# Enabling a Sustainable Future

## Zero-Emission Vehicles Cost Analysis to Inform Decarbonization Pathways

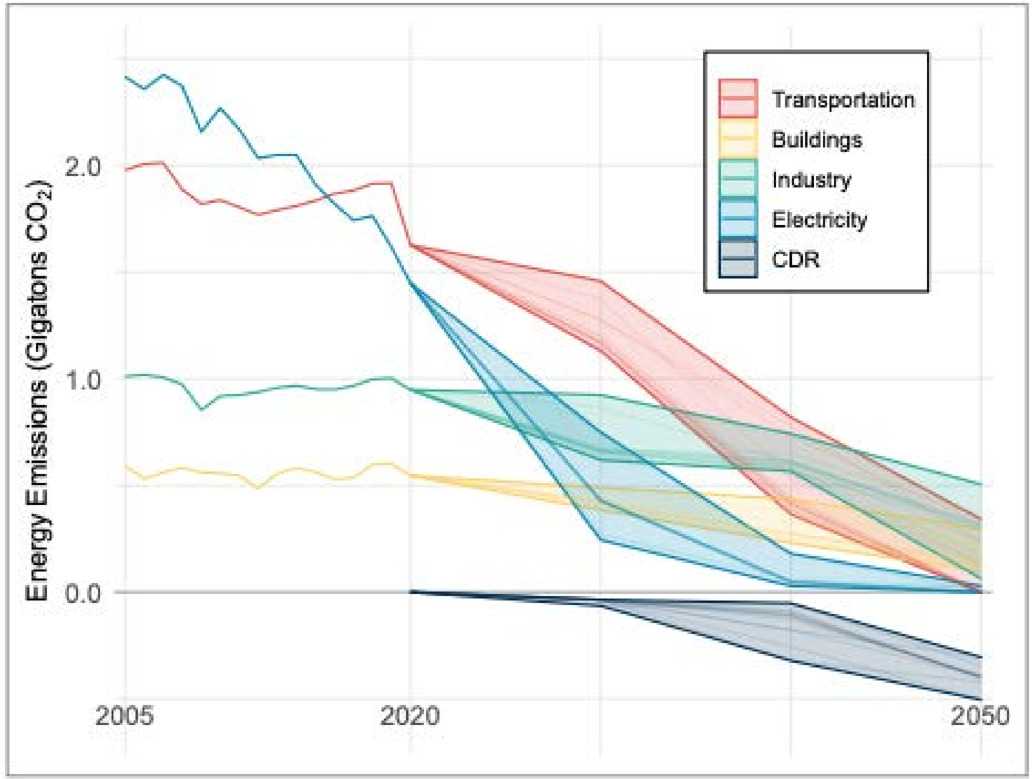
Matteo Muratori (based on NREL work with Ledna, Jadun, Yip, and Hoehne)

Energy Insights 2022 – Dec, 8th 2022

*Photo from iStock-627281636*

# U.S. Clean Energy Transition

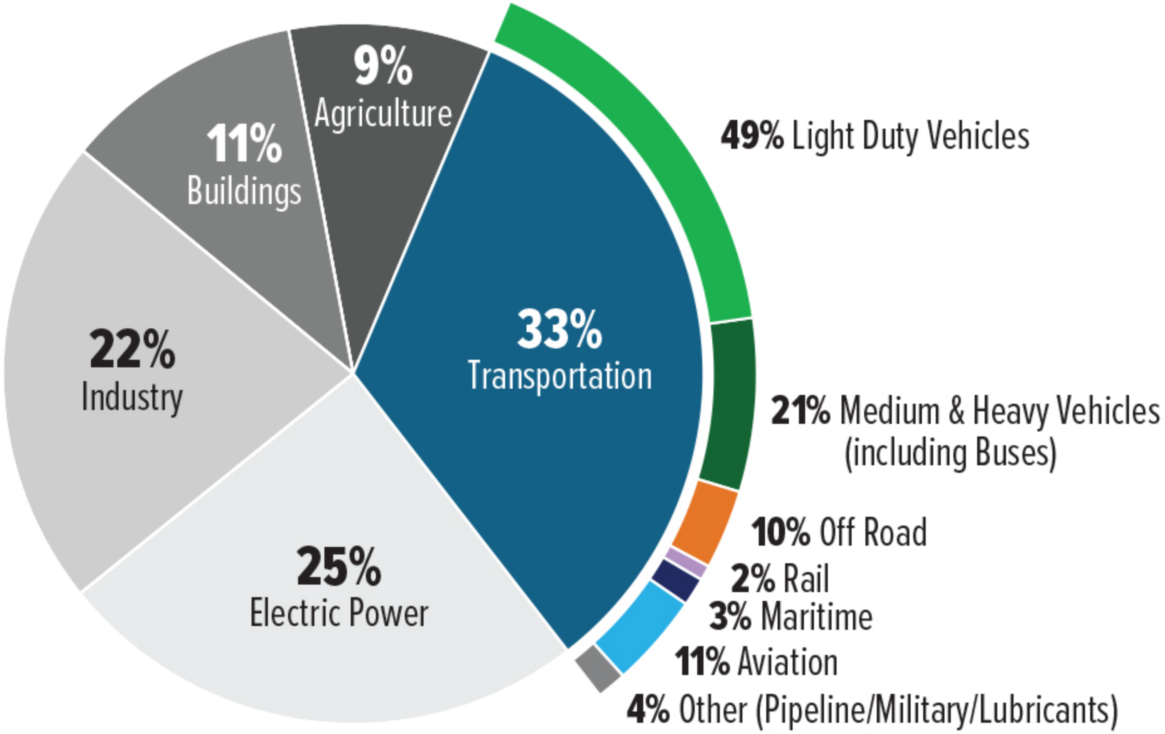
- The Long-Term Strategy of the United States establishes a goal of **net-zero greenhouse gas emissions by no later than 2050 and a 50-52% reduction by 2030** (from 2005 levels) in economy-wide net GHG emissions.
- The **sense of urgency is high:** climate crisis requires rapid, widespread, and major transformation of many complex systems that are closely intertwined.
- Transportation projected to remain largest source of emissions until 2040, but on a **pathway to 80-100% emissions reduction by 2050.**




https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf

# Transportation is the largest source of US GHG emissions

**2019 U.S. GHG emissions**




Aviation and Maritime include emissions from international aviation and maritime transport. Fractions may not add up to 100% due to rounding.

- Different transportation applications require different solutions

Despite being **only** **5% of vehicles on the road**, **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).

Ledna *et al.*, 2022. Decarbonizing Medium- & Heavy-Duty On-Road Vehicles: Zero-Emission Vehicles Cost Analysis

# Landmark endorsement of zero-emission transport at COP27

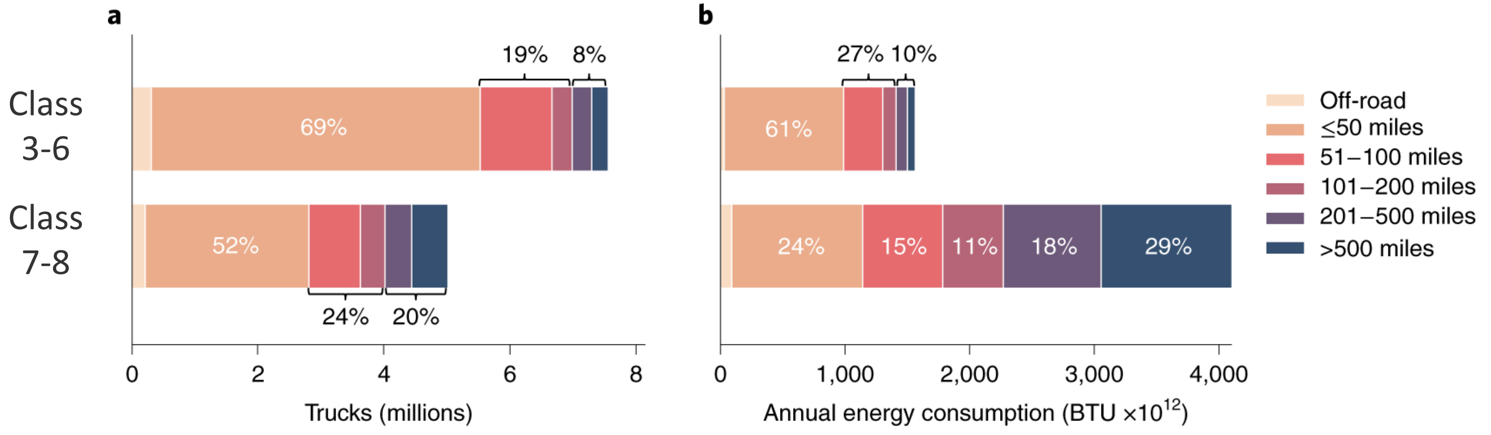

- At COP-27 on Nov 16th 2022 the United States signed the [Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles] (Global MOU).

- First introduced at COP26, the Global MOU puts countries on a path to **100% new zero-emission medium- and heavy-duty vehicle (MHDV) sales by 2040** at the latest, with an interim goal of at least **30% new sales by 2030.**

# ZEVs eliminate tailpipe emissions, but will they be affordable?

- ZEV have higher purchase cost, but **thanks to high efficiency and lower maintenance costs they can become cost effective over time**

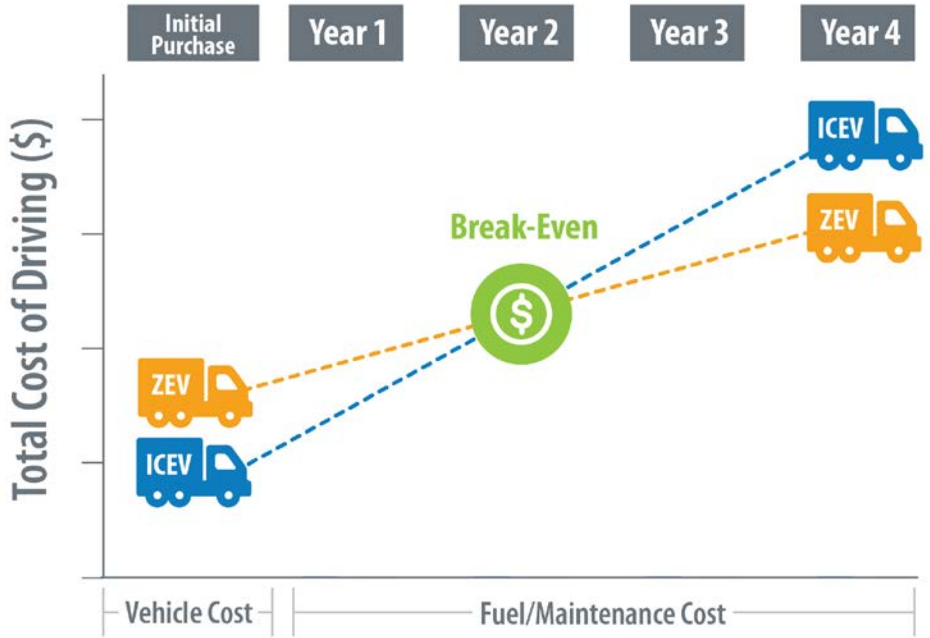
- Trucks experience a wide range of use patterns (ranging from <10,000 miles/year to over 200,000), and **the use case heavily impacts the financial comparison**




https://www.nature.com/articles/s41560-021-00855-0

### 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)



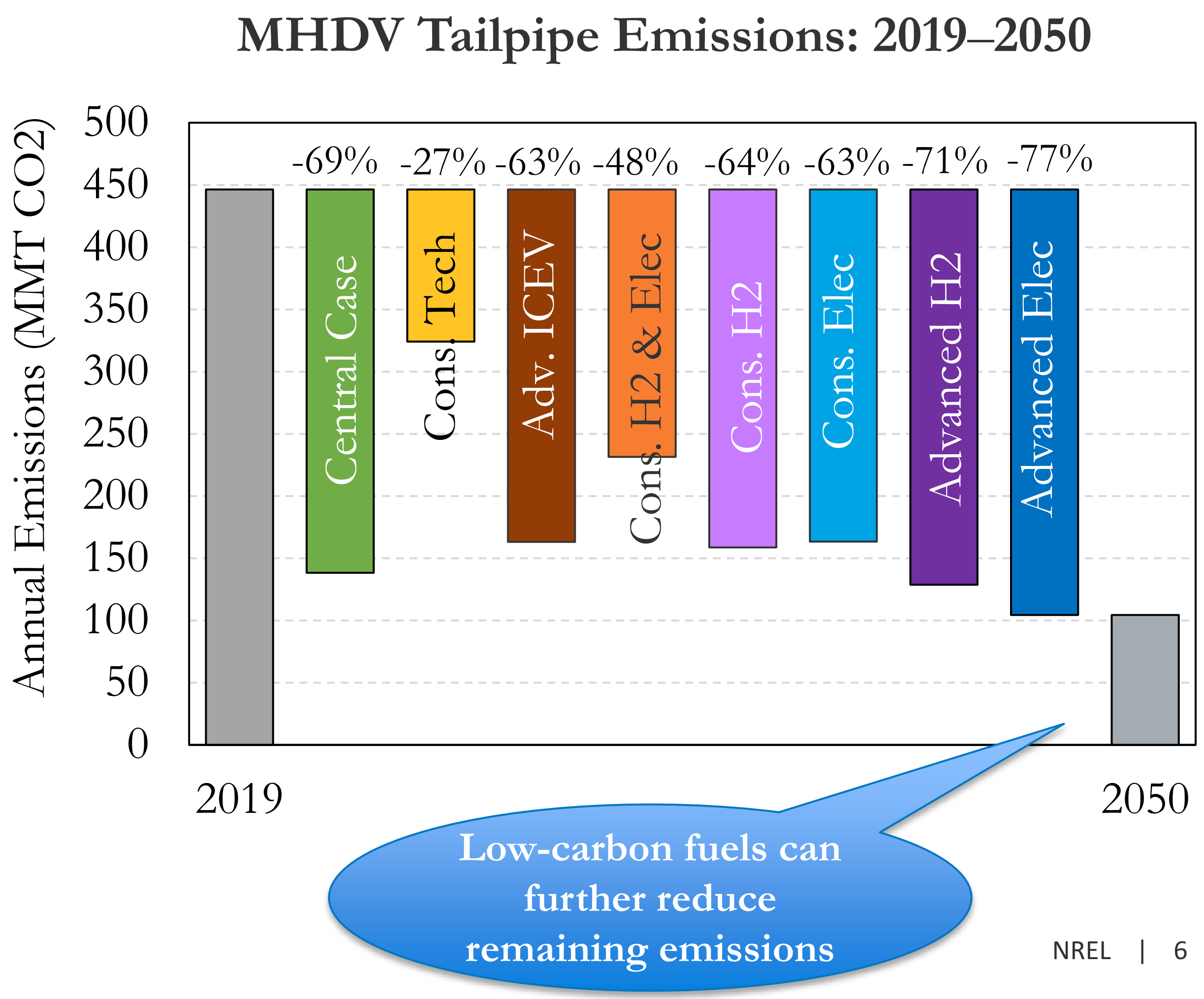
# We Developed Multiple Scenarios to Explore Cost-Effective Adoption Opportunities for ZEVs Based on TCD

TEMPO

Eight scenarios varying technology progress for vehicles (ICEV, FCEV, and BEV) and fuels

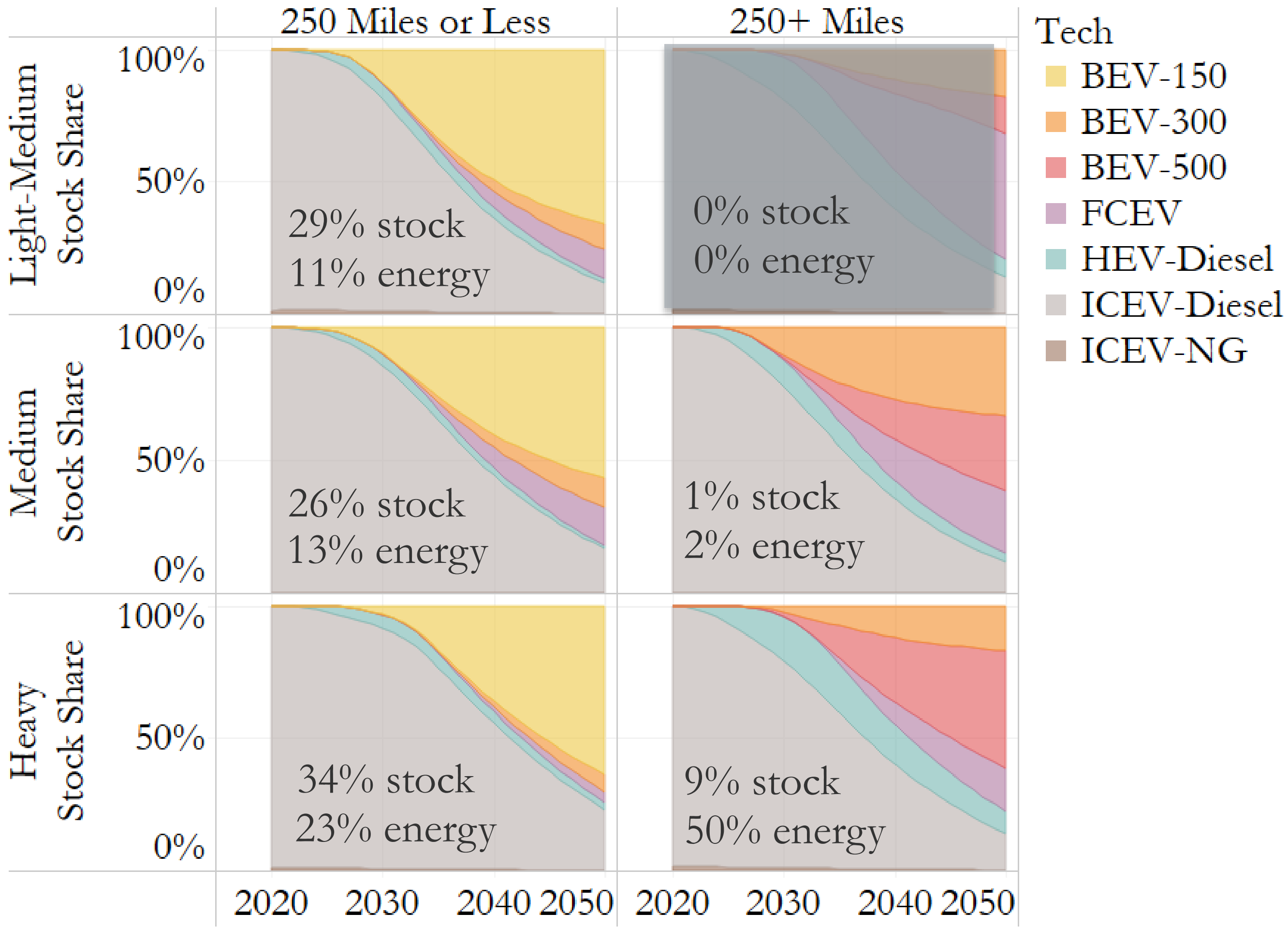
Central scenario:

- **Vehicle** MSRP and fuel economy improving in line with DOE projections and vetted with industry:
  - **Batteries**: $80/kWh in 2035 and $50/kWh in 2050
  - **Fuel Cells**: $80/kW in 2035 and $60/kW in 2050
  - **ICEV fuel economy** improves by 32%–37% across vehicle classes by 2050.
- **Fuels:**
  - **BEV** charging is assumed to become progressively available as BEVs are adopted, costing **$0.18/kWh**
  - **FCEV fueling** is assumed to phase in and be **fully available by 2040, at $4/kg by 2035**
  - **Diesel:** AEO Ref, ~$4/Gal
- **Financial horizon: 3–5 years**



# Vehicle Stock Share – *Central Case*

- Class 3: **BEVs achieve cost parity with ICEVs before 2035** in every distance bin
- Class 4-6: **ZEVs achieve cost parity with ICEVs before 2035** in every distance bin (with a combination of BEV and FCEV)
- Class 7-8: **ZEVs achieve cost parity with ICEVs by 2035** in every distance bin. Shorter-distance bins dominated by BEVs; longer bins dominated by FCEVs.




- **2030 sales**: **42% ZEV** (40% BEV/2% FCEV)
- **2040 sales: 98% ZEV** (77% BEV/21% FCEV)
- **2050 sales: 100% ZEV** (83% BEV/17% FCEV)

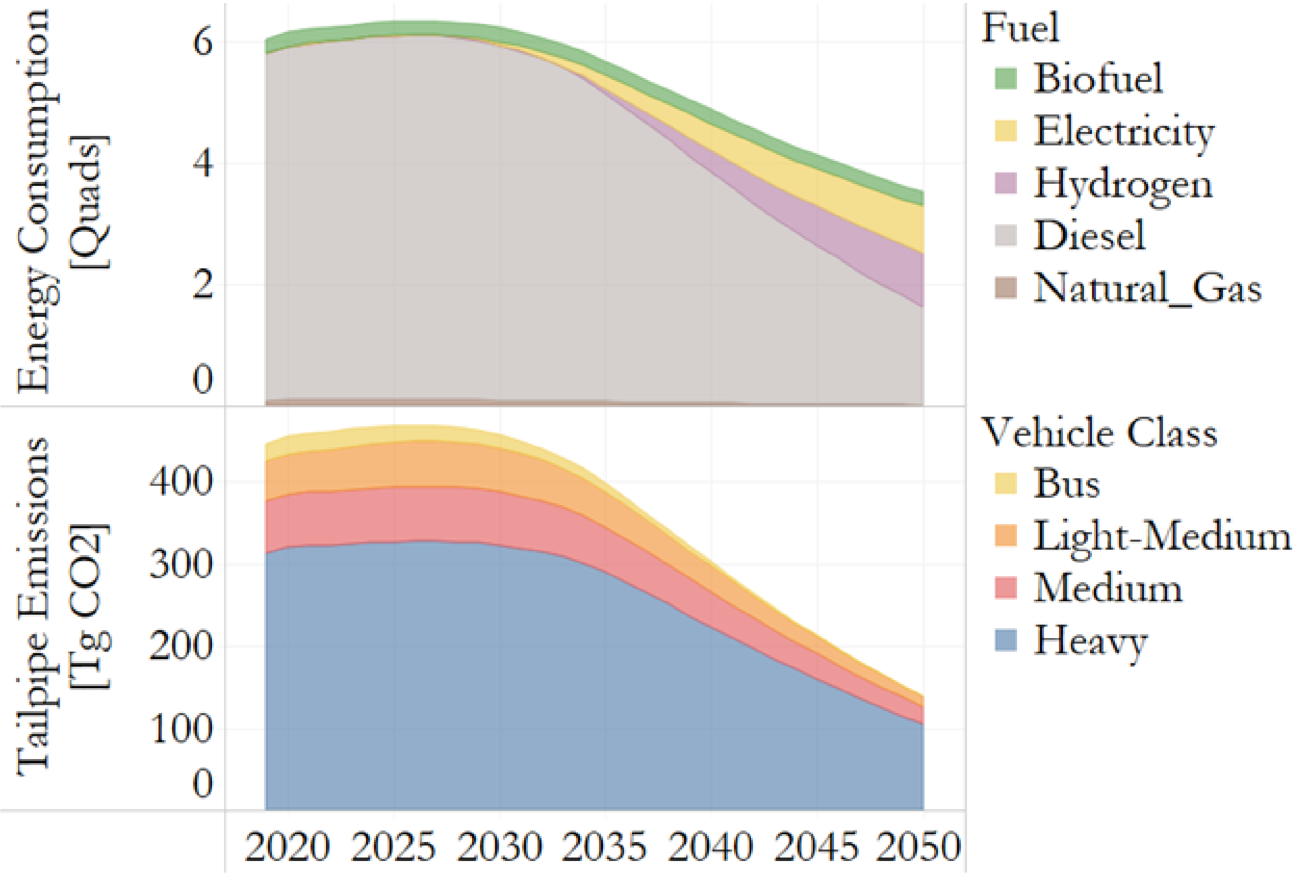
# MHDV Energy Consumption and Emissions

TEMPO

**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, and 227 TWh in 2050.
- **Hydrogen** demand is 0.1 MMT (2.8 TWh) in 2030 and 7.8 MMT (399 TWh) in 2050.[1]
- **Liquid fuel** demand is 44.1 billion gallons in 2030 and 13.5 billion gallons in 2050
    - **Low-carbon fuels (not modeled)** can further reduce remaining emissions.

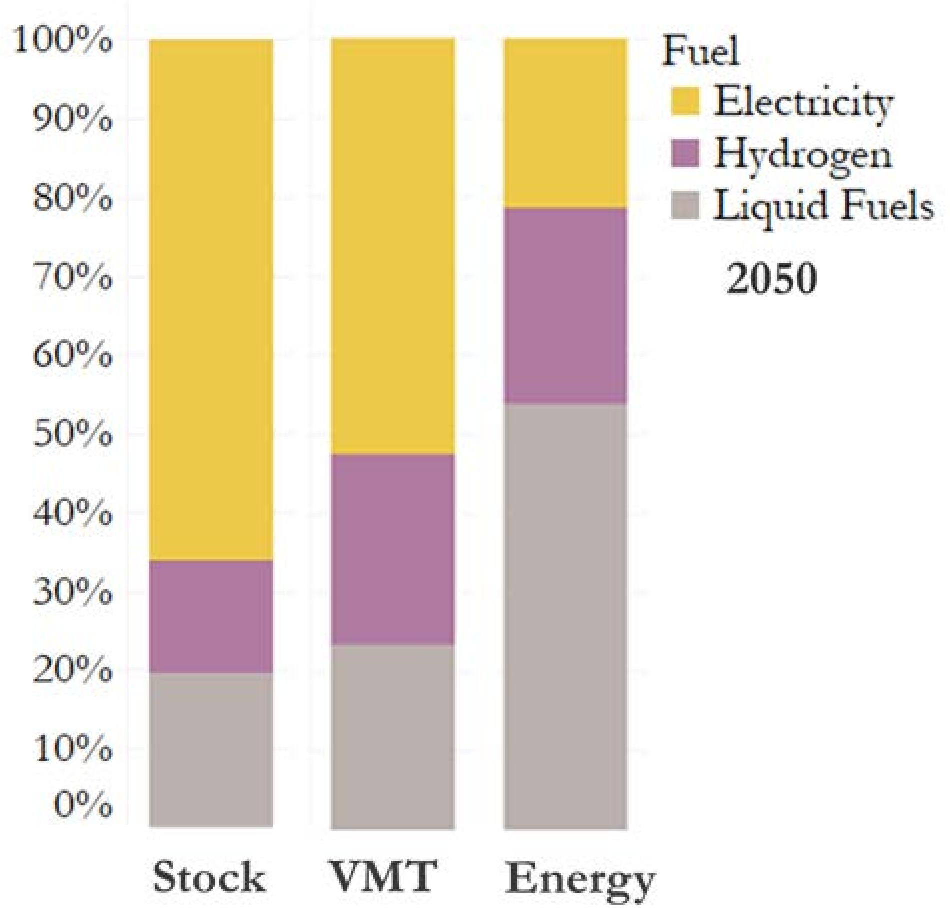
**MHDV Tailpipe Emissions and Energy Consumptions**




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

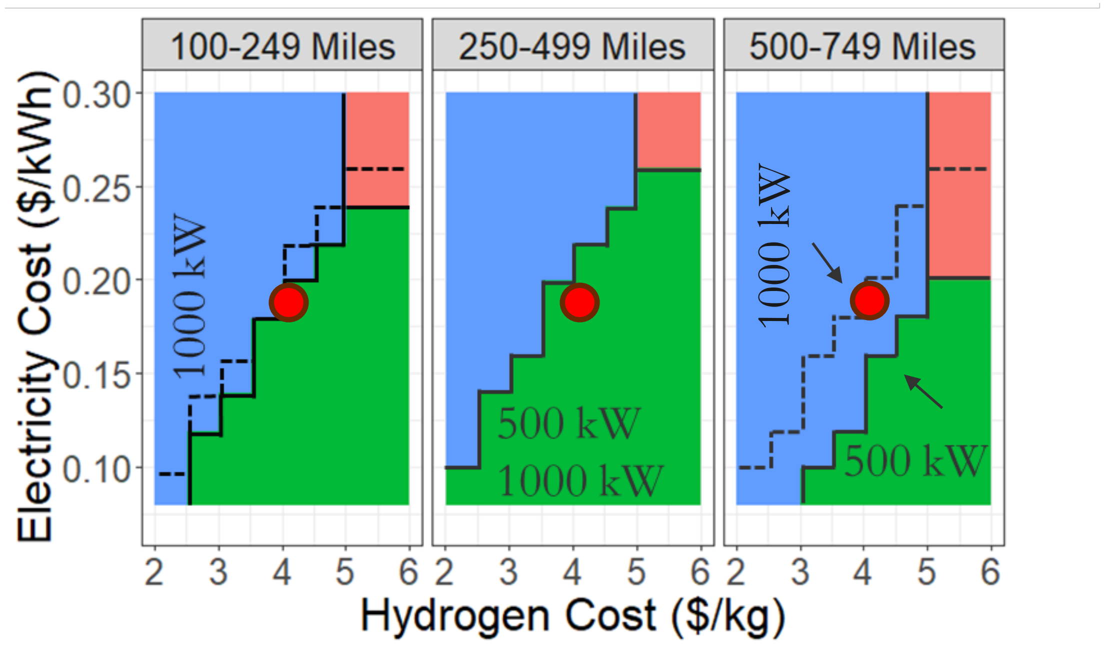
# For MHDV, talking about X% of sales or stock can mean very different emissions savings

- **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**.

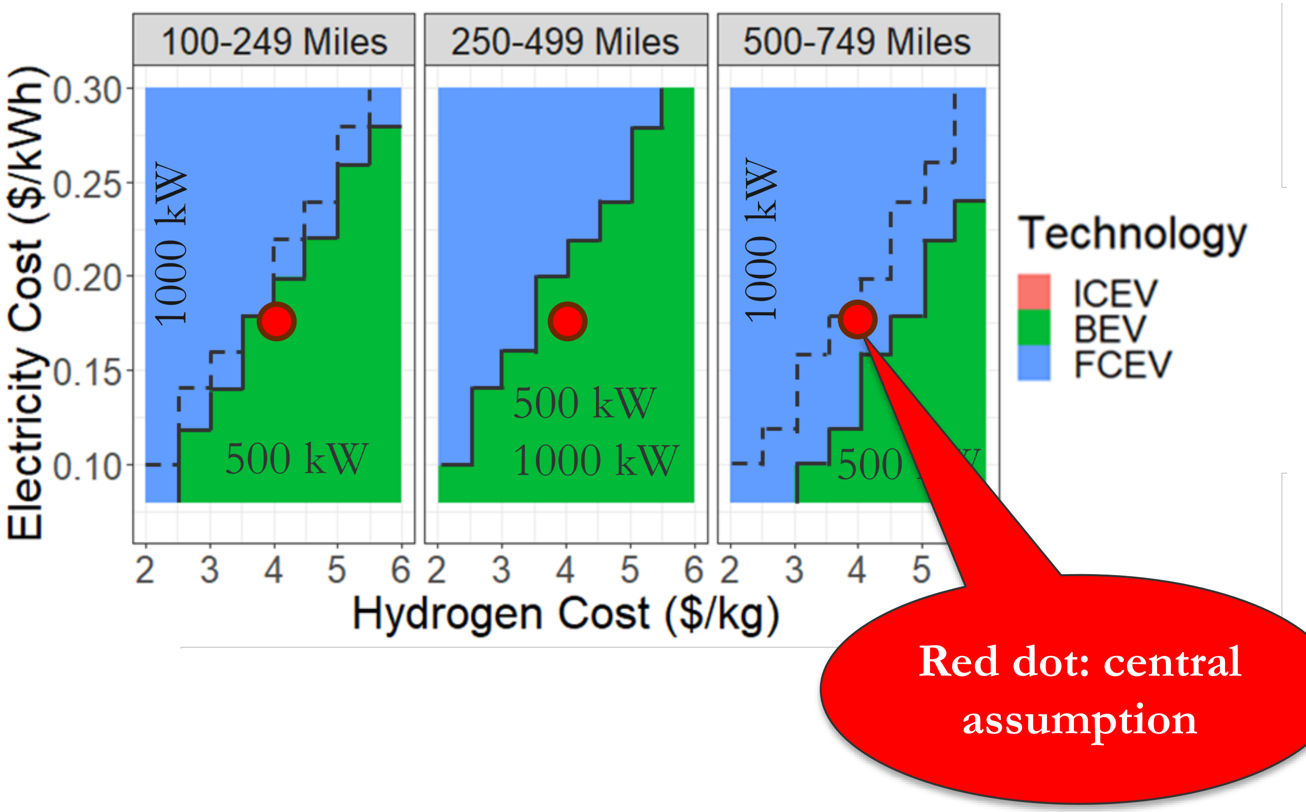


# Results are Highly Sensitive to Assumed Fuel Prices

**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.
- 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.

# Conclusions

- 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 drives 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).
- **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.
- Results are very sensitive to **technology improvement trajectories, adoption decision-making, and uncertain assumptions about future freight demand, logistics, and vehicle use**.

# What's Next?

- Understand the impact of **IRA** and supply/manufacturing constraints
- Better **data on vehicle use** to further understand required BEV range to minimize fleet costs
- Refine understanding of **BEV charging costs** and relationship between electricity and $H_2$ costs
- **Infrastructure analysis** (BEV charging and FCEV refueling) and **grid integration**
- Availability and cost of **sustainable liquid fuels**

Biden-Harris Administration Announces Interagency (DOE/DOT/EPA/HUD) Commitment to Lower Transportation Emissions and Consumer Costs, Bolster Domestic Energy Security

> *"With this agreement, we will collaborate across the federal government to reduce greenhouse gas emissions and deliver the clean transportation future that Americans want and deserve," said **U.S. Transportation Secretary Pete Buttigieg**.*

Release of the **U.S. NATIONAL BLUEPRINT FOR TRANSPORTATION DECARBONIZATION** at the Transportation Research Board **(TRB) Annual Meeting on January 10th**

# Blueprint Rollout – TRB

TRB 102nd Annual Meeting
January 8–12, 2023; Washington, DC

**Online Program**

**Join Us!!**

**Your feedback needed**

**Lectern Session 3194**

## Transportation Decarbonization: An Interagency Approach at the Federal Level

Tuesday, January 10 3:45 PM- 5:30 PM ET

Sign in to reveal location

*Lectern | PDH*

**Sponsored by:**

Executive Committee (E0000)

# Blueprint Rollout – SAE Gov/Ind

**Join Us!!**

**Your feedback needed**

**Wednesday, January 18**

**Luncheon Roundtable: Transportation Decarbonization Blueprint**
*(Session Code: G800)*

**Room TBD  12:30 p.m.**

This discussion will begin with a point of view statement video from each of the Secretary/Directors followed by representatives from each agency participating in a panel discussion. Topics to be addressed include XYZ with the intent to answer the following questions

Learn more about the Participants

**Moderators** - Rachel Muncrief, International Council On Clean Transport
**Panelists** -
Michael Berube, US Department of Energy
Austin L. Brown, The White House Council on Environmental Quality
Michael Freedberg, HUD
Alexis Pelosi, HUD
Karl Simon, US Environmental Protection Agency
Andrew Wishnia, US Department of Transportation

# Questions?

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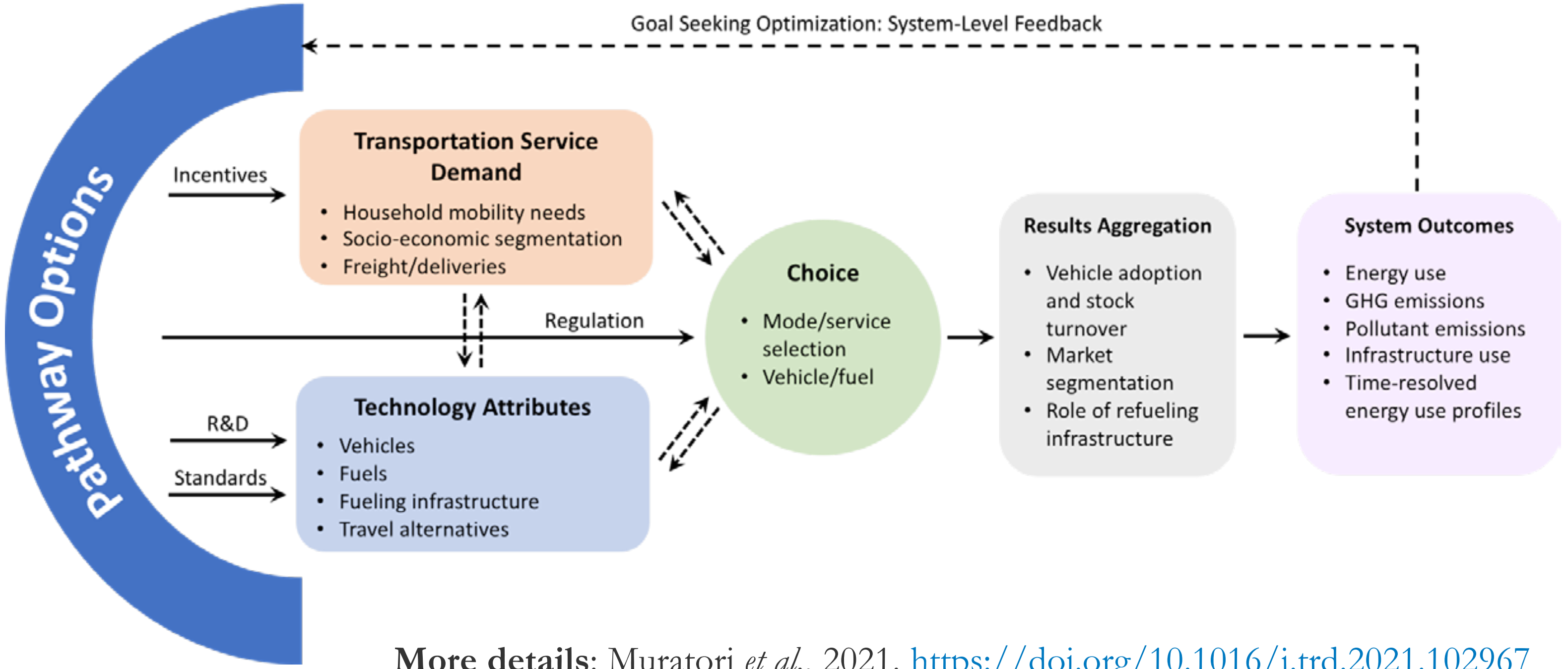
*Photo from iStock-627281636*

NREL Transforming ENERGY 45Th anniversary

# SUPPLEMENTAL SLIDES

# What is TEMPO?

The Transportation Energy & Mobility Pathway Options (TEMPO™) 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 and estimate energy/emissions (high res) implications
- Alternative **scenarios** can be run by varying inputs on technology cost and performance, consumer behavior, system attributes, etc.

# 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

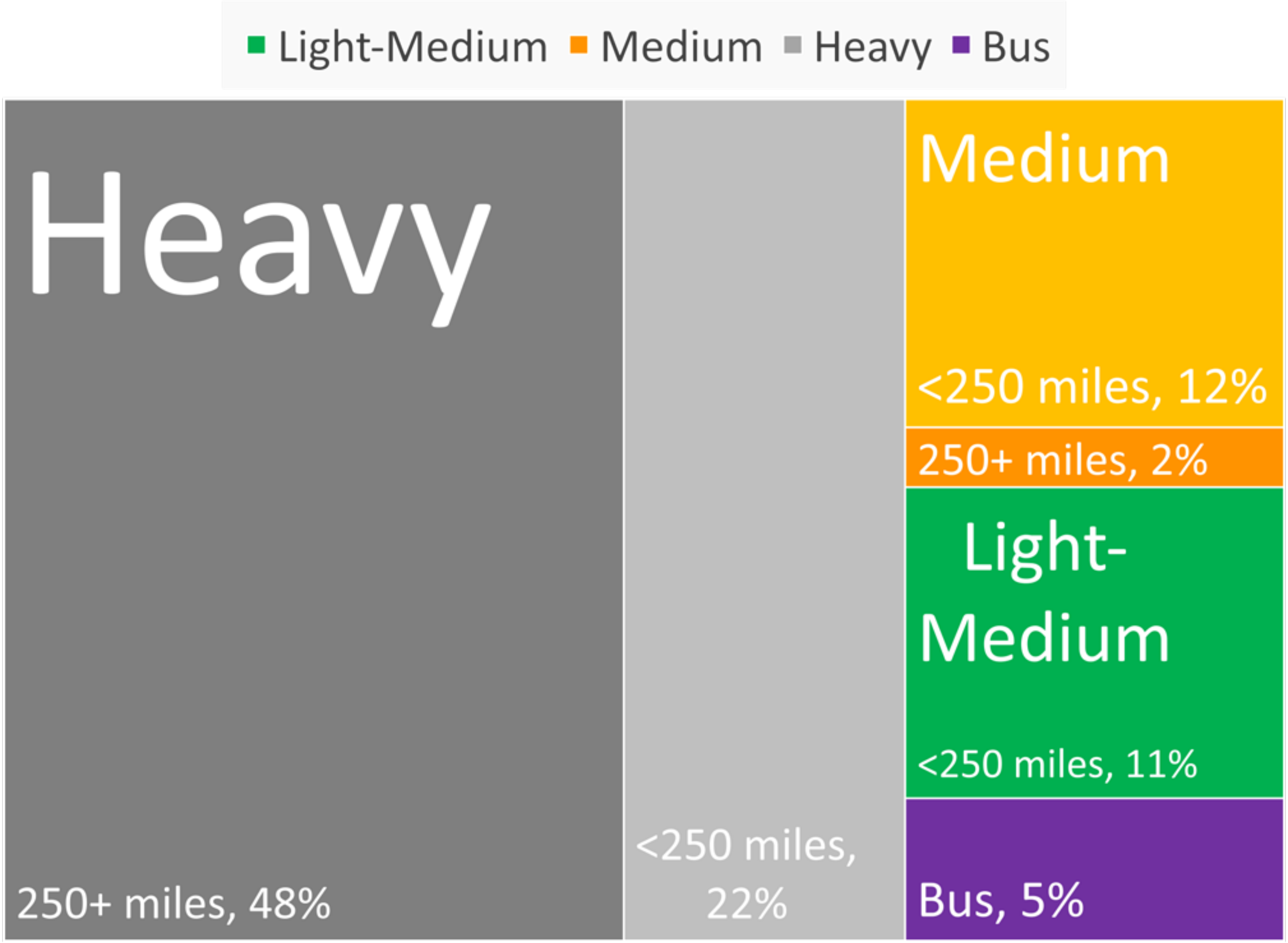
**Freight and non-freight stock and activity based on analysis of VIUS, FAF, and AEO.**

# 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.

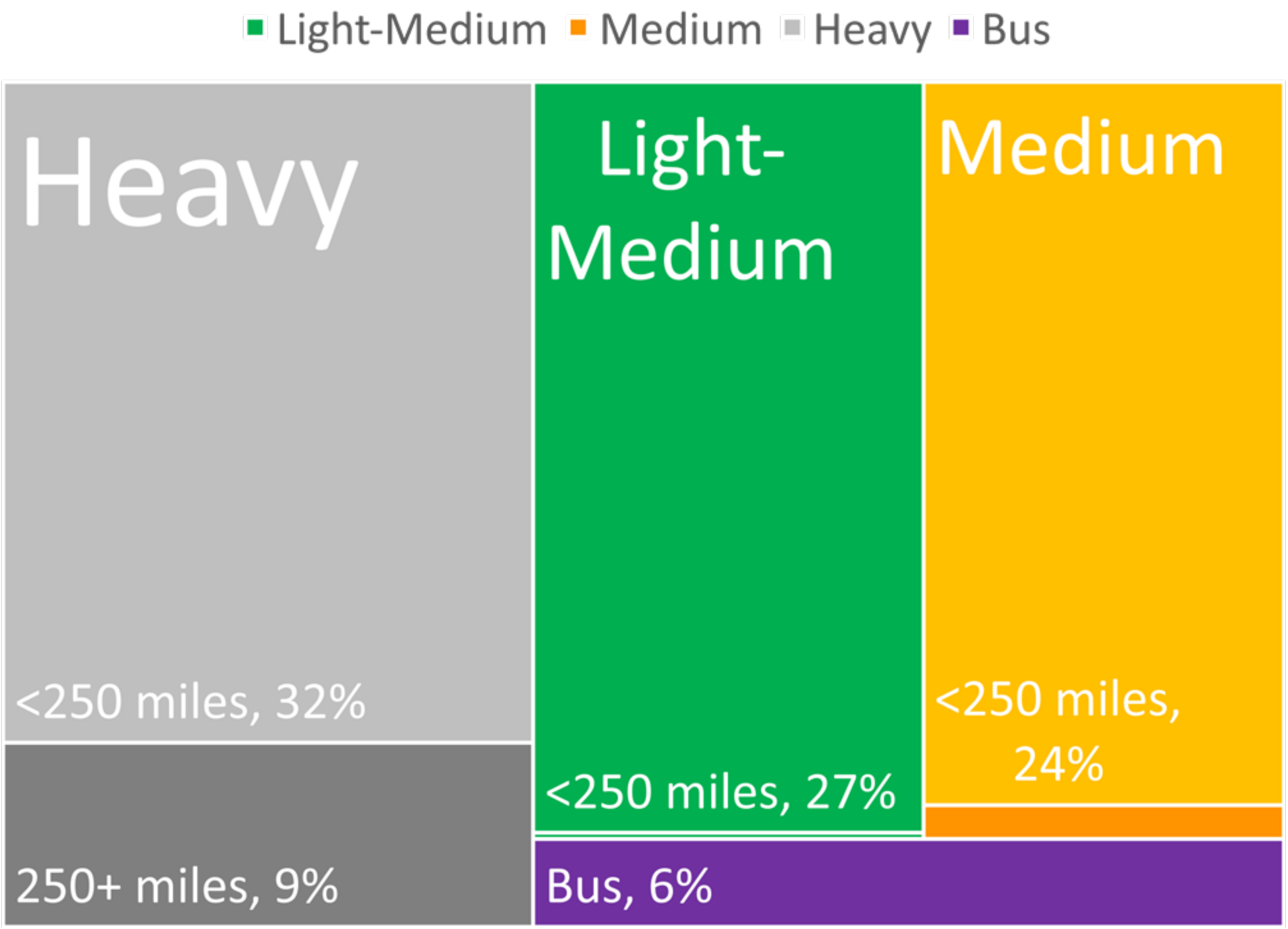
**2019 MHDV Emissions (445 MM ton $CO_2$)**



# 2019 MHDV Stock

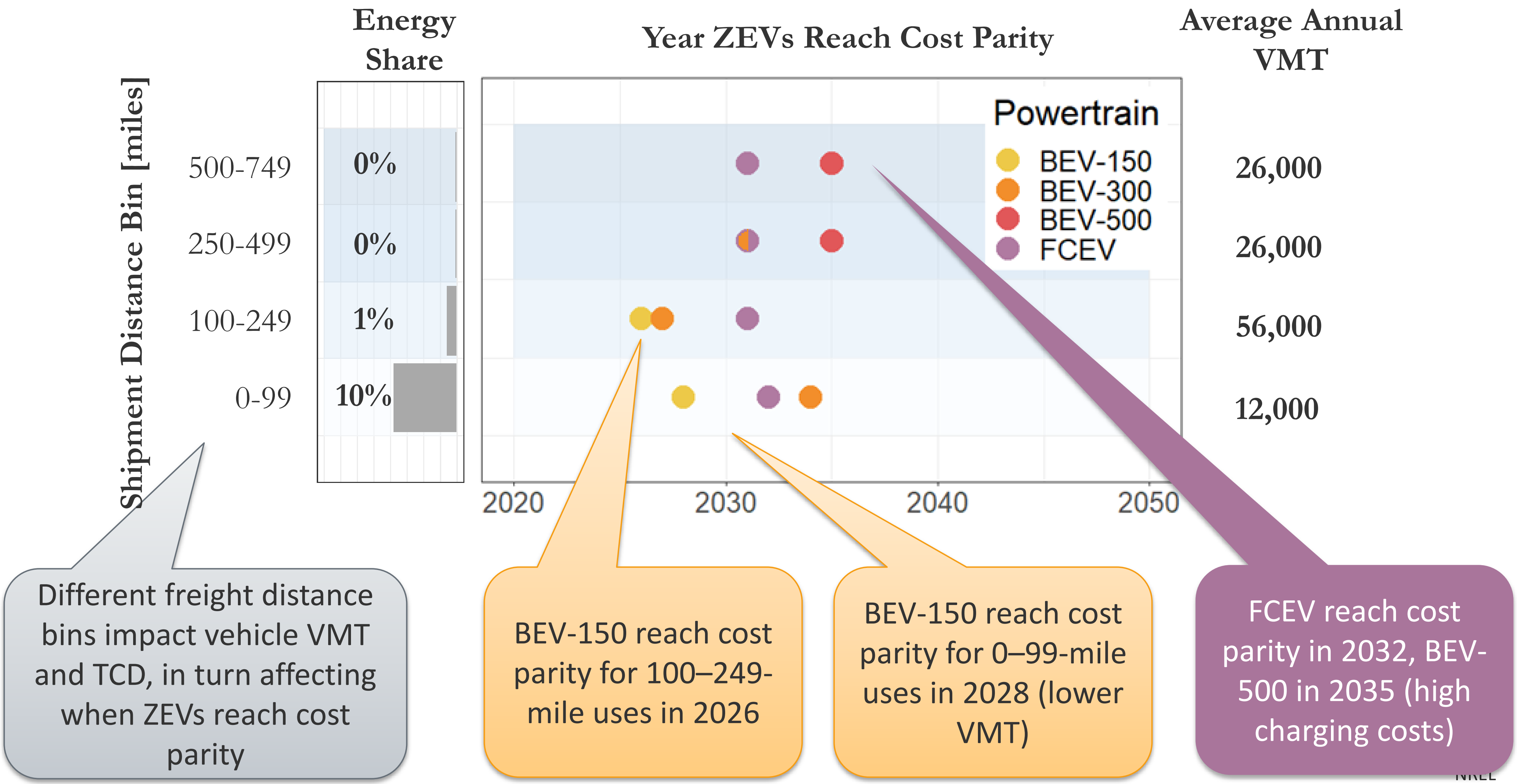
- Stock and sales shares are not necessarily proportional to contributions to emissions, due to wide disparities in VMT and fuel economy.
- Heavy trucks are ~40% of total vehicle stock but are responsible for about 70% of emissions due to lower fuel economy and greater VMT.
- For trucks, 2019 total stock 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)**



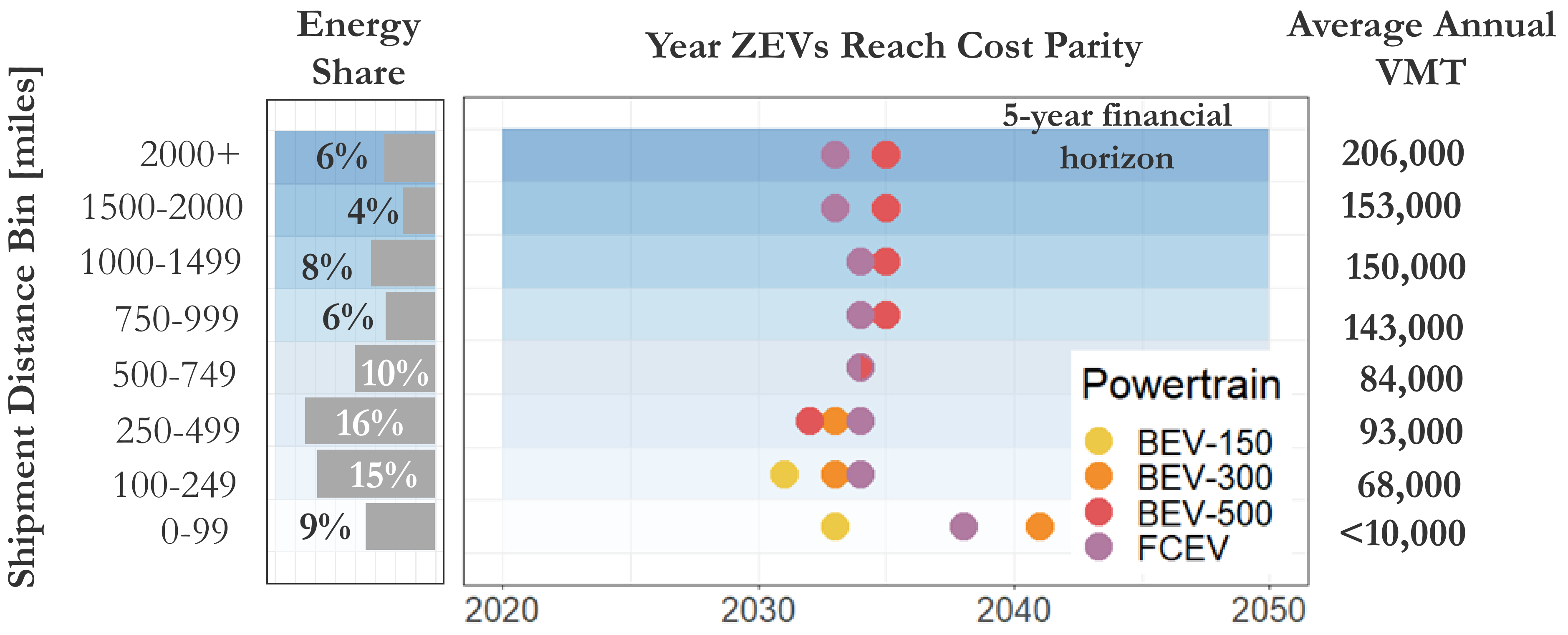
# Cost Parity by Distance Bin
## Light-Medium Trucks

| Vehicle Sales | Energy Share |
|---|---|
| 35% | 11% |



# 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.

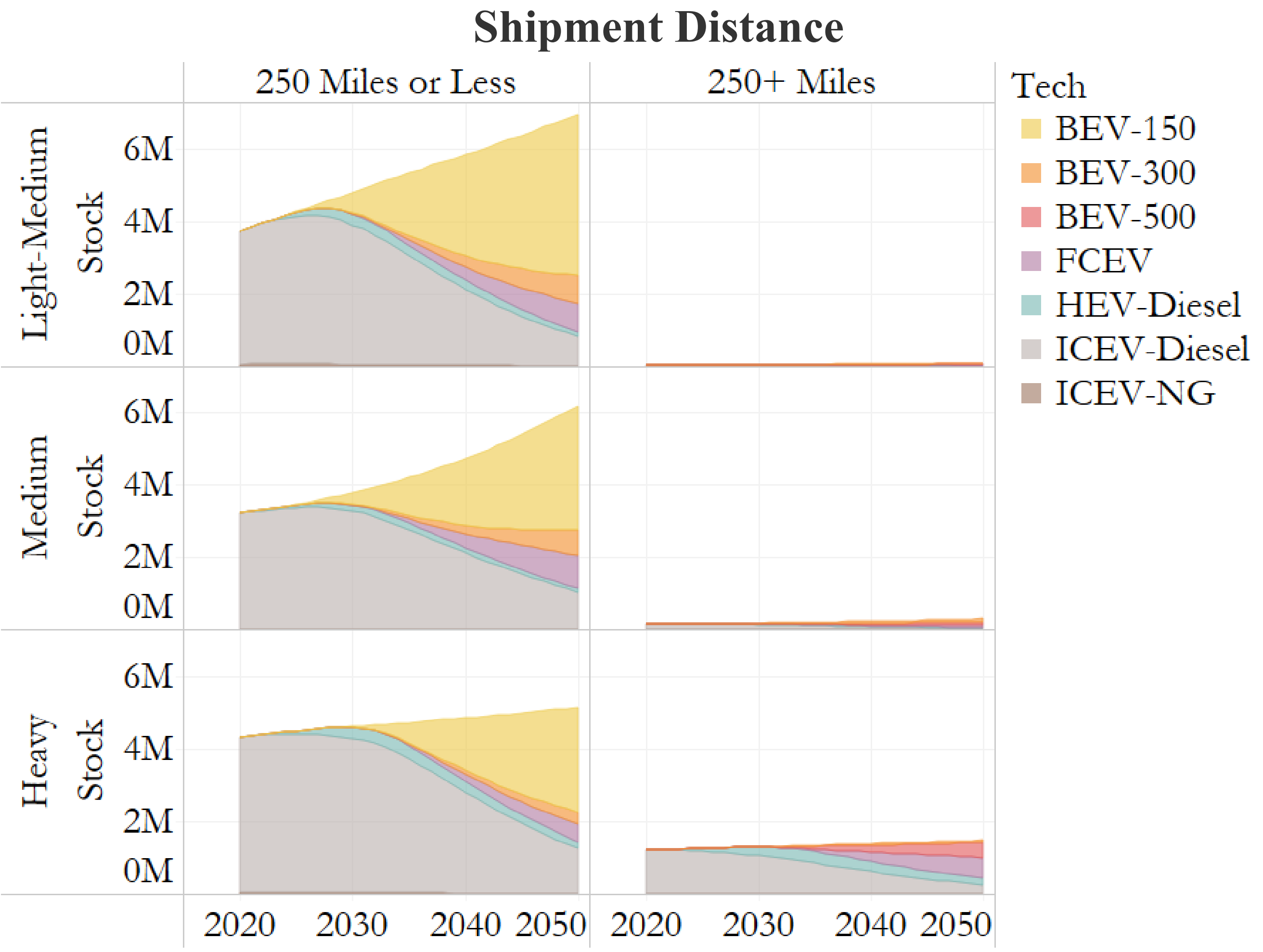
# Truck Sales

- Total light-medium and medium sales grow substantially from 2020 to 2050 (due to assumed total VMT growth).
- **ZEV sales** across all modes (and travel distance bins):
  - **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.

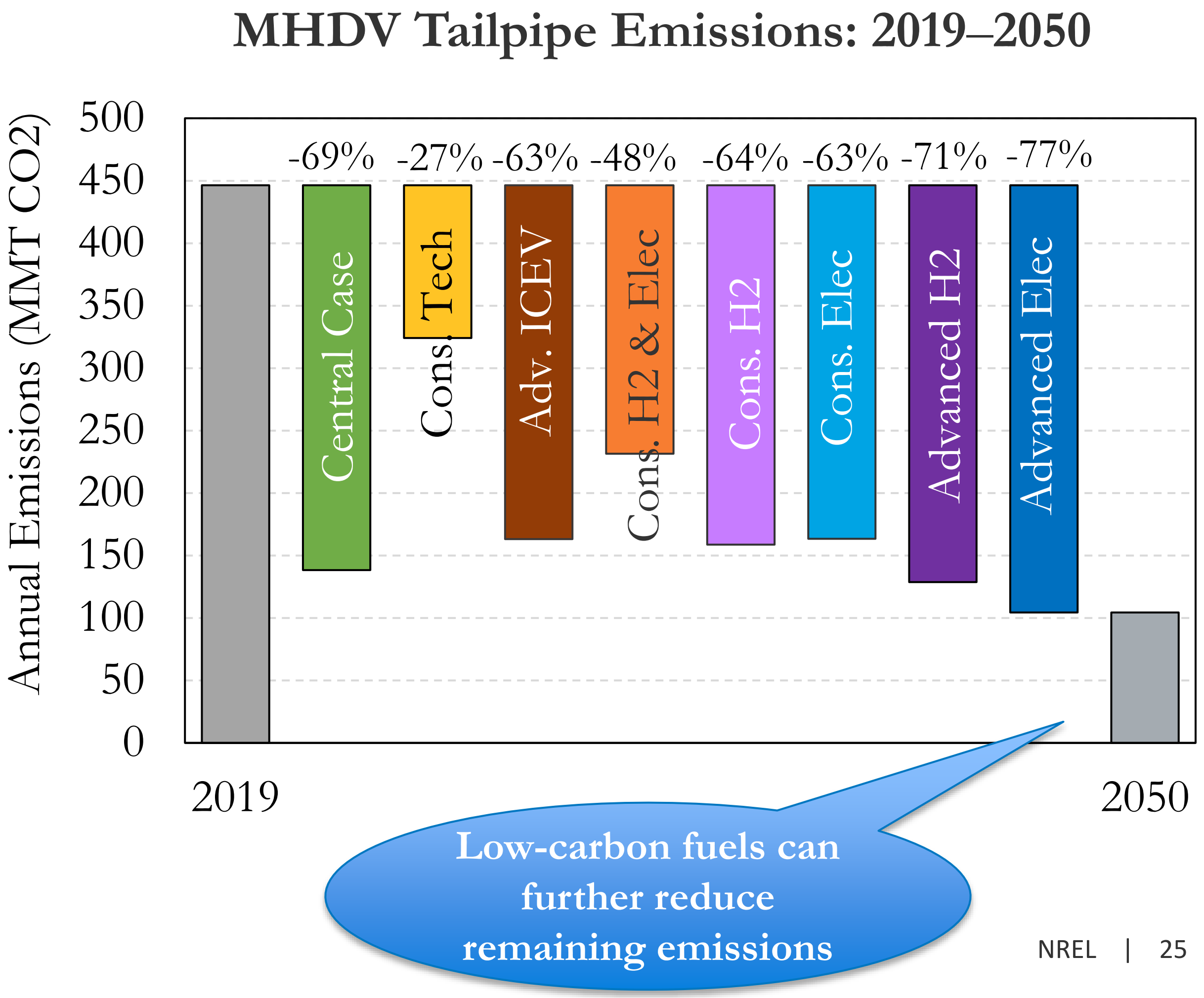
# Truck Stock

- Vehicle stock 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 and 80% by 2050** (66% BEV; 14% FCEV).



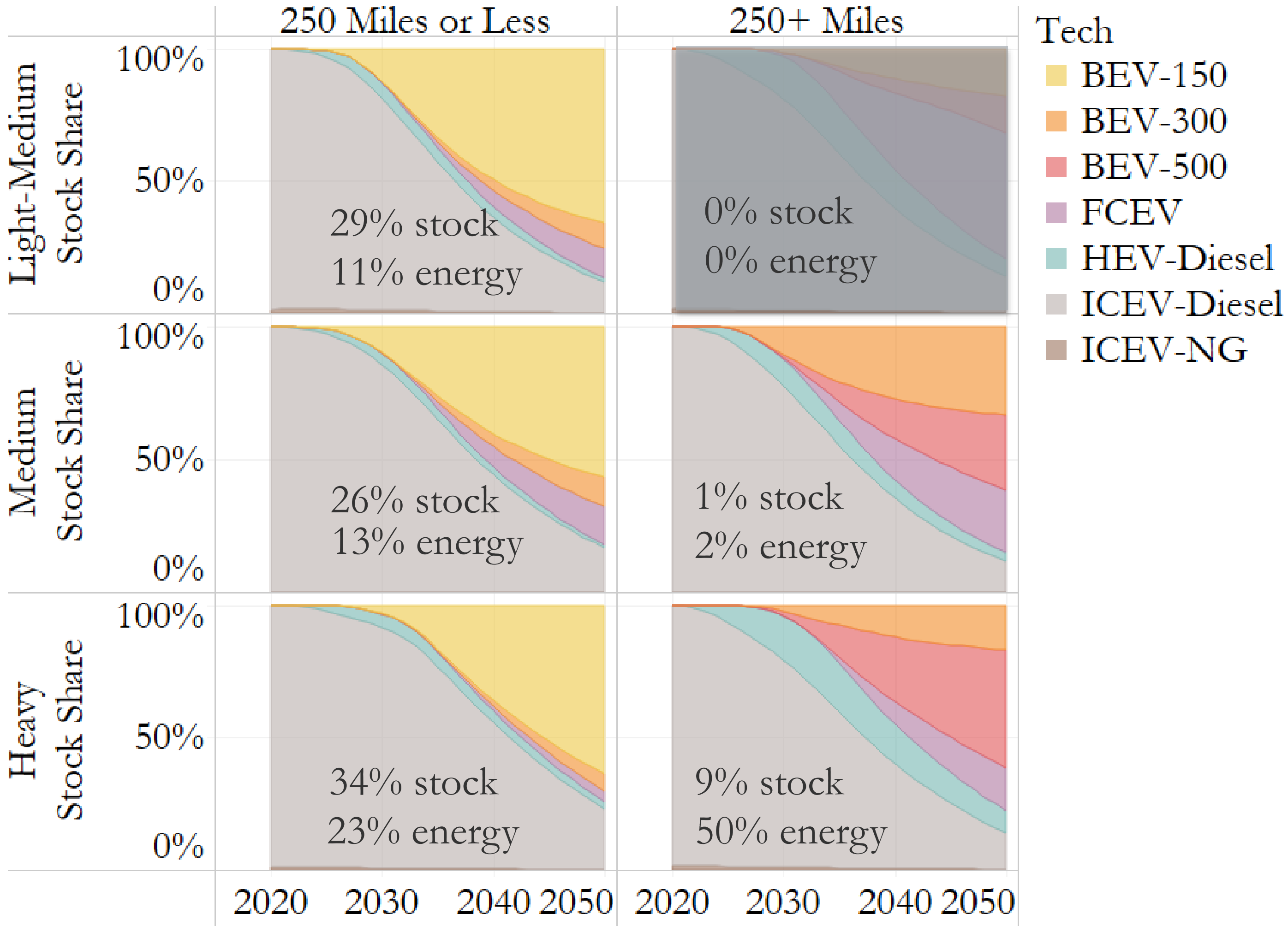
# 2050 Emissions Reductions: Additional Scenarios

- 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.



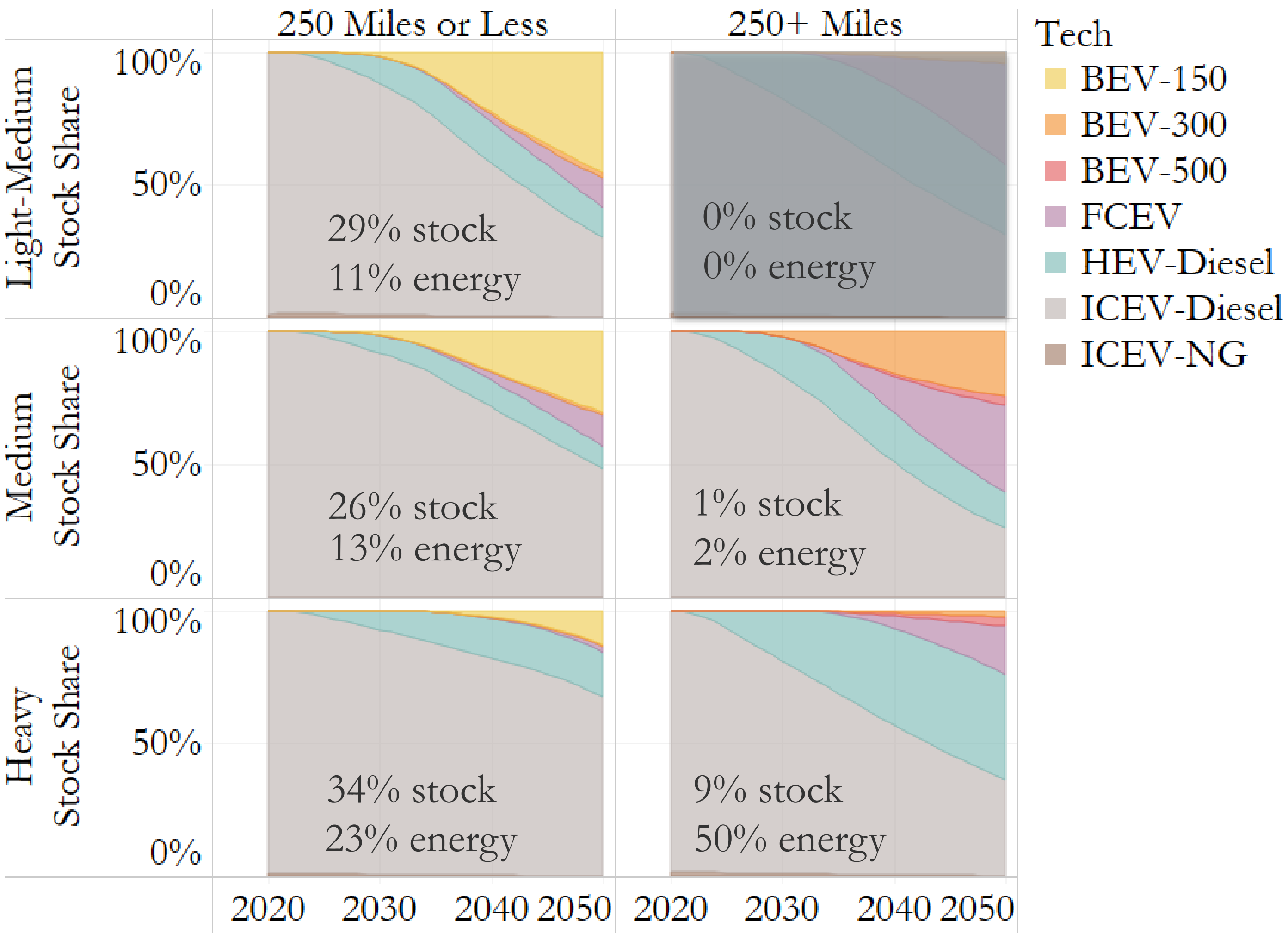
# Vehicle Stock Share – *Central Case*

- 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.



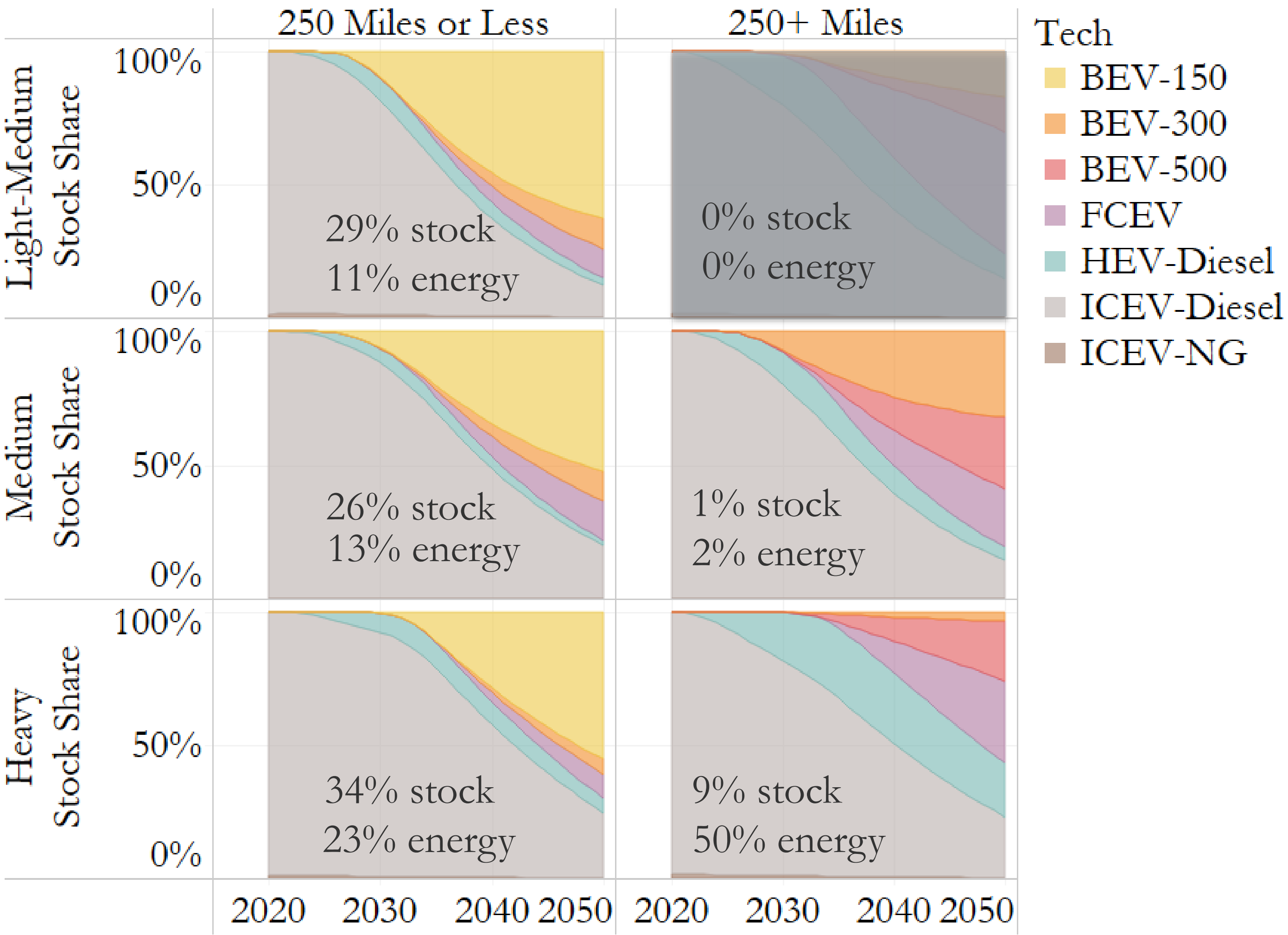
# Vehicle Stock Shares – *Conservative ZEV Technology Sensitivity*

- 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.



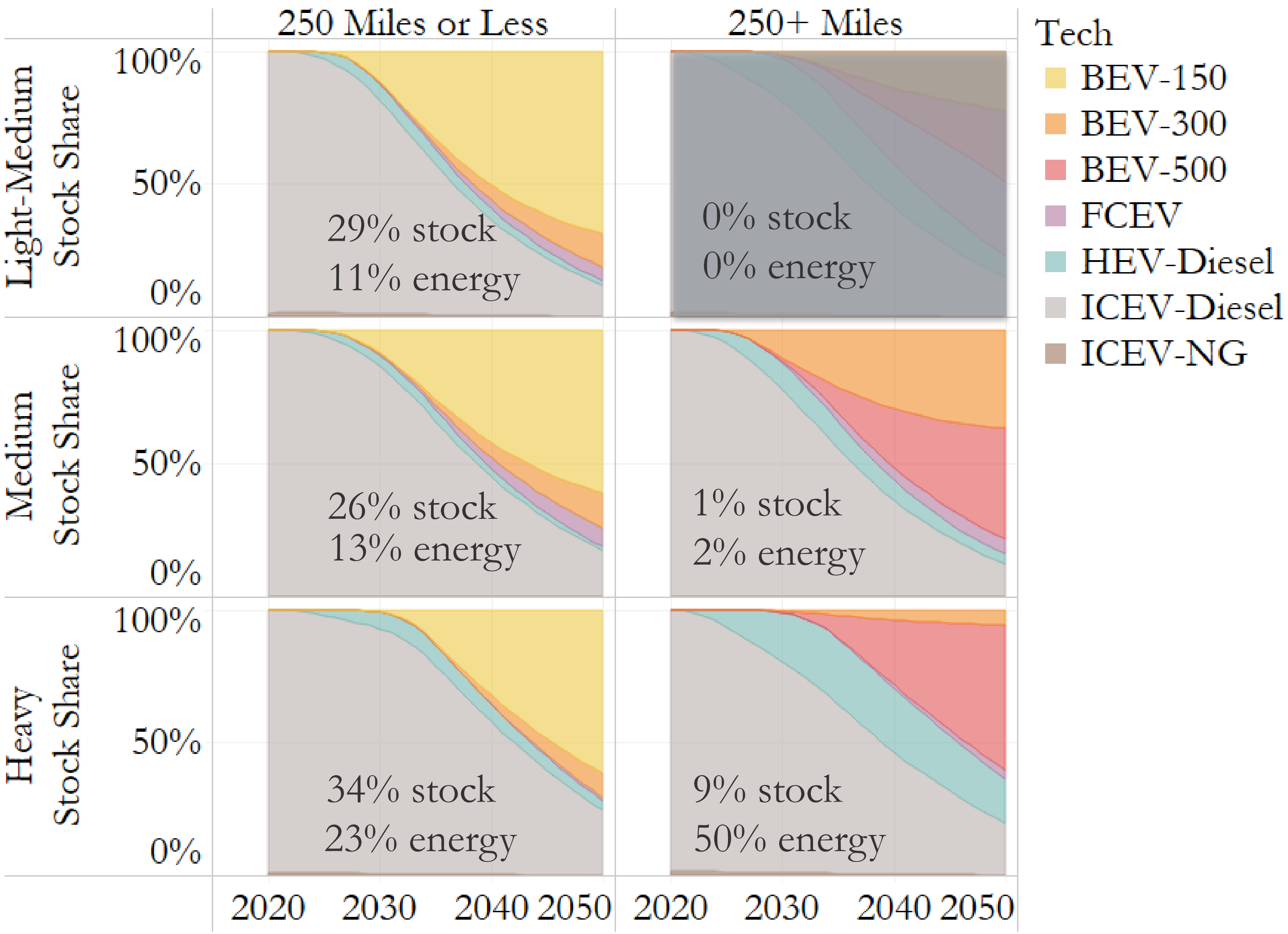
# Vehicle Stock Shares – *Advanced ICEV Sensitivity*

- 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.



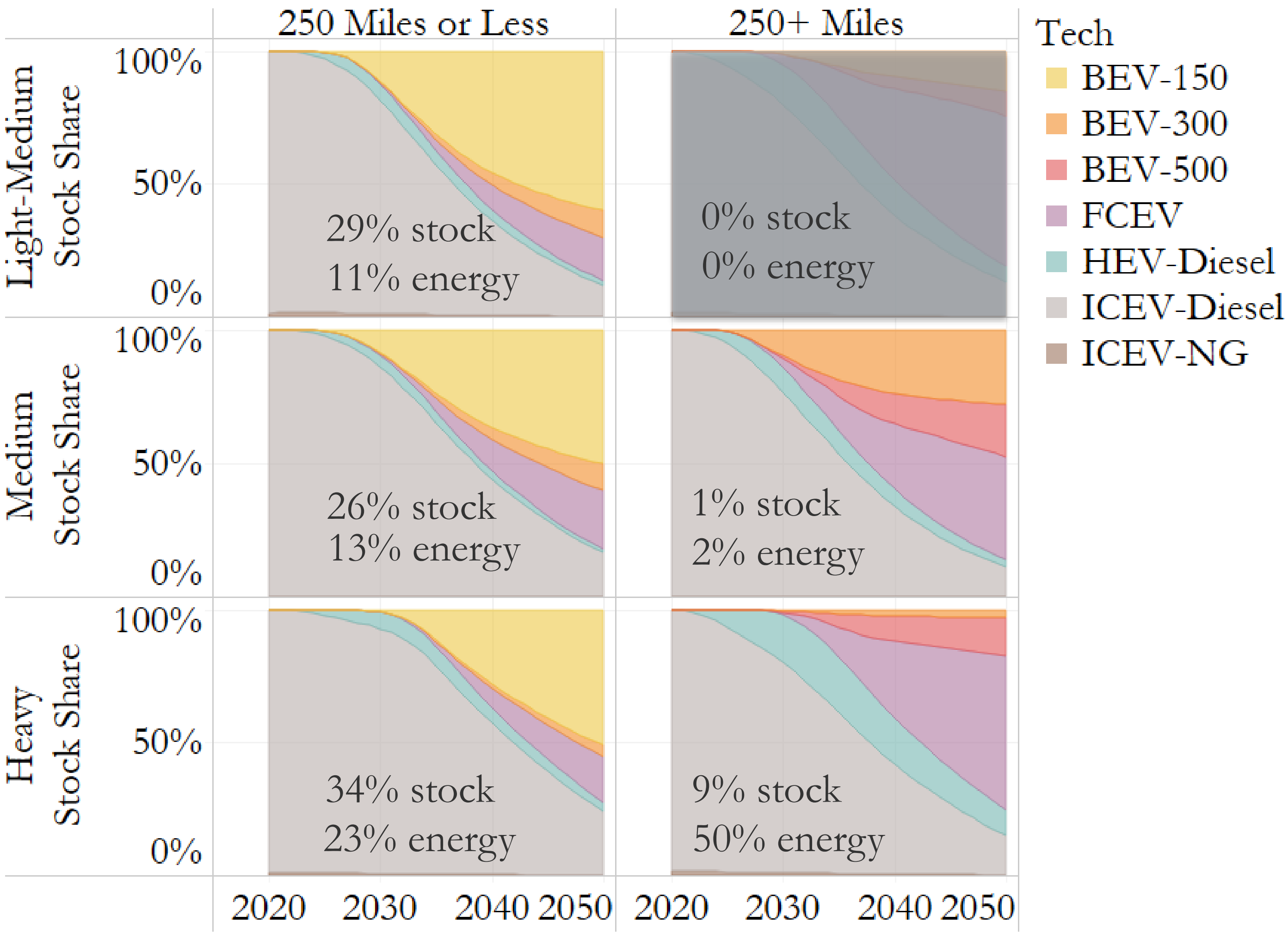
# Vehicle Stock Shares – *Conservative $H_2$ Sensitivity*

- 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.



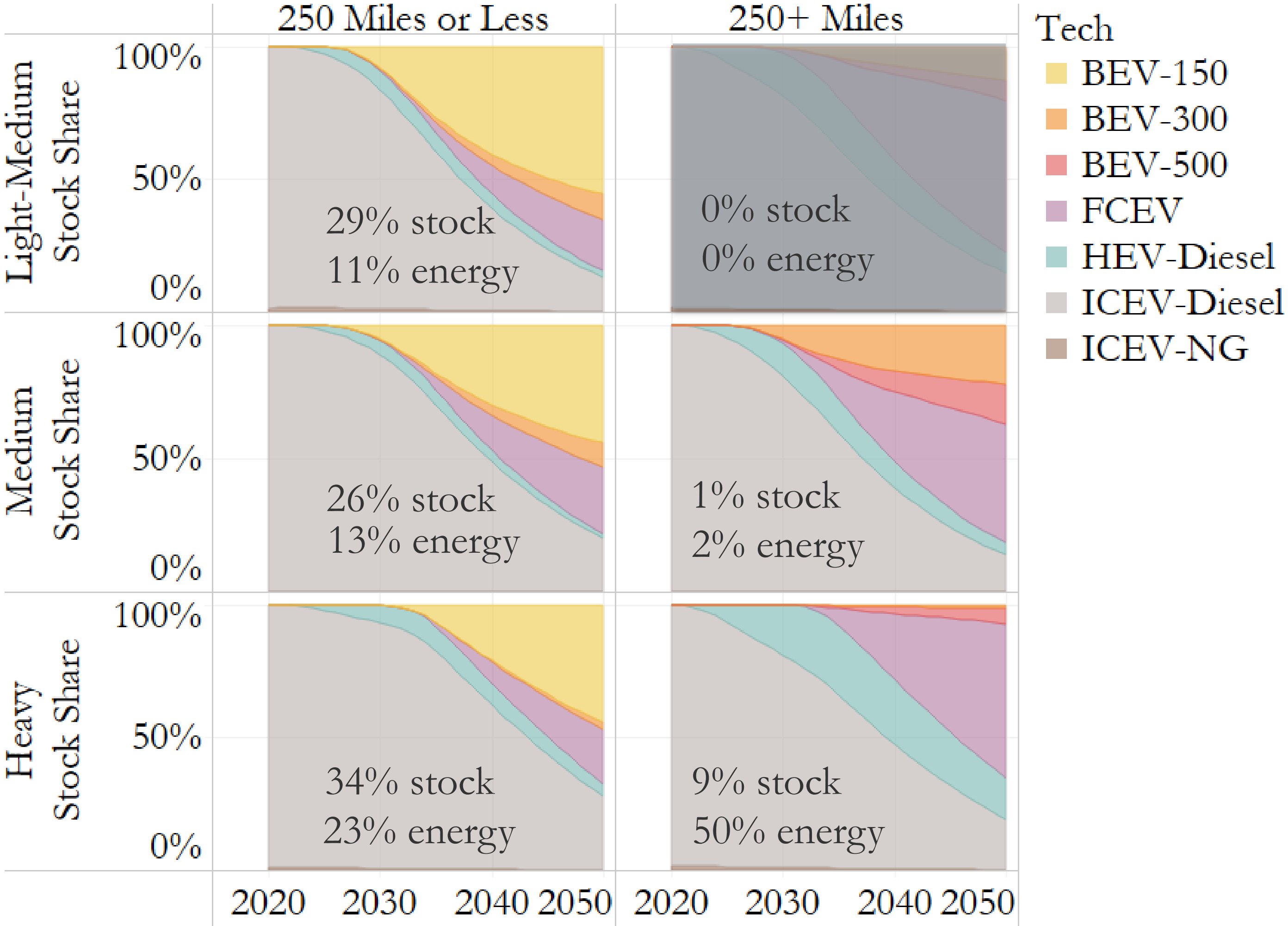
# Vehicle Stock Shares – *Advanced $H_2$ Sensitivity*

- 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.



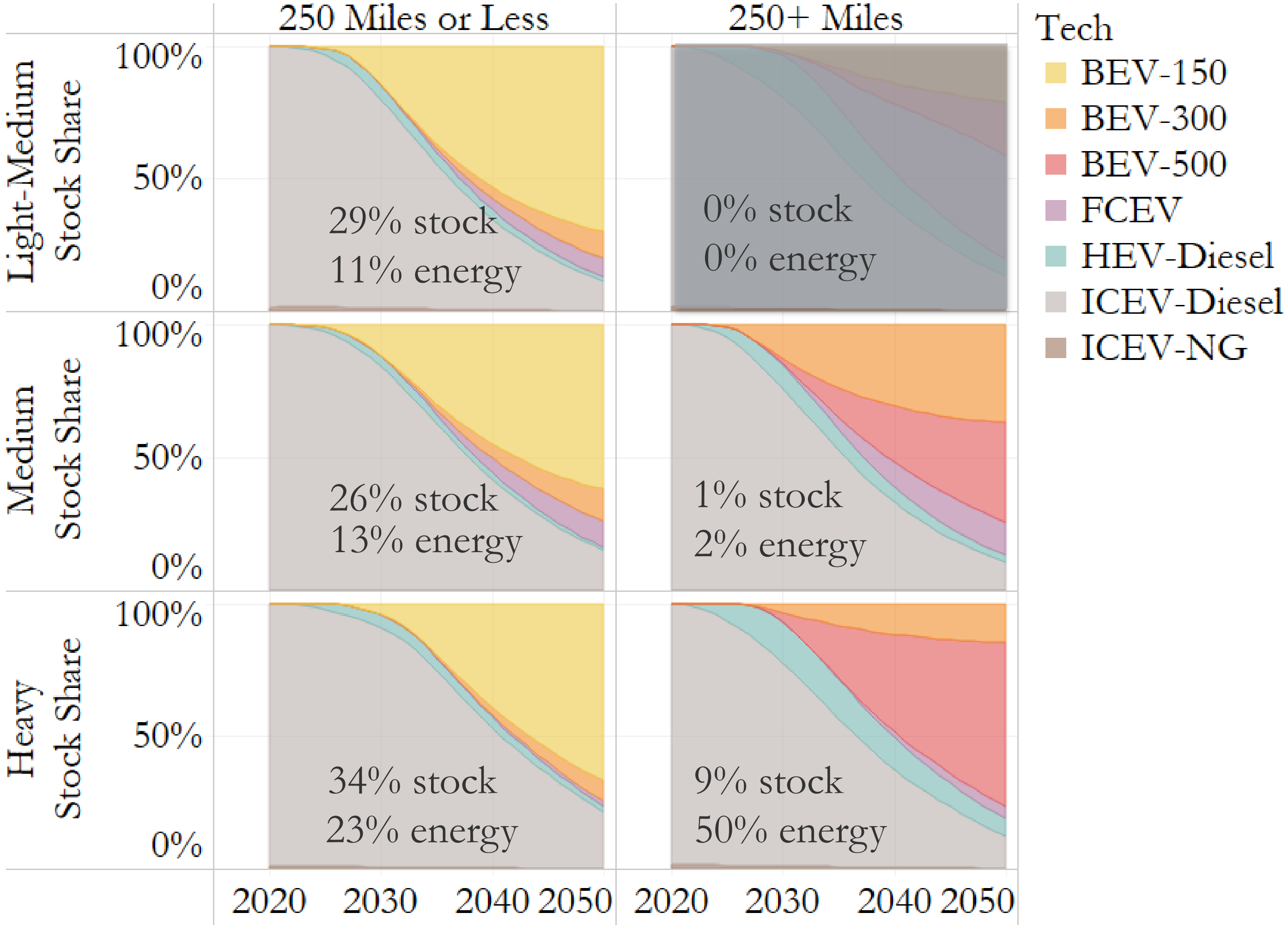
# Vehicle Stock Shares – *Conservative Electricity Sensitivity*

- 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.

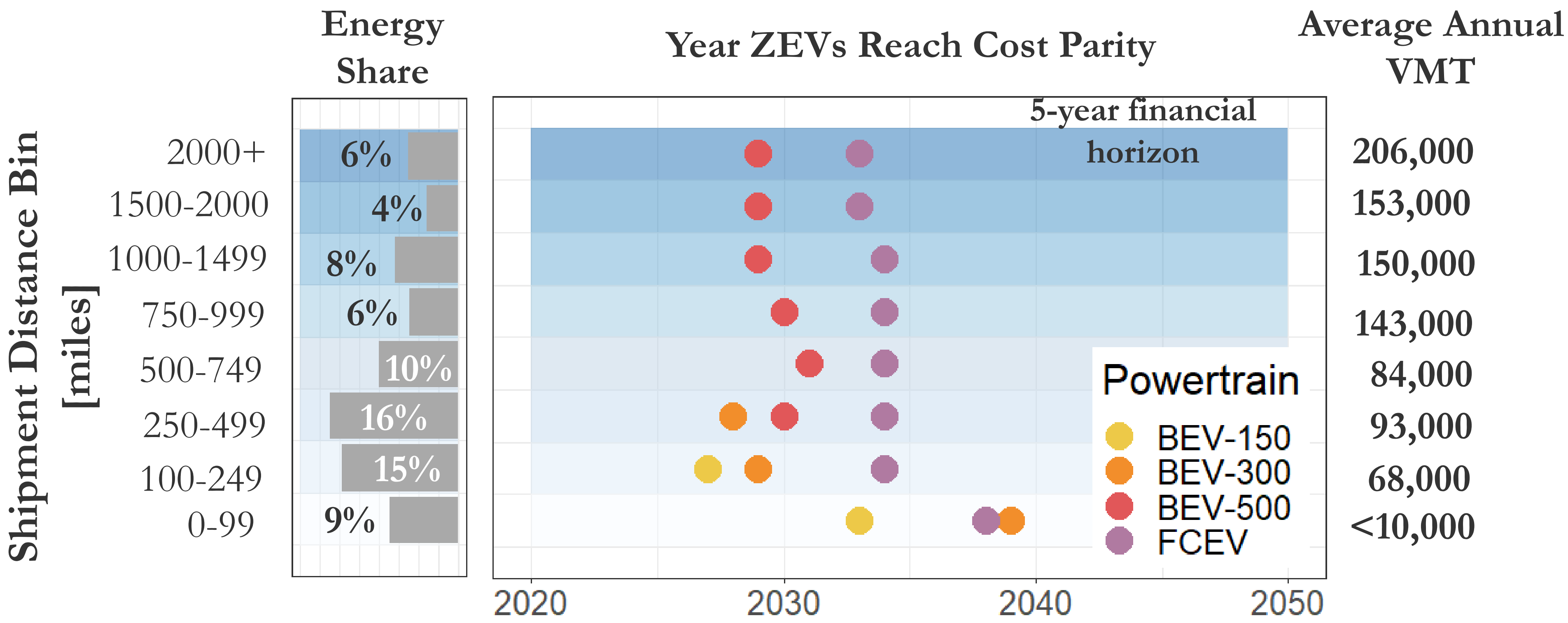


# Vehicle Stock Shares – *Advanced Electricity Sensitivity*

- 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.