EPRI

NRDC
NATURAL RESOURCES DEFENSE COUNCIL

White Paper

Valuing Improvements in Electric Vehicle Efficiency

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Story In Brief

Today's accelerating shift from internal combustion engine vehicles to electric alternatives provides an essential path to decarbonization but requires retooling of the auto industry, rapid expansion and updating of the electric grid, and creation of new, secure mineral supply chains. In this paper, the Natural Resources Defense Council (NRDC) and EPRI[1] explore the fundamental role that future vehicle efficiency improvements—additional and complementary to electrification—can play in lessening infrastructure and energy needs and reducing consumer costs. Electrification by itself brings major energy savings and other benefits, but the additional and often-overlooked improvements considered here reduce the amount of electricity needed to power vehicles, which is projected to be a large future load. This study characterizes key automotive technology advances and examines their potential impacts from the perspective of consumers, electricity and charging infrastructure providers, and automakers. Efficiency and lightweighting steps could effectively cut energy consumption per mile in half over the next 30 years. If these steps are achieved without raising vehicle costs, the study projects consumer energy cost savings of more than $200 billion annually for on-road transportation traveled by 2050, including reduced investments in the physical grid and charger buildout needed to support the shift towards electric mobility. Further work is suggested to examine in more detail the cost of the proposed vehicle efficiency strategies, to estimate the supply chain benefits of getting more miles from less battery material, and to conduct a broader assessment of additional ways that more efficient vehicles can contribute to consumer, automaker, and grid value.

1 NRDC and EPRI earlier collaborated on two landmark studies examining the impacts of electric vehicle adoption. *Environmental Assessment of Plug-in Hybrid Electric Vehicles*, released in 2007, demonstrated that PHEVs could contribute to significant reductions in greenhouse gas emissions and contribute to improved air quality. A 2015 report, *Environmental Assessment of a Full Transportation Portfolio*, updated and extended the earlier analysis to explore impacts that widespread adoption of electric transportation would have on greenhouse gas emissions and air quality.

Background

Energy efficiency gains have provided a broad array of benefits over the past half century. While today's U.S. economy is four times the size of the 1970 economy, energy use has increased only about 50 percent.[2] Efficiency, along with structural changes in the economy and behavioral shifts, has been an essential factor driving this improvement. For example, large efficiency gains have been achieved in household appliances. Electricity needs for refrigerators dropped by a factor of four since 1975, even as size and service quality increased and refrigerator cost per cubic foot dropped by half.[3] In transportation, the average fuel economy of new light-duty internal combustion engine vehicles (ICEVs) sold in the U.S. gradually doubled over the same period despite a shift in this century towards larger, heavier, more powerful vehicles.[4]

Today's battery electric vehicles (BEVs) provide a step-change efficiency improvement, with passenger cars already achieving 135 miles per gallon-equivalent (mpge) versus a comparable hybrid ICE model getting 59 mpg.[5] But vehicle electrification presents some challenges. For example, production of batteries and other electric components will need to increase significantly as will the supply chains providing their raw materials. Similarly, shifting from the gas stations that fuel 280 million on-road ICEVs[6] in the U.S. today to electric charging for most vehicles will require large investments in charging equipment and the grid. Also, as electric vehicle adoption expands to more segments of the market, the EV fleet can be expected to include larger, heavier vehicles such as SUVs and trucks with higher energy requirements. Based on the model projections in this study, electricity demand for on-road vehicle charging (including medium- and heavy-duty trucks) in 2050 could be as much as 65% of today's total demand. BEVs represent a major new load and thus a major new opportunity for efficiency.

Recognizing these trends, this study explores a variety of technologies for improving EV and ICEV efficiency—BEVs to 250 mpge and above and ICEVs to over 90 mpg—by reducing the amount of energy needed to move the vehicle. This can be achieved by combining body, tire, and auxiliary system improvements in addition to electric powertrain and battery improvements. In other words, there are opportunities to improve efficiency of both the propulsion systems in turning energy into motion and the efficiency of the car itself in moving along the road and through the air. Key measures evaluated include reduced weight (without reducing size or safety), reduced aerodynamic drag, reduced tire rolling resistance, more-efficient accessories, improved battery/powertrain efficiency, and higher battery energy density (which provides more range from a lighter and/or smaller battery pack).

The study applies EPRI's US-REGEN model[7] to provide initial estimates of "the size of the prize" potentially available by realizing these efficiency gains over the decades ahead. US-REGEN is a regional model of the U.S. energy system, which includes detailed models of end-use demand and the power grid and charging infrastructures needed to meet these demands. The model has been used over the past 15 years to assess consumer energy choices and optimal grid/energy system buildout under a wide range of policy and technology scenarios.[8] Specific to the vehicle modeling, US-REGEN considers different consumer types (e.g., urban/rural, different driving patterns) and weather (e.g., the impact of daily temperatures on battery and cabin heating/cooling efficiency) to derive real-world vehicle efficiencies. The model estimates purchase shares of BEVs versus ICEVs based on the regional economics, including delivered electricity and fuel prices, combined with household driving patterns.

2 Economic growth from Department of Commerce. Energy growth is end-use (or final energy) from EIA Monthly Energy Review.

3 Calculated based on data compiled by the Appliance Standards Awareness Project. Energy consumption and volume data from the Association of Home Appliance Manufacturers and refrigerator price data from the U.S. Census Bureau.

4 Trends from *The 2022 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology Since 1975*.

5 EPA efficiency estimates for the most efficient 2023 EV, the Hyundai *Ioniq 6*, compared to the efficiency of the similarly sized *Ioniq 5* hybrid ICE.

6 The figure includes registrations for passenger cars, motorcycles, trucks, buses, and other vehicles.

7 The version of the model used for this study was adapted from the version documented at https://us-regen-docs.epri.com/. For this study, the on-road vehicle modules were updated to provide a more-detailed representation of vehicle efficiency improvements and additional granularity for auxiliary and battery conditioning loads and charging infrastructure requirements.

8 https://esca.epri.com/Decarbonization-Pathways-and-Impacts.html lists many of the publicly-available US-REGEN analyses.

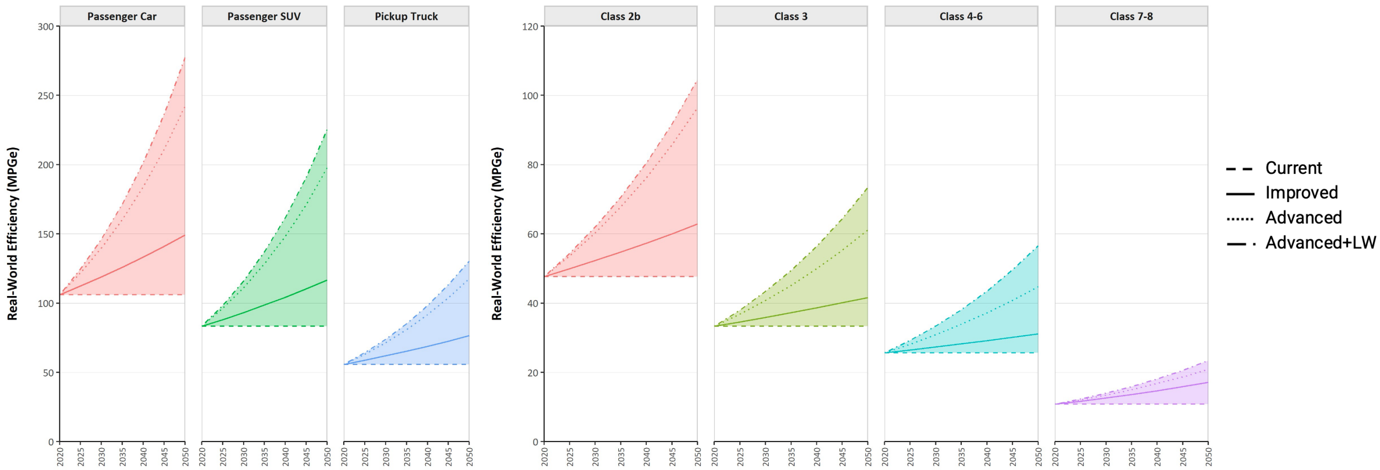

Figure ES-1. BEV Efficiency Assumptions Across Vehicle Classes in US-REGEN. Figure shows projected real-world efficiency (at 68°F, i.e., before temperature impacts) by scenario for new vintage vehicles across light-duty classes (lefthand panel) and medium- and heavy-duty truck classes (righthand panel). Figure A-1 in Appendix A shows projected real-world efficiency by scenario for ICEVs.

The analysis in this study was performed in the context of an economy-wide, net-zero future target where there are increasing demands on the electric sector to decarbonize while electrifying large portions of transportation, buildings, and industry, and to potentially produce clean fuels. Non-electric energy activities are also decarbonizing through a combination of alternative fuels, carbon capture, and carbon removals from the atmosphere. Efficiency improvements across all sectors of the economy play an important role in reducing the scale of the energy system despite growing service demands and economic output.

Electric Vehicle Technology Scenarios

Four technology scenarios are modeled with specific assumptions regarding aerodynamic drag, rolling resistance, powertrain efficiency, battery density, lightweighting, auxiliary efficiency, hybridization and other factors made for light-, medium-, and heavy-duty vehicles (see Figure ES-1):

- **Current** – efficiency is fixed for each vehicle class near the 2023 model year average (with estimates of current technology for BEVs in larger vehicle segments where adoption is not yet observed). Includes hybridization of light-duty ICEVs.
- **Improved** – today's best-in-class aerodynamic drag and tire rolling resistance coupled with gradual improvements in battery density for BEVs and increasing hybridization for all ICEVs.
- **Advanced** – significant improvements to reduce drag and tire rolling resistance, and to increase powertrain efficiency and battery density, plus a moderate reduction in vehicle weight through some material substitutions, but a continued reliance on high-strength steel. ICEVs adopt the same vehicle body improvements.
- **Advanced + lightweighting** – the advanced scenario plus an additional significant reduction in vehicle weight through the use of carbon fiber, with compounded lightweighting for BEVs from the reduced battery size requirement.

The four scenarios span a range that starts from assuming today's technology doesn't improve over time, to an intermediate scenario assuming improved technology at a rate roughly consistent with historic efficiency trends, and finally to two scenarios that reflect an accelerated trend toward advanced efficiency gains.

To simplify comparisons, the driving range for each vehicle class is held constant across vehicle efficiency scenarios.[9] Therefore, the benefits from efficiency gains are seen mainly through reductions in grid and charging infrastructure needs and consumer energy bills. In reality, the benefits of vehicle efficiency improvements could be realized in many ways, all driven by consumer preferences and system constraints.[10] For example, increased efficiency could enable longer range for the same size battery pack. In

9 See Appendix A, Table A-1 driving range assumptions by vehicle class.
10 Additionally, faster per-mile charging could reduce the number of public charging points needed to service a fixed number of vehicles, efficiency gains could provide more time flexibility in charging, speed of charging in minutes/mile could be maintained at lower voltages (potentially reducing needed grid capacity investments and increasing the viability of 120V charging at home for some), or air quality and greenhouse gas reductions could be prioritized.

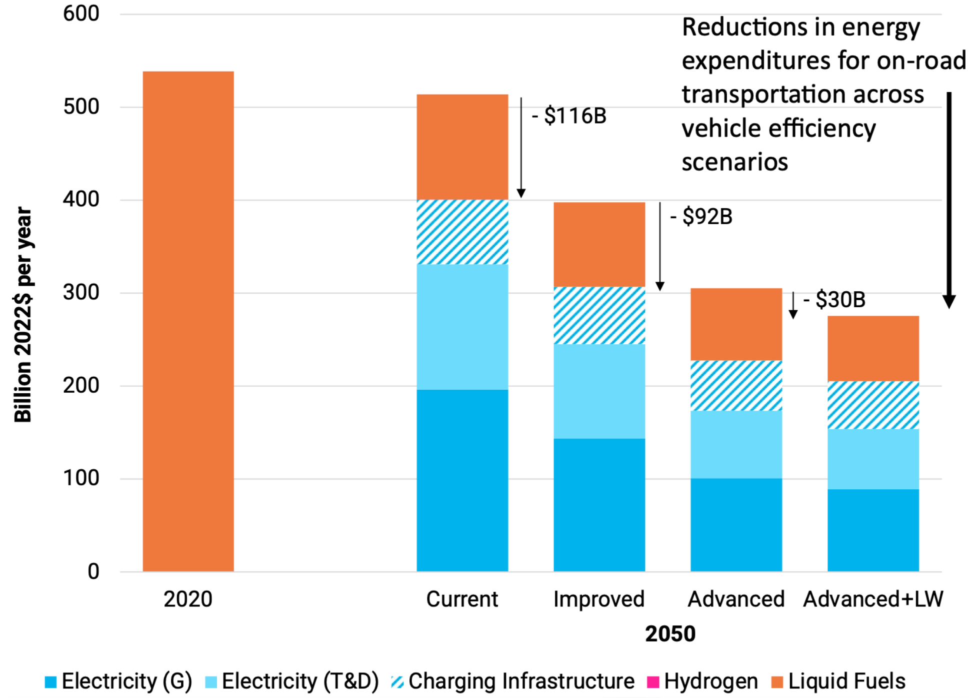

Figure ES-2. **U.S. Total Annual Energy Expenditures for On-Road Transportation**. Expenditures on delivered energy for cars and trucks are reduced as assumed vehicle efficiency increases. Delivered electricity costs are broken into generation (G) and transmission and distribution (T&D) components, with charging infrastructure costs shown separately. Comparing the *Advanced+Lightweighting* scenario to the *Current* scenario, total annual energy expenditure savings from EV efficiency improvements are $238B, including $195B on electricity and charging infrastructure.

this study, the implication of holding range constant is that improved efficiency translates into a smaller battery pack. Moreover, the increased cost of more advanced components to achieve efficiency gains is assumed to be offset by decreased battery weight/size and other savings,[11] leaving the vehicle purchase price unchanged across scenarios.[12]

Vehicle Efficiency Improvement Impacts

Analysis of the driving cycles of various classes of on-road vehicles across the study's four scenarios yielded several significant results for consumers, automakers, and the electric power industry.[13]

- Consumer: With vehicle purchase price assumed to be fixed across the vehicle efficiency scenarios, the biggest impacts for consumers come from saved charging cost. Today, electric passenger cars have an average real-world efficiency of 106 mpge.[14] This could jump to 250 mpge or more by 2050, as in the *Advanced + Lightweighting* scenario, significantly reducing electricity consumption. When similar approaches are applied to ICEV passenger vehicles coupled with strong hybridization, their current 28 mpg average could improve to 92 mpg. The assumed improvements apply broadly across all segments, including larger personal light-duty vehicles (LDVs) and fleet medium- and heavy-duty vehicles.[15] These assumed efficiency improvements significantly reduce the total U.S. energy expenditures for on-road transportation by 2050. Figure ES-2 highlights savings rising to over $200 billion per year (2022 $) in

11 The costs of the efficiency measures modeled were not examined in detail. This assumption is principally important for the calculation of consumer savings. Substantial vehicle price increases could also impact adoption rates and stock turnover.

12 For the fourth scenario, which requires carbon fiber construction for many components, there is empirical evidence that the increased material costs of carbon fiber construction can be offset by simpler automaking and smaller batteries. This appears to be the case for the 2013–22 BMW i3, which profitably sold a quarter-million copies, and was Germany's most popular EV before the Tesla *Model 3* entered that market. Details are in A.B. Lovins, "Reframing automotive fuel efficiency," *SAE J. STEEP* 1(1):59-84, 2020, https://doi.org/10.4271/13-01-01-0004.

13 BEVs are projected to provide 80–90 percent of U.S. on-road service demand by 2050 across all four scenarios. This is largely driven by cost and performance assumptions that make most classes of BEVs cheaper to own and operate than ICEVs by 2030, independent of the efficiency scenario.

14 106 mpge is estimated real-world efficiency (before temperature impacts) for current new vintage light-duty passenger cars in US-REGEN. It is based on vehicle modeling and observed rated efficiencies.

15 Efficiency time paths assumed for all vehicle classes are summarized in Appendix A.

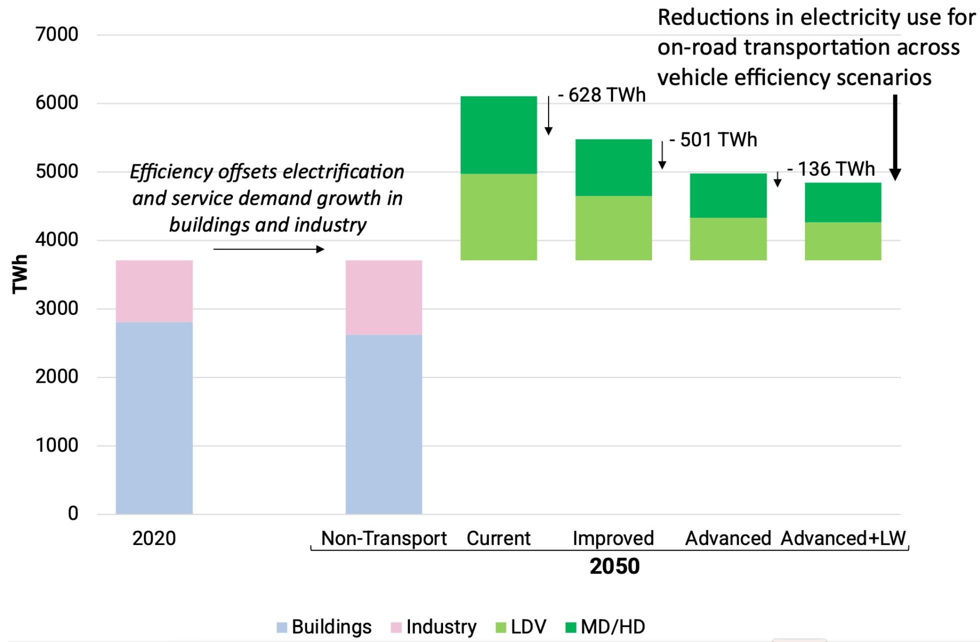

Figure ES-3. U.S. Total Annual Electricity Demand by End-Use Sector. Efficiency gains are projected to largely offset demand growth in buildings and industry, reducing the overall impact of electrification on the grid. Electrification of on-road transportation leads to large new loads (shown in green). With EV efficiency improvements, projected 2050 electricity demand is reduced by 1,265 TWh in the *Advanced+Lightweighting* scenario compared to the *Current* scenario, cutting electricity use for vehicles in half and reducing total demand by around 20%.

2050 in the *Advanced + lightweighting* scenario versus the *Current* technology scenario. As noted earlier, consumer benefits of efficiency gains could accrue in many additional ways that we did not quantify. With significantly lower charging time per mile, for example, charging from standard household outlets could be sufficient on most days for more households, creating space on electrical panels for other home electrification actions, potentially avoiding costly home electrical upgrades and reducing the need for electric distribution upgrades.

- Automakers: While automakers face many challenges in shifting production from ICEVs to BEVs, technical assessments supported by conversations with several of these companies suggested that they would not need to dramatically alter their planning cycles or manufacturing processes to adopt measures that could double vehicle efficiency. In many cases, the technologies and supply chains already exist and are at or near viability at scale. Near-term pressures to improve vehicle range, reduce operating costs, and integrate other features that customers want provide added incentives to invest in technologies that improve vehicle efficiency. Automakers identified reduced material supply chain needs as another potential win. For example, by 2050, this could mean 40 fewer gigafactories (each producing 40 GWh of batteries per year) and 1 million tonnes less annual U.S. demand for lithium carbonate equivalent (for comparison, 732,000 tonnes were produced globally in 2022).
- Electric Power Supply and Infrastructure: EV efficiency improvements temper increasing demands on the grid. Analysis using EPRI's US-REGEN model suggested that these vehicle efficiency improvements could substantially reduce investment needs for grid buildout. Relative to the *Current* technology scenario, the *Advanced + lightweighting* scenario reduces vehicle electricity use by 53 percent in 2050, declining from 2400 TWh/year to approximately 1136 TWh/year (see Figure ES-3). For utilities, this reduced demand shrinks how much generation, transmission, and distribution infrastructure they will need to install, reducing projected expenditures by as much as $170 billion annually. Anticipating and planning for these efficiency gains is important at the system level, but also at the local level, where vehicle efficiency gains (for a vehicle fleet, for example) can dramatically lessen the needed buildout.

Technical efficiency of vehicles is not the only way to save energy and cost. This study also analyzed the additional power and grid savings if demand for vehicle miles traveled were to grow more slowly, for example through effective land use, city planning, and shared transport policies. Specifically, if the assumed growth rate in U.S. vehicle-miles traveled (VMT) were halved—the growth rate, not the level—then VMT traveled in 2050 would fall by 14 percent. Fuel costs and grid investment costs are estimated to fall by similar amounts, adding to the gains from vehicle efficiency improvements if both strategies are pursued together.[16]

Conclusions

The potential savings from improving U.S. on-road transportation efficiency over the next three decades are substantial, totaling in the trillions of dollars (cumulatively), realized as reduced transportation costs for consumers. The efficiency gains reduce electricity demand by hundreds of terawatt-hours annually and reduce associated grid build-out, reducing peak demand by almost 300GW.

For consumers, lower cost of vehicle ownership (similar purchase price plus lower fuel costs) and lower home power demands together make electric mobility more accessible to all communities, assuming (and facilitating) a commitment to building out an accessible charging infrastructure.

For the companies that are rapidly introducing new electric vehicles, efficiency gains create opportunities for vehicles with lower ownership cost and better performance. In addition, the improved battery technology should lessen supply-chain concerns by reducing the quantity of raw materials needed to produce batteries.

For the electricity sector, it is important to project accurately the pace and amount of infrastructure needed to enable on-road transportation electrification. Plausible vehicle efficiency gains could change these demands substantially. Declining power demands (e.g., half the demand for a given fleet of vehicles) can help the grid keep pace with customer demand. In addition, society would reap further savings from needing less charging infrastructure (regardless of who provides it) to charge a given fleet of autos with a given range.

16 Reducing the VMT for an efficient vehicle yields somewhat smaller savings than the same VMT reduction for an inefficient vehicle. Therefore, combining the two strategies does not simply add the reductions from each. Nevertheless, pursuing them together lessens overall supply chain and infrastructure needs.

1. BACKGROUND

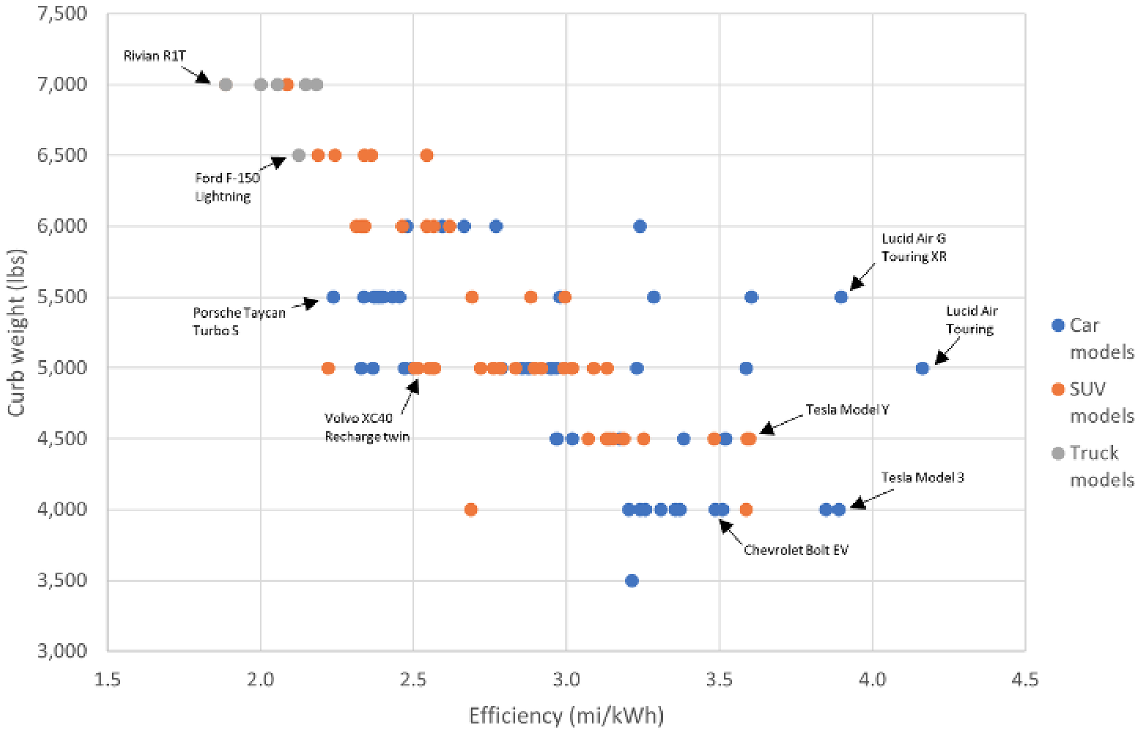

Figure 1. 2023 BEV Rated Model Efficiency versus Weight (Source: ACEEE, https://www.aceee.org/blog-post/2023/04/boosting-ev-efficiency-would-cut-emissions-and-reduce-strain-grid).

Electric vehicles today provide a step-change efficiency improvement, with passenger BEVs already increasing to 106 miles per gallon-equivalent (mpge)[17] versus comparable ICEVs getting 35 to 60 mpg.[18] But underlying that simple comparison lies a more complex reality. Today's new BEVs span a wide range of efficiencies even among passenger vehicles in each major class—cars, SUVs, and pickup trucks. Figure 1 shows the range of efficiencies for new 2023 EV models in the United States, highlighting both the correlation between efficiency and vehicle weight as well as wide efficiency variations within weight categories:

- Vehicle weights in the 2023 models range from 3500 to 7000 pounds.
- Efficiencies range from 1.8 miles/kWh for Rivian to 4.2 miles/kWh for Lucid Air Touring.[19]
- Efficiencies in the 5500 lb category range from 2.2 miles/kWh to 3.9 miles/kWh, highlighting the importance of the many vehicle design decisions and trade-offs governing efficiency apart from weight.

Globally, the trend in the light-duty vehicle market has been towards larger batteries (greater range) and larger BEVs as automakers have begun to offer electric versions of SUVs, crossover vehicles, and light-duty trucks (Figure 2). For example, at the global level, BNEF reports that average battery size in new light-duty EV purchases increased 10% from 2018 to 2022, and the International Energy Agency (IEA) noted in their *2023 Global EV Outlook* that 60% of EV models for sale in China and Europe in 2022 were SUVs or large cars and an even higher percentage of BEV models in the U.S. were SUVs or Crossovers.

Heavier, less efficient vehicles create several challenges. Less efficient vehicles, of course, require more electricity per mile, making electricity generation requirements grow faster. Larger batteries increase the demand per vehicle for raw materials, stressing an emerging supply chain, which could create more demand for rapid charging ("filling the tank" in a short period of time) that can stress the local capacity of the grid.

17 106 mpge is estimated real-world efficiency (before temperature impacts) for current new vintage light-duty passenger cars in US-REGEN. It is based on vehicle modeling and observed rated efficiencies.

18 For a more specific comparison, EPA estimates 135 mpge for the most efficient 2023 EV, the Hyundai *Ioniq 6*, compared to 59 mpg for the similarly sized *Ioniq 5* hybrid ICE.

19 The Hyundai *Ioniq 6* Long Range Rear Wheel Drive, not graphed, also achieved 4.17 miles/kWh and weighs 4222 pounds.

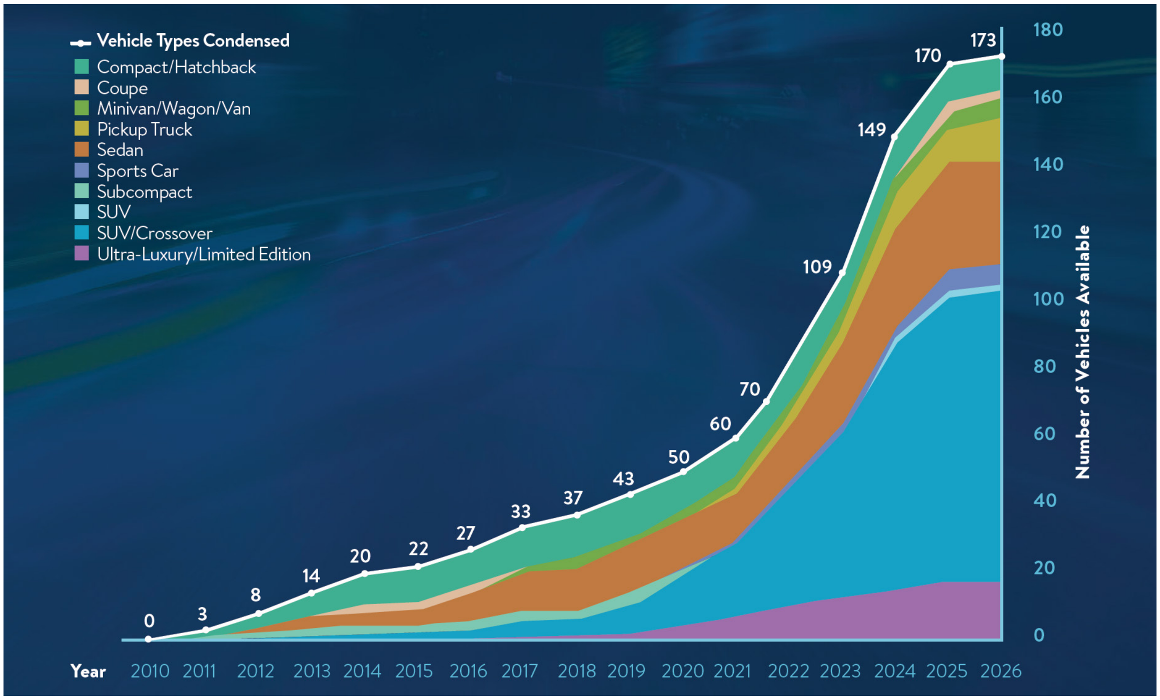

Figure 2. U.S. electric vehicle on-road model availability through 2026. Estimates for 2024-2026 based on manufacturers' announcements. (Source: *EPRI's Consumer Guide to Electric Vehicles, September 2023*, https://www.epri.com/research/products/000000003002026815.)

In addition, heavier vehicles increase tire and brake emissions and roadway damage, and they can do more harm in collisions.[20]

Recognizing these trends, this study explores a variety of technologies for improving EV and ICEV efficiency—BEVs to 250 mpge and above and ICEVs to over 90 mpg—by reducing the amount of energy needed to move the vehicle. This can be achieved by combining body, tire, and auxiliary system improvements in addition to electric powertrain and battery improvements. In other words, there are opportunities to improve efficiency of both the propulsion systems in turning energy into motion and the efficiency of the car itself in moving along the road and through the air. Key measures evaluated include reduced weight (without reducing size or safety), reduced aerodynamic drag, reduced tire rolling resistance, more-efficient accessories, improved battery/powertrain efficiency, and higher battery energy density (which provides more range from a lighter and/or smaller battery pack).

The discussion is organized as follows:

- Section 2 introduces the US-REGEN model, which was used to assess vehicle adoption and BEV implications for charging infrastructure and the electric grid.
- Section 3 describes the foundational assumptions about EV efficiency gains that drive this study.
- Section 4 highlights key results.
- Section 5 presents conclusions and ideas for future research.
- Appendix A provides additional detail on key modeling assumptions.

20 It was long thought that auto safety depends on weight. Actually, it depends on size—on the "crush length" in which crash energy can be dissipated by crash-resisting structures. After a 2003 reanalysis of Fatality Analysis Reporting System (FARS) data (Van Auken & Zellner, separated size from weight in the FARS database), the National Highway Traffic Safety Administration and the National Academies accepted this conclusion. Lighter but stronger materials like carbon-fiber composites, in structures designed to exploit their properties, can absorb 6–12 times more energy per pound than steel, decoupling size from weight. Then autos can be made big (hence safer and more comfortable) without also making them heavy and inefficient.

2. USING US-REGEN TO MODEL EV ADOPTION AND IMPLICATIONS FOR CUSTOMERS, THE GRID, AND ENERGY SYSTEM

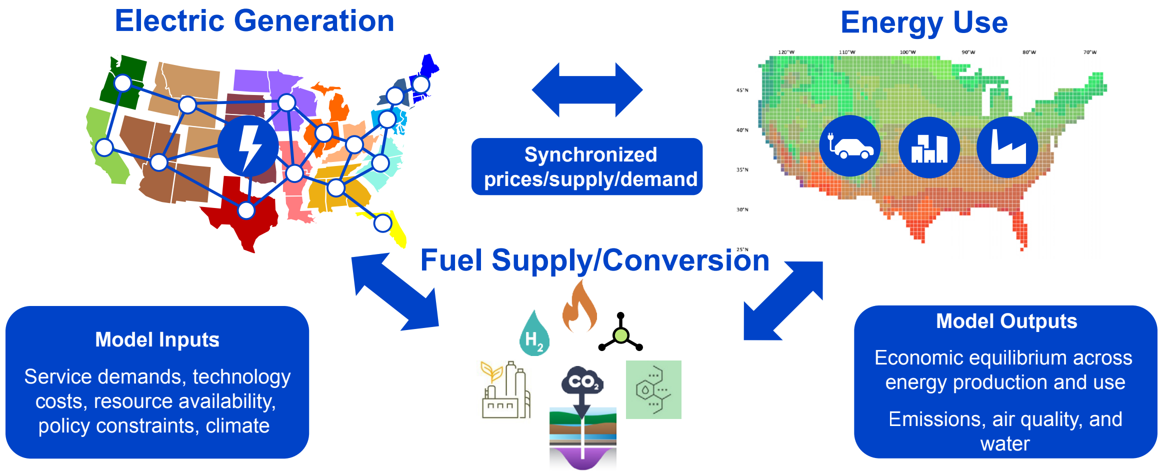

Figure 3. Overview of US-REGEN Energy-Economy System Model.

The study applies EPRI's US-REGEN model[21] (Figure 3) to provide initial estimates of "the size of the prize" potentially available by realizing these efficiency gains over the decades ahead. US-REGEN is a regional model of the U.S. energy system, which includes detailed models of end-use demand and the power grid and charging infrastructures needed to meet these demands. The model has been used over the past 15 years to assess consumer energy choices and optimal grid/energy system buildout under a wide range of policy and technology scenarios.[22] Specific to the vehicle modeling, US-REGEN considers different consumer types (e.g., urban/rural, different driving patterns) and weather (e.g., the impact of daily temperatures on battery and cabin heating/cooling efficiency) to derive real-world vehicle efficiencies. The model estimates purchase shares of BEVs versus ICEVs based on the regional economics, including delivered electricity and fuel prices.

The analysis in this study was performed in the context of an economy-wide, net-zero future target where there are increasing demands on the electric sector to decarbonize while electrifying large portions of transportation, buildings, and industry, and to potentially produce clean fuels. Non-electric energy activities are also decarbonizing through a combination of alternative fuels, carbon capture, and carbon removals from the atmosphere. Efficiency improvements across all sectors of the economy play an important role in reducing the scale of the energy system despite growing service demands and economic output.

Key features of US-REGEN for this analysis include:

- A detailed end-use model that projects the pace of vehicle adoption—based on cost, performance, miles driven, and other factors—and the implications of vehicle operation and charging needs across 16 different regions. Daily temperature profiles are used for each region to examine the real-world implications of temperature variation for vehicle battery and auxiliary systems efficiency, which are important for measuring EV customer costs.[23]
- The economy-wide focus, which places transportation electrification demands in the context of a decarbonizing grid alongside the emerging pressures of decarbonizing buildings and industry.
- The detailed examination of least-cost approaches to building out the grid to meet new loads, matching supply, demand, and storage on an hourly basis.
- The internal estimation of future fuel and electricity prices to reflect fuel demand and investments in grid buildout. Reference fuel prices are calibrated to recent EIA Annual Energy Outlook scenarios.

21 The version of the model used for this study was adapted from the version documented at https://us-regen-docs.epri.com/. For this study, the on-road vehicle modules were updated to provide a more-detailed representation of vehicle efficiency improvements. For example, this version includes a range of scenarios for efficiency improvements over time across vehicle classes. It also includes additional granularity for auxiliary and battery conditioning loads and charging infrastructure requirements.

22 https://esca.epri.com/Decarbonization-Pathways-and-Impacts.html lists many of the publicly available US-REGEN analyses.

23 See Appendix A Figure A-3 for assumptions about the cabin and battery sensitivity to temperature. Maintenance costs are also assumed to be significantly lower for BEVs, with savings varying by vehicle class.

3. EV EFFICIENCY ASSUMPTIONS AND SCENARIO STRUCTURE

Central to this analysis was the development of advanced but realistic assumptions about EV efficiency improvements for seven classes of vehicles covering the majority of on-road transportation: passenger cars, passenger SUVs, pickup trucks, and heavier trucks in Classes 2b, 3, 4–6, and 7–8 (e.g., 18-wheel combination trucks).

To quantify the potential for vehicle efficiency advances, a useful benchmark is the Mercedes Benz EQXX full-sized luxury concept car introduced in January 2022.

EQXX uses five key approaches to improve efficiency relative to a current, high-efficiency car. It reportedly reduced electricity use per mile by these amounts and methods:[24]

- **- 20% by reducing tire rolling resistance** through use of specially designed tires.[25]
- **-18% by improving powertrain efficiency** (to 95% battery-to-wheels) and **battery roundtrip efficiency** (the fraction of energy put into storage that can be retrieved from storage).
- **-16% by reducing vehicle weight** through selective use of lightweight materials (though still mostly steel) and smaller battery packs.
- **-8% by reducing aerodynamic drag coefficient** (to 0.17) through closer attention to styling, wheel wells, and vehicle rear geometry.
- **-6% by reducing frontal area** with smarter packaging, reducing width by setting front as well as rear wheels completely flush with the sides.

The combined effect of these modeled improvements for a 2050 high-efficiency car was a doubling of efficiency, from around 4 miles per kWh to 8 miles per kWh. In demonstration runs in 2022, the EQXX achieved 7.5 miles per kWh over a 751-mile route.[26] Elements of the EQXX design will begin appearing in production vehicles in 2024. While automakers face many challenges in shifting production from ICEVs to BEVs, technical assessments supported by conversations with several of these companies suggested that they would not need to dramatically alter their planning cycles or manufacturing processes to adopt these measures. In many cases, the technologies and supply chains already exist and are at or near viability at scale. Near-term pressures to improve vehicle range, reduce operating costs, and integrate other features that customers want provide added incentives to invest in technologies that improve vehicle efficiency.

Using the EQXX efficiency strategies as a starting point,[27] Oberon Insights (a strategic consultancy in mobility and powertrain) developed four vehicle efficiency scenarios for each vehicle class. The four scenarios—*Current* (i.e., MY 2023 technology), *Improved* (improvements consistent with recent trends), *Advanced*, and *Advanced+ Lightweighting*—are described in Table 1. They include improvements both in BEVs and in ICEVs.

Specific technical assumptions for the light-duty electric cars are detailed in Table 2 with 2050 real-world efficiencies ranging from 106 mpge in the *Current* technology scenario to 277 mpge in the *Advanced + Lightweighting* scenario.

24 A “current high efficiency car” was assumed to achieve 250 Wh/mile = 4 mile/kWh = 135 mpge. From Figure 1, this is slightly more efficient than a Tesla *Model 3*.

25 Bridgestone measured the rolling resistance reduction of 20% relative to other tires, independent of the vehicle. It’s described at: https://press.bridgestone-emia.com/bridgestone-develops-hyper-efficient-tyre-for-the-mercedes-benz-vision-eqxx/.

26 https://www.topgear.com/car-reviews/eqxx/first-drive

27 This study did not consider reductions in vehicle frontal area. The cabin-comfort analysis was based only on outdoor temperature. It did not consider other variables like humidity or air movement, and didn’t consider potential superefficient methods like those described by A.B. Lovins, “Hot cars, cool bodies, no air conditioners?,” *SAE J. STEEP* 4(1):149–153, 2023.

Table 1. Summary of Vehicle Efficiency Scenarios

	BEV Assumptions	ICEV Assumptions
Current	No efficiency improvements relative to today's new vintage average	LD adopts hybrid drivetrains MD/HD no improvements
Improved	Moderate improvements to drag, tire friction, powertrain efficiency, higher battery density	Moderate improvements to drag, tire friction, powertrain efficiency; MD/HD adopts hybrid drivetrains
Advanced	Significant improvements to drag, tire friction, powertrain efficiency, moderate reduction in GVWR from high-strength steel and higher battery density	Significant improvements to drag, tire friction, powertrain efficiency, moderate reduction in GVWR from high-strength steel
Advanced + Lightweighting	Significant improvements to drag, tire friction, powertrain efficiency, significant reduction in GVWR from carbon fiber and higher battery density	Significant improvements to drag, tire friction, powertrain efficiency, significant reduction in GVWR from carbon fiber

Table 2. Specific BEV Efficiency Assumptions for Light-Duty Passenger Cars

	Frozen (Current & 2050)	Reference (2050)	Advanced (2050)	Advanced + LW (2050)
Powertrain Efficiency *motor* *battery*	84% 90%	90% 90%	95% 95%	95% 95%
Coefficient of drag	0.28	0.23	0.17	0.17
Tire resistance	1.0%	0.75%	0.5%	0.5%
Heating/cooling auxiliary load (Wh/mile @ 0F, 100F)	340 / 67	222 / 49	164 / 36	164 / 36
Battery Density (Wh/kg)	171	277	277	277
Vehicle mass (lbs) *glider* *+battery (@ 300-mile range)*	2,700 4,104	2,700 3,485	2,508 3,076	1,491 1,952
Vehicle Efficiency ***mpg-e*** *(real-world @ 68F)* ***Wh/mile***	*106* *317*	*150* *226*	*242* *139*	*277* *121*

Notes: Coefficient of drag is a measure of the aerodynamic resistance of the vehicle's frontal area. Tire resistance refers to the rolling resistance coefficient, a measure of the friction created by the tire and the road. See Appendix Figure A-3 for more details on heating and cooling auxiliary loads

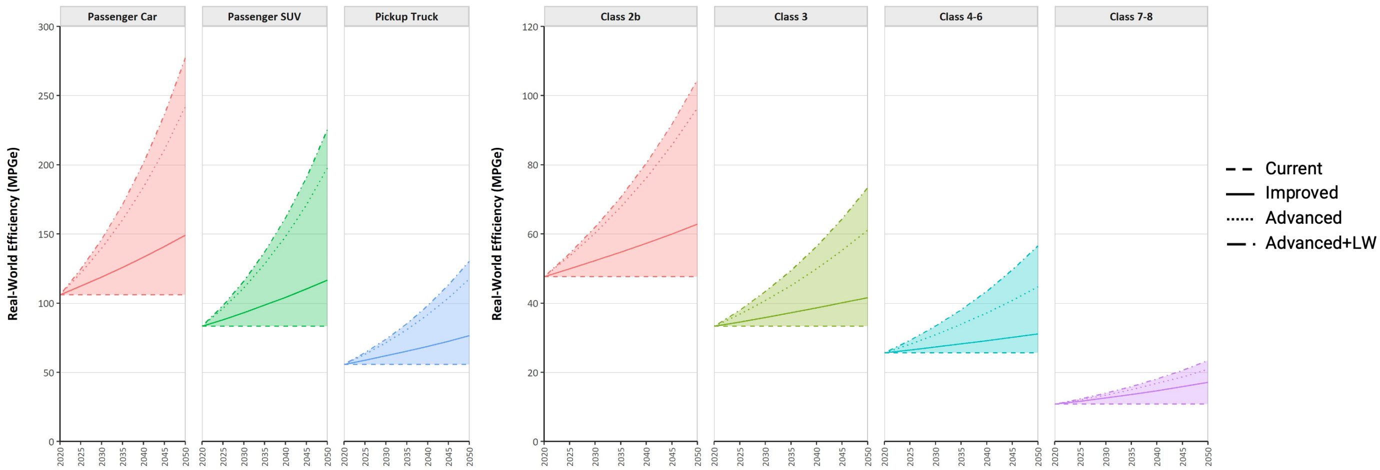

Figure 4. **BEV Efficiency Assumptions Across Vehicle Classes in US-REGEN**. Figure shows projected real-world efficiency (at 68°F, i.e. before temperature impacts) by scenario for new vintage vehicles across light-duty classes (lefthand panel) and medium- and heavy-duty truck classes (righthand panel). Figure A-1 in Appendix A shows projected real-world efficiency by scenario for ICEVs.

Overall vehicle efficiency is assumed to improve steadily over time until it achieves the 2050 assumed target levels. Figure 4 provides an overview of the estimated real-world efficiency improvements over time for new vintage electric vehicles. The fleet average efficiency of all vehicles evolves more slowly as a function of stock turnover.[28]

To simplify comparisons, the driving range is held constant across vehicle efficiency scenarios.[29] Therefore, the benefits from efficiency gains are seen mainly through reductions in grid and charging infrastructure needs and consumer energy bills. In reality, the benefits of vehicle efficiency improvements could be realized in many ways, driven by consumer preferences and system constraints. For example, increased efficiency could enable longer range for the same size battery pack.[30] In this study, the implication of holding range constant is that improved efficiency translates into a smaller battery pack. Moreover, the increased cost of more advanced components to achieve efficiency gains is assumed to be offset by decreased battery weight/size and other savings,[31] leaving the purchase price unchanged.[32] Vehicle cost assumptions for light-duty vehicle classes are shown in Figure 5. See Appendix A, Figure A-2 for cost assumptions for medium- and heavy-duty classes.

28 US-REGEN explicitly models capital stock turnover for each vehicle class and type. To highlight the difference between new vehicle sales and the fleet, consider that there are 280 million registered on-road vehicles (cars, SUVs, trucks, buses) in the U.S. today and new LDV sales have reached about 17 million annually. Even at the U.S. target for 2030 of BEVs' becoming half of new car sales, that is adding only 8.5 million new BEVs to the overall fleet each year. Unless accelerated, fleet turnover, averaging ~14 years, dilutes the effect of new autos entering the fleet. Data source: Energy.gov.

29 See Appendix A, Table A-1 for driving range assumptions for each vehicle class.

30 Additionally, faster per-mile charging could reduce the number of public charging points needed to service a fixed number of vehicles, efficiency gains could provide more time flexibility in charging, speed of charging in minutes/mile could be maintained at lower voltages (potentially reducing needed grid capacity investments and increasing the viability of 120V charging at home for some), or air quality and GHG reductions could be prioritized.

31 The costs of the efficiency measures modeled were not examined in detail. This assumption is principally important for the calculation of consumer savings. Substantial vehicle price increases could also impact adoption rates and stock turnover.

32 For the fourth scenario, which requires carbon fiber construction for many components, there is empirical evidence that the increased material costs of carbon fiber construction can be offset by simpler automaking and smaller batteries. This appears to be the case for the 2013–22 BMW *i3*, which profitably sold a quarter-million copies, and was Germany's most popular EV before the Tesla *Model 3* entered that market. Details are in A.B. Lovins, "Reframing automotive fuel efficiency," *SAE J. STEEP* 1(1):59-84, 2020.

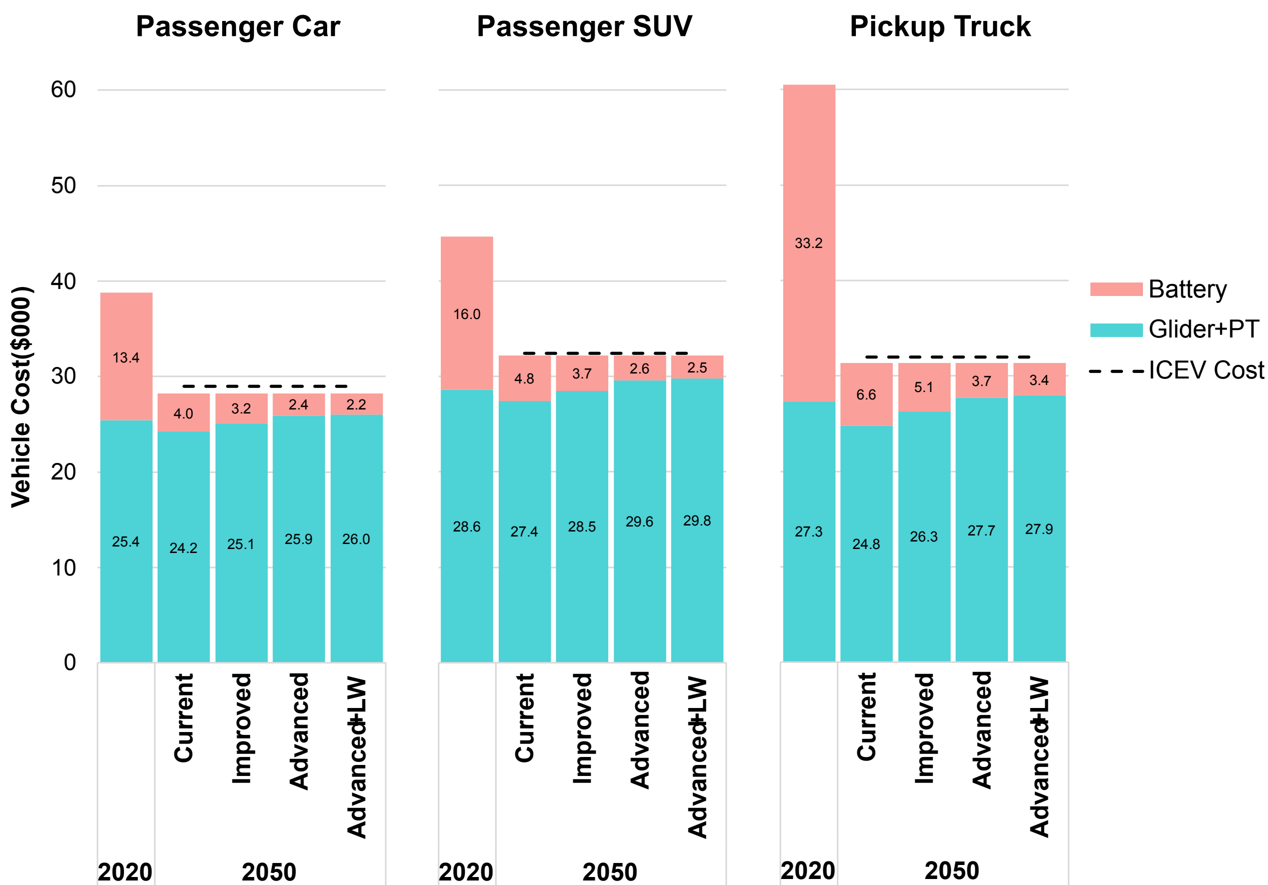

Figure 5. **Light-Duty BEV Cost Assumptions in US-REGEN**. Figure shows projected cost in real $2022 for a representative vehicle with 300-mile range, with battery pack costs broken out from other costs, including the glider and non-battery components of the powertrain (PT). The reduction in battery cost over time reflects declining unit cost (isolated in comparison between 2020 and 2050 *Current* scenario) as well as declining battery size due to efficiency improvements and improved battery density in 2050 *Improved* and *Advanced* scenarios. Vehicle costs are assumed to be the same across efficiency scenarios by construction, i.e., reduced battery cost is assumed to be exactly offset by increased glider cost. Total cost of a comparable ICEV is shown for comparison.

4. KEY STUDY RESULTS

4.1 Vehicle Adoption

To understand the impacts of vehicle efficiency gains on the overall demand for electricity and charging infrastructure, it is necessary to model the evolution of the vehicle stock for each scenario. BEVs are projected to provide 80–90 percent of U.S. on-road service demand by 2050 across all four scenarios (Figure 6). This is largely driven by cost and performance assumptions that make most classes of BEVs cheaper to own and operate than ICEVs by 2030, independent of the efficiency scenario. Efficiency gains do not noticeably affect the projected adoption rate of BEVs. However, the reduced battery pack size per vehicle does imply lower demands for battery materials and manufacturing capacity. For example, by 2050, the *Advanced + Lightweighting* scenario compared to the *Current* scenario requires around 1,580 GWh/year less battery capacity output (i.e., new vintage battery capacity across all on-road vehicle classes). This implies roughly 40 fewer gigafactories (each producing 40 GWh of batteries per year) and roughly 1 million tonnes less annual U.S. demand for lithium carbonate equivalent (for comparison, 732,000 tonnes were produced globally in 2022). Relieving potential battery supply chain constraints is viewed as a major advantage by automakers.

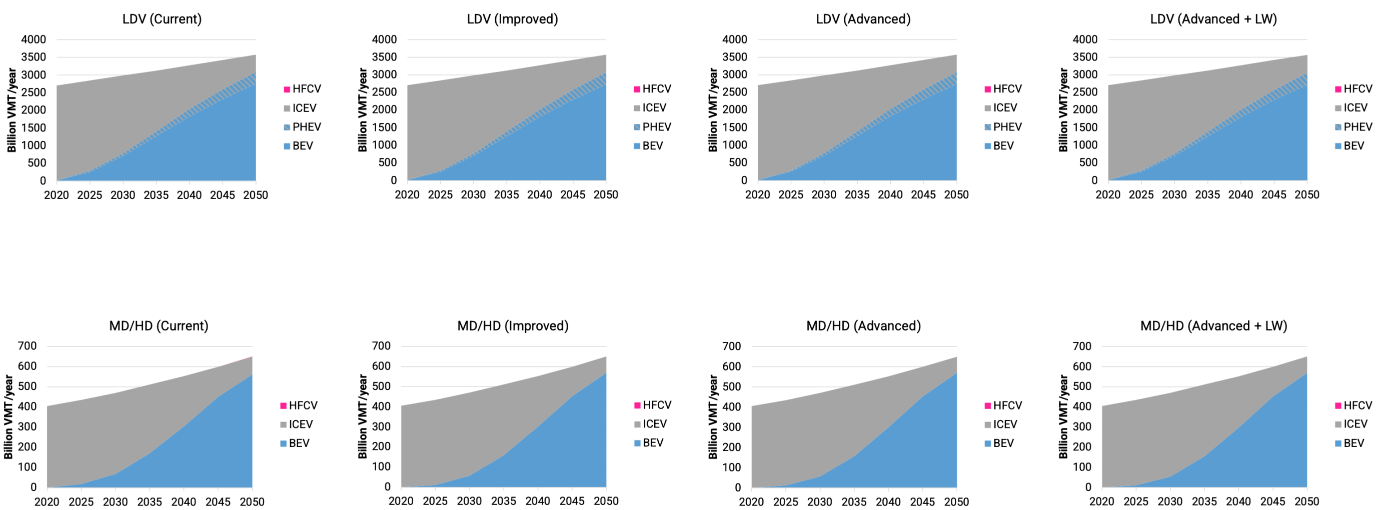

Figure 6. **U.S. Total Vehicle Miles Traveled (VMT) by Technology Type Across Scenarios**. Top-row panels shows aggregate VMT for light-duty classes, bottom-row panels show aggregate VMT for medium- and heavy-duty classes. Electric vehicles (BEVs and PHEVs) provide 80-90% of on-road service demand by 2050. Adoption of BEVs is nearly identical across efficiency scenarios.

4.2. Consumer Expenditures for On-Road Transportation

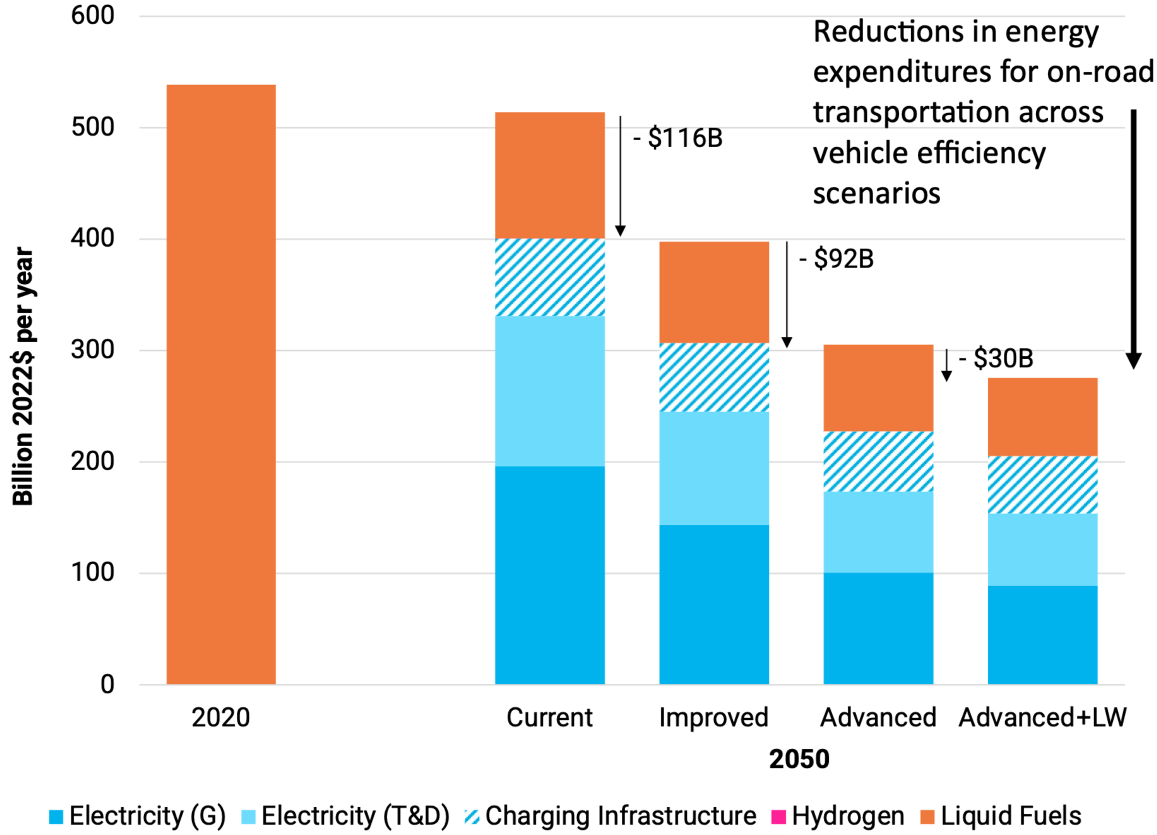

Figure 7. U.S. Total Annual Energy Expenditures for On-Road Transportation. Expenditures on delivered energy for cars and trucks are reduced as assumed vehicle efficiency increases. Delivered electricity costs are broken into generation (G) and transmission and distribution (T&D) components, with charging infrastructure costs shown separately. Comparing the *Advanced+Lightweighting* scenario to the *Current* scenario, total annual energy expenditure savings from EV efficiency improvements are $238B, including $195B on electricity and charging infrastructure.

With vehicle purchase price assumed to be fixed across efficiency scenarios, the biggest impacts for consumers come from saved energy costs. Today, electric passenger cars have an average real-world efficiency of 106 mpge.[33] This could jump to 250 mpge or more by 2050, as in the *Advanced + Lightweighting* scenario, significantly reducing electricity consumption. When similar approaches are applied to ICEV passenger vehicles coupled with strong hybridization, their current 28 mpg average could improve to 92 mpg. The assumed improvements apply broadly across all segments, including larger personal light-duty vehicles (LDVs) and fleet medium- and heavy-duty vehicles.[34] These assumed efficiency improvements significantly reduce the total U.S. energy expenditures for on-road transportation by 2050 as shown in Figure 7.

In 2020, U.S. consumers spent over $500 billion on gasoline, diesel, and other fuels[35] to power on-road transportation, but very little on electricity for that purpose. For the *Current* technology scenario, total expenditures in 2050 are projected to remain about the same as in 2020, despite service demand increases due to the cost-savings of shifting from liquid fuels to electricity.[36] But with advances in vehicle efficiency, annual energy expenditures are reduced by up to $238B, including annual electricity savings of around $195B. As noted earlier, consumer benefits of efficiency gains could accrue in many additional ways that we did not quantify. With significantly lower charging time per mile, for

33 106 mpge is estimated real-world efficiency (before temperature impacts) for current new vintage light-duty passenger cars in US-REGEN. It is based on vehicle modeling and observed rated efficiencies.

34 Efficiency time paths assumed for all vehicle classes are summarized in Figure 4.

35 Includes other liquid fuels and compressed natural gas.

36 Electricity costs are subdivided into three components: 1) the cost of electricity generation, 2) the grid cost for delivering the electricity to a charging site, and 3) the charging infrastructure.

example, charging from standard household outlets could be sufficient on most days for more households, creating space on electrical panels for other home electrification actions, potentially avoiding costly home electrical upgrades, and reducing the need for electric distribution upgrades.

Cost savings on a per vehicle basis depend on vehicle class, region, and duty cycle. For example, considering a light-duty passenger car with 12,000 miles per year in the Southeast, annual electricity expenditure for BEV charging is reduced by $369 in the *Advanced + Lightweighting* scenario compared to the *Current* scenario. Although charging costs represent a relatively small share of total ownership costs for EVs, these savings are nonetheless significant and improve affordability broadly across customer classes.

4.3. EV Efficiency Impacts on Electricity Demand

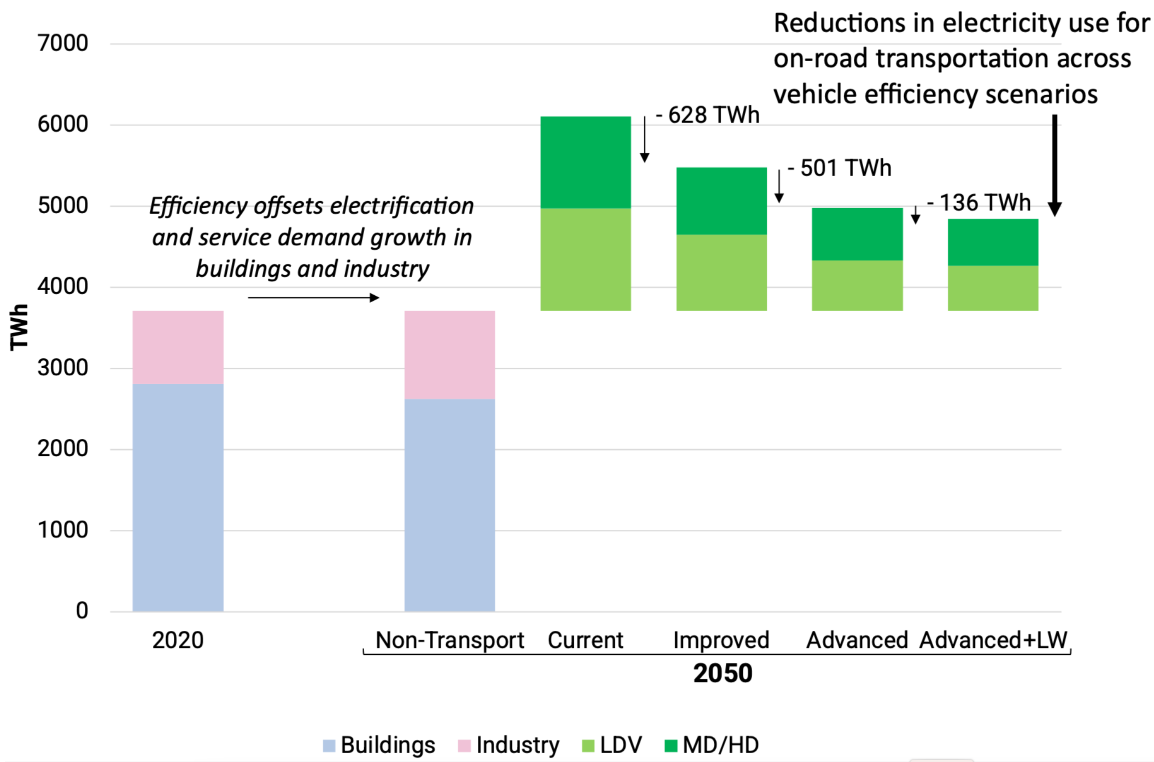

Figure 8. **U.S. Total Annual Electricity Demand by End-Use Sector**. Efficiency gains are projected to largely offset demand growth in buildings and industry, reducing the overall impact of electrification on the grid. Electrification of on-road transportation leads to large new loads (shown in green). With EV efficiency improvements, projected 2050 electricity demand is reduced by 1,265 TWh in the *Advanced+Lightweighting* scenario compared to the *Current* scenario, cutting electricity use for vehicles in half and reducing total demand by around 20%.

EV efficiency improvements reduce overall demand on the grid. Analysis using EPRI's US-REGEN model suggested that these vehicle efficiency improvements could substantially reduce investment needs for grid buildout. Relative to the *Current* technology scenario, the *Advanced + lightweighting* scenario reduces vehicle electricity use by 53 percent in 2050, declining from 2400 TWh/year to approximately to 1136 TWh/year (see Figure 8). For utilities, this reduced demand shrinks how much generation, transmission, and distribution infrastructure they will need to install reducing projected expenditures by as much as $170 billion annually.

Additional highlights include:

- EV efficiency improvements are projected to reduce total U.S. delivered electricity demand in 2050 by 1265 TWh—more than a 20% reduction, from over 6,000 TWh to under 5,000 TWh.
- LDVs and MD/HD vehicles contribute roughly equally to the savings as service demands for MD/HD vehicles are assumed to grow faster than demands for LDVs.
- The reduced generation requirement is important both as an endpoint and in lessening the rate at which the grid needs to expand to meet demand.[37]
- Efficiency is also critically important in buildings and industry as they electrify. The shift to electric space, water, and process heat is largely offset by more efficient electricity use in current applications (e.g., appliances, heating, cooling).

Anticipating and planning for these efficiency gains is important at the system level, but also at the local level, where vehicle efficiency gains (for a vehicle fleet, for example) can lower the need for distribution and local transmission buildout.

37 All scenarios assumed hourly charging patterns based on modeling a mixture of charging behaviors. The rate of grid buildout, which is often governed primarily by peak rather than average demand could be slowed somewhat by significant participation in dynamically managed charging programs or by simpler and more distributed innovations, such as chargers whose charging rate depends on grid frequency.

4.4 U.S. Generation Mix Across Scenarios

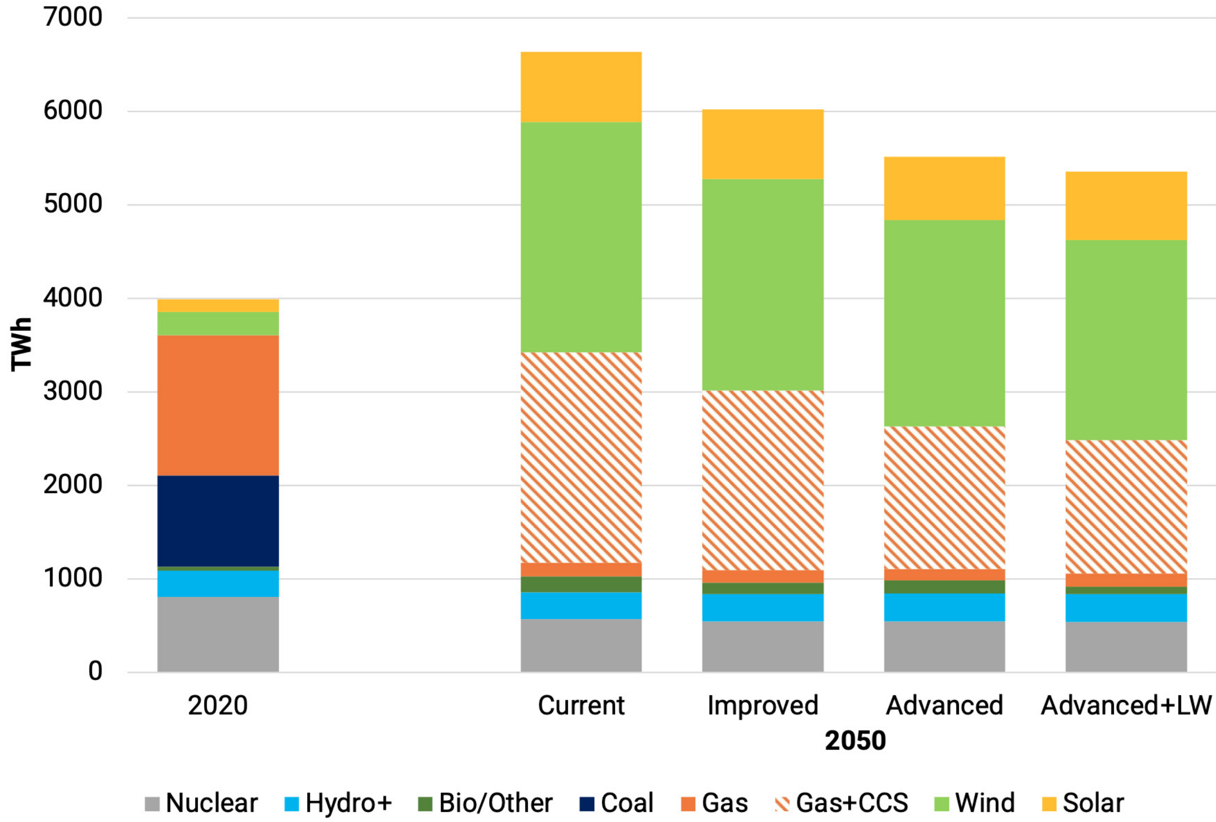

Figure 9. U.S. Total Electric Generation by Technology in 2050 Across Scenarios. All scenarios include IRA incentives and achieve economy-wide net-zero emissions by 2050. In addition to reduced generation from EV efficiency improvements, installed capacity is lower. Comparing the *Advanced+Lightweighting* scenario to the *Current* scenario, gas with CCS is 140 GW lower, conventional gas capacity is 140 GW lower, and coincident peak load is reduced by roughly 280 GW.

The vehicle efficiency improvements were assessed against the backdrop of a scenario where the economy reaches net-zero CO_2 emission by 2050. With a 1,275 TWh reduction in annual demand from improved BEV efficiency, substantially less power generation is needed. Figure 9 communicates both the reduction in generation and the technologies that are most affected by this reduction. Wind and gas with carbon capture and storage, the two largest sources of low-carbon electricity, make up over 90% of the generation reductions projected as demand is reduced. With lower demand in the higher vehicle efficiency scenarios, the generation system has a higher share of renewable energy. In all cases, there remains a role for conventional natural gas peaking capacity (operated rarely, providing around 0.5% of generation across the year) and storage to help balance hourly loads and supplies.[38]

38 Electric sector emissions decline to 3% of their 2005 level by 2050 (i.e., a 97% reduction) with the remaining emissions offset by carbon removals from the atmosphere using bioenergy with CCS.

4.5 Implications of Slower Growth in Vehicle Miles Traveled (VMT) for Light-duty Vehicles

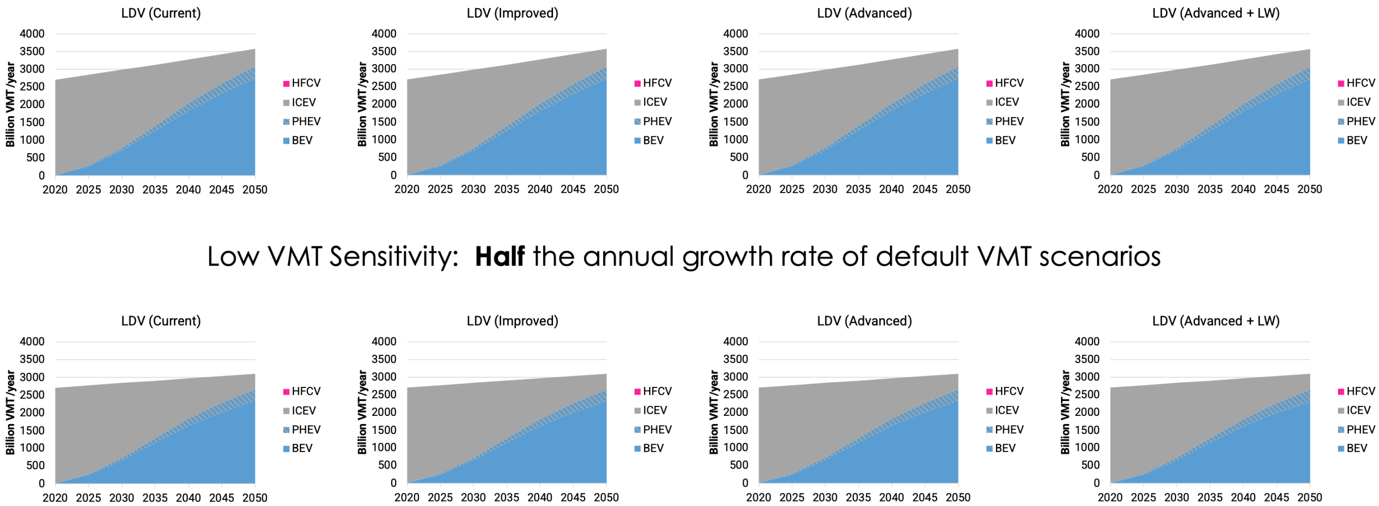

Figure 10. **U.S. Total Vehicle Miles Traveled (VMT) in Reference versus Low-VMT Sensitivity Cases**. The top-row panels show light-duty VMT by technology type in the reference versions of each of the efficiency scenarios, as shown in Figure 6. The bottom-row panels show the evolution of light-duty VMT with half the assumed growth rate of the reference scenarios. While the share of EVs is similar, the lower total demand for mobility leads to fewer vehicles and fewer VMT powered by electricity.

In the scenarios presented thus far, national aggregate VMT are assumed to increase significantly from 2020 to 2050 driven by population and economic growth.[39] However, an evolution to more walkable communities and shifts to less energy-intensive transportation (e.g., public transit, e-bikes) or to virtual transportation could slow VMT growth. To gain a perspective on the implications of slower VMT growth, a sensitivity analysis was performed that assumed LDV VMTs grow at half the rate assumed in the other scenarios (Figure 10). Note that VMT for medium- and heavy-duty vehicles were not altered.

Slower growth in LDV VMT further reduces the requirements to expand electricity infrastructure. Overall electricity demand is reduced from 6109 TWh to 5902 TWh in the *Current* technology scenario and from 4891 TWh to 4761 TWh in the *Advanced + Lightweighting* scenario (Figure 11), providing savings to the consumer and lessening pressure on rapid electric grid expansion.

The combined effects of lower VMT and *Advanced + lightweighting* reduces electricity demand from 6109 TWh to 4761 TWh, a 22% reduction relative to the *Current* scenario with reference VMT growth.

39 Adapted from EIA Annual Energy Outlook 2021.

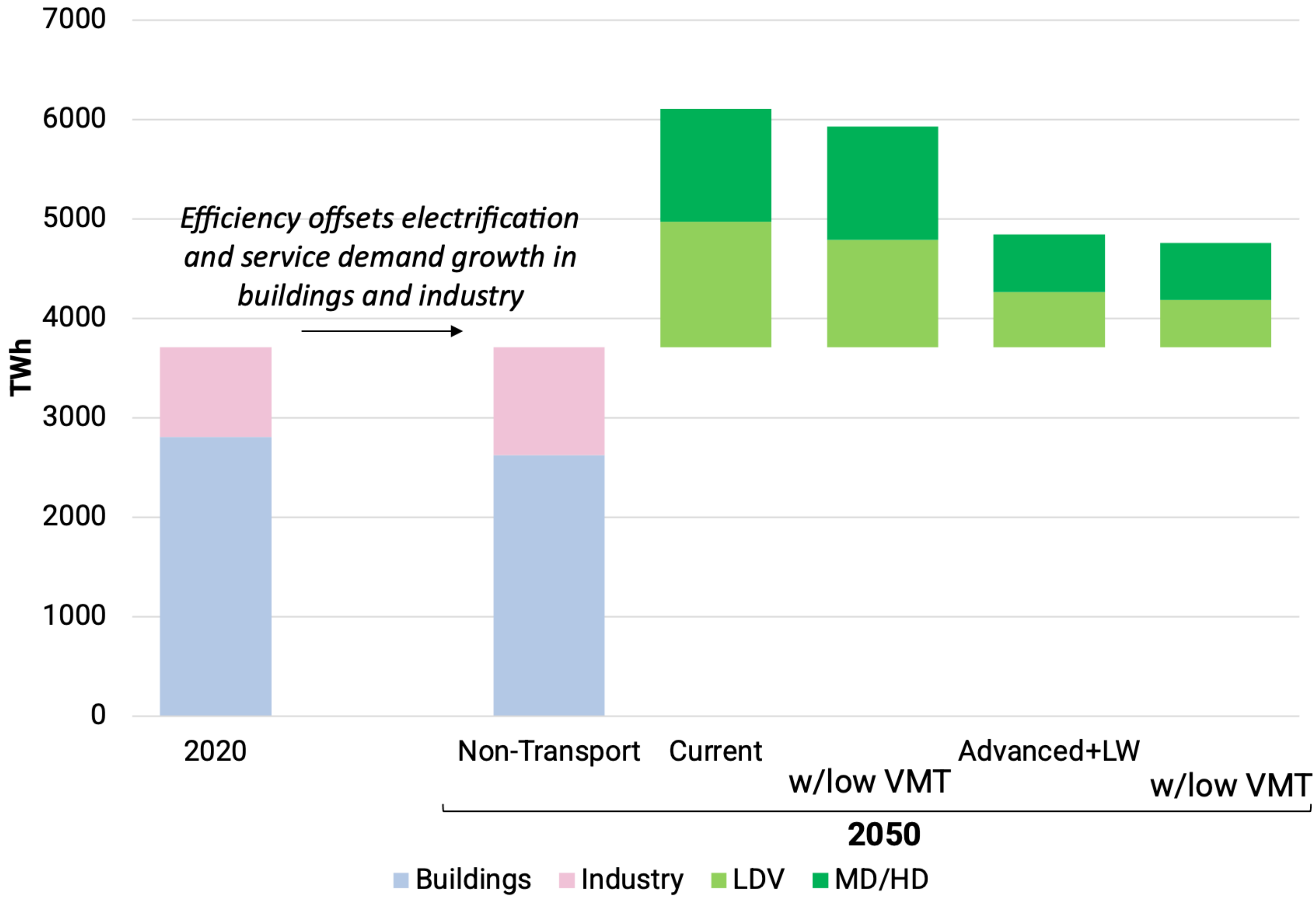

Figure 11. **U.S. Total Electricity Demand, Low VMT Sensitivity Cases**. The figure shows electricity demand by end-use sector with transportation sector shown for alternative EV efficiency and VMT scenarios. The reference versus low VMT sensitivity is shown for the *Current* and *Advanced+Lightweighting* EV efficiency scenarios. When EV efficiency improvements are combined with slower VMT growth, electricity demand becomes lower, with savings of 1,349 TWh in the *Advanced+Lightweighting* scenario with low VMT compared to the *Current* scenario with reference VMT.

5. CONCLUSIONS AND NEED FOR FURTHER STUDY

The potential savings from improving U.S. on-road transportation efficiency over the next three decades are substantial, totaling in the trillions of dollars (cumulatively), realized as reduced transportation costs for consumers. The efficiency gains reduce electricity demand by hundreds of terawatt-hours (annually) and reduce associated grid build-out, reducing peak demand by almost 300GW.

For consumers, lower cost of vehicle ownership (similar purchase price plus lower fuel costs) and lower home power demands together make electric mobility more accessible to all communities, assuming (and facilitating) a commitment to build out accessible charging infrastructure.

For the companies that are rapidly introducing new electric vehicles, efficiency gains create opportunities for vehicles with lower ownership cost and better performance. In addition, the improved battery technology should lessen supply chain concerns by reducing the quantity of raw materials needed to produce batteries.

For the electricity sector, it is important to project accurately the pace and amount of infrastructure needed to enable on-road transportation electrification. Plausible vehicle efficiency gains could change these demands substantially. Declining power demand (e.g., half the demand for a given fleet of vehicles) can help the grid keep pace with customer demand. In addition, society would reap further savings from less charging infrastructure (regardless of who provides it) to charge a given fleet of autos with a given range.

Additional work is needed in at least five key areas:

- Provide more detailed engineering analysis of the potential cost and gains from vehicle energy efficiency improvements.
- Deepen the dialogue with automakers and their suppliers regarding opportunities and obstacles to improve vehicle efficiencies along the more advanced paths analyzed here.
- Quantify supply chain benefits from efficiency improvements in terms of overall supply capacity for minerals, materials, and labor and the required rate of growth.
- Examine a broader set of potential benefits from vehicle efficiency gains. While the current study focuses on reduced energy expenditures and infrastructure build-out, there are many other ways to gain value from efficiency.
- In addition to economic and decarbonziation benefits, consider other environmental benefits from vehicle efficiency gains such as reduced particulate emissions from tire and brake wear.

APPENDIX A

This appendix includes additional details about model assumptions.

Table A-1. EV Range Assumptions by Vehicle Class and Type.

Vehicle Class	Vehicle Type	Assumed Range
Light-Duty (car, SUV, pickup, van)	PHEV	50
	BEV (Short-Range)	150
	BEV (Standard)	300
	BEV (Long-Range)	400
Class 2b (Commercial Truck)	BEV	150
Class 3 (Medium-Duty)	BEV	200
Class 4-6 (Medium-Duty)	BEV	200
Class 7-8 (Vocational, Local Freight)	BEV	300
Class 7-8 (Long-Haul Freight)	BEV	500
Bus (School, Transit, Inter-city)	BEV	300

Notes: Personal light-duty vehicles are modeled for a range of household types with varying driving intensity, which drives adoption of different range options. Fleet vehicles are modeled with less granularity and assume a single range option for each class, although real-world applications will likely exhibit variation in range requirements across fleets. Assumed nominal range is held constant over time and translated into a battery size for each vehicle class in each new vintage based on assumed vehicle efficiency.

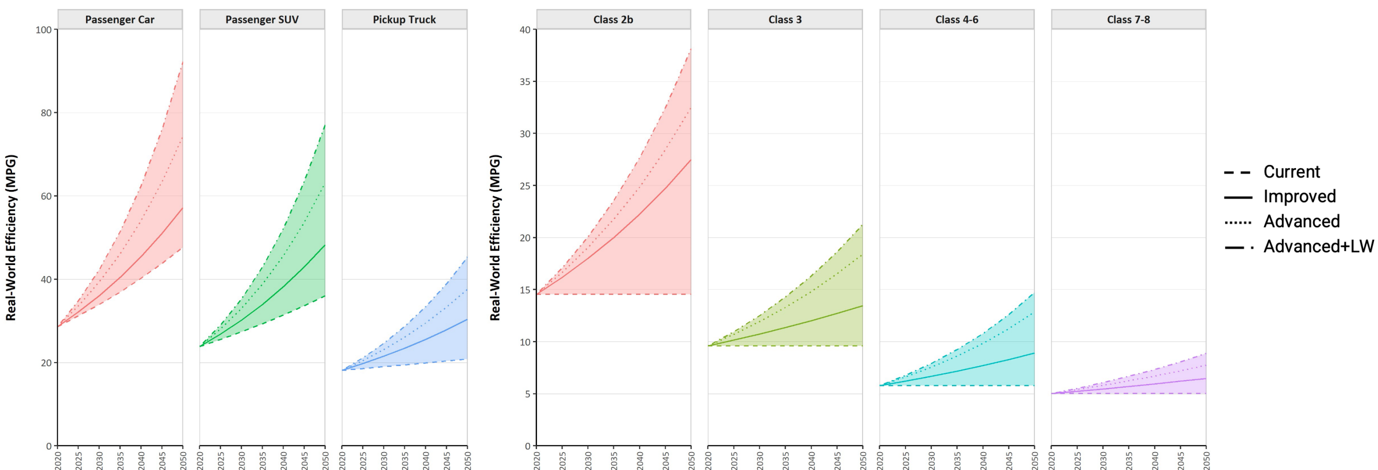

Figure A-1. ICEV Efficiency Assumptions Across Vehicle Classes in US-REGEN. Figure shows projected real-world efficiency by scenario for new vintage vehicles across light-duty classes (lefthand panel) and medium- and heavy-duty truck classes (righthand panel). Assumed improvements for light-duty classes over time in "Current" scenario reflect an increasing share of hybrid drivetrains in the new vintage ICEV stock.

Figure A-2. Medium- and Heavy-Duty BEV Cost Assumptions in US-REGEN. Figure shows projected cost in real $2022 for a representative vehicle in each class, with battery pack costs broken out from other costs, including the glider and non-battery components of the powertrain (PT). Battery pack costs are based on an assumed 150-mile range for Class 2b, 200 miles for Class 3-6, and 500 miles for Class 7-8, reflecting long-haul freight trucks (see Table A1). Total cost of a comparable ICEV is shown for comparison.

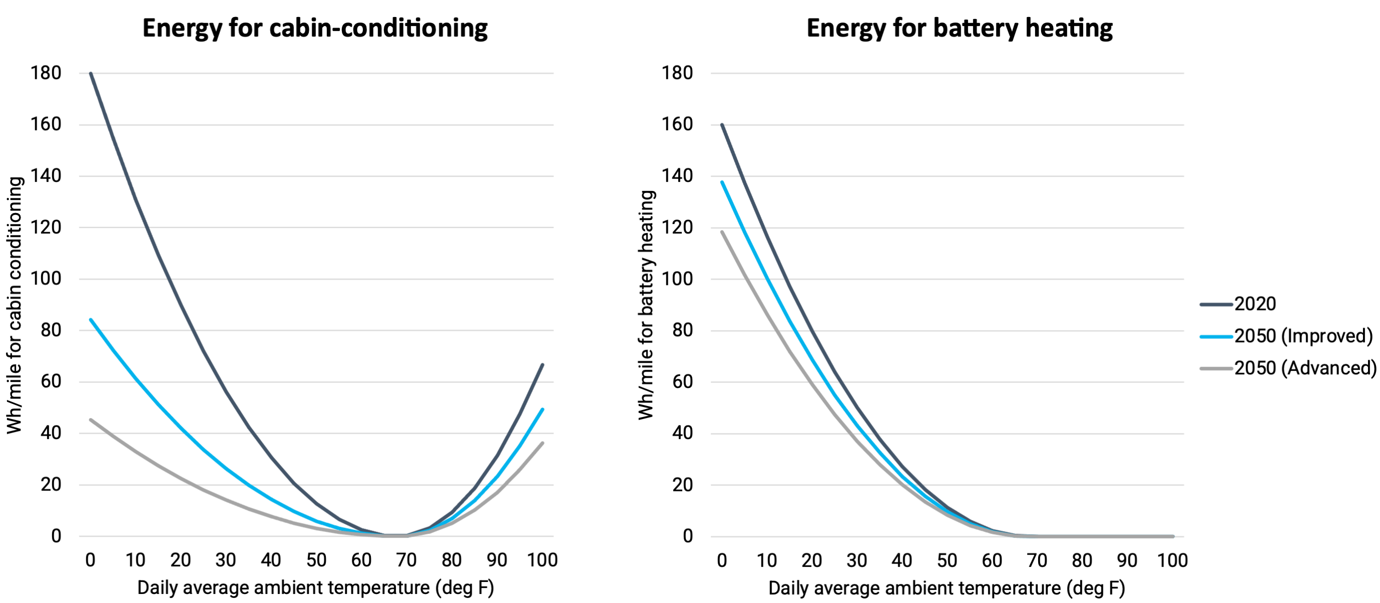

Figure A-3. BEV Heating and Cooling Auxiliary Load Assumptions in US-REGEN. Cabin-conditioning loads shown are based on a light-duty vehicle; these loads are assumed to be slightly higher for larger vehicles. Battery heating loads shown are based on a light-duty vehicle with 80 kWh battery and 30 driving miles per day. For other classes, these loads scale with battery size, and the translation to Wh/mile depends on duty cycle. Auxiliary loads are applied to BEV energy use in each region during the year based on daily average temperature. For regions with colder climates, BEV energy use per mile will be greater, and charging loads on colder days will be higher. Improvements are realized over time through the use of heat pumps and thermal management strategies.

Acknowledgement

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