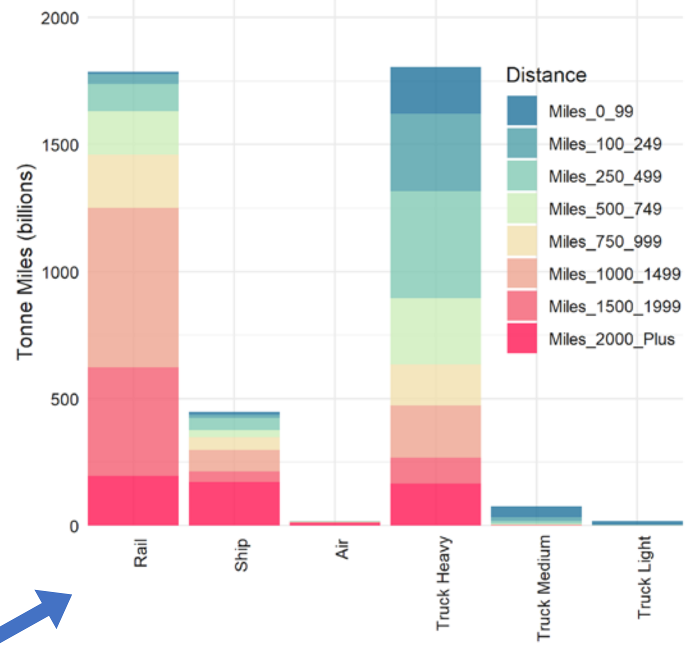
- ~10% of heavy-duty trucks have an operating range of 500 miles or more, whereas **~70% operate primarily within 100 miles**.
- Recent industry trends (e.g., the rise of e-commerce and low driver retention) produced a shift away from interregional and national hauls in favor of decentralized hub-and-spoke distribution models, which culminated in a **37% decrease in the average length of haul from 2000 to 2018** (not factored in the figure).

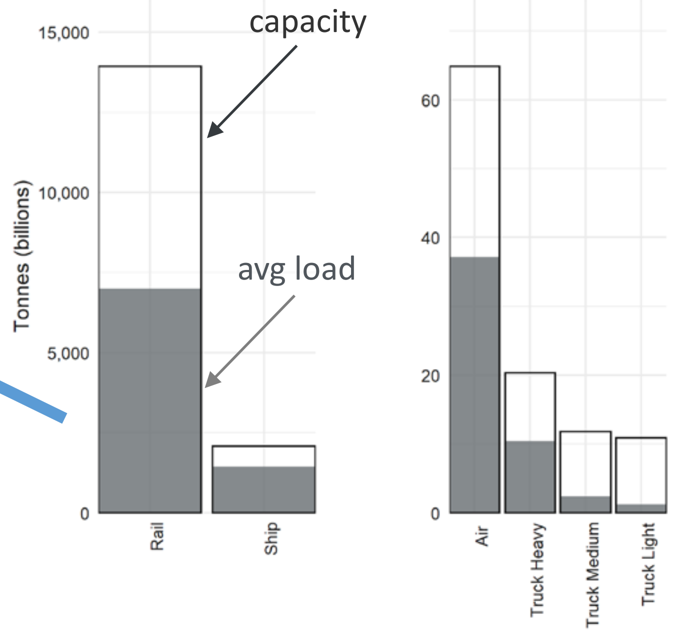
TEMPO FAF-VIUS Synthesis

TEMPO

- Goal: break down freight demand by shipment distance to represent varying trip requirements.
- Problems:
  - Disagreements across sources/models.
  - Gaps in key metrics, time periods, modes.
- Solution(s) often require **merging multiple data sets together** to meet desired input data needs.
- Key assumptions/caveats:
  - We assume trucks are assigned to a single shipment distance bin for the entire vehicle lifetime.
  - We do not represent the used vehicle market or changes in applications over the vehicle lifetime.



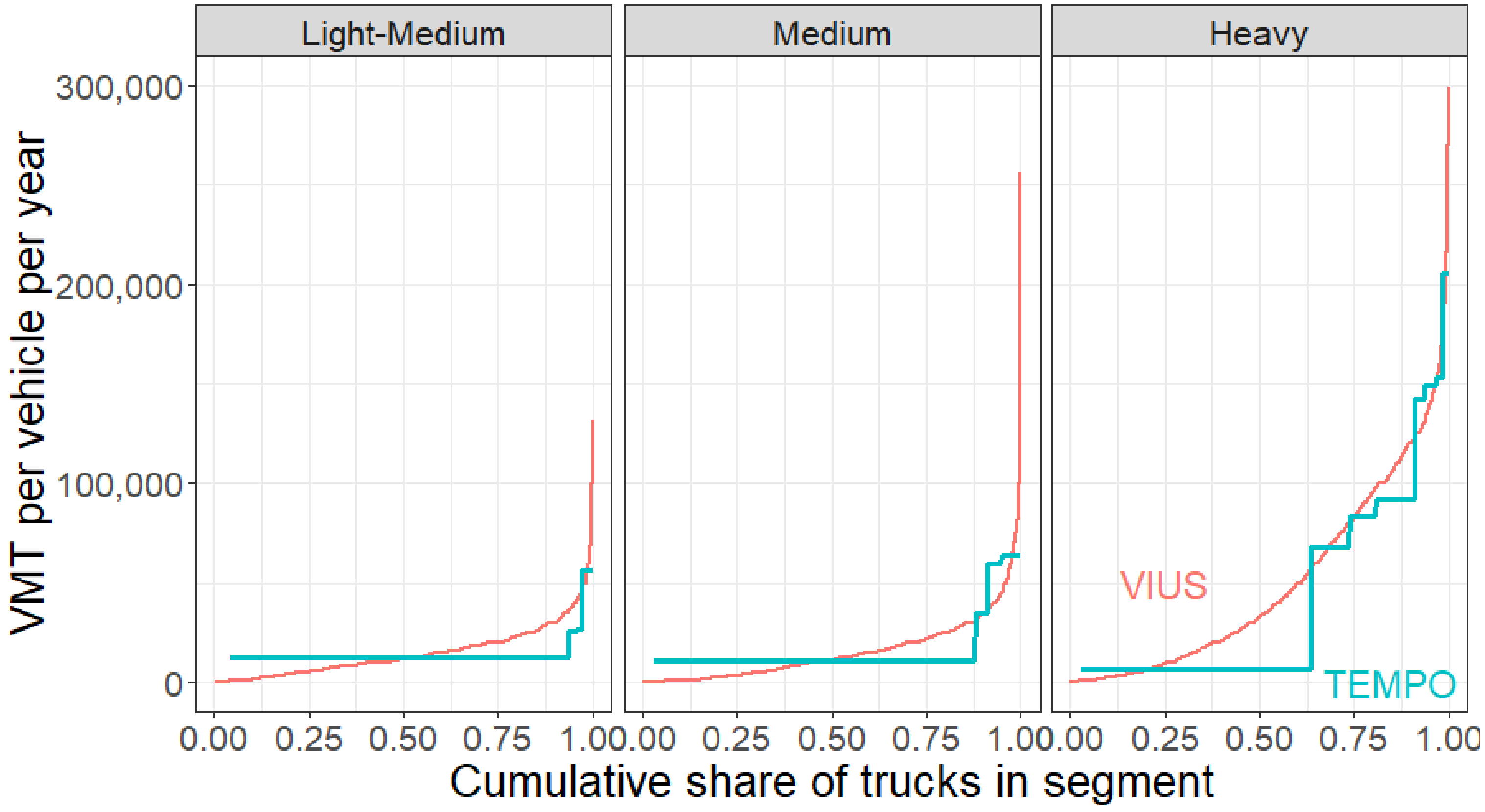




TEMPO FAF-VIUS Synthesis: Validation

- We compare the outcomes of TEMPO's FAF-VIUS synthesis to VIUS VMT. VIUS VMT was not directly used to inform TEMPO VMT, only shares across modes and distances.
- We find that, accounting for TEMPO's binning into shipment distances based on FAF, we match VIUS distributions of VMT by truck stock.
- To some extent, we underestimate the VMT of the lowest-driving heavy trucks in TEMPO due to our distance binning. This might imply that we overestimate the time it takes to reach cost parity in the 0–99-mile bin for heavy vehicles.

Distribution of VMT by Truck Class, TEMPO & VIUS



Drivers of MHDV Adoption in TEMPO

Vehicle adoption in TEMPO is determined by total cost of driving (TCD):

- Upfront **vehicle cost** (MSRP)
- **Fuel costs** (vehicle fuel economy and fuel price)
- **Maintenance** costs
- **Vehicle usage** (VMT)
- **Financial horizon** considered (or discount rate)
- Monetized **charging time cost** for BEVs (charging availability and speed)
- Logit formulation—captures heterogeneities
- No difference in resale value across powertrains due to uncertainty (battery replacement/depreciation).

Non-financial factors like availability of make/models, driver preferences, manufacturing or infrastructure constraints, other external drivers of adoption are not considered.

TEMPO Technology Choice Logit[1]

$$w_t = e^{(-K \times TCD_t)}$$

$$s_t = \frac{w_t}{\sum_{t=1}^{T} w_t}$$

- w_t is the weight of technology t
- K is the cost coefficient
- TCD_t is the total cost of driving of technology t
- s_t is the sales share

- **TCD parity** in TEMPO implies a sales share **evenly divided** between technologies.
- We assume that **five years of consistent cost savings** are required to reach 95% adoption after achieving TCD parity in each market segment.

[1]More details: Muratori *et al*., 2021. https://doi.org/10.1016/j.trd.2021.102967

Total Cost of Driving Limitations

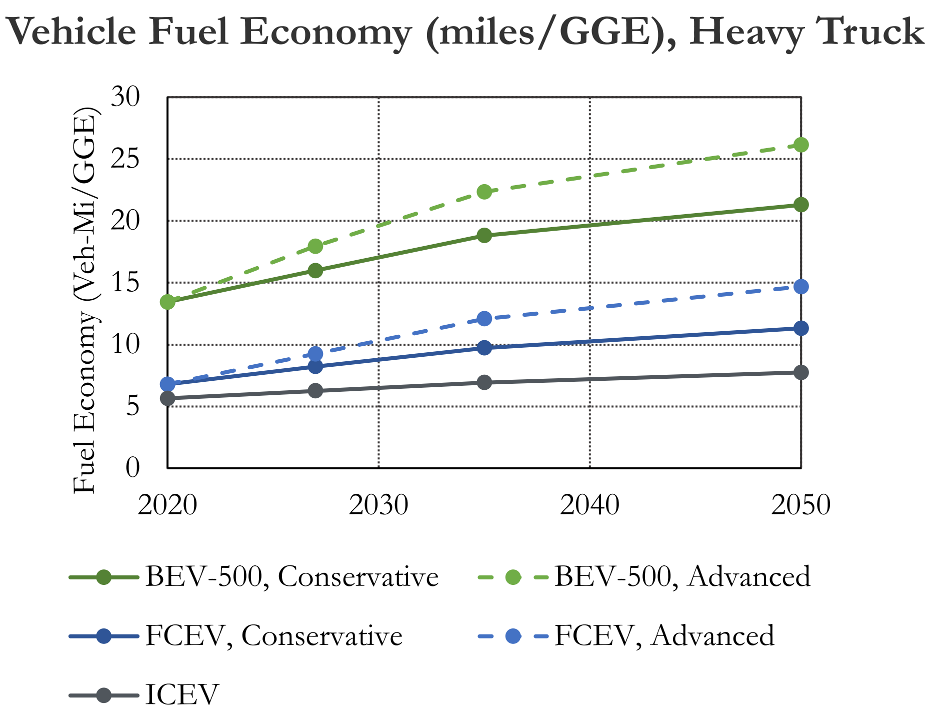
- Adoption assumed to be driven by economics only.
  - Non-financial factors like availability of make/models and manufacturing or infrastructure constraints, driver preferences, acceleration and safety, fleet or stakeholder preferences (e.g., decarbonization pledges), and other externalities (e.g., cost of pollution) are not considered.

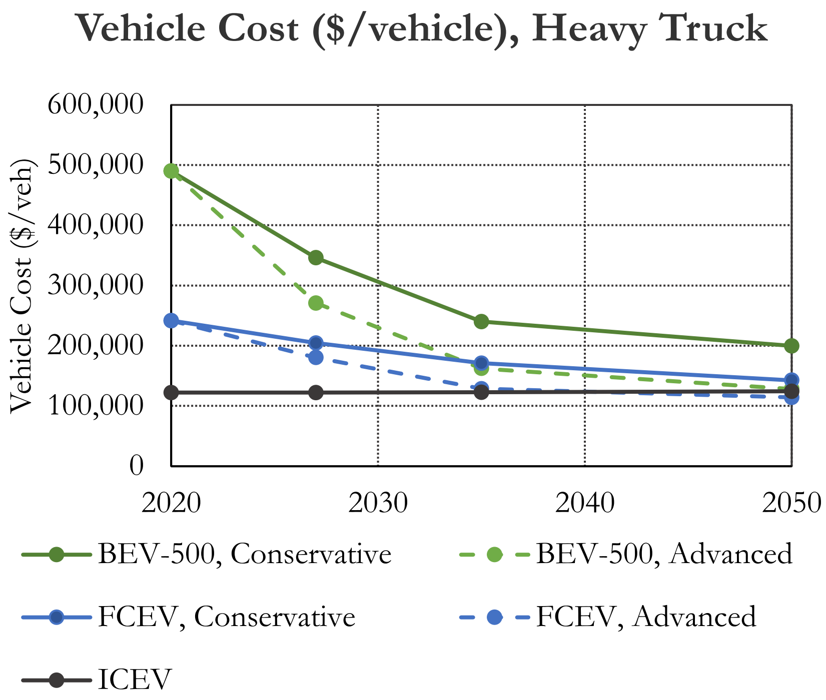
- Distinct from total cost of ownership (TCO) analyses, we do not explicitly consider some cost elements (e.g., insurance, driver cost) due to lack of data and high uncertainty. We instead implicitly assume these factors are constant across powertrains.
  - General operational costs (driver wages, insurance, permits/tolls)[1]
  - Resale value across powertrains (due to uncertainty in battery replacement/depreciation).

[1]Consistent with assumptions made in Hunter, C., Penev, M., Reznicek, E., Lustbader, J., Birky, A. & Zhang, C. 2021. Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. *National Renewable Energy Laboratory,* NREL/TP-5400-71796.

ASSUMPTIONS

Input Assumptions: Vehicles





- All assumptions are from Autonomie simulations - Low (Conservative) and High (Advanced) scenarios.[1]
- Advanced assumptions are used in our central scenario, while conservative assumptions inform sensitivities.
- ICEVs follow conservative assumptions in all cases.

[1] Islam *et al.*, forthcoming.

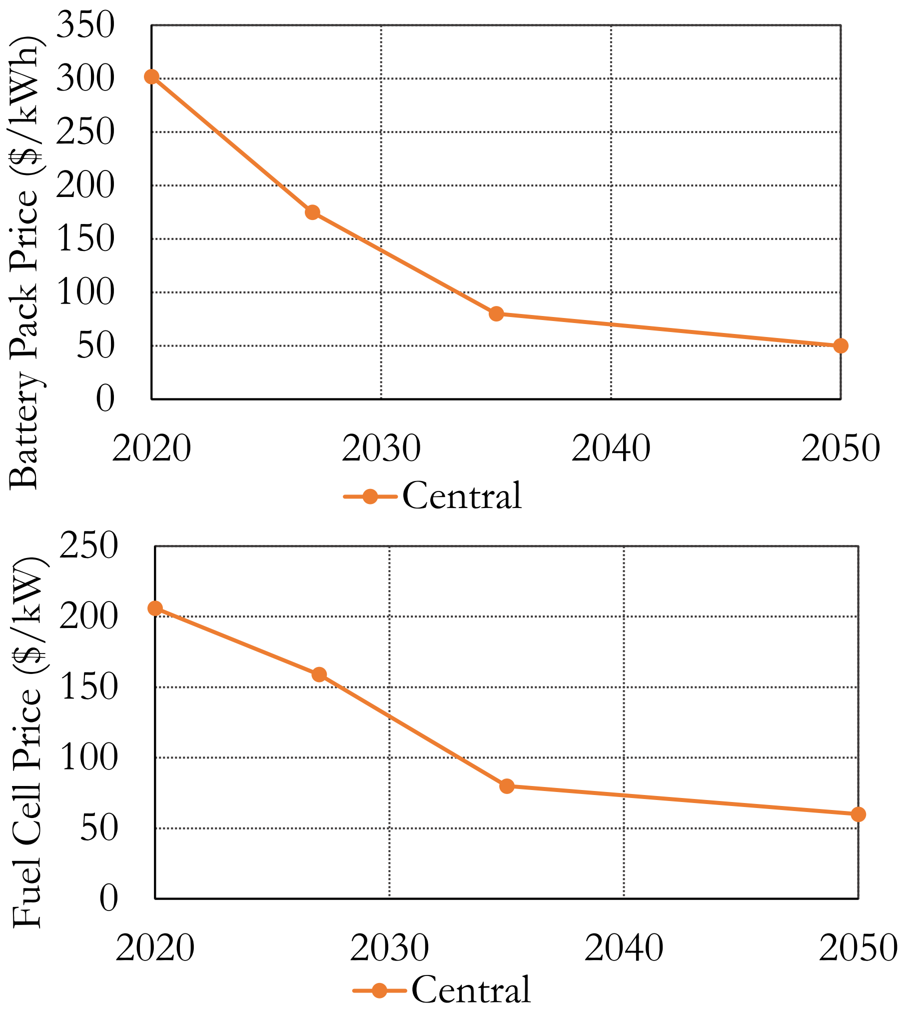
Input Assumptions: TEMPO-AUTONOMIE Mapping

TEMPO Class	TEMPO Powertrain	Autonomie Mapping	Notes
Light-Medium (Class 3, 10,000–14,000 lbs.)	All	Class 3 Van	Starting from available BEV-150, BEV-300, and BEV-500 cost updated to account for larger battery, assuming same efficiency.
Medium (Class 4–6, 14,000–26,000 lbs.)	All	Weighted average of Class 4 PnD (41%); Class 6 Box (59%)	Weights based on VIUS; starting from available BEV-150, BEV-300, and BEV-500 cost updated to account for larger battery, assuming same efficiency.
Heavy (Class 7–8, 26,000+ lbs.)	All	Weighted average of Class 7 tractor (4%); Class 8 Tractor (27%); Class 8 Sleeper (69%)	Weights based on VIUS; starting from available BEV-500, BEV-150, and BEV-300 cost updated to account for larger battery, assuming same efficiency.

Input Assumptions – Batteries and Fuel Cells

- Battery pack and fuel cell prices are embedded in Autonomie[1] estimates of vehicle purchase cost.
- Our central case assumes that battery and fuel cell prices follow the *High* case from Autonomie.
- Conservative cost estimates are explored in sensitivities.

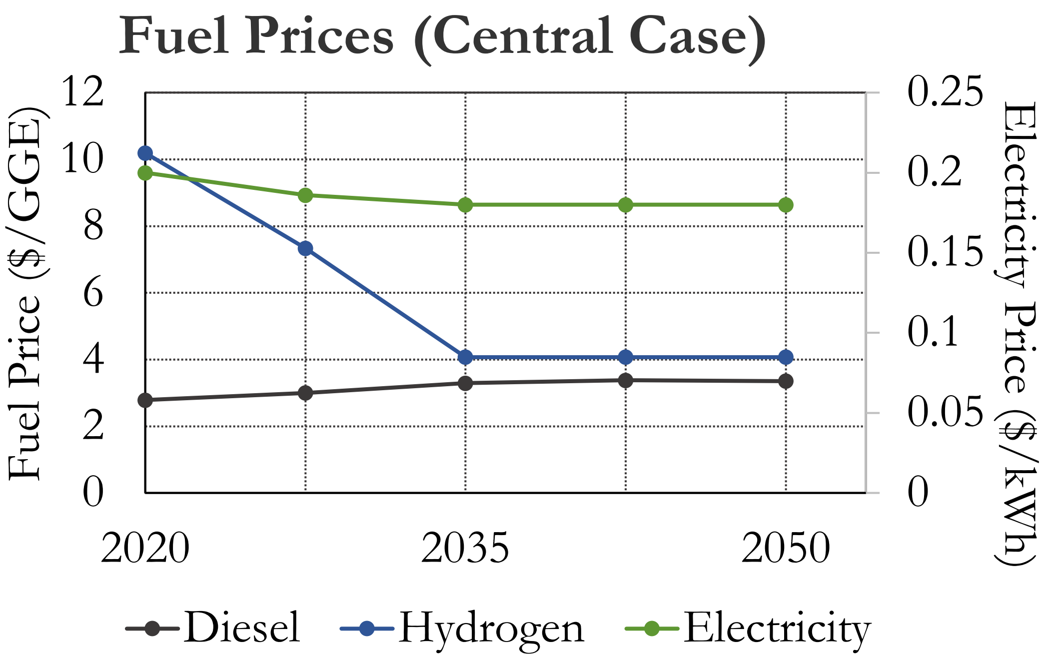
Battery and Fuel Cell Prices, *Central* scenario



[1] Islam *et al.*, forthcoming

Input Assumptions – Fuel Prices

- Central fuel price assumptions are from AEO 2019 for diesel.[1]
- Hydrogen and electricity prices are highly uncertain.
- We explore multiple fuel price sensitivities in addition to our central assumptions.



[1] U.S. Energy Information Administration. 2019. Annual Energy Outlook 2019. https://www.eia.gov/outlooks/aeo/.

BEV Charging Penalty

- We assume no cost associated with refueling ICE/HEV/FCEV (availability of refueling everywhere, long vehicle range, and refueling time comparable across technologies).
- BEV are penalized if trucks need to add an intraday stop to recharge: value of time added to charging costs ($75/h).[1]
- The fraction of charging that is monetized is a function of daily driving distance, vehicle range, and access to overnight charging.
- Daily driving distance is computed from assumed annual VMT (derived from FAF-VIUS synthesis), dividing by 250 (short-haul) or 300 (long-haul) operation days. The number of intraday charging events is calculated from daily driving distance and range. If daily driving distance does not exceed range, zero intraday charging events are assumed.
- Monetized charging fractions are computed as the fraction of total charging events (intraday and overnight) that are monetized, considering an average across the vehicle fleet. All intraday stops are assumed to be monetized; overnight charging varies by class and application.
- We assume all light-medium, medium, and short-haul (<500−mile) heavy vehicles have access to overnight charging, which is not monetized.
- 6.2% of heavy trucks (38% of long-haul heavy trucks) are assumed to be team drivers, with all charging monetized.[2] All other overnight charging events are assumed to be non-monetized for long-haul heavy trucks.

[1]Hunter, C., Penev, M., Reznicek, E., Lustbader, J., Birky, A. & Zhang, C. 2021. Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. *National Renewable Energy Laboratory,* NREL/TP-5400-71796.

[2]Schoettle, B., Sivak, M., & Tunnell, M. 2016. A survey of fuel economy and fuel usage by heavy-duty truck fleets. University of Michigan Sustainable World Transportation & American Transportation research Institute, SWT-2016-12.

BEV Charging Penalty

Vehicle Class	Powertrain	Shipment Distance	Share of Non-Monetized Charging
Heavy (Class 7–8, 26,000+ lbs.)	BEV-150	0–250 Miles	100% to 30% (varying with individual bin)
	BEV-300	0–250 miles; 250+ miles	100% to 16%
	BEV-500	250+ miles	100% to 22%
Medium (Class 4–6, 14,000–26,000 lbs.)	BEV-150	0–250 Miles	100% to 31%
	BEV-300	0–250 miles; 250+ miles	100% to 48%
	BEV-500	250+ miles	100%
Light-Medium (Class 3, 10,000–14,000 lbs.)	BEV-150	0–250 miles	100% to 35%
	BEV-300	0–250 miles; 250+ miles	100%
	BEV-500	250+ miles	100%

- Shares refer to the percent of charging events that are not penalized monetarily. Shares vary with assumed daily driving distance, inferred from annual VMT associated with shipment distance.

Input Assumptions – Financial Horizon

- Assumed financial horizon refers to the number of years considered by vehicle purchasers when calculating cost of driving ($/mile).
  - Shorter financial horizon may reflect technology uncertainty, higher value of time, and warranties among other factors
  - Due to higher upfront costs and high mileage expectations, we assume owners of heavy trucks may consider longer time horizons than lighter vehicles

Vehicle Class	Financial Horizon (Years)[1]
Light-Medium (Class 3, 10,000–14,000 lbs.)	3
Medium (Class 4–6, 14,000–26,000 lbs.)	4
Heavy (Class 7–8, 26,000+ lbs.)	5

[1] The authors would like to thank Mike Roeth and Pick Mihelic (NACFE) for the useful discussions on this topic

Input Assumptions – Maintenance Costs

- Maintenance costs are from Hunter *et al.* (2021)[1], Mid scenario, and held constant over time.
- Light-medium (Class 3) trucks assumed to have the same maintenance costs as medium (Class 4-6), due to lack of data.

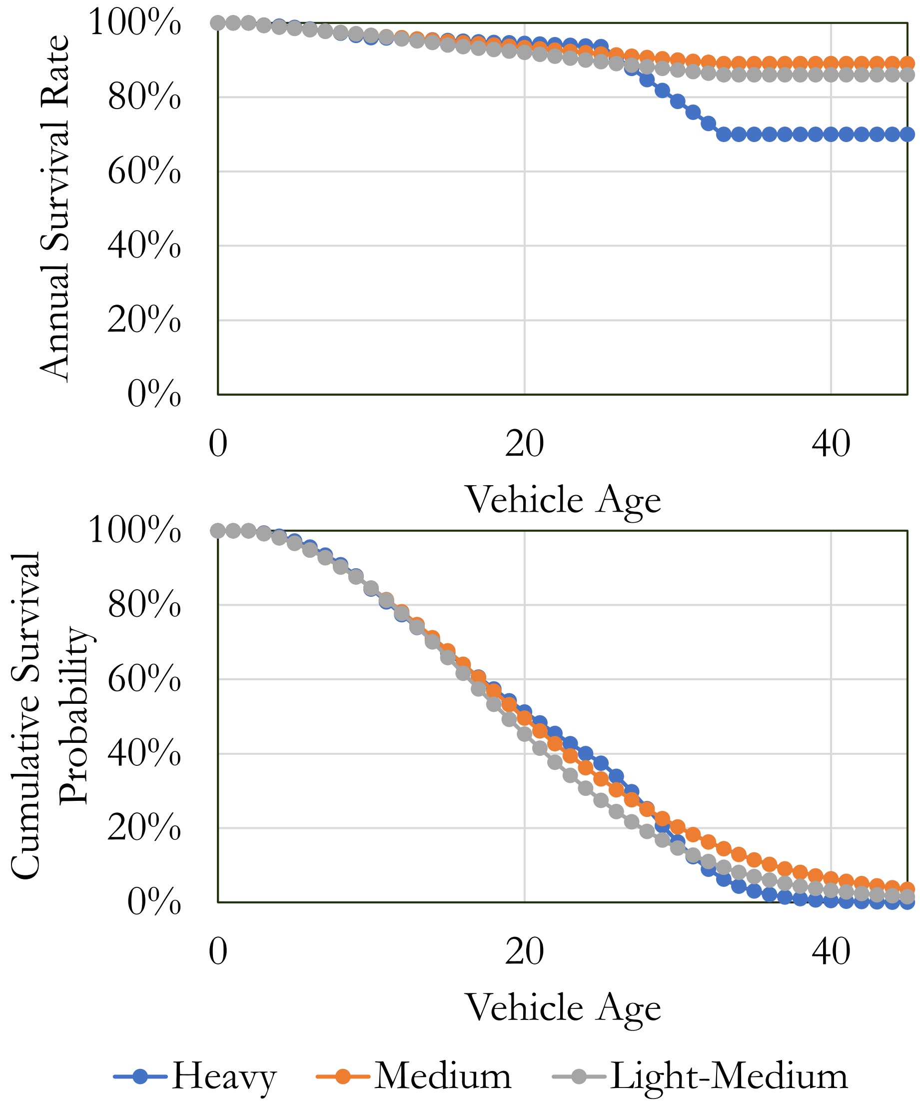
Maintenance Cost ($/mile) by Vehicle Class and Powertrain, from Hunter *et al.*[1]

Vehicle Class	ICEV/HEV	BEV	FCEV
Light-Medium (Class 3, 10,000–14,000 lbs.)	0.118	0.076	0.118
Medium (Class 4–6, 14,000–26,000 lbs.)	0.118	0.076	0.118
Heavy (Class 7–8, 26,000+ lbs.)	0.152	0.098	0.153

[1]Hunter, C., Penev, M., Reznicek, E., Lustbader, J., Birky, A. & Zhang, C. 2021. Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks. *National Renewable Energy Laboratory,* NREL/TP-5400-71796.

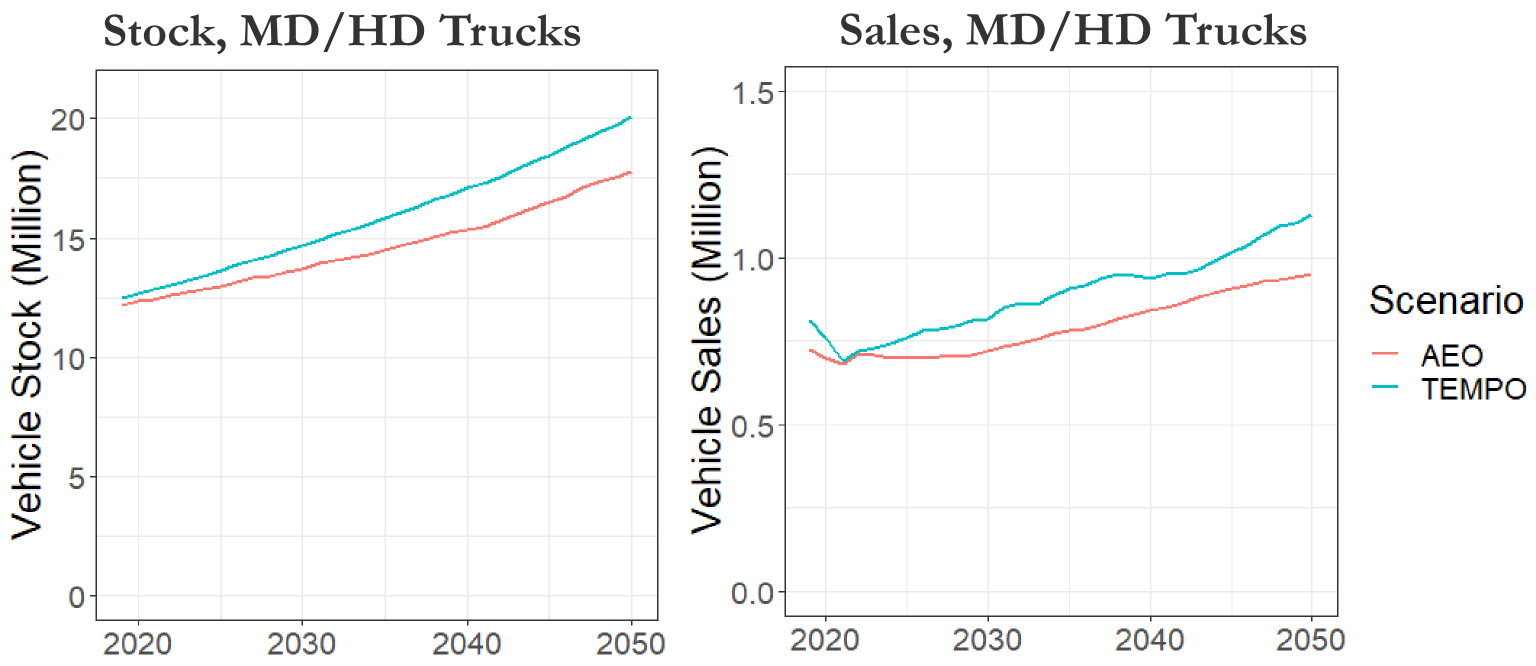
Input Assumptions – Fleet Turnover

- MD/HD survival rates are derived from the VISION model[1] and calibrated to match AEO sales.
- Initial (2017) vehicle age distributions are from MOVES.[2] We assume an average age of 11 years for heavy trucks and 12 years for light-medium and medium trucks in 2017.
- We assume that non-freight vehicles have the same survival rate as freight vehicles.



[1]Argonne National Laboratory. 2019. "VISION Model." Argonne, IL: Argonne National Laboratory. https://www.anl.gov/es/vision-model
[2]U.S. Environmental Protection Agency. 2021. Population and Activity of Onroad Vehicles in MOVES3. *US Environmental Protection Agency,* EPA-420-R-21-01, https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1011TF8.pdf.

Stock and Sales Comparison with AEO



- TEMPO assumes constant load factors, which implies that vehicle stock and sales grow at the rate of VMT. This leads to some long-term divergence from AEO in the number of vehicles.
- Historical years (2019–2021) match closely.

Comparison with Other Works

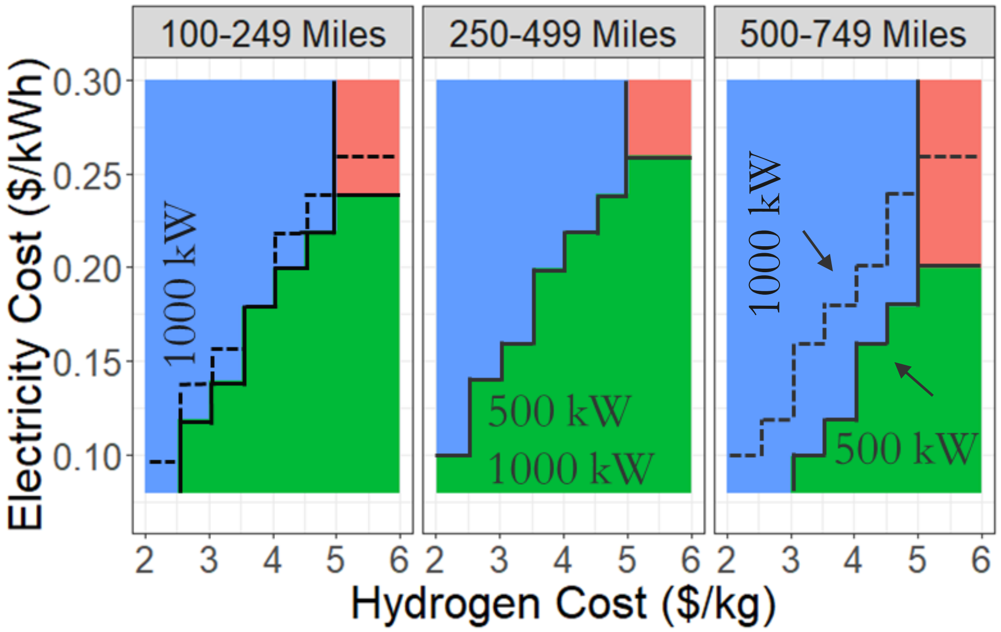
- Vehicle assumptions (cost and fuel economy) are taken from with Islam *et al.* (forthcoming).
- Despite some differences, total cost of driving estimates in the TEMPO central scenario are aligned with Islam *et al.* for BEVs and are more optimistic for FCEVs (due to more optimistic hydrogen price assumptions).
- The central scenario is aligned with Hunter *et al.* for medium BEVs. Differences in vehicle attributes, fuel price, vehicle use and dwell time may account for differences observed in heavy long-haul applications.

Vehicle Class	TEMPO – *Central* Scenario	Islam et al, Forthcoming	Hunter et al. 2021
Light-Medium (Class 3, 10,000–14,000 lbs.)	BEVs: majority reach TCD parity with ICEV before 2030; FCEVs before 2035	BEVs: parity by 2027; FCEVs before 2035	Not included
Medium (Class 4–6, 14,000–26,000 lbs.)	BEVs: majority reach parity between 2025 and 2035; FCEVs before 2035	BEVs achieve parity before 2035; FCEVs before 2050	Single-shift BEVs: parity by 2025; FCEVs: parity assuming ultimate targets met; multi-shift BEVs do not achieve parity
Heavy (Class 7–8, 26,000+ lbs.)	BEVs & FCEVs: parity between 2030 & 2035	BEVs: approach parity by 2035; FCEVs achieve, or almost achieve, parity by 2050	Parity depends on usage; short-haul single-shift BEVs: by 2025; long-haul BEV & FCEV: if ultimate targets & optimistic fuel prices achieved

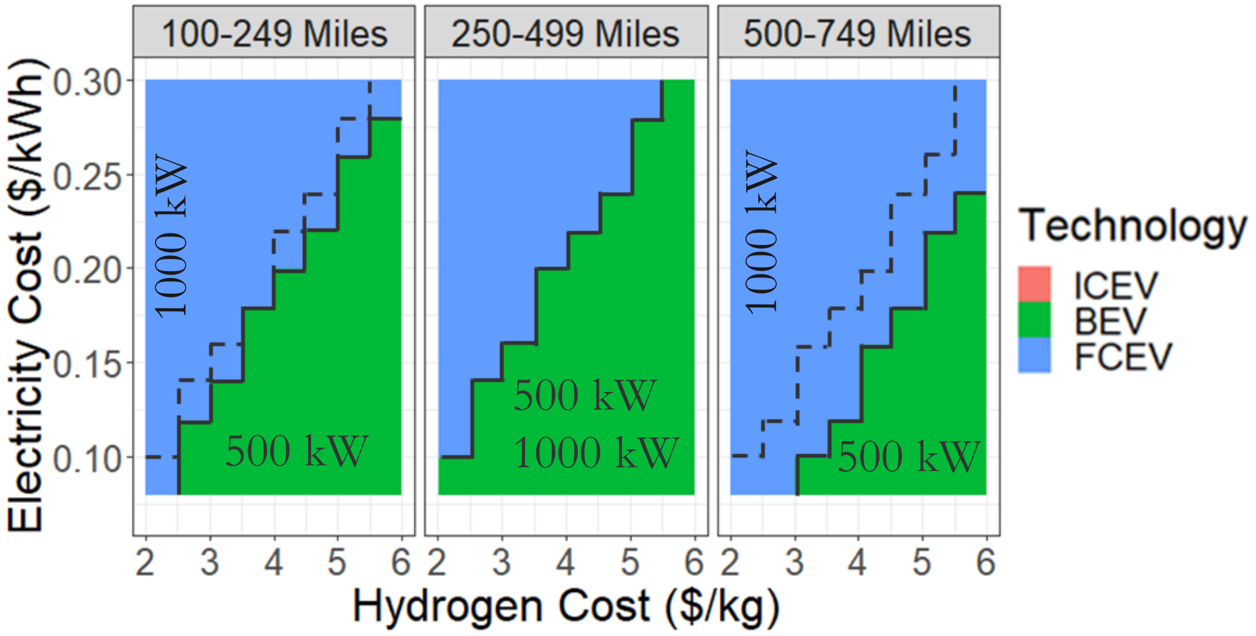
SENSITIVITIES

Impact of Fuel Prices

Heavy Trucks, 2035 (AEO Ref Diesel – $4/gal)

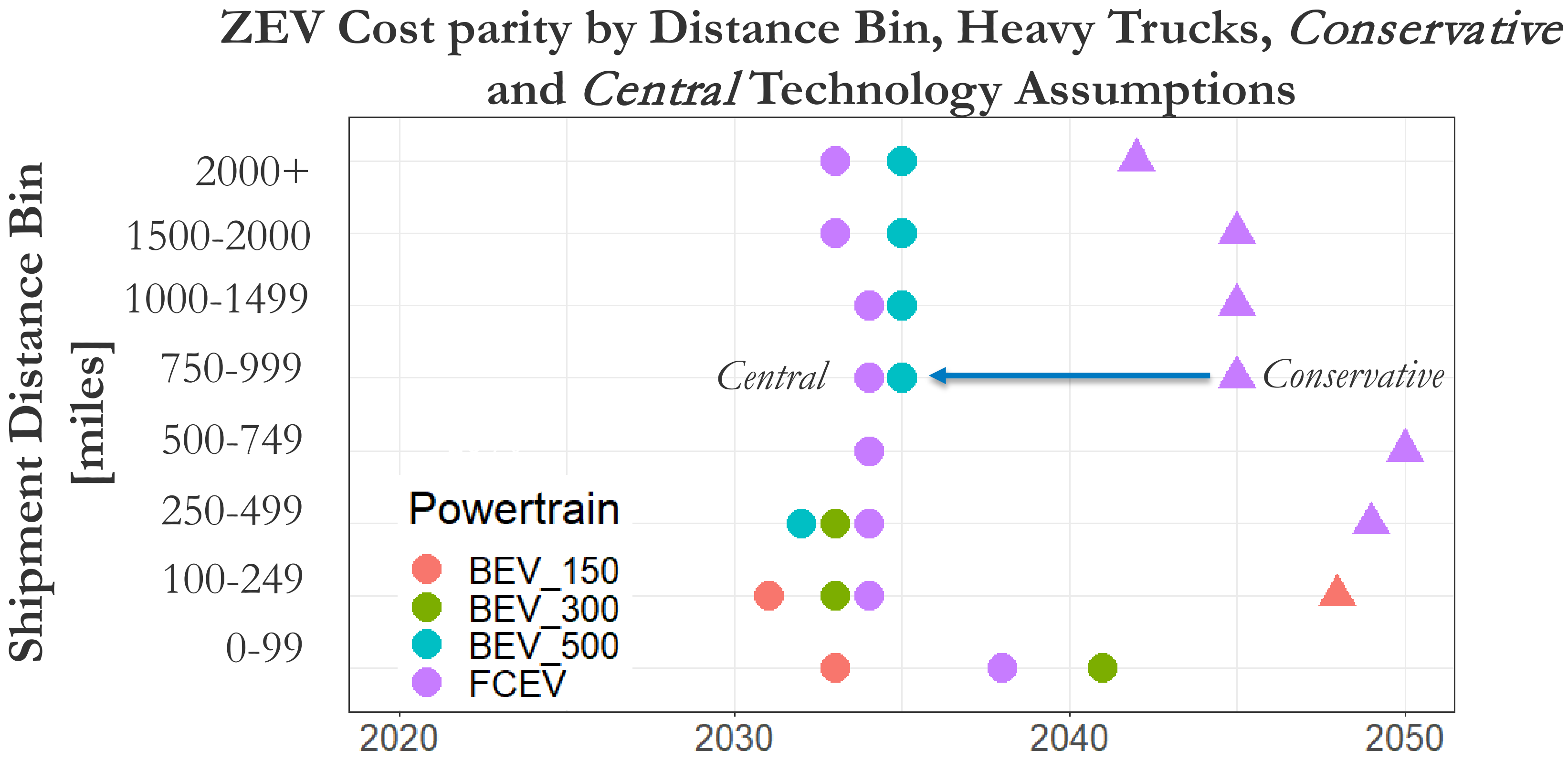


Heavy Trucks, 2035 (AEO High Diesel – $6/gal)



- Fuel prices and charging speeds are highly uncertain and vary by location and for different vehicles and distances.
- Under high diesel price assumptions, BEVs and FCEVs dominate the market.
- Hydrogen becomes most competitive in longer shipment distances (higher VMT) and at higher electricity prices.
- 500 kW (central; solid lines) and 1000 kW (dashed lines) charging speeds are considered, illustrating how reducing dwell time penalties improves the viability of BEVs.

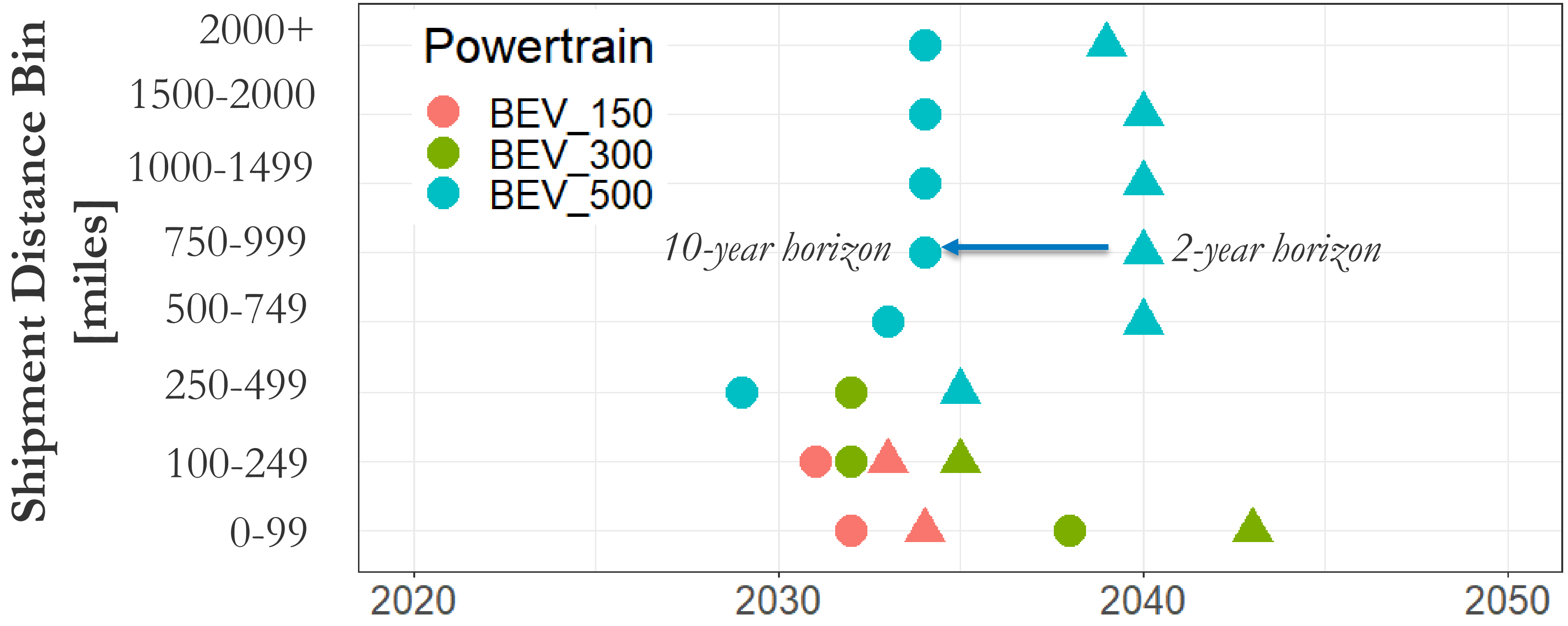
Impact of Vehicle Cost and Fuel Economy



- Vehicle cost and fuel economy evolution is highly uncertain, especially for ZEV powertrains.
- Conservative vehicle costs delay ZEV parity by 10 years or more for heavy trucks.
- Fuel cells reach parity after 2040 in most bins.
- BEV-300s and BEV-500s do not achieve parity in most bins under conservative assumptions.

Impact of Financial Horizon

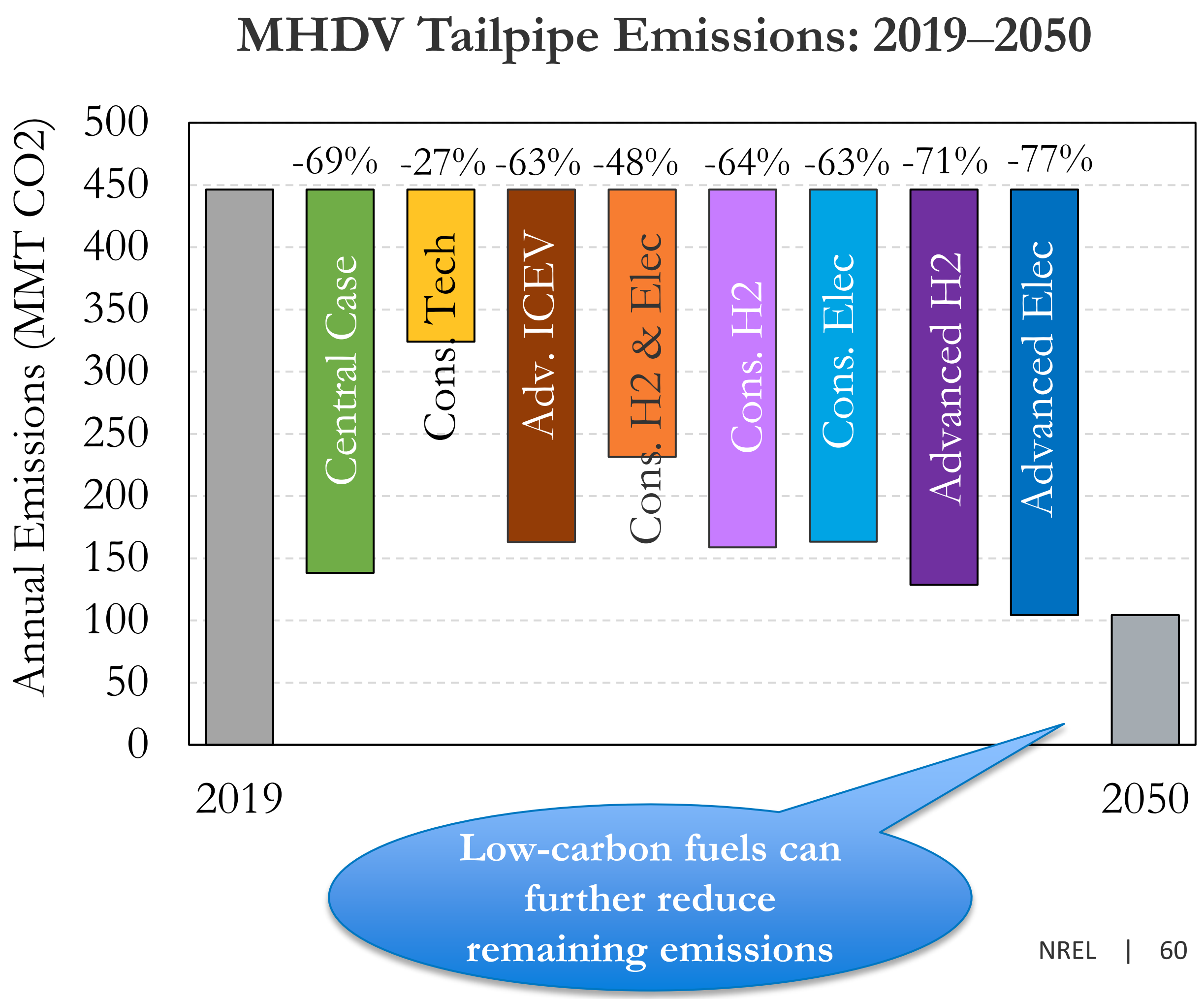
Heavy Trucks, BEV Cost Parity by Shipment Distance and Financial Horizon



- 2–10-year financial horizons may delay or increase parity by up to 6 years.
- Longer horizon shifts importance to incremental costs; shorter horizon emphasizes upfront cost more.
- BEV-500s are most sensitive to financial horizon due to high upfront costs.
- FCEVs and short-range BEVs are less affected (0–2-year difference).

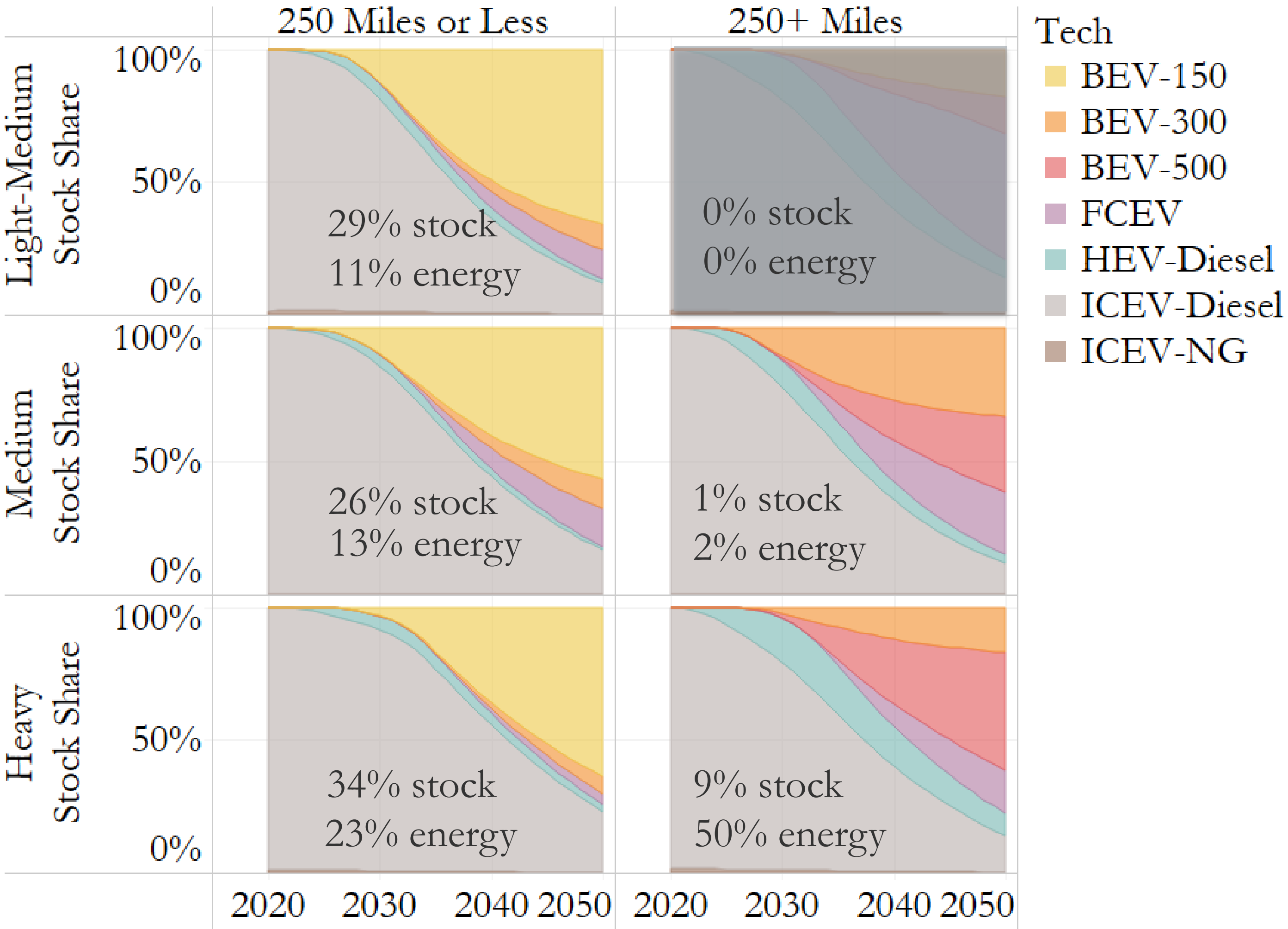
2050 Emissions Reductions: Additional Scenarios

- Additional scenarios/sensitivities:
  - **Conservative ZEV technology** progress (vehicle cost and fuel economy improvements)
  - **Advanced ICEV technology** (ICEV and HEV vehicle cost and fuel economy improvements)
  - **Advanced H2:** $3/kg by 2040 (vs $4/kg by 2035)
  - **Conservative H2:** $6/kg 2030-2050
  - **Conservative Electricity:** $0.27/kWh and 500 kW charging (vs. $0.18/kWh and 500 kW)
  - **Advanced Electricity:** $0.12/kWh and 1000 kW charging
  - **Conservative H2 & Electricity:** $6/kg H2 2030-2050; $0.27/kWh and 500 kW charging.
- Reduced technology improvements strongly hinder decarbonization potential.
- Advanced hydrogen has a small impact, as most benefits are incurred after 2040.
- Advanced electricity assumptions improve decarbonization potential.



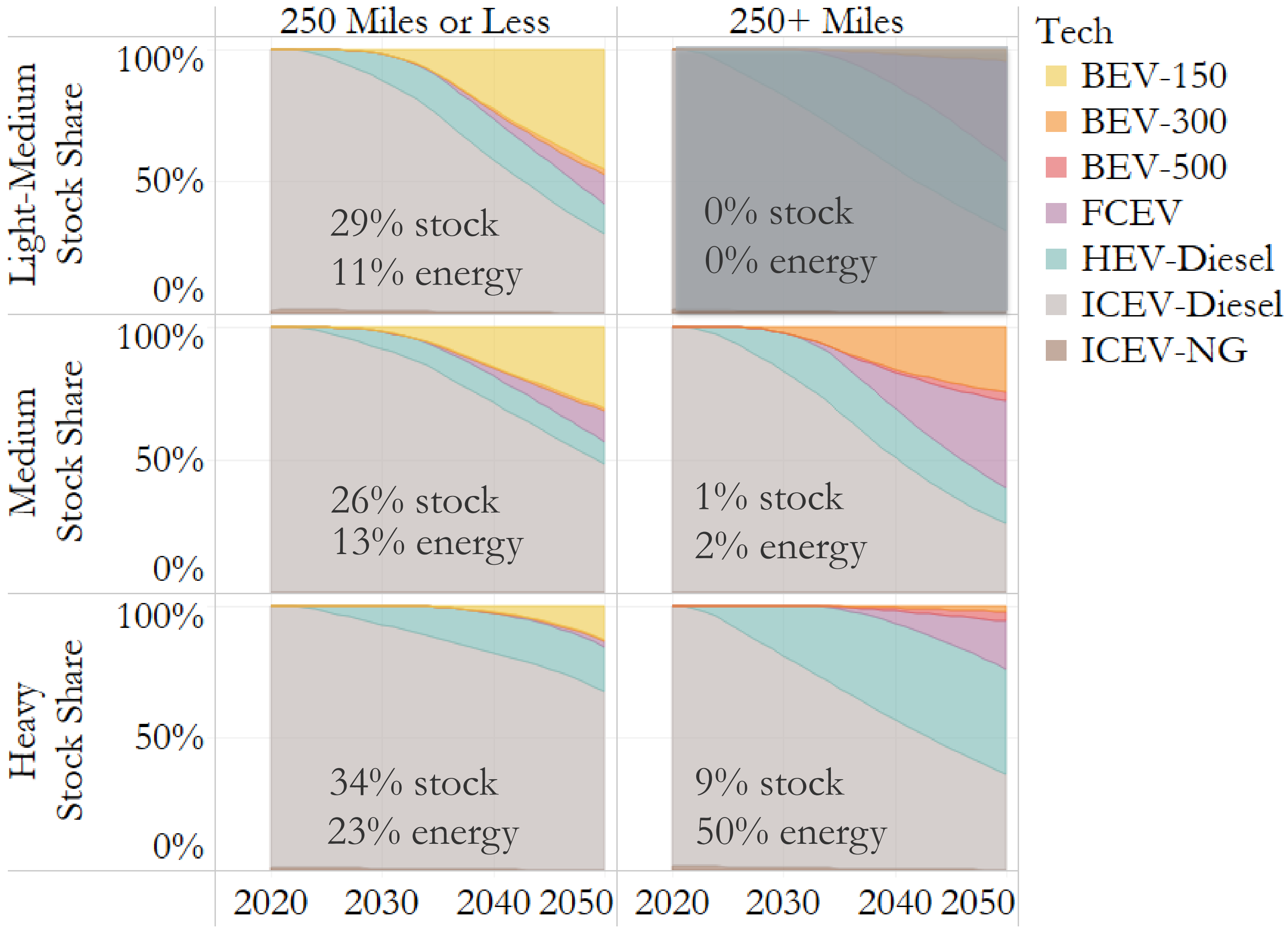
Vehicle Stock Share – *Central Case*

- Central fuel and technology assumptions ($4/kg hydrogen after 2035, $0.18/kWh electricity after 2030, *High* ZEV cost and fuel economy assumptions).
  - 2030 sales: **42% ZEV** (40% BEV/2% FCEV)
  - 2040 sales: 98% ZEV (77% BEV/21% FCEV)
  - 2050 sales: **100% ZEV** (83% BEV/17% FCEV)
  - 2050 stock: **80% ZEV** (66% BEV/14% FCEV).
  - 2050 stock in the heavy 250+ mile bin: 72% ZEV (32% BEV/40% FCEV).
- Total 2050 electricity consumption is 626 TWh, including buses and electricity for hydrogen. Hydrogen consumption is 7.8 MMT.
- 2050 emissions reductions are 69% relative to 2019. Liquid fuel consumption is 13.5 billion gallons in 2050.



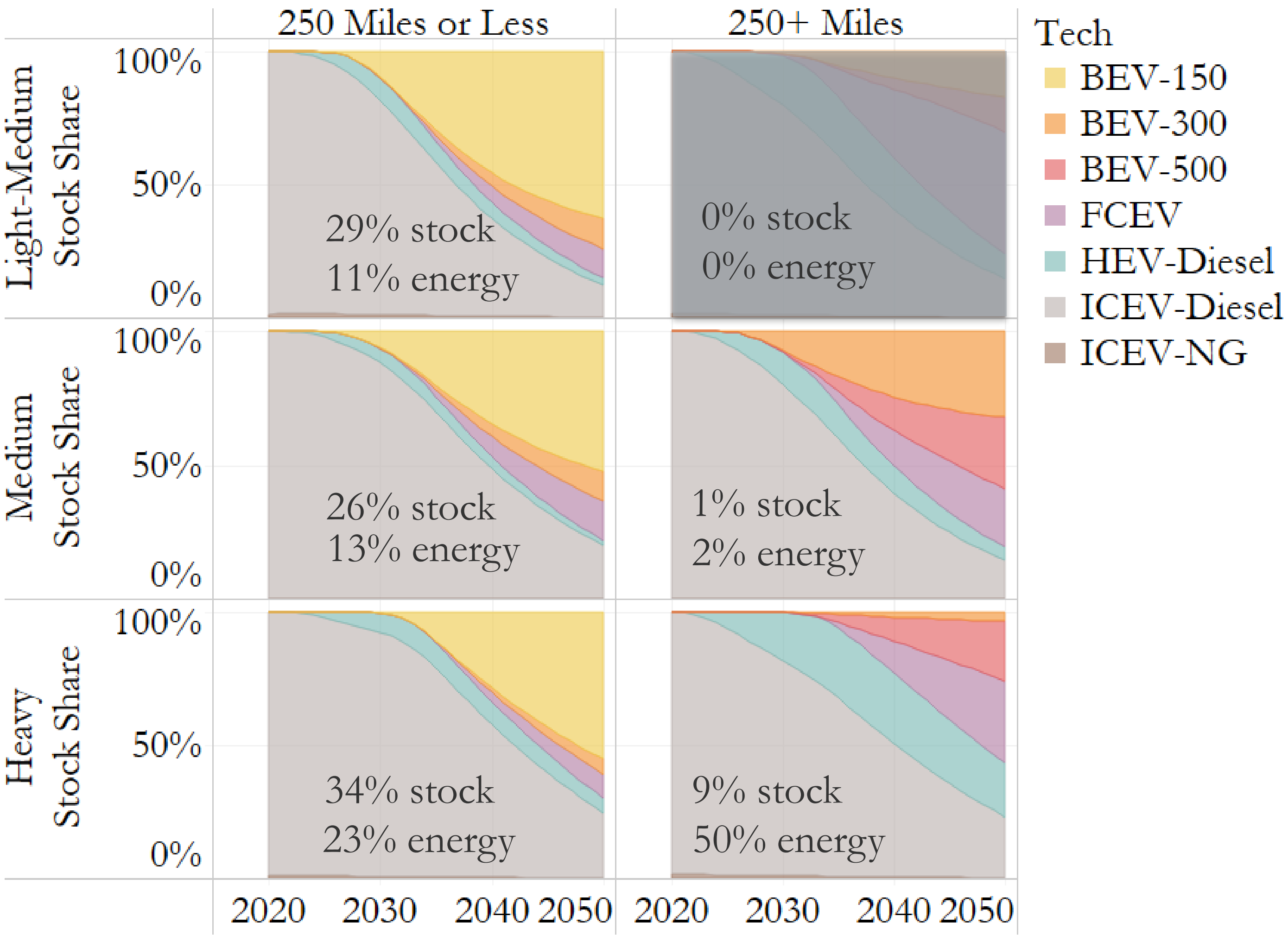
Vehicle Stock Shares – *Conservative ZEV Technology Sensitivity*

- Conservative technology assumptions (vehicle cost and fuel economy) substantially increase emissions relative to the *Central* scenario.
  - 2030 sales: **7% ZEV** (7% BEV/0% FCEV)
  - 2040 sales: 45% ZEV (35% BEV/10% FCEV)
  - 2050 sales: **71% ZEV** (49% BEV/22% FCEV)
  - 2050 stock: **40% ZEV** (30% BEV/10% FCEV)
  - 2050 stock in the heavy 250+ mile bin: 24% ZEV (6% BEV/18% FCEV).
- Total 2050 electricity consumption is 349 TWh, including buses and electricity for hydrogen. Hydrogen consumption is 4.8 MMT.
- 2050 emissions reductions are 27% relative to 2019. Liquid fuel consumption is 31.6 billion gallons in 2050.



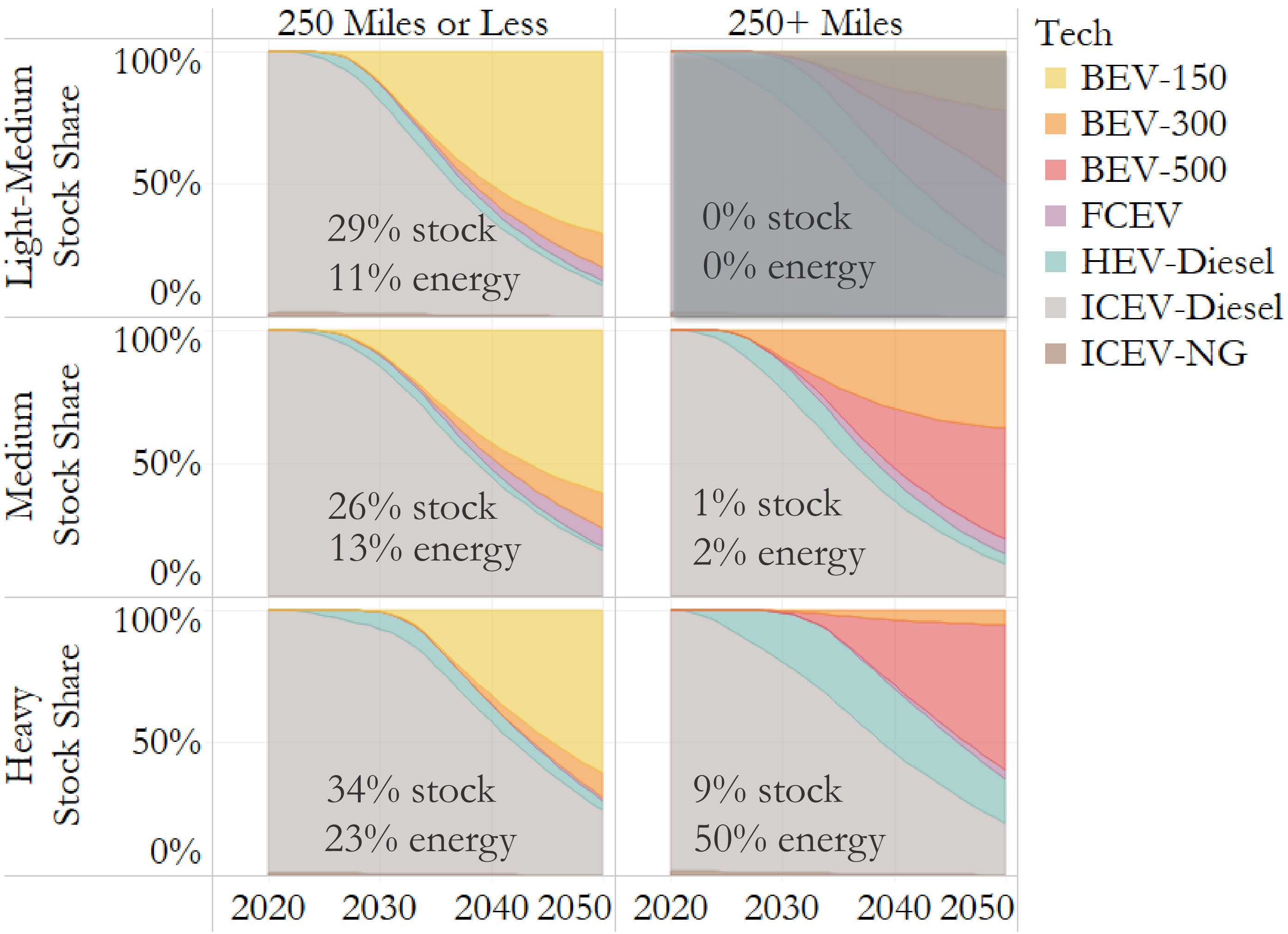
Vehicle Stock Shares – *Advanced ICEV Sensitivity*

- Advanced ICEV and HEV cost and fuel economy assumptions (Autonomie – *High* scenario) increase emissions relative to the *Central* scenario but still enable almost 100% ZEV sales by 2050.
  - 2030 sales: **33% ZEV** (32% BEV/1% FCEV)
  - 2040 sales: 95% ZEV (76% BEV/19% FCEV)
  - 2050 sales: **99% ZEV** (82% BEV/17% FCEV)
  - 2050 stock: **77% ZEV** (64% BEV/13% FCEV)
  - 2050 stock in the heavy 250+ mile bin: 57% ZEV (26% BEV/31% FCEV).
- Total 2050 electricity consumption is 525 TWh, including buses and electricity for hydrogen. Hydrogen consumption is 6.3 MMT.
- 2050 emissions reductions are 63% relative to 2019, driven in part by more aggressive ICEV and HEV improvements. Liquid fuel consumption is 15.9 billion gallons in 2050.



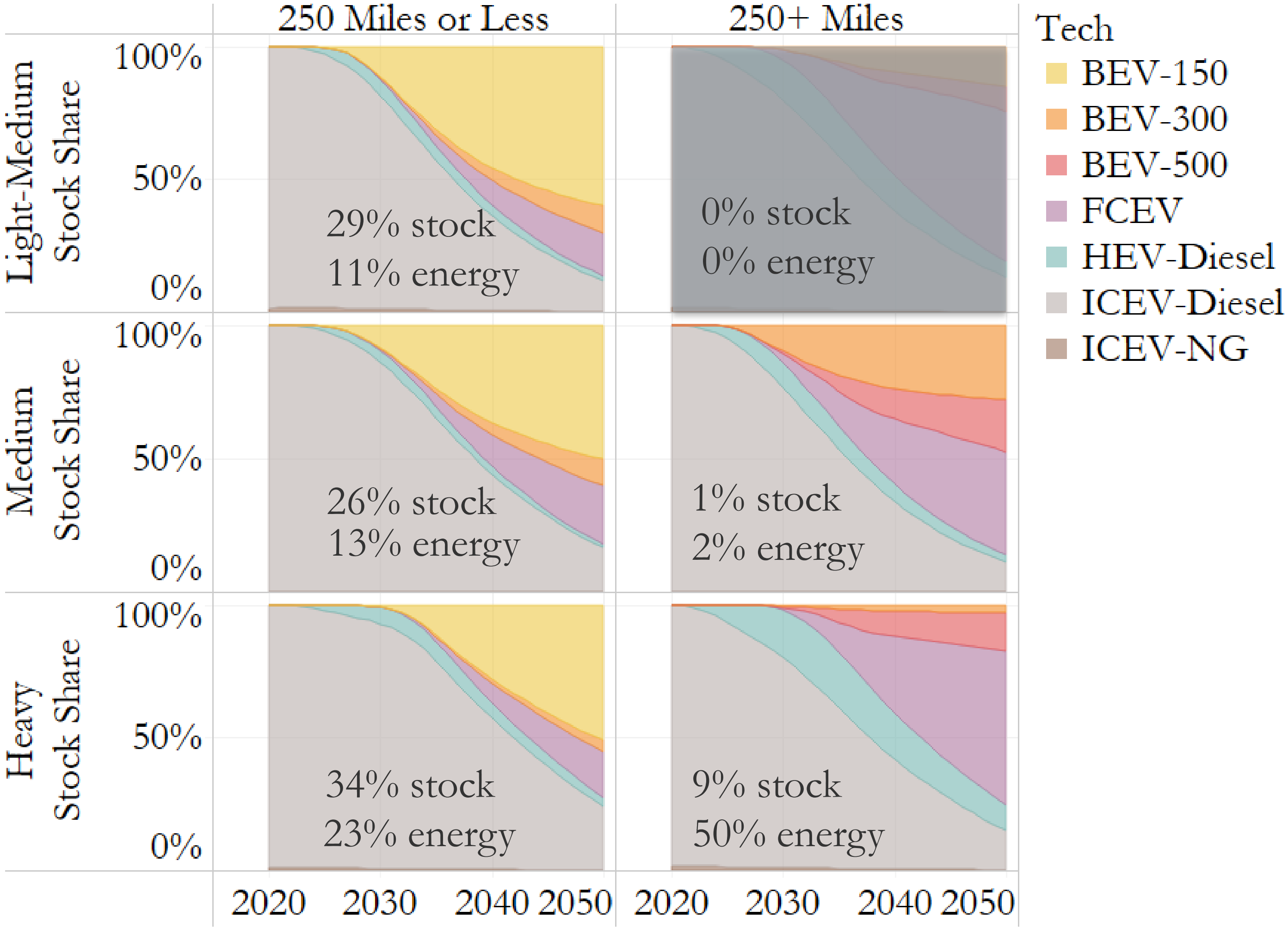
Vehicle Stock Shares – *Conservative H_2 Sensitivity*

- Conservative hydrogen assumptions ($6/kg held constant from 2030–2050) result in minimal FCEV sales/stock.
  - 2030 sales: **42% ZEV** (40% BEV/2% FCEV)
  - 2040 sales: 97% ZEV (90% BEV/7% FCEV)
  - 2050 sales: **100% ZEV** (95% BEV/5% FCEV)
  - 2050 stock: **79% ZEV** (74% BEV/5% FCEV), Most FCEV losses are offset by gains in BEVs, except in heavy long-haul bins
  - 2050 stock in the heavy 250+ mile bin: 64% ZEV (61% BEV/3% FCEV).
- Total 2050 electricity consumption is 381 TWh, including buses and electricity for hydrogen. Hydrogen consumption is 1.2 MMT.
- 2050 emissions reductions are 64% relative to 2019. Liquid fuel consumption is 15.4 billion gallons in 2050.



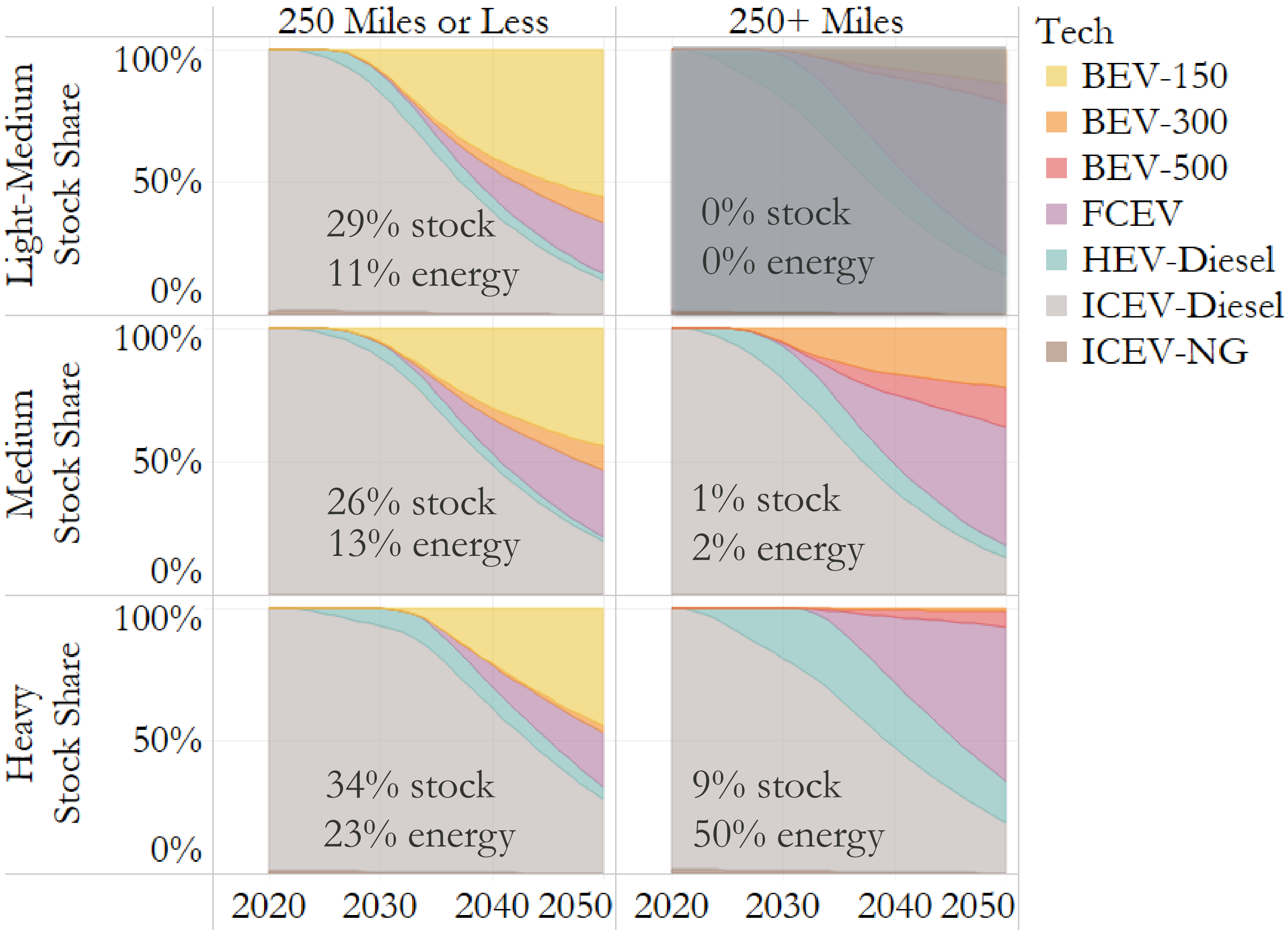
Vehicle Stock Shares – *Advanced H_2 Sensitivity*

- The *Advanced H_2* scenario assumes a 2030 hydrogen price of \$4/kg, rather than \$6, and a 2040 price of \$3/kg rather than \$4.
  - 2030 sales: **44% ZEV** (38% BEV/6% FCEV)
  - 2040 sales: 98% ZEV (67% BEV, 31% FCEV)
  - 2050 sales: **100% ZEV** (73% BEV/27% FCEV)
  - 2050 stock: **81% ZEV** (59% BEV/22% FCEV). Lower H2 prices primarily affect competition between ZEV powertrains rather than replacing ICEVs
  - 2050 stock in the heavy 250+ mile bin: 75% ZEV (17% BEV/58% FCEV).
- 2050 electricity consumption is 769 TWh including buses and electricity for hydrogen. Hydrogen consumption is 11.6 MMT.
- 2050 emissions reductions are 71% relative to 2019. Liquid fuel consumption is 12.5 billion gallons in 2050.



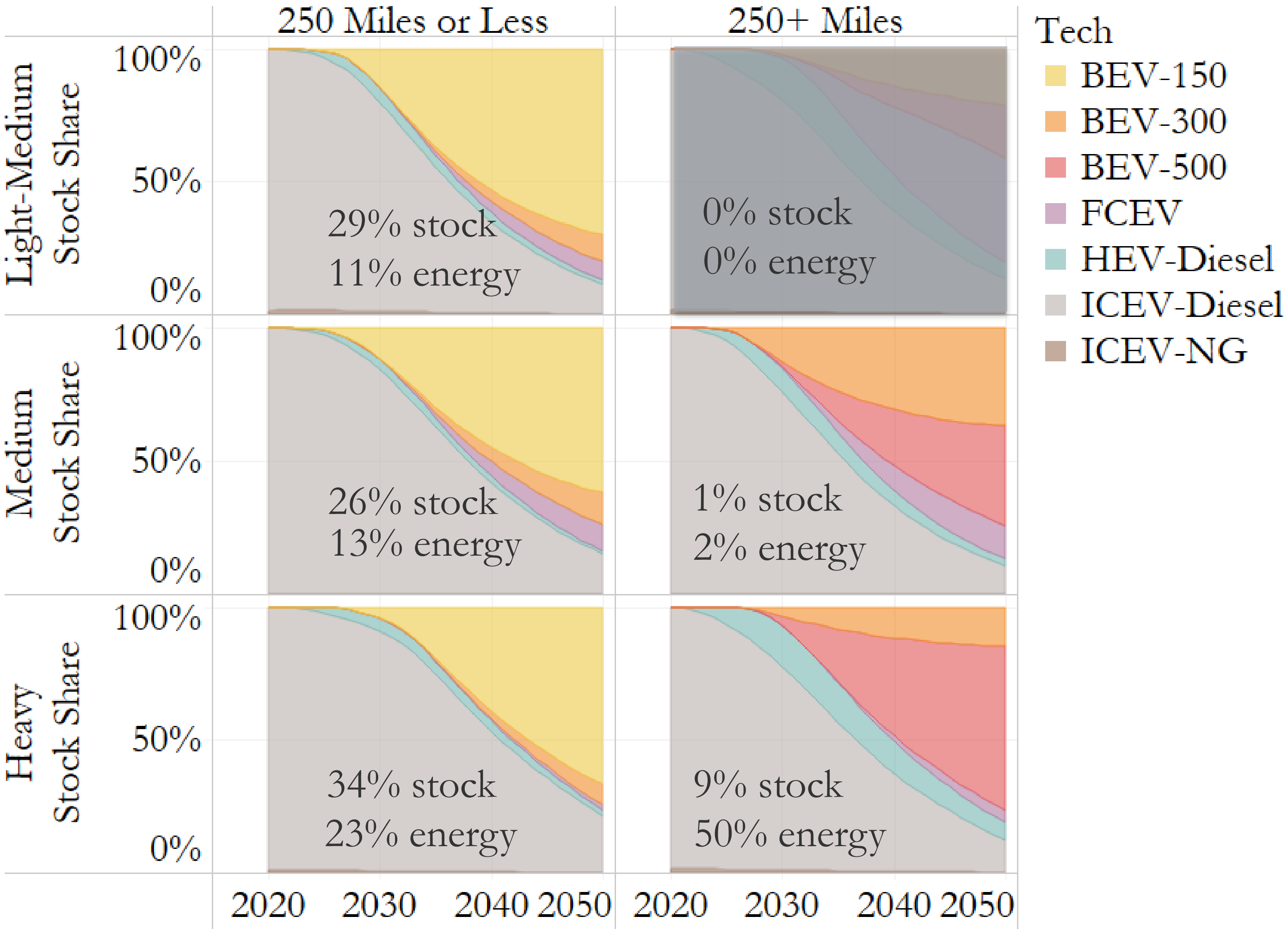
Vehicle Stock Shares – *Conservative Electricity Sensitivity*

- The *Conservative Electricity* scenario assumes an electricity price of $0.27/kWh from 2030-2050, rather than $0.18/kWh, which could capture higher power system costs. Charging speed is unchanged.
  - 2030 sales: **30% ZEV** (28% BEV/2% FCEV)
  - 2040 sales: 96% ZEV (61% BEV/ 35% FCEV)
  - 2050 sales: **100% ZEV** (68% BEV/32 % FCEV)
  - 2050 stock: **77% ZEV** (52% BEV/25% FCEV). FCEVs are not able to fully replace lost ZEV.
  - 2050 stock in the heavy 250+ mile bin: 65% ZEV (7% BEV/58% FCEV).
- 2050 electricity consumption is 737 TWh including buses and electricity for hydrogen. Hydrogen consumption is 11.8 MMT.
- 2050 emissions reductions are 63% relative to 2019. Liquid fuel consumption is 15.9 billion gallons in 2050.

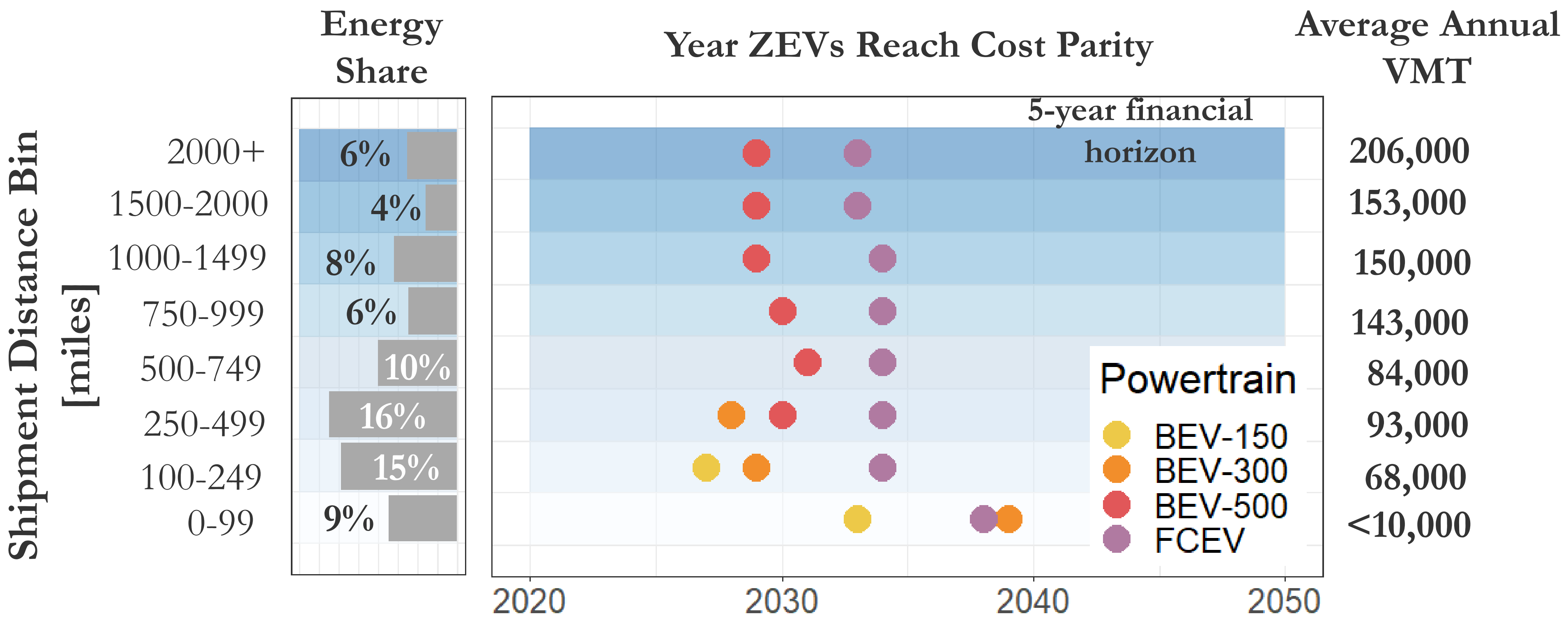


Vehicle Stock Shares – *Advanced Electricity Sensitivity*

- Advanced electricity assumptions ($0.12/kWh and 1000 kW charging) substantially reduce emissions relative to the *Central* scenario. FCEVs are sold in lower numbers due to enhanced BEV competitiveness, and substantially decline in heavy vehicle segments.
  - 2030 sales: **56% ZEV** (55% BEV/1% FCEV)
  - 2040 sales: 99% ZEV (89% BEV/10% FCEV)
  - 2050 sales: **100% ZEV** (92% BEV/8% FCEV)
  - 2050 stock: **83% ZEV** (76% BEV/7% FCEV).
  - 2050 stock in the heavy 250+ mile bin: 81% ZEV (77% BEV/4% FCEV)
- Total 2050 electricity consumption is 460 TWh, including buses and electricity for hydrogen. Hydrogen consumption is 1.6 MMT.
- 2050 emissions reductions are 77% relative to 2019. Liquid fuel consumption is 10.1 billion gallons in 2050.



Cost Parity By Distance Bin
Heavy Trucks, *Advanced Electricity*



- Under more aggressive assumptions for charging speed and electricity costs, BEVs achieve **cost parity with ICEVs before 2035** in every distance bin, **and 100% sales overall by 2040.**
- All bins are dominated by BEVs:
  - 2050 **stock**: 75% BEV, 3% FCEV, 22% ICEV (2050 **sales**: 97% BEV; 3% FCEV)
  - 2050 **ton-miles**: 76% BEV; 3% FCEV; 21% ICEV.

Vehicle Stock Shares – *Conservative H_2 & Electricity Sensitivity*

- Conservative electricity and hydrogen price assumptions ($0.27/kWh electricity and $6/kg hydrogen) substantially increase emissions relative to the *Central* scenario but still enable almost 100% ZEV sales by 2050.
  - 2030 sales: **30% ZEV** (28% BEV/2% FCEV)
  - 2040 sales: 90% ZEV (77% BEV/13% FCEV)
  - 2050 sales: **96% ZEV** (84% BEV/12% FCEV)
  - 2050 stock: **73% ZEV** (63% BEV/10% FCEV)
  - 2050 stock in the heavy 250+ mile bin: 38% ZEV (23% BEV/15% FCEV).
- Total 2050 electricity consumption is 369 TWh, including buses and electricity for hydrogen. Hydrogen consumption is 3.4 MMT.
- 2050 emissions reductions are 48% relative to 2019. Liquid fuel consumption is 22.6 billion gallons in 2050.