GOLDMAN SCHOOL OF PUBLIC POLICY
UNIVERSITY OF CALIFORNIA BERKELEY

2035 THE REPORT APPENDICES

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TRANSPORTATION

PLUMMETING COSTS AND DRAMATIC IMPROVEMENTS IN BATTERIES CAN ACCELERATE OUR CLEAN TRANSPORTATION FUTURE

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This report is a technical appendix to the 2035 Report 2.0. The main 2035 Report 2.0 can be found here, with supporting documents available at 2035report.com.

The authors thank Moya Melody, Technical Writer/Editor, for her support on this report.

APPENDIX 1

CONTRIBUTIONS OF THIS STUDY TO THE LITERATURE

The 2035 transport report performs a deeper analysis of many of the issues identified in the studies described below.

Most of the studies reviewed here do not assume that all sales of light-duty vehicles (LDVs) can be electric by 2030 and of medium-duty vehicles (MDVs) and heavy-duty trucks (HDTs) by 2035 despite recent evolving indications that the above goals can be reached at both state and national levels. Most of the studies also assume high costs for the needed technologies; assumptions that appear to be outdated given the rapidly dropping prices for electric vehicles (EVs), lithium-ion batteries, and charging infrastructure. Assuming high costs for the technologies leads to overly conservative estimates of benefits (see for example the Princeton University and the Resources for the Future studies). None of the studies described below evaluate the clean power and charging infrastructure required to provide a 90% clean grid by 2035 combined with all vehicle sales being electric by 2030/35. Yet both those goals must be achieved to follow the only trajectory consistent with an emissions reduction scenario that limits global warming to 1.5ºC.

As this literature review shows, the 2035 report is unique in combining expansive techno-economic modeling of 100% electrification of LDVs and HDVs by 2030 and 2035 with a full suite of policy recommendations to achieve that goal and maximize its economic and environmental benefits.

LITERATURE REVIEW

This section highlights a few noteworthy studies that illustrate the approaches various national labs, universities, non-profits, and consulting firms have taken to forecast and analyze deployment of electric vehicles (EVs) at the national, international, and state levels.

Some common themes emerge from the literature we examined.

- Most studies present conservative projections of deployment of electric LDVs by 2030.
- Electrification of HDTs has not been analyzed in depth—current studies forecast reaching a 100% target sometime between 2040 and 2050.

- The reports described below identify market trends that we use as a basis for our analysis. Costs of EV cars, lithium-ion batteries, and charging infrastructure continue to follow a positive learning curve, with prices dropping rapidly as goods and materials are produced at scale.

NATIONAL STUDIES

We found the following national studies to be of interest for our analysis.

Brattle Group (2020)

Getting to 20 Million EVs by 2030: Opportunities for the Electricity Industry in Preparing for an EV Future

This presentation by the Brattle Group assesses what investments in the power sector are needed to facilitate the deployment of what they predict to be 20 million EVs by 2030. They focus on charging infrastructure. Given that 20 million EVs will add about 60-95 TWh of annual electric demand and 10-20 GW of peak load to the national system, they find that $75 billion to $125 billion is needed to enable the electric power sector to meet EV energy demand. Those investments will be needed throughout the supply chain—$30 billion to $50 billion for generation and storage, $15 to $125 billion for transmission and distribution upgrades, and $30 to $50 billion for EV chargers and customer-side infrastructure. The report also finds that total fuel savings of $12 billion/year relative to internal combustion engine (ICE) vehicles translates to an estimated societal payback of 8.6 years to recover the costs of investments in the electricity sector. This number declines to 7.2 years when adding the benefits of reducing greenhouse gas (GHG) emissions. Finally, the report notes that installation of public EV chargers must increase by 40% annually to reach the 1-2 million public chargers needed by 2030. Their methodology for obtaining their 10-35 million EVs aggregates several projections, including some by the Electric Power Research Institute, Boston Consulting Group, Bloomberg New Energy Finance (BNEF), Edison Electric Institute (EEI), Wood Mac, and Annual Energy Outlook (AEO).

Center for American Progress (2020)

Electric Vehicles Should Be a Win for American Workers: How Federal Policies To Expand Electric Vehicle Production Can Ensure a Good Jobs Future for the United States

This paper showcases the ways in which the EV industry can revitalize America’s manufacturing sector, arguing that U.S. investment in EVs is lagging, threatening the country’s ability to reach its climate goals and reducing the competitiveness of its domestic auto industry. The authors recommend that policymakers adopt a consistent definition of what constitutes a good clean energy job, including standards to provide that all associated workers earn fair wages and high-quality benefits, can access such jobs no matter who they are or where they come from, and have a fair shot at joining a union. To make those protections real, the authors say that policymakers should attach the labor standards to government investments in boosting consumer demand for EVs, spur manufacturers to invest in domestic manufacture of EVs and critical EV components, such as batteries, and build a nationwide network of electric charging stations.

Consumer Reports (2020)

Electric Vehicle Ownership Costs: Today's Electric Vehicles Offer Big Savings for Consumers

Using current data on EV depreciation rates, maintenance and repair costs, and average vehicle prices, this study assesses the costs of EV ownership and savings compared to owning an ICE car. They find that, when adjusted for federal purchase incentives, EV values are expected to depreciate at the same rate as ICE vehicles in the same class during the first five years of ownership. Drivers, however, save 50% in repair and maintenance costs when averaged over a typical vehicle lifetime. EVs overall were estimated to save consumers about 60% on fuel costs compared with the average ICE vehicle in the same class. For all EV models analyzed, the lifetime ownership costs were between $6,000 and $10,000 lower than for all comparable ICE vehicles.

Department of Energy (2019)

Summary Report on EVs at Scale and the U.S. Electric Power System

This report was prepared by the Grid Integration Tech Team and Integrated Systems Analysis Tech Team of the U.S. DRIVE partnership. The authors examine a range of EV market penetration scenarios (low, medium, and high), along with associated changes to energy generation and capacity of the U.S. electric power system. The paper's summary conclusion is that, based on historical growth rates, sufficient energy generation and generation capacity will be available to support a growing EV fleet, even if EV market growth is high. The report's analysis utilized scenarios involving low, medium, and high market projections developed by EPRI: EV sales in 2030 at 320 thousand (2%), 2.2 million (12%), or 6.8 million (40%) of new vehicle sales. Those scenarios result in EVs representing 3 million (1%), 14 million (5%), or 40 million (15%) of the passenger vehicle fleet by 2030. The incremental generation capacity needed annually to support EV charging demand under the high scenario was projected to have a peak of 15 GW from 2035 to

2039. The medium scenario peak of 8.5 GW occurs from 2045 to 2049. The high scenario involves exceeding the historical average annual expansion in dispatchable capacity of 12 GW observed during the past decade.

Environmental Defense Fund (2021)

Clean Cars, Clean Air, Consumer Savings: 100% New Zero Emissions Vehicle Sales by 2035 **Will Deliver Extensive Economic, Health and Environmental Benefits to all Americans**

This report identifies the pathways to providing that all passenger vehicles sold are zero emission by 2035 and new medium and heavy-duty trucks are zero emission by 2040. The report has three key findings. By 2030, the buyer of a new EV will save $7,200 during the life of the car compared to an ICE vehicle. A new 2030 EV also will deliver $8,000 in societal benefits as a result of reduced particulate pollution and climate damage, effects that increase the total net benefits to more than $15,000 per vehicle. Those results are estimated to reduce GHG emissions by 600 million metric tons in 2040, roughly the annual climate emissions from Canada, and cumulatively eliminate more than 11.5 billion tons by 2050.

M.J. Bradley & Associates (2021)

Electric Vehicle Market Status–Update: Manufacturer Commitments to Future Electric Mobility in the U.S. and Worldwide

This paper describes the current status and projected growth of the U.S. electric vehicle industry and its products, including light-, medium-, and heavy-duty vehicles. The report finds that carmakers worldwide will spend more than $257 billion through 2030 to produce new electric models, investing more than $22 billion to open new or renovated plants in the United States. Those expected new and renovated plants will employ 24,000 people directly, adding to the almost 130,000 people the EV industry employs throughout the United States. The report provides other important information, including projections of EV market penetration between 2021 and 2023. The authors estimate that the number of electric vehicle models available to U.S. consumers will increase from 60 to 76 and will include SUVs and pick-up trucks. The report also projects that by 2030 the cost of electric car batteries will be as low as $61 per kilowatt-hour (kWh).

National Renewable Energy Laboratory (2018)

Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States

This analysis presents scenarios for adoption of electric end-use technologies in the contiguous U.S. energy system through 2050. The end uses considered for electrification include all on-road transport, most of the buildings sector, and parts of the industrial sector. The study scenarios indicate that the transport sector experiences the greatest transition toward electrification. Stock penetration of plug-in electric vehicles in the 2050 light-duty fleet is estimated to be about 11% in the base-case scenario and nearly 84% in the high scenario. The pervasive penetration in the high scenario is designed to include some plug-in electric vehicle sales beyond those assumed in many studies. This analysis estimates that by 2050 more than 240 million light-duty electric cars and trucks, 7 million medium- and heavy-duty electric trucks, and 80,000 electric transit buses will travel on U.S. roads. The study also finds that although electrification of vehicles potentially will increase demand for electricity, the rates of growth in compound annual electricity consumption, even under the high scenario, are less than long-term historical growth rates.

Princeton University (2020)

***Net-Zero America:* Potential Pathways, Infrastructure, and Impacts**

The Net-Zero America study describes a pathway for state and national action to meet the 2050 net-zero emissions target. The study argues that energy demand for transportation ultimately must be one-third to one-half of 2020 levels, an achievement requiring reductions in energy use for every mode of transport except aviation. The authors demonstrate that LDV energy use must decrease the most: given aggressive electrification, 17% of LDVs on the road will be electric by 2030 and 96% by 2040. With less aggressive electrification, the 2030 and 2050 shares are 6% and 61%, respectively. Their model assumes that electric LDVs will reach cost parity with ICE cars around 2030. In their scenario the fleet of HDVs makes achieves cost parity by 2050 because their 2030 costs will be relatively high compared to costs for LDVs. The study uses the Energy PATHWAYS model to construct scenarios, one specifying 5-year time steps for the electrification of transportation (as well as of buildings and water heating), and the other reflecting slower electrification. They use a detailed optimization model, RIO, to calculate the lowest-cost mix of supply-side and network infrastructure to meet demand targets and reach net zero by 2050.

Resources for the Future (2020)

[Progress and Potential for Electric Vehicles to Reduce Carbon Emissions]

This report forecasts EV deployment in 2025 and beyond. The authors conclude that even as more EV models enter the market in the next few years, EVs will continue to have only a modest effect on transportation sector emissions, because most ICE vehicles on the road today will remain on the road in 2025. To accelerate the transition, the paper recommends continuing federal and state EV tax credits, removing the credit sales cap on manufacturers, establishing zero-emissions mandates at the state or federal level, and developing strong federal CAFE and GHG standards for passenger cars. The paper estimates that before 2030 overall costs of ownership for EVs likely will fall below the costs for ICE cars for all but the largest vehicles. They also predict that cars having a 250-mile range will be available by 2027. The report uses EPRI forecasts of EV sales to develop an optimistic scenario that estimates that 65% of cars sold will be EVs by 2035. The authors caveat those results, however, by noting that aggressive policies are required to overcome barriers to widespread deployment of EVs.

Rocky Mountain Institute (2019)

Breakthrough Batteries: Powering the Era of Clean Electrification

This report describes current battery technologies, their potential applications, and projections for their future uses. The authors state that advances in technology and manufacturing will keep Li-ion batteries at the forefront of electrochemical energy storage through 2025. The report claims that emerging innovations will improve all aspects of Li-ion battery performance and costs likely will decline to about $87/kWh by 2025. In addition, low-cost Li-ion batteries will contribute to a rapid scale-up of personal and commercial EVs in the U.S. market after 2025. Rocky Mountain Institute (RMI) predicts that as early as 2025, and no later than 2030, non-Li-ion battery technologies will make significant progress in commercialization of long-duration energy storage, electrification of heavy transport, and battery-integrated approaches to fast-charging infrastructure. To harness this rapid development of batteries, however, RMI recommends that utilities and regulators assess the potential for decreasing battery prices to minimize investment in stranded assets.

Rocky Mountain Institute (2020)

Reducing EV Charging Infrastructure Costs

This paper provides a cost analysis of EV charging infrastructure by analyzing industry data, current levelized costs of charging infrastructure, publicly available information on utility procurements, and interviews with representatives of industry, utilities, software firms, transit agencies, and consultancies. RMI uses their core findings to draw comparisons to the trajectory of the solar sector during the past decade: As with solar components, the costs of EV hardware components, when manufactured at scale, decline along a learning curve as manufacturers find ways to squeeze cost out of their processes. Because costs for software systems are a relatively small part of total infrastructure cost, they do not offer a significant cost-reduction opportunity. RMI found that the greatest opportunities for cost reduction are in soft costs such as those for processes, marketing, opportunity, delays, and permitting.

STATE STUDIES

Below we describe two reports on states' progress toward electrifying the transport sector.

American Council for an Energy-Efficient Economy (February 2021)

ACEEE State Transportation Electrification Scorecard

This report evaluates the progress states have made in electrifying their transportation sectors. The scorecard evaluates states' planning and goal setting related to EV adoption, creation of charging infrastructure, incentives for EV deployment, efficiency of transport systems, optimization of the electric grid, enacting of EV equity, and outcomes of transport electrification. California leads the United States in adopting EVs, having set deadlines for electrification of transit buses, heavy-duty trucks, and commercial vehicles as well as having adopted statewide building codes for EV charging. The other states in the top 10 are New York, Washington, D.C., Maryland, Massachusetts, Vermont, Colorado, Oregon, Washington, and New Jersey. California and New York are identified as among the few states developing programs for providing equitable access to electrified transport for low-income communities. All states, even early adopters of transport electrification, have room to improve in expanding EV sales and installing charging infrastructure.

Resources for the Future (2019)

California's Evolving Zero-Emissions Vehicle Program: Pulling New Technology into the Market

This paper analyzes California's Zero Emission Vehicle (ZEV) program, a key state policy for reducing GHG from the state's transport sector. The program reduces the cost for industry's overall compliance. The report concludes that ultimately the program succeeds because it has spurred innovation and has proved a major driver for vehicle electrification both in the United States and worldwide. The paper suggests that the program can remain viable by continuing the market for vehicle credits as well as including price transparency and a backstop price for credits sold to manufacturers. The program's continued success depends on decreases in the cost of batteries, expanding EV infrastructure, and suggested changes to the credit market. This paper was published before California announced its target of 100% EV sales by 2035.

INTERNATIONAL STUDIES

We include one international report, which evaluates China's success with deploying large numbers of EVs.

International Council on Clean Transportation (2021)

Driving a Green Future: A Retrospective Review of China's Electric Vehicle Development and Outlook for the Future

This report outlines how China, during the past decade, has created the world's largest market for electric vehicles. China today accounts for half of the world's electric cars and more than 90% of electric buses and trucks. China now is entering a new era as if faces both increasingly fierce global competition and the nation's new pledge to achieve carbon neutrality by 2060. The report concludes that China's success was built on 1) a clear strategy for the EV industry; 2) top-down planning that set clear development targets and policies to achieve those targets; 3) aligned industry, energy, and environmental goals; 4) multi-stakeholder partnerships among government, industry, academia, and research programs to form strategies and roadmaps; 5) fiscal and regulatory policies to help launch and grow the market; and 6) innovation at the level of local governments.

THE 2035 TRANSPORTATION REPORT

The 2035 Report 2.0 outlines ways to develop a clean electric grid, identifying the investments and policies needed to boost renewable base load. The report also offers ambitious market forecasting for EVs and analyzes the consumer benefits of electrification of LDVs, MDVs, and HDTs and ownership of passenger EVs. The benefits include overall consumer savings, savings in total cost of individual ownership, and improvement in health and the environment.

The 2035 Report 2.0 presents a socio-economic analysis that identifies links between 100% EV sales and revitalization of the U.S. manufacturing industry. The analysis also describes the social benefits of reducing transport pollution and greenhouse gas emissions, specifically discussing the ways in which frontline and minority communities will benefit.

As the above literature review illustrates, this report is unique in combining expansive techno-economic modeling of 100% electrification of LDVs and MDVs and HDTs by 2030 and 2035, respectively, with a full suite of policy recommendations to achieve those goals and reap their benefits.

APPENDIX 2

METHODS, DATA, AND SCENARIOS

This appendix describes the core methods, data, scenarios, and results that underlie the 2035 Report 2.0, which focuses on the decarbonization of the transportation sector. As our methods borrow extensively from the 2035 Report 1.0, whose methodology can be found here, this appendix focuses on modeling and analytical methods specific to the transportation sector.

METHODS AND DATA

Our study analyzes the effects of two policy scenarios on electrification of the transportation sector. A baseline scenario, termed the No New Policy scenario, assumes the continuation of existing (2020) state and federal policies and assumes the extant barriers to EV adoption persist. The second scenario, termed the Drive Rapid Innovation in Vehicle Electrification (DRIVE Clean), describes the requirements and benefits of achieving 100% electric vehicle sales by 2035.

Eight discrete analyses underpin the findings reported here and in the 2035 Report 2.0.

- Total cost of ownership (TCO)
- Stock turnover
- Fleet-level cost
- Grid modeling
- LDV charging infrastructure
- MDV and HDT charging infrastructure
- Health and environmental effects
- Jobs impacts

Figure 1 shows the interactions and dependencies among the eight analyses. The TCO and stock turnover models are independent of each other, but jointly inform the analysis of fleet-level consumer and environmental savings. All other analyses, including estimated needs for charging infrastructure, environmental benefits, and grid and jobs impacts are based on the fleet dynamics estimated in the stock turnover model and on external inputs. The methodology, data inputs, and assumptions underlying each of the eight analyses are described in the following sections.

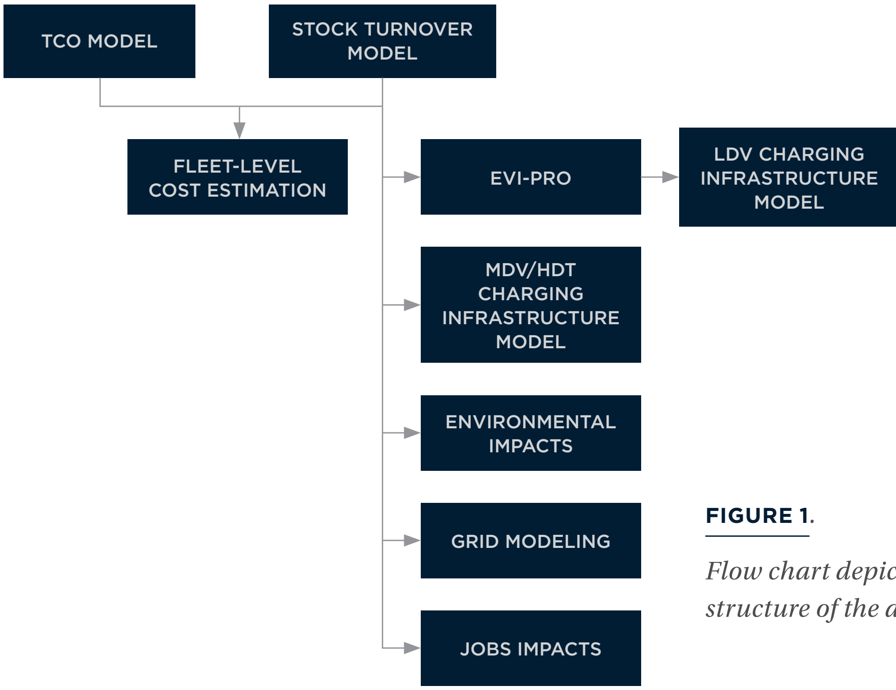

FIGURE 1.

Flow chart depicting the structure of the analysis

Total Cost of Ownership

A combination of operational, economic, and technical input assumptions and data inform the TCO model, as shown in **Figure 2**. The outputs of the TCO model are the lifetime-averaged TCO on a per-vehicle and per-mile basis by vehicle class for both ICE vehicles and EVs sold between 2020 and 2050.

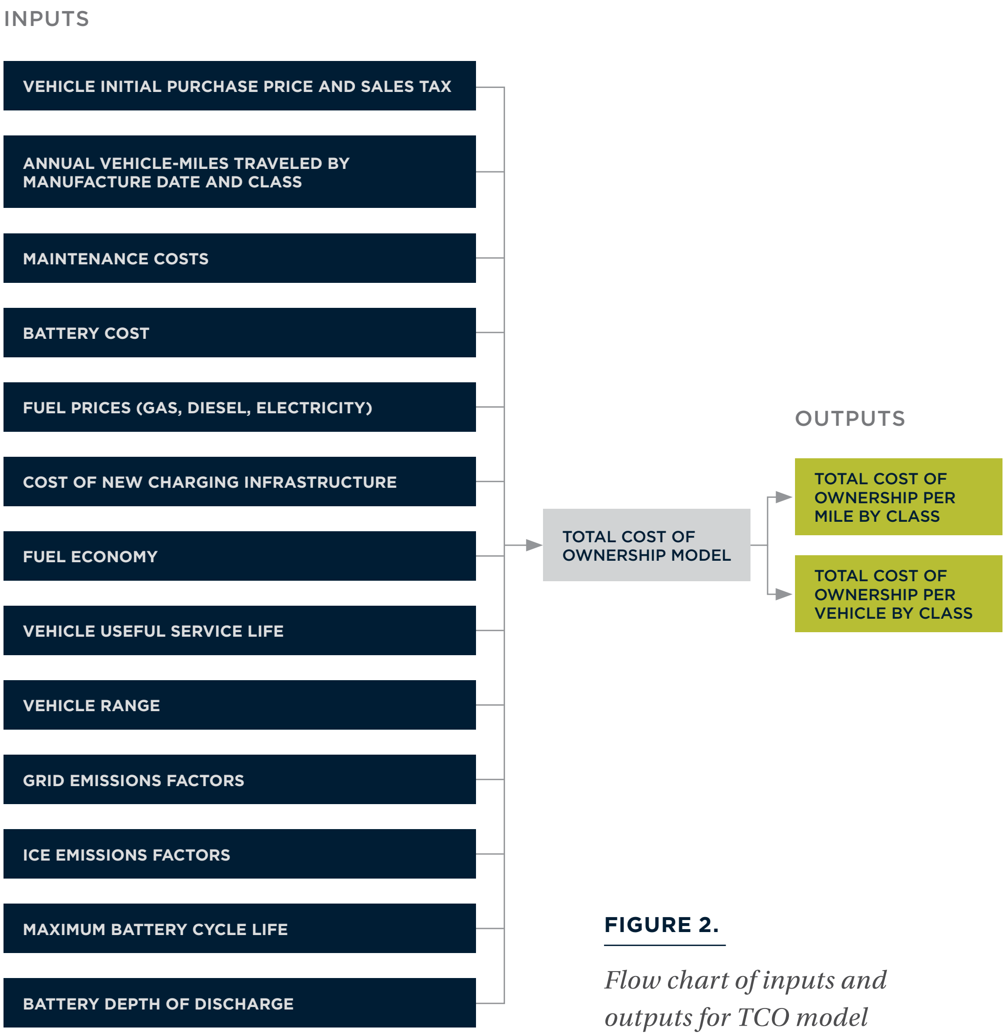

FIGURE 2.

Flow chart of inputs and outputs for TCO model

We establish six vehicle classes based on gross vehicle weight rating (GVWR) as defined by the Federal Highway Administration (DOE 2021): class 1, class 2a, class 2b-3, class 4-5, class 6-7, and class 7-8 tractors. **Table 1** presents the characteristics of the six classes by GVWR, fuel used (for ICE vehicles), the aggregate classification of the vehicles, and example vehicles. For both ICE and electric vehicles, the TCO is the total cost of purchasing, operating, and maintaining the vehicle divided by the total miles driven during the vehicle's useful lifetime. Operational specifications such as vehicle miles traveled (VMT) per year over the vehicle's useful service life were derived from California's 2017 EMission FACtors (EMFAC) data [California Air Resources Board (CARB) 2017]; Environmental Protection Agency (EPA) rulemaking analyses (Federal Register 2002); and industry reports. Annual VMT by vehicle class and age are shown in **Figure 3**. Average useful lifetimes of vehicles range from 9 to 15 years. Note that the inputs to the TCO calculation rely only on exogenous economic and technical data and are agnostic to any policy scenario.

TABLE 1.

Descriptions of vehicle classes

CLASS	GVWR (LB)	AGGREGATED CATEGORY	ICE FUEL USED*	EXAMPLE VEHICLE
Class 1	0 - 6,000	LDV	100% gasoline	Sedan
Class 2a	6,001 - 8,500		100% gasoline	SUV
Class 2b-3	8,501 - 14,000		50% gasoline 50% diesel	Heavy-duty pickup
Class 4-5	14,001 - 19,500	MDV	100% diesel	Box truck Large walk-in truck City delivery truck
Class 6-7	19,501 - 33,000		100% diesel	School bus Refuse truck City transit bus
Class 7-8	26,001 - 33,001 +	HDT	100% diesel	Tractor-trailer

** We assume national average ethanol blending (10%) per the U.S. Energy Information's (EIA's) Annual Energy Outlook 2021.*

† Although class 6–7 and class 7–8 tractors overlap in GVWR, the latter specifically denotes vehicles designed for pulling trailers.

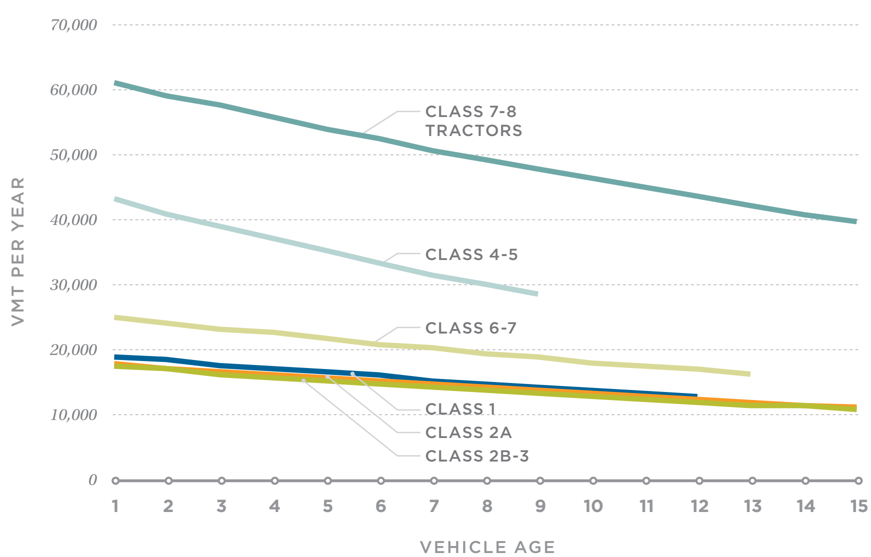

FIGURE 3.

Vehicle miles traveled by vehicle class over vehicle lifetime[1]

1 The endpoint of the VMT trends correspond with the assumed average useful life for that vehicle class.

The TCO comprises eight elements: sales tax and upfront cost,[2] fuel (electricity for EVs, gas or diesel for ICE vehicles), maintenance, battery replacement during the EV's lifetime,[3] and the cost of building charging infrastructure nationwide. The final two elements apply only to EVs. Additionally, we include the environmental cost of CO_2 equivalent emissions and air pollution, which corresponds to direct tailpipe emissions for ICE vehicles and grid-related emissions for EVs. We discuss assumptions and data inputs for each of these TCO components in further detail in the following sections.

Upfront Vehicle Costs

Sales tax is assumed to be 8% of vehicle purchase price, in line with CARB 2019. We source ICE upfront costs from the CARB 2019 analysis except for classes 1, 2a, and 7-8 tractor, which we determine through bottom-up modeling. Given that the technology and manufacturing are well established for ICE vehicles, we assume their upfront costs remain constant throughout the study period. For EVs, the upfront costs of all vehicle classes are determined through bottom-up modeling based on Lutsey and Nichols 2019 and Bauer et al. 2021. Results of the bottom-up modeling, which accounts for battery costs, electric drivetrains, vehicle assembly, and indirect costs, are then harmonized with the sales prices of current or proposed EV models. **Figures 4a-c** illustrate assumptions regarding upfront costs for ICE vehicles and EVs in the six classes listed in Table 1.

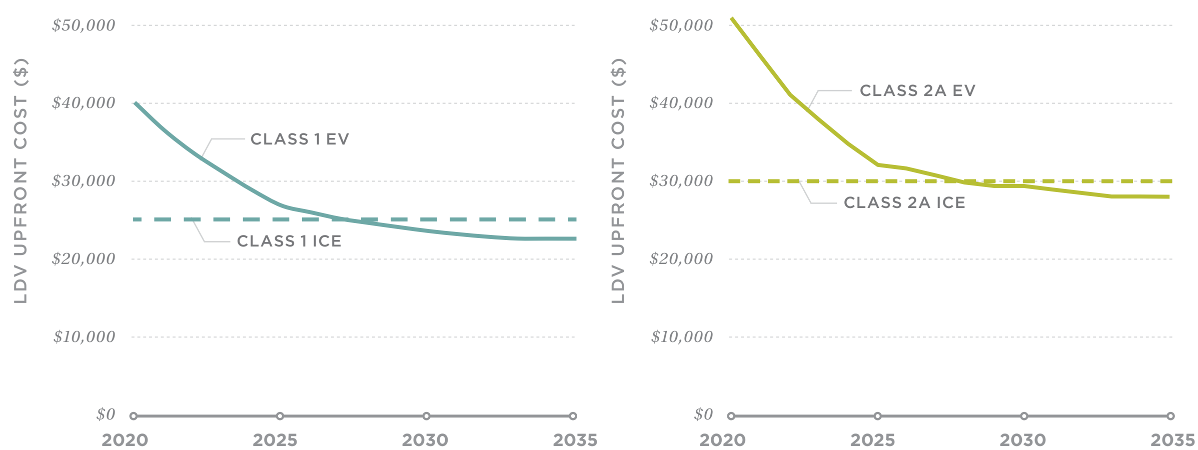

FIGURE 4A.

Upfront cost by vehicle technology for LDV classes

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2 Referred to jointly as upfront cost.
3 Battery replacement cost is included in maintenance costs in the TCOs for EVs.

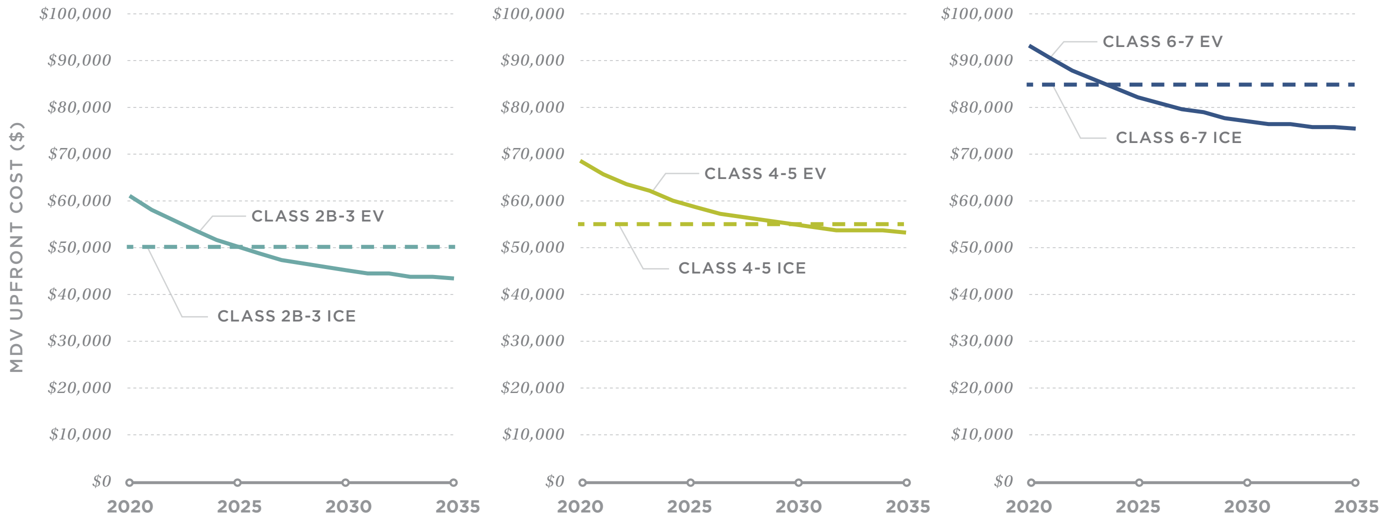


FIGURE 4B.

Upfront cost by vehicle technology for MDV classes

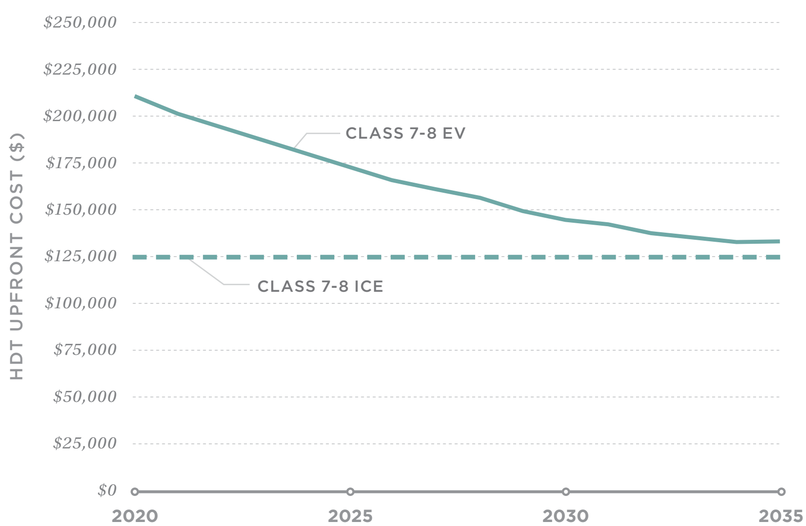


FIGURE 4C.

Upfront cost by vehicle technology for HDTs

Maintenance Costs

We derive vehicle maintenance costs on a per-mile basis for all ICE and EV medium- and heavy-duty vehicle classes from CARB 2019. Maintenance costs for ICE and EV LDVs are borrowed from Lutsey and Nicholas 2019.

Fuel Costs

The key assumptions for estimating fuel costs are fuel efficiency and fuel price. Electricity is the sole fuel source for all EV classes. We specify electricity rates by aggregate vehicle class. We assume that LDVs access a residential rate starting at $0.13/kWh, MDVs a commercial rate starting at $0.11/kWh, and HDTs an industrial rate of $0.08/kWh. Electricity rates increase slowly throughout the study period, in line with electricity prices in the 2035 Report. Among ICE vehicles, LDVs are assumed to operate on gasoline that has a 10% ethanol content. We assume that MDVs and HDTs are fully diesel-powered, with the exception of class 2b, which is 50% diesel and 50% gasoline (again blended with 10% ethanol). As we did with EVs, we project gasoline and diesel prices based on Annual Energy Outlook (AEO) 2020. Diesel prices begin at $2.5/gallon in 2020, increasing to $3.3/gallon by 2030. Similarly, gasoline prices are assigned a $2.3/gallon price in 2020 and $2.8/gallon in 2030**. Figures 5 and 6** show the price trends for fossil fuels and electricity during the study period.

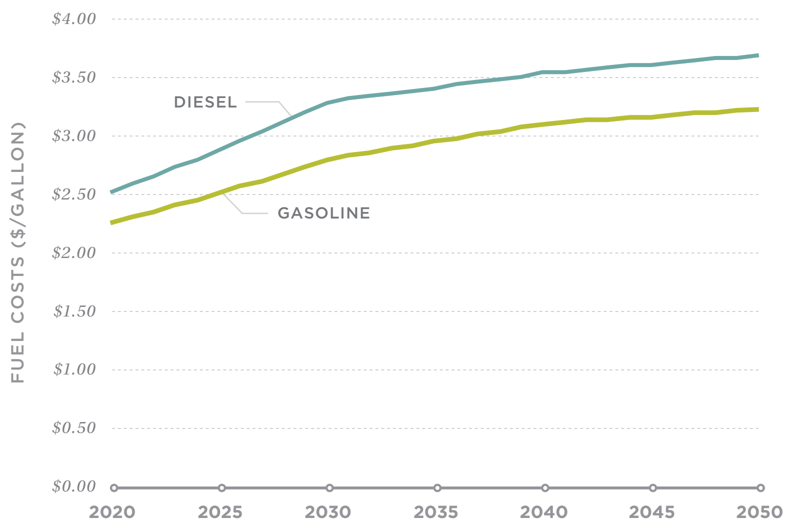


FIGURE 5.

Fossil fuel prices

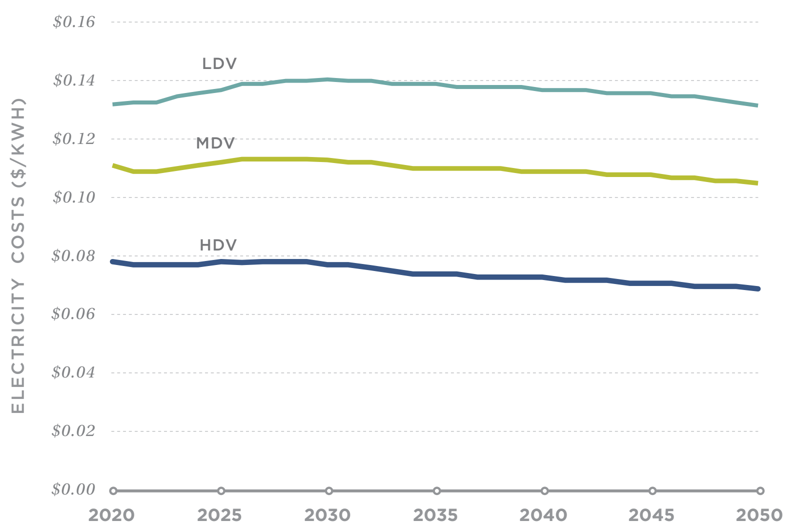


FIGURE 6.

Electricity prices

We obtain fuel efficiencies for ICE vehicles from CARB 2019, but apply correction factors ranging from 0.7 to 0.95 to harmonize those estimates with projections developed by the U.S. Energy Information Administration[4] and the National Renewable Energy Laboratory (NREL 2018). Fuel economies for ICE LDVs begin in the range of 27 to 30 mpg in 2020 and increase to 30 to 35 mpg by 2030. In 2020 fuel efficiency of MDVs range from 6.6 to 7.5 mpg, increasing to 6.8 to 8.1 mpg by 2030. Finally, in 2020 HDTs get 6.1 mpg, increasing to 6.3 mpg in 2030.[5] Fuel efficiencies for electric LDVs and MDVs are sourced from Murphy et al. 2021; HDT fuel efficiencies are in line with a recent LBNL study (Phadke et al. 2021). For EVs, 2020 LDV efficiencies range from 3.1 to 3.5 miles per kilowatt-hour (mi/kWh), increasing to 3.4 to 4.0 mi/kWh by 2030. In 2020 MDV efficiencies range from 0.5 to 1.8 mi/kWh in 2020, increasing marginally to 0.5 to 1.9 mi/kWh by 2030. Electric HDTs are assumed to have an efficiency of 0.4 mi/kWh throughout the study period. **Table 2** presents details of our assumptions about fuel efficiency.

TABLE 2.

Summary of vehicle fuel efficiency assumptions by class 2020-2050

	FUEL EFFICIENCIES BY VEHICLE CLASS (MPG, MI/KWH)				
VEHICLE CLASS	TECHNOLOGY	2020	2030	2040	2050
Class 1	ICE	29.7	34.5	40.2	45.1
	EV	3.5	4.1	4.7	5.3
Class 2a	ICE	26.7	29.1	31.5	33.7
	EV	3.1	3.4	3.7	4.0
Class 2b-3	ICE	7.5	8.1	8.1	8.1
	EV	1.8	1.9	1.9	1.9
Class 4-5	ICE	9.5	9.9	9.9	9.9
	EV	0.5	0.5	0.5	0.5
Class 6-7	ICE	6.6	6.8	6.8	6.8
	EV	0.5	0.5	0.5	0.5
Class 7-8 (tractor)	ICE	6.1	6.3	6.3	6.3
	EV	0.4	0.4	0.4	0.4

4 2021. EIA website. 2021. Open Data. https://www.eia.gov/opendata/qb.php?category=711246&sdid=TOTAL.TRFRRUS.A [accessed 05/21/2021]

5 A range of values represents variation among classes within an aggregate weight class (LDV, MDV, or HDT). For example, fuel efficiency of MDVs range from a lower bound of 6.6 mpg for the lightest MDV class (class 2b) to an upper bound of 7.5 mpg for the heaviest MDV class (class 6-7). Class 4-5 lies in the middle of the range.

Costs of Battery Replacement and Charging Infrastructure

The TCO components of battery replacement and charging infrastructure apply exclusively to EVs. To calculate the cost of battery replacements required over a vehicle's useful lifetime, we assume a maximum battery life of 10 years or 1,500 cycles at an 80% depth of discharge—whichever comes first. The cost of a replacement battery is determined by the capacity of the battery, which depends on the modeled range of the vehicle class, multiplied by the per-kWh cost of the battery in the year of replacement. Small adjustments are made to account for the battery's packing fraction and overcapacity factors. The average cost of charging infrastructure for LDVs, which includes both home and public charging infrastructure, is estimated to be 0.71 ¢/mi between 2020 and 2035, falling to 0.57 ¢/mi from 2036 onward. These estimates, which are based on a bottom-up calculation of the infrastructure needed to support electrification under the DRIVE Clean scenario, are calculated using NREL's EVI Pro tool. Charging infrastructure for HDTs is mostly highway charging at already established highway truck stops. The average cost of HDT charging infrastructure is estimated to be 1.94 ¢/mi between 2020 and 2035, dropping to 1.46 ¢/mi from 2036 onward. Those figures again are based on a bottom-up estimate of the charging infrastructure needed under the DRIVE Clean scenario. For MDVs, most of the charging infrastructure will be located at existing parking lots and warehouses. The average cost of charging infrastructure for MDVs is estimated to be 50 ¢/mile until 2035, decreasing to 47 ¢/mile from 2036 onward.

Stock Turnover

We use a bespoke vehicle stock turnover model to examine the dynamics of the national vehicle fleet under the two policy scenarios we analyze. As **Figure 7** shows, the stock turnover model uses the starting 2020 vehicle population, EV sales targets, and historical sales data as inputs, then estimates the number of ICE vehicles and EVs sold and retired each year between 2020 and 2050.

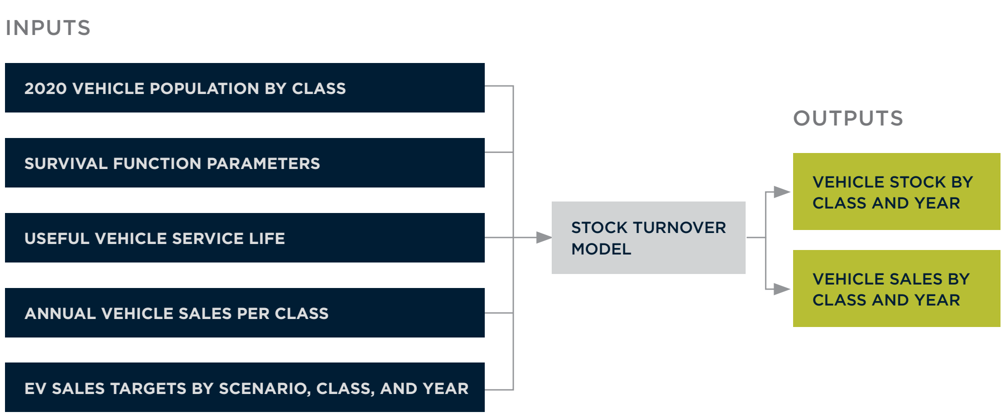


FIGURE 7.

Flow chart of inputs and outputs for stock turnover model

We estimate the number of new vehicles sold per year using historical sales data from the Federal Reserve Bank of St. Louis (FRED 2021).[6] **Table 3** shows our assumptions for starting vehicle populations and sales in 2020. The 2020 vehicle populations are triangulated from several sources, including the EMFAC 2017 database,[7] Federal Highway Administration (FHWA) 2020, the U.S. Census Bureau 2004, and EPA 2015.

TABLE 3.

Vehicle populations and sales by class in 2020

AGGREGATE VEHICLE CLASS	POPULATION IN 2020	NATIONAL SALES IN 2020
Class 1	115,114,000	7,441,000
Class 2a	116,590,000	6,772,000
Class 2b-3	8,586,000	484,100
Class 4-5	953,600	90,800
Class 6-7	1,128,000	80,300
Class 7-8 tractors	3,244,000	205,000

Annual sales are allocated between ICE vehicles and EVs based on the EV sales target for each year. That target scales logarithmically from 2020 levels as estimated by Bloomberg New Energy Finance (BNEF) 2019, to reach 100% of sales in the scenario target year. The No New Policy scenario assumes that EV sales follow BNEF 2019 projections.

We calculate the probability of a vehicle retiring at the end of its useful life using a Weibull distribution function (survival function) applied at the class level. The methodology and parameters for the survival functions are informed by International Council on Clean Transportation (ICCT) modeling (ICCT 2012) but use the characteristic service lives defined in **Table 7**. **Figures 8-10** show the survival functions for the aggregated categories, where the x-axis represents the age of the vehicle and the y-axis represents the probability that the vehicle is still in operation.

6 Although our sales trends reflect FRED data, the magnitude of sales differ given that we use more disaggregated vehicle categorizations than does FRED.

7 California Air Resources Board online database. https://arb.ca.gov/emfac/2017/ [last accessed 05/21/02021]

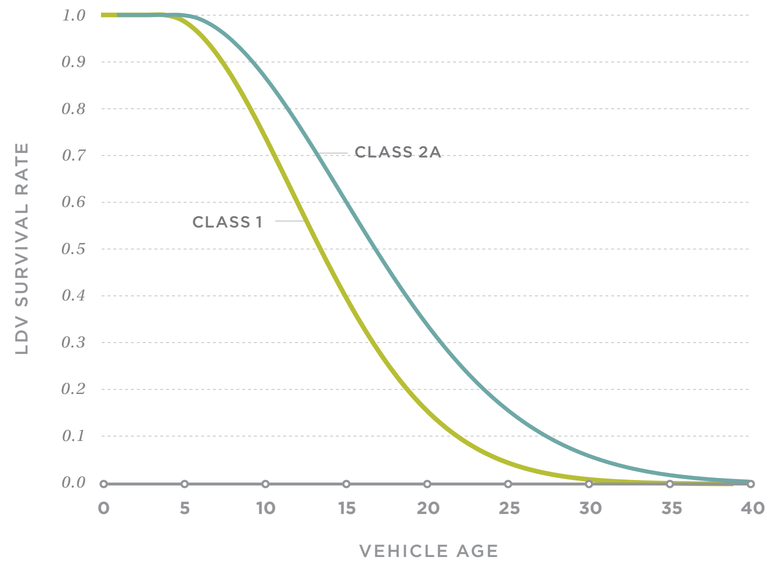


FIGURE 8.

LDV survival rates

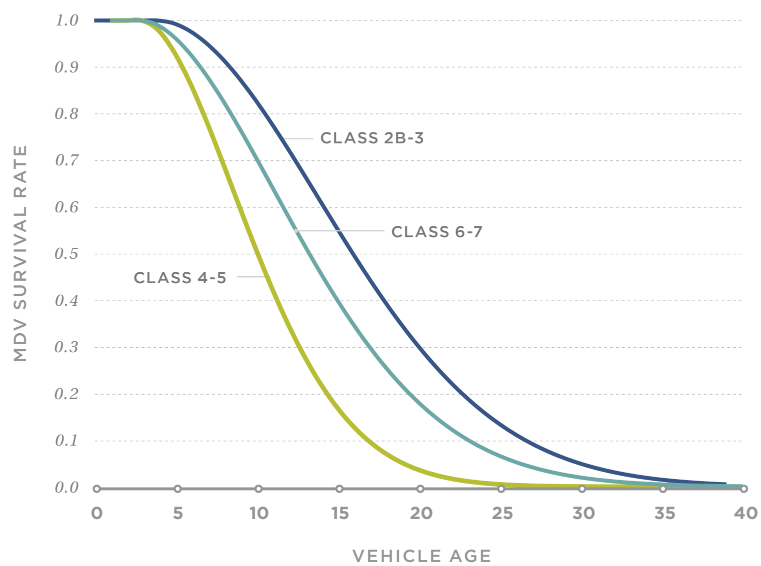


FIGURE 9.

MDV survival rates

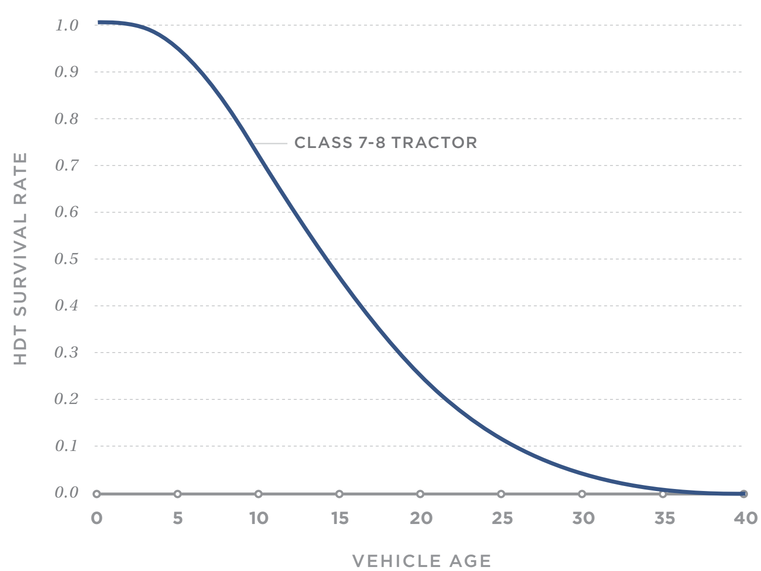


FIGURE 10.

HDT survival rate

The survival functions enable us to estimate the number of both electric and ICE vehicles retired each year. Combined with the projections of vehicles sales, for each policy scenario the stock turnover model produces estimates of ICE, EV, and total vehicles retired and sold each year nationwide between 2020 and 2050 by class.

Fleet-Level Cost Estimation

Costs at the fleet level are estimated by combining the vehicle-level TCO estimates, the populations of both ICE vehicles and EVs as estimated by the vehicle stock turnover model, and annual VMT, as shown in **Figure 11**.

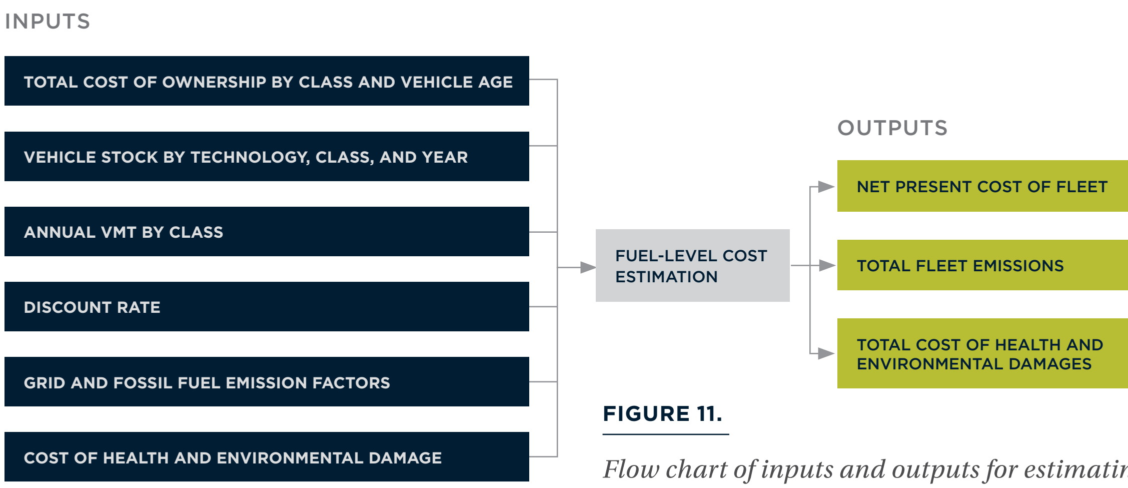


FIGURE 11.

Flow chart of inputs and outputs for estimating fleet-level costs

For each scenario, we estimate the total cost per year for each component of the TCO: upfront costs, fuel expenditures, and maintenance costs. The sum of those elements is the total fleet-wide cost. This total cost enables us to compare the effects of fleet electrification under the DRIVE Clean scenario on consumer costs, along with health and environmental effects, compared to the No New Policy baseline.

Grid Modeling

Assessing the effects of extensive penetration of renewable energy on electric power systems relies on state-of-the-art capacity-expansion models, production cost models, or a combination of the two. For this study we use a combination of a capacity-expansion model, the Regional Energy Deployment System (ReEDS) from Brown et al. 2020, and the industry-standard production cost model PLEXOS, employed by grid operators and utilities worldwide (Energy Exemplar).

Capacity Expansion

Capacity-expansion models identify the optimal resource mix to meet future peak and annual energy requirements at the lowest cost. Large-scale regional or national models such as the National Energy Modeling System, Integrated Planning Model, and ReEDS typically are used to evaluate federal policies and forecast how those policies will affect electricity generators. Capacity-expansion models can examine generation, transmission, and attempts to co-optimize generation and transmission deployment. Most capacity-expansion models rely on simplified dispatch methodologies and thus do not consider unit commitment or hourly dispatch and so do not produce outputs regarding detailed plant operation.

ReEDS identifies the least-cost portfolio of power sector assets required for electric generation (by technology and fuel), storage, and transmission required to meet regional electric power demand. The models consider grid reliability (reserve) requirements, technology resource constraints, and policy constraints. The U.S. power system is represented by 134 interconnected zones, which primarily represent key load-balancing areas (**Figure 12**). The 134 zones are connected by 310 transmission lines. ReEDS incorporates all generation and high-voltage transmission assets up to 2018. For future years, it includes planned capacity additions and retires generation assets at the end of their technical lives. ReEDS obtains potential generation from renewable resources (primarily wind and solar) from NREL's Wind Integration National Dataset (WIND) Toolkit[8] and National Solar Radiation Database (NSRDB)[9]. The resources represent 356 resource regions, which are subdivisions of the 134 zones. Those smaller regions provide additional granularity regarding resource variability. The ReEDS documentation provides additional details (Brown et al. 2020).

8 NREL. No date. Wind Integration National Data Set Toolkit. [last accessed 05/21/2021]
9 NREL. No date. National Solar Radiation Database. [last accessed 05/21/2021]

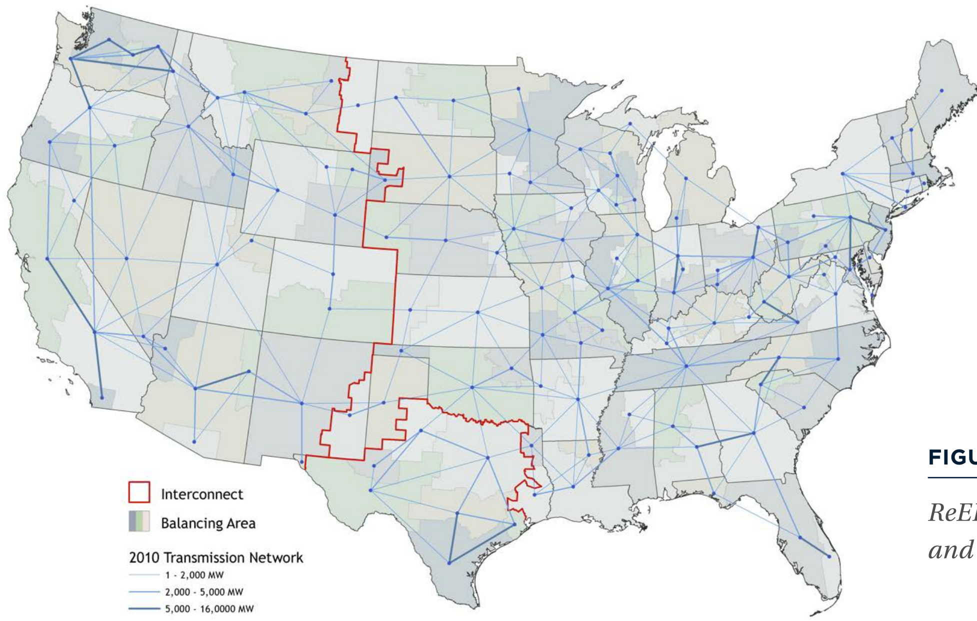


FIGURE 12.

ReEDS load-balancing zones and transmission network

Source: Brown et al. 2020

Grid Dispatch

To assess future operational feasibility, we use the production cost model PLEXOS by Energy Exemplar[10] to simulate the hourly dispatch of generators, storage, and transmission ties for 2035. Production cost models determine how to meet electricity demand at least cost by optimizing unit commitment and hourly dispatch. The optimization considers variable costs and operational constraints for a given power generation mix and transmission capacity.

Based on the EIA's data and operational constraints at the generator level, we use PLEXOS to model more than 15,000 generators within the 134 ReEDS zones. After correlating the map of ReEDS regions to PLEXOS, we apply the transmission line limits from ReEDS to the 310 transmission lines/connections modeled in PLEXOS. We then add to the PLEXOS model the generation and transmission expansion and retirement outputs from ReEDS, including renewable energy generators. We simulate hourly grid dispatch and operations in 2035 based on seven weather years (2007 to 2013), more than 60,000 hours in all, using time-synchronized hourly wind, solar, and load data at the regional level.

To get hourly profiles of solar and wind generation, we use the supply-curve approach, using data from NREL. NREL's WIND Toolkit gives hourly profiles of wind generation for 126,000 candidate sites nationally,

10 Energy Exemplar. https://energyexemplar.com/ [last accessed 05/22/2021]

selected using certain key criteria such as resource quality, proximity to the existing transmission and load centers, and land exclusion constraints, such as bodies of water, protected lands, and urban areas.[11] The total capacity from these 126,000 sites adds up to around 2TW. Within each ReEDS resource region (356 total), we choose the best resource quality sites from the candidate sites until we reach the ReEDS optimized installed capacity in that region. We then add the hourly generation profiles of all chosen sites within each resource region to create resource region level profiles for the given wind portfolio. If a resource region does not have enough sites to meet the capacity requirement from ReEDS, we scale up the capacity from all the candidate sites within the region to match the requirement.

NREL's National Solar Radiation Database gives hourly radiation data (global horizontal, direct normal, and diffuse horizontal irradiance) and meteorological data for each 2km by 2km grid cell within the contiguous U.S.[12] We use NREL's System Advisor Model Software Development Kit (SAM SDK) to convert the hourly radiation and meteorological data into power output.[13] Within each ReEDS zone (134 total), we choose 50 grid cells at random, and spatially average the power output data over the zone. Note that if the ReEDS output changes, the hourly wind generation profiles used in PLEXOS would also change, but not the solar generation profiles.

Estimating the Total Cost of Generation

New Investments

ReEDS output includes capital investment in new generation and transmission assets (starting in 2010, with actuals up to 2018). Based on NREL's Annual Technology Baseline (ATB) 2019,[14] we annualize investment costs by using a weighted average real cost of capital (WACC) of 2.75% (5.25% nominal).

Existing Assets

Because ReEDS does not report the cost of investing in generation capacity built before 2010, we estimate those costs exogenously. First, we use plant-level specifications from EIA Form 860 to assess the undepreciated value of generation assets built before 2010. For conventional technologies, we use the capital cost assumptions in NREL's ATB 2019 shown in **Table 4**, to assess the value of each generation plant during its commissioning year.

11 National Renewable Energy Lab. Wind Toolkit.
12 National Renewable Energy Lab. National Solar Radiation Database.
13 National Renewable Energy Lab. System Advisor Model.
14 NREL. 2019. Annual Technology Baseline (ATB). [last accessed 05/22/2021]

TABLE 4.

Capital cost of key conventional technologies in $/kW ($2018 real)

TECHNOLOGY	$/KW ($2018 REAL)
Hydro (NSD1)	7,277
Coal	4,036
Nuclear	6,742
Gas-CCGT	927
Gas-CT	919
Geothermal (Hyd-binary)	5,918
Biopower	3,990

Source: NREL. ATB 2019

We add $1,000/kW to all coal power plants to reflect the cost of installing the emission control equipment. We then apply straight-line depreciation to estimate the remaining economic value of every generation plant, assuming an economic life of 30 years for all technologies except batteries, which we assign an economic life of 15 years. We use the average utility WACC of 6.2% (real) to annualize these costs of current capacity, then add them to our total costs.

For newer technologies such as wind and solar PV, we use historical capital costs from Wiser et al. 2019 and Bolinger et al. 2019. For example, capital costs for wind energy started at approximately $3,000/kW in the 1990s, decreasing to about $1,400/kW by the late 2000s, with a weighted-average capital cost of $1,600/kW in $2018 real.

Charging Infrastructure

We examine the costs associated with installing charging infrastructure for EVs. Charging infrastructure requirements for LDVs are calculated separately from heavier MDV and HDT classes, and as such are discussed separately in the following sections.

Light-Duty Vehicles

We use a bottom-up charging infrastructure model to estimate the number of chargepoints and the investment necessary to support LDV electrification under the DRIVE Clean scenario (**Figure 13**).

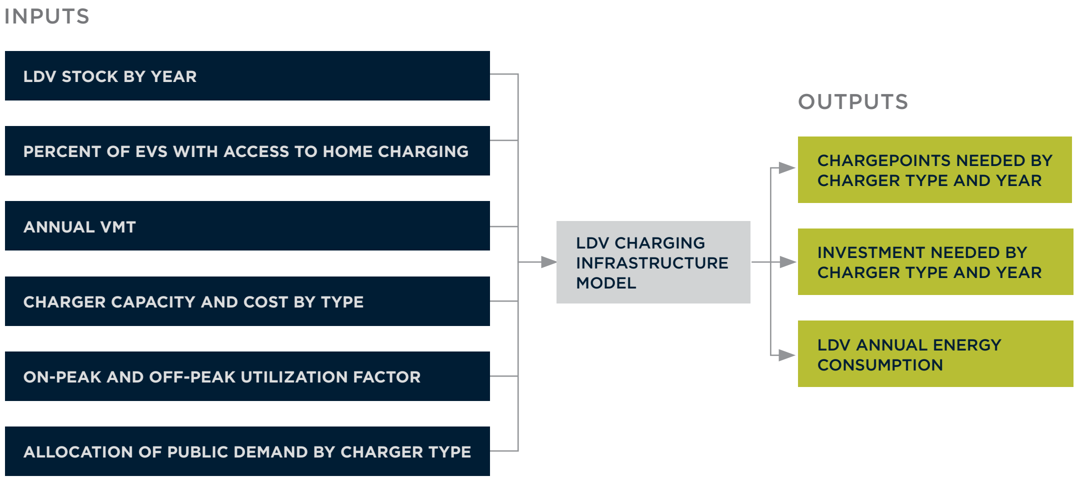


FIGURE 13.

Flow chart of inputs and outputs for model of LDV charging infrastructure

The key input to the model is the maximum electricity demand from vehicle charging per year in each state, which we estimate using NREL's EVI-Pro tool.[15] First we downscale the number of LDVs nationwide to the state level using scalar factors from Murphy et al. 2021. Downscaling is necessary to stay within the maximum vehicle population allowed by EVI-Pro Lite. We then use the EVI-Pro API to calculate the yearly load in 15-minute intervals for each state during the study's 31-year timeframe in six charging categories: home L1, home L2, work L1, work L2, public L2, and public L3. A separate script identifies the maximum demand for each year, now re-aggregated to the national level.

We make several adjustments to the six vehicle charging categories. First, we assume that home L1s will be phased out by 2025 given the increasing availability of inexpensive L2 home chargers. Thus after 2025 the home L1 load is reallocated to the home L2 category. Similarly, we assume that work L1 chargers will phase out, so that beginning in 2020 all work L1 demand is allocated to work L2. We also add a category for 100-kW L3 fast charging. To correct EVI-Pro results, which favor work charging, we combine the maximum demand from all work and public charging, then reallocate it nearly equally among work L2 (25%), public L2 (35%), public 50-kW L3 (25%), and public 100-kW L3 (20%).

Within each charging category, we convert from maximum demand to the number of chargepoints by assuming a factor for coincident use of peak demand and chargepoint capacity. This factor represents the utilization of the charging infrastructure at the moment of peak demand. For example, a coincident use factor of 0.75 would indicate that at the time of peak demand 75% of available chargepoints are in use. Using this number of chargepoints and the estimated cost per chargepoint (including both hardware and installation) from **Table 5**, we estimate the total investment needed for expanding charging infrastructure. Table

15 NREL. Developer Network. EVI-Pro Lite https://developer.nrel.gov/docs/transportation/evi-pro-lite-v1/

5 lists the coincident use factors, capacities, and cost assumptions for each charging category.

TABLE 5.

Coincident use, capacity, and cost per charger type

CHARGER TYPE	PEAK COINCIDENT USE FACTOR	CAPACITY (KW)	COST ($/CHARGEPOINT) (2020-2035)	COST ($/CHARGEPOINT) (2036-2050)
Home L2	0.15	11	1,476	1,179
Work L2	0.90	11	4,500	3,600
Public L2	0.57	11	4,500	3,600
Public L3	0.72	50	28,874	18,983
High-Capacity Public L3	0.75	100	55,409	37,858

To check that our chargepoint estimates are within reason, we use the LDV population from the stock turnover model and vehicle efficiencies to calculate the expected energy consumption per year from the LDV fleet. This estimate is exogenous to the chargepoint calculation. Using the chargepoint estimates and introducing an average utilization factor in 2020 of 17% for home charging and 7% for work and public charging (and scaling slowly over time), we calculate the total annual energy consumed by charging. We compare the results year by year to the expected fleet energy consumption to check that we are not oversizing or undersizing the charging infrastructure needed to support the electric LDV fleet.

Medium-Duty Vehicles and Heavy-Duty Trucks

We assume that the HDT charging infrastructure will be installed at existing highway truck stops. We estimate the overall requirement for charging infrastructure by modeling every current U.S. highway truck stop and optimally siting 125-, 350-, and 1,000-kW chargepoints so as to cover every freight mile a truck might travel. We assume that the MDV charging infrastructure (50-, 125-, and 350-kW chargepoints) will be built at warehouses and parking lots in ways that allow for an MDV to be reliably charged for all miles driven in any given day. MDVs are also assumed to have access to the LDV and HDT charging infrastructure. The MDV and HDT traffic flows and miles traveled are obtained from FHWA data (2020). Estimated cost per chargepoint is shown in **Table 6**.

TABLE 6.

Estimated cost per chargepoint for MDV and HDT

CHARGING TYPE	CAPACITY (KW)	COST (HARDWARE + INSTALLATION) ($/CHARGEPOINT) (2020-2035)	COST (HARDWARE + INSTALLATION) ($/CHARGEPOINT) (2036-2050)
MDV 50	50	28,874	18,983
MDV 125	125	69,261	47,322
MDV 350	350	169,175	103,905
HDT 125	125	69,261	47,322
HDT 350	350	169,175	103,905
HDT 1000	1000	483,358	296,872

Environmental Impacts

We rely on the peer-reviewed literature to estimate the value of the environmental and public health effects of selling only electric vehicles. We use national average mortality factors per vehicle miles traveled from Thakrar et al. 2020 to estimate total premature deaths due to vehicular air pollutant emissions, specifically from primary and secondary particulate matter ($PM_{2.5}$). As efficiencies of ICE vehicles improve between 2020 and 2050, we reduce the mortality factors for each vehicle category in proportion to efficiency increases.

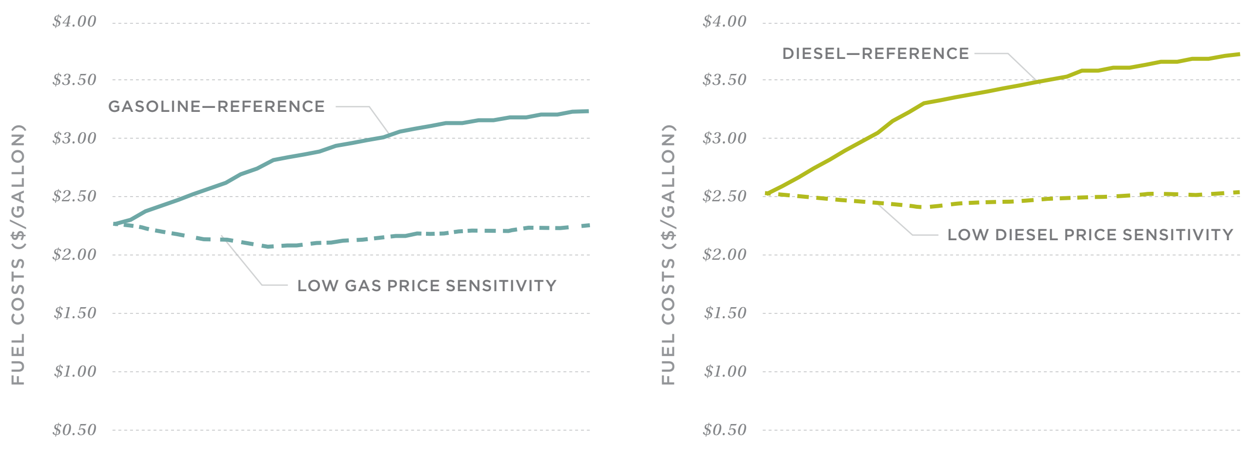
We use the methodology applied in developing the 2035 Report to evaluate health impacts related to the power sector. We estimate the change in yearly sulfur dioxide (SO_2) and nitrogen oxide (NOx) emissions (which contribute to forming secondary $PM_{2.5}$ in the atmosphere) in each of the 134 ReEDS regions. We then apply state-level mortality factors from Thind et al. 2019 to estimate total premature deaths attributable to SO_2 and NO_x emissions in each state. Our estimate of the economic benefits of avoided CO_2 and $PM_{2.5}$ emissions relies on a methodology and values consistent with the 2035 Report. We multiply the value of a statistical life from Holland et al. 2020, $9.6 million (2020 real), with the premature deaths avoided through reductions in primary and secondary $PM_{2.5}$ emissions. The economic benefit of avoided CO_2 emissions is estimated using a social cost of carbon derived from Baker et al. 2019 and Ricke et al. 2018 which in 2020 is $49.6/MT, increasing at 3% per year ($66.1/MT by 2030 and $76.6/MT by 2035). We multiply the social cost of carbon by the net reductions in CO_2 emissions from the transportation and power sectors.

Sensitivity Analyses

We validate the robustness of our TCO analysis and fleet-level cost assumptions using two sensitivity scenarios that are adverse to vehicle electrification:

1. Low gas and diesel prices (taken from the AEO 2020s High Oil and Gas Supply case; AEO 2020.)
2. High electricity prices

Figure 14 compares the gas and diesel prices and electricity prices used in the core scenarios compared to the sensitivities. **Figure 15** show the assumed sensitivity of electricity prices for LDVs, MDVs, and HDTs.

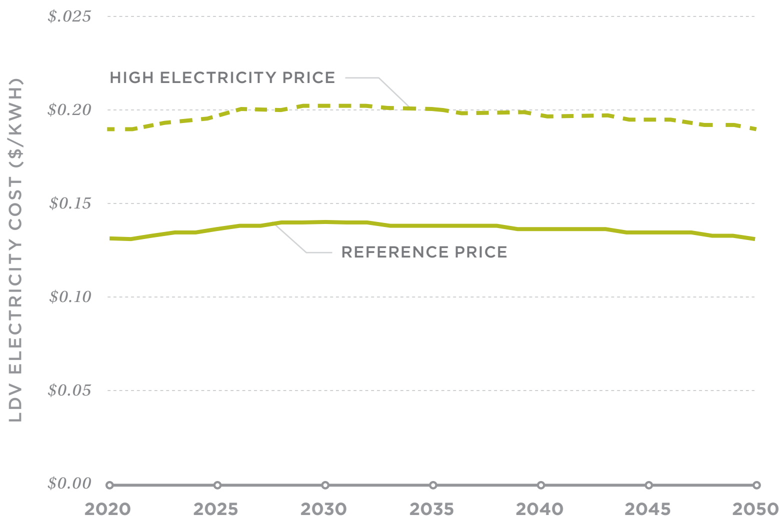


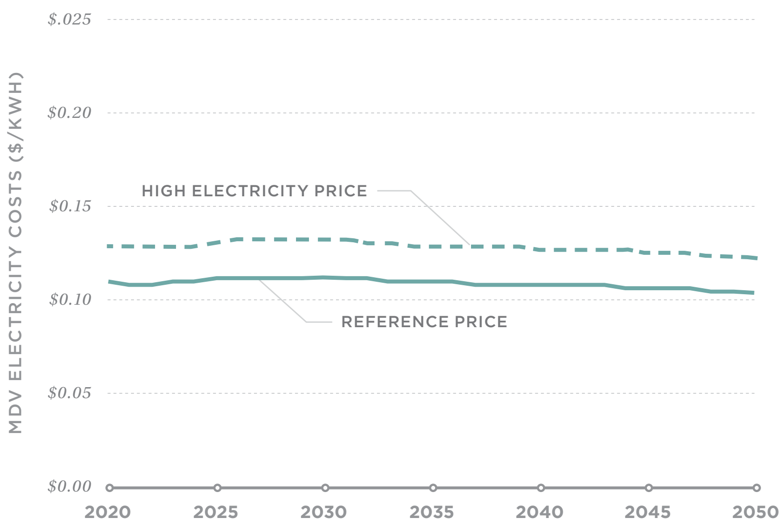
FIGURES 14.

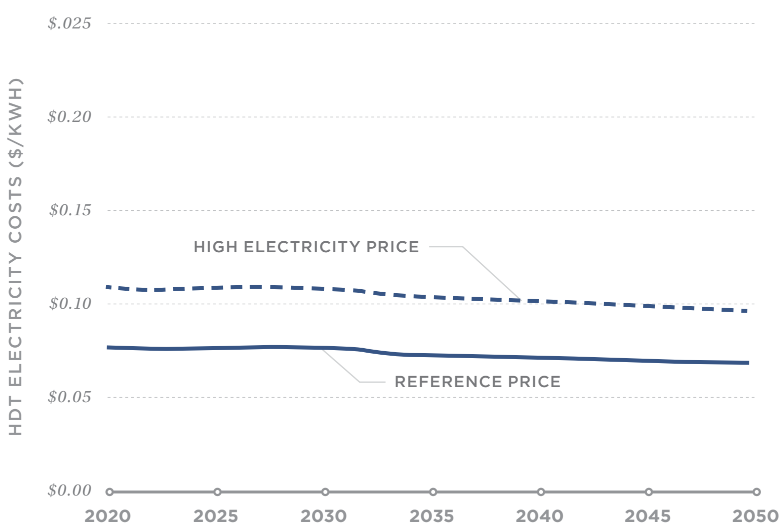
Cost assumptions for gasoline and diesel sensitivity prices

FIGURES 15.

LDV, MDV, and HDT electricity sensitivity prices







Data Overview

Table 7 summarizes the key variables and assumptions underlying the data we used for our TCO analysis and estimation of fleet-level costs.

TABLE 7.

Summary of key variables and assumptions

PARAMETERS	ASSUMPTIONS OR VALUES	SOURCE
OPERATIONAL PARAMETERS		
Vehicle populations	Nationwide fleet population by class in 2020. Class 1: 115,000,000 Class 2b: 117,000,000 Class 2b-3: 8,590,000 Class 4-5: 954,000 Class 6-7: 1,130,000 Class 7-8 tractor: 3,240,000	Analysis of CARB's 2017 EMFAC database; EPA MOtor Vehicle Emission Simulator (MOVES) methodology (EPA 2020).
Vehicle useful service lives	Maximum useful service life is 15 years. Class 1: 12 years Class 2a: 15 years Class 2b-3: 15 years Class 4-5: 9 years Class 6-7: 13 years Class 7-8 Tractor: 15 years	Analysis of EMFAC2017 database (CARB 2017).
Vehicle miles traveled	Average VMT by class and age. Figures are for first year after manufacture. VMT declines by 3%-5% per year in all classes throughout their useful service life. Class 1: 18,800 Class 2a: 17,700 Class 2b-3: 17,300 Class 4-5: 43,000 Class 6-7: 24,900 Class 7-8 Tractor: 60,900	EMFAC2017 database (CARB 2017), EPA rulemaking analysis (FR 2002), and industry reports.

PARAMETERS	ASSUMPTIONS OR VALUES	SOURCE
Fuel economy	Assumptions about fuel economies for 2020, 2030, and 2050 in mi/gallon for ICE vehicles and kWh/mi for EVs. For both types, fuel economy for LDVs increases slowly while remaining close to static for MDVs and HDTs. ICE: Class 1: 29.7 | 34.5 | 45.1 Class 2a: 26.7 | 28.9 | 33.7 Class 2b-3: 7.5 | 8.1 | 8.1 Class 4-5: 9.5 | 9.9 | 9.9 Class 6-7: 6.6 | 6.8 | 6.8 Class 7-8 Tractor: 6.1 | 6.3 | 6.3 EVs: Class 1: 3.5 | 4.1 | 5.3 Class 2a: 3.1 | 3.4 | 4.0 Class 2b-3: 1.8| 1.9 | 1.9 Class 4-5: 0.5 | 0.5 | 0.5 Class 6-7: 0.5 | 0.5 | 0.5 Class 7-8 Tractor: 0.4 | 0.4 | 0.4	ICE: CARB 2019 analysis with correction factors ranging from 0.7-0.95 to harmonize estimates with EIA and projections from NREL 2018. EVs: CARB 2019 (for MDVs and HDTs). NREL 2018 for LDVs (CARB 2019).
EV range	250 mi for LDVs/MDVs; 300 mi for HDTs	LDV/MDV range based on most popular vehicles sales and average daily miles traveled; HDT range based on average VMT using FHWA 2020 data.
Battery operational characteristics	Assume a maximum battery service life of 1,500 cycles (at 80% depth of discharge) or 10 years, whichever comes first.	Phadke et al. 2021.
ECONOMIC PARAMETERS		
ICE vehicle: Initial purchase price	Purchase prices remain constant throughout the 2020-2050 timeframe. Class 1: $25,000 Class 2a: $30,000 Class 2b-3: $50,000 Class 4-5: $55,000 Class 6-7: $85,000 Class 7-8 Tractors: $125,00	CARB 2019; market analysis of current LDV models.
EV: Initial purchase price	Purchase prices in 2020, 2030, and 2050. Prices drop steeply between 2020 and 2030 as battery costs decline. Class 1: $40,000 | $23,000 | $23,000 Class 2a: $52,000 | $29,000 | $28,000 Class 2b-3: $61,000 | $45,000 | $43,000 Class 4-5: $71,000 | $55,000 | 53,000 Class 6-7: $93,000 | $77,000 | $75,000 Class 7-8 Tractor: $210,000 | $146,000 | $125,000	Bottom-up cost model.

PARAMETERS	ASSUMPTIONS OR VALUES	SOURCE
Maintenance costs	Costs are in 2020 USD per mile by vehicle class. Values are assumed to remain static. Maintenance costs for EV LDVs are about half of those for ICE LDVs. For MDVs and HDTs, costs for EVs are 25% lower than for ICE vehicles. ICE: Class 1: $0.06 Class 2a: $0.09 Class 2b-3: $0.17 Class 4-5: $0.31 Class 6-7: $0.31 Class 7-8 Tractor: $0.19 EVs: Class 1: $0.03 Class 2a: $0.04 Class 2b-3: $0.13 Class 4-5: $0.23 Class 6-7: $0.23 Class 7-8 Tractor: $0.14	For MDVs and HDTs: CARB 2019. For LDVs: Lutsey and Nichols 2019.
Electricity prices	Assume 2020 residential rates of $0.13/kWh for LDVs; commercial rates of $0.11/kWh for MDVs; and Industrial rates of $0.08/kWh for HDTs. By 2050, rates decrease modestly by 7%-13%. A sensitivity case considers unexpectedly high rates. In the high-price scenario, electricity prices for all classes remain relatively stable at $0.19/kWh (LDV), $0.13/kWh (MDV), and $0.11/kWh (HDT).	EIA Annual Energy Outlook 2020.
Fossil fuel prices	Average national prices for gas and diesel follow EIA projections. Prices below are for 2020, 2030, and 2050 in $/gallon. Gas: $2.26 | $2.80 | $3.23 Diesel: $2.52 | $3.29 | $3.69 The low fuel price sensitivity scenario assumes the following prices for 2020, 2030, and 2050 in $/gallon. Gas: $2.26 | $2.06 | $2.24 Diesel: $2.52 | $2.41 | $2.53	EIA AEO 2020.
Charging infrastructure costs	A per-mile cost for charging infrastructure is applied based on aggregate vehicle weight classes. The values shown below are for 2020-2035 and 2036-2050. LDVs: $0.0071 | $0.0057 MDVs: $0.0050 | $0.0047 HDTs: $0.0194 | $0.0146	Based on required number of chargepoints and estimated hardware and installation costs per chargepoint (authors' estimates).
Tax	8% of purchase price	CARB 2019.
Battery price	Predicted rapid decreases in battery prices drive the analysis. Assume that 2020 battery costs are $121/kWh, which drop to $62/kWh in 2030 and plateaus at $50/kWh after 2031.	BNEF 2019.
Discount rate	We assume a discount rate of 2.75%.	

PARAMETERS	ASSUMPTIONS OR VALUES	SOURCE
ENVIRONMENTAL PARAMETERS		
Grid emissions factors	Assume an average CO_2 emissions factor of 360 g/kWh in 2020, dropping to 160 g/kWh in 2030 and to 30 g/kWh in 2050.	Based on ReEDS results for capacity/generation mix needed for a 90% clean grid by 2035.
Grid environmental damage	Health and environmental damages quantified in ¢/kWh. Includes damages from CO_2, SO_2, and NO_x. Damages lessen over time as the penetration of renewables reaches 90% in 2035. Starting value is 2.1 ¢/kWh in 2020, decreasing to 1.1 ¢/kWh in 2030 and 0.21 ¢/kWh in 2050.	Based on ReEDS results on capacity/generation mix needed for a 90% clean grid by 2035.
Fossil fuel emissions factors	Assume CO_2 emission of E10 gasoline to be 0.008 ton/gallon and of diesel 0.010 ton/gallon. These emissions factors remain constant.	EIA 2016.*
Fossil fuel environmental damage	Environmental damages are considered separately for LDVs and MDVs/HDTs.† Below are costs of environmental damages relating to fossil fuel tailpipe emissions in ¢/mile in 2020, 2030, and 2050. LDVs: 2.7 | 2.3 | 1.8 MDV/HDTs: 19.9 | 19.0 | 19.0	Based on Thakrar et al. 2020 using a statistical value of life of $9M adjusted to account for increasing energy efficiency of ICE vehicles.
Cost of carbon	Assume cost of carbon in $/ton to be $49.2 in 2020, $66.1 in 2030, and $119.4 in 2050.	Ricke et al. 2018; Baker et al. 2019.
CHARGING INFRASTRUCTURE PARAMETERS		
Charger capacity	Assumed capacities in kW by charger type: L1: 1.4 L2: 11.0 DCFC: 50 High-capacity DCFC: 100	Wood et al. 2017.
On-peak utilization	Assume utilization factors at time of peak demand for home, work, public L2, Direct Current Fast Charging (DCFC), and high-capacity DCFC. Factor represents percent of available chargepoints in each category in use at hour of peak demand. Factors scale slowly during the study period, except for home charging, which remains stable. Home L2: 15% Work L2: 90% Public L2: 57% Public DCFC: 72% High-capacity public DCFC: 75%	

** EIA. 2016. Carbon dioxide emissions coefficients. https://www.eia.gov/environment/emissions/co2_vol_mass.php [last accessed 0/522/2021]*

† Roughly half of class 2b vehicles use diesel. Environmental damages of class 2b are estimated as the average of the per-mile damages for LDVs and trucks.

SCENARIOS

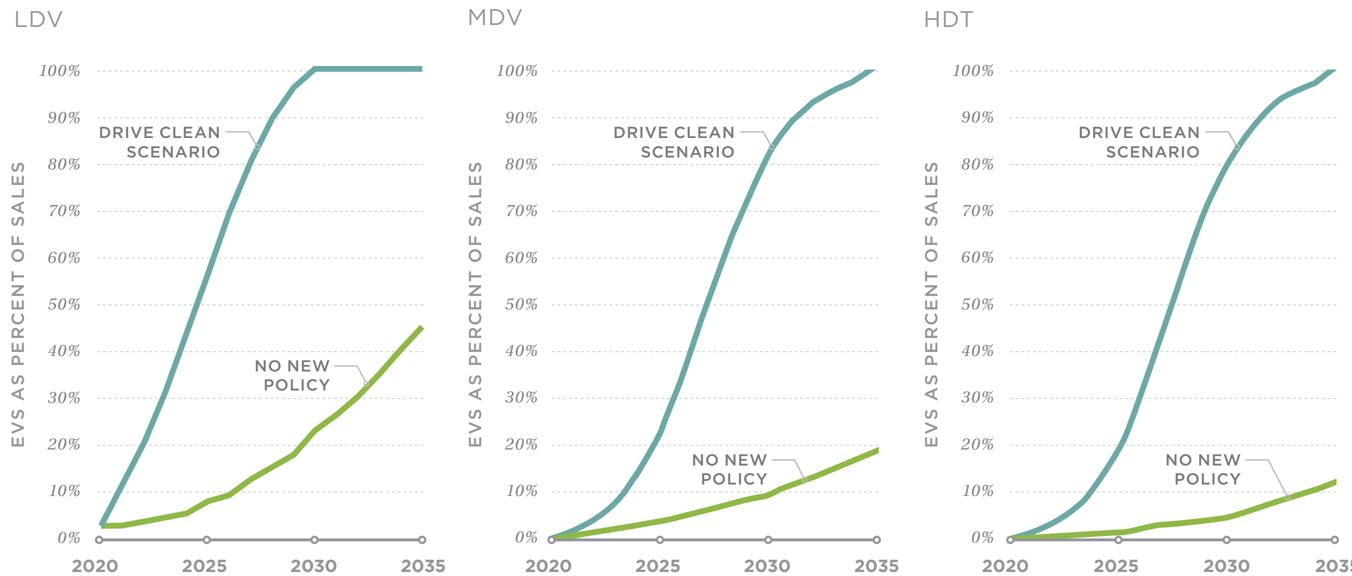
Our analysis evaluates the two scenarios described below, the No New Policy and the DRIVE Clean scenarios.

No New Policy

No New Policy is a business-as-usual scenario in which electrification of the nation's fleet proceeds as determined by current market forces without assistance from new state or federal policies. This scenario assumes that 2020 state and federal policies continue and that the current barriers to EV adoption persist. Barriers include underdeveloped charging infrastructure, higher upfront price premiums, no widespread adoption of EV-specific electricity rates, low levels of consumer awareness and acceptance, few policies aimed at addressing equitable access to EVs, and poor accounting for the societal advantages of EVs over conventional vehicles. In this scenario, by 2035 EVs constitute about 45% of new LDV sales, 38% of new MDV sales, and 12% of new HDT sales. The scenario is based on projections from BNEF, which suggest that—absent policy intervention—ICE vehicles will constitute 46% of the on-road vehicle population by 2050 (McKerracher et al. 2021). In that scenario, the electric grid decarbonizes as determined by current state and federal power-sector policies. This business-as-usual approach closely mirrors the projections of NREL's standard scenarios, in which the percentage of clean (carbon-free) electricity reaches 47% by 2035 (Cole et al. 2020).

Drive Rapid Innovation in Vehicle Electrification (DRIVE Clean)

DRIVE Clean is a scenario that projects that EVs constitute 100% of U.S. LDV sales by 2030 and 100% of MDV and HDT sales by 2035. The DRIVE Clean scenario assumes new policies are adopted and market forces shift to quickly overcome EV-related barriers. EV sales scale logarithmically to 100% between 2020 and the target year. By 2050, EVs constitute 97% of all on-road vehicles. In this scenario, all coal-fired power plants retire by 2030, no new natural gas plants are built, and the electric grid reaches 90% clean electricity nationwide by 2035—similar to the situation detailed in the first 2035 Report (Phadke et al., 2020). **Figure 16** shows EV sales as a percentage of total vehicle sales under each of the two scenarios.



FIGURES 16.

EVs as a percentage of vehicle sales under the No New Policy and DRIVE Clean scenarios

APPENDIX 3

DETAILED RESULTS

SUMMARY OF RESULTS

The methodologies and assumptions presented above directly affect total cost of vehicle ownership, vehicle stock turnover, and the total cost of the vehicle fleet across all classes. Those inputs, which impact the cost and environmental benefits of the transition from ICE vehicles to EVs, have significant implications for the overall results of our electrification analysis. This appendix also analyzes two sensitivity cases to highlight the effects of key assumptions on vehicle costs and overall trends in decarbonizing transportation.

TOTAL COST OF OWNERSHIP

For each of the six vehicle classes, we calculate a per-mile TCO for both ICE vehicles and EVs. The TCO includes upfront costs, fuel costs, maintenance, health and environmental damages attributable to the grid or to tailpipe emissions, and, for EVs, the cost of establishing charging infrastructure nationwide. **Figure 17** shows the components of the TCO for the six classes of EVs and ICE vehicles.

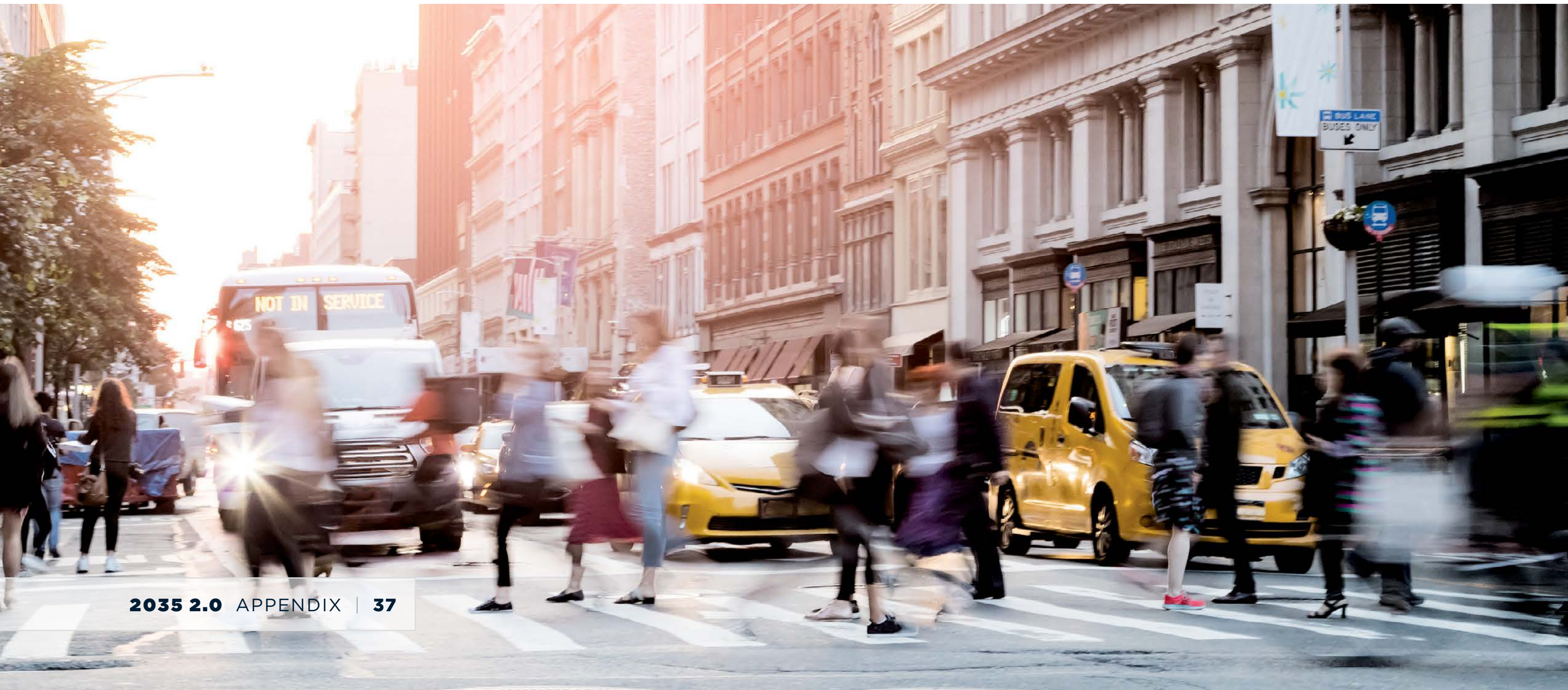


FIGURE 17.

Total cost of ownership by class and vehicle technology (coninued on next page)

FIGURE 17.

Total cost of ownership by class and vehicle technology (coninued from previous page)

In the early 2020s, ICE LDVs have a TCO advantage of roughly $0.05 per mile, although that drops to $0.02 per mile when accounting for environmental and health damages. Because LDVs have a relatively low VMT compared to heavier vehicle classes, the TCO advantage of ICE vehicles is driven by high upfront costs of EVs, which constitute 77% of their total TCO. Our model indicates, however, that given the forecasted dramatic decline in battery prices, light-duty EVs will reach upfront cost parity with their ICE counterparts within 5 years. Between 2020 and 2030, the per-mile upfront cost of EVs is predicted to decline from $0.24 to $0.14—a $20,000 difference in TCO during the vehicle's lifetime. Additionally, the operating costs (maintenance and fuel) of light-duty EVs are only 41% those of ICE vehicles. Although upfront cost is a major consideration in vehicle ownership, this analysis suggests that EV buyers will start saving money almost immediately. The faster upfront costs fall, the sooner consumers will realize the TCO savings.

Our analysis suggests that, even when excluding environmental damages, TCO parity already has been achieved for electric MDVs and HDTs. The cost competitiveness of EVs in heavier categories is driven by the large annual VMT and corresponding operational savings from fuel switching and by lower maintenance costs. We estimate that in the early 2020s, for example, per-mile electricity costs for HDTs ($0.13) are 53% those of their diesel counterparts. Maintenance costs are also lower, although those savings are partly offset by the cost of eventual battery replacements and charging infrastructure. Although the upfront cost of heavier classes of EVs does not affect the TCO as it does for LDVs, all classes of MDVs are expected to reach cost parity with ICE vehicles by 2030 or sooner. HDTs are expected to achieve near-parity by the early 2030s. It is important to consider the high cost of environmental and health damages when comparing the TCO of heavier-duty vehicle classes. Those classes contribute an outsized percentage of ground transport-related air pollution and CO_2 emissions relative to their numbers. Environmental damages account for roughly 25% of the total TCO for class 7-8 tractors throughout the 2020s. In 2035, this percentage is equivalent to $229,000 in health and environmental damages over the lifetime of the vehicle, compared to only $6,000 for an electric class 7-8 tractor fueled by a 90% clean grid.

STOCK TURNOVER

Under the DRIVE Clean scenario we take as inputs the 2020 vehicle population, projections of annual vehicle sales, and electric vehicle sales targets. The stock turnover model estimates the number of EV and ICE vehicles sold annually and the composition of vehicle stock. **Figure 18** illustrates the dynamics of vehicle sales and stock by class under the DRIVE Clean and No New Policy scenarios. The green represents the stock and sales of EVs that would go to ICE vehicles under the No New Policy scenario.

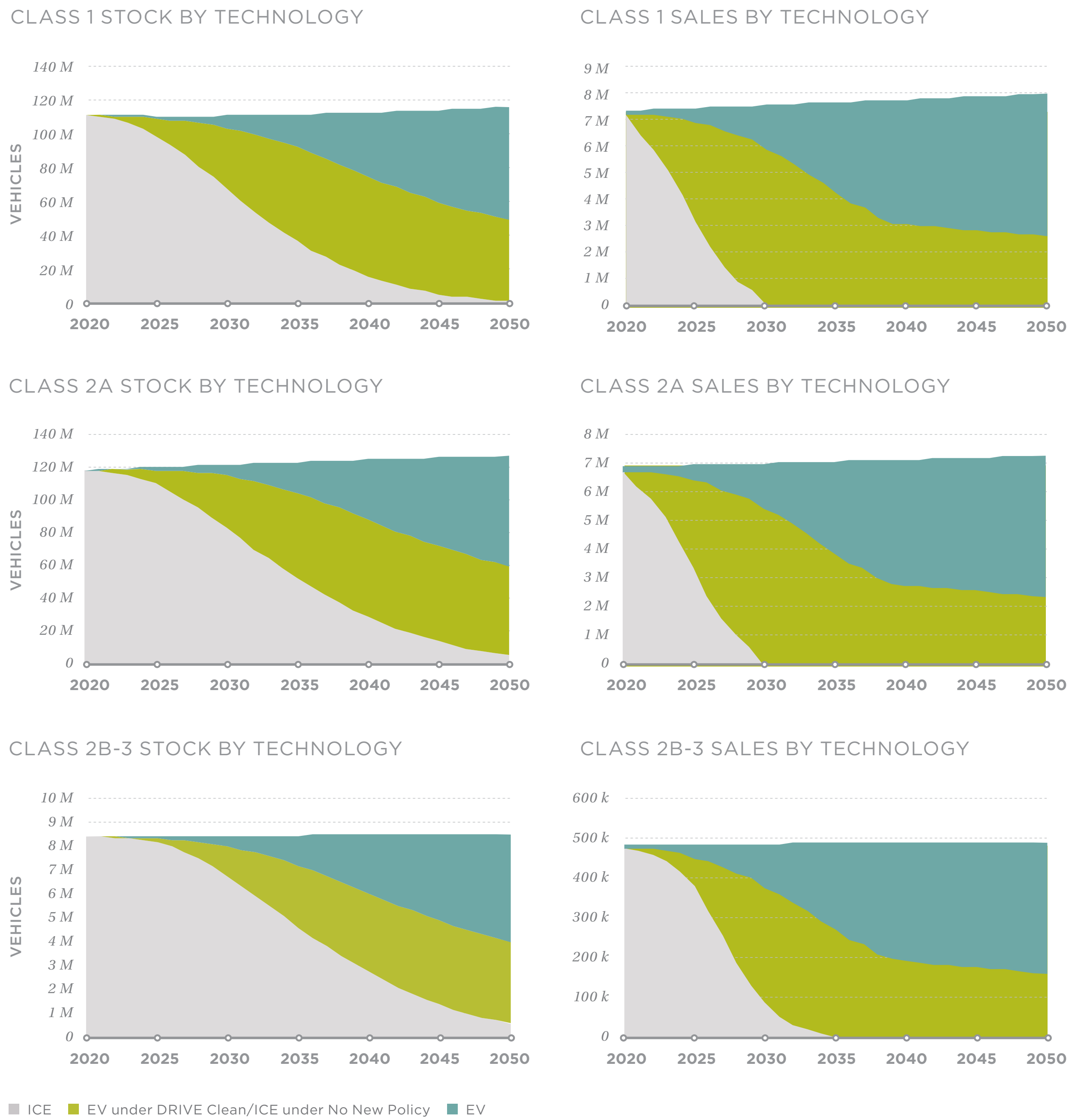


FIGURE 18.

EV and ICE vehicle stock and sales by class under No New Policy and DRIVE Clean scenarios (coninued on next page)

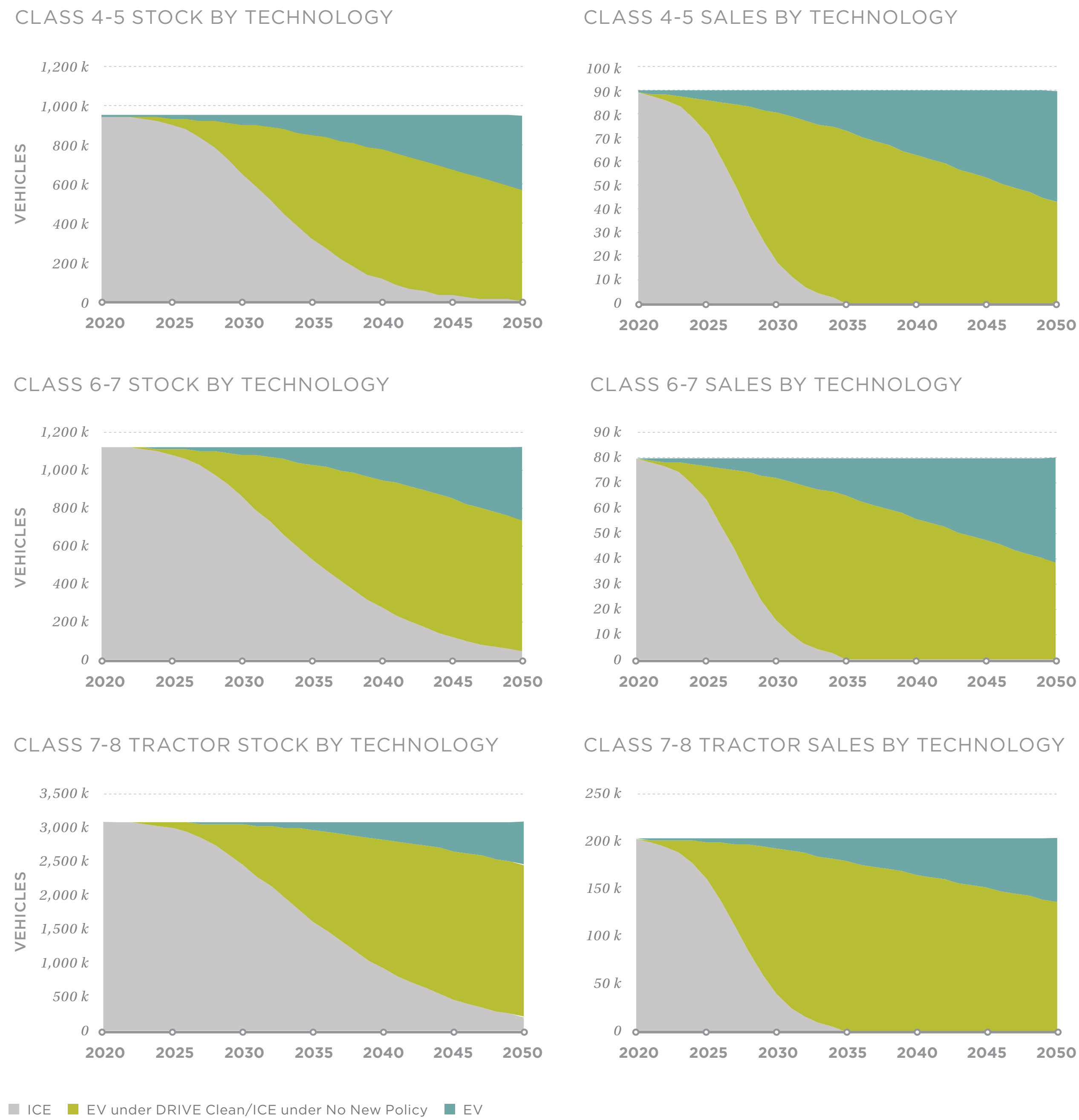


FIGURE 18.

EV and ICE vehicle stock and sales by class under No New Policy and DRIVE Clean scenarios (coninued from previous page)

The penetration of light-duty EVs in the No New Policy scenario, projected to be about 67% of sales in 2050, is higher than that of heavy-duty EVs (33% of sales in 2050). Given the large population of light-duty class 1 and 2a vehicles, the DRIVE Clean scenario, with its target of 100% electric LDV sales by 2030, results in 202 million would-be ICE sales being converted to EVs between 2020 and 2050. Although the population of HDTs is smaller, at 3.9 million, it represents a larger percentage (61%) of total sales than do LDV sales (44%).

There is an enormous difference between the DRIVE Clean and No New Policy scenarios vis-a-vis the number of ICE vehicles remaining in the national fleet in 2050. Under the No New Policy scenario, in 2050 ICE vehicles account for 43%-47% of LDVs, 47%-65% of MDVs, and 80% of HDTs. Under the DRIVE Clean scenario, those figures are reduced to 1%-5% for LDVs, 1%-7% for MDVs, and 7% for HDTs. The high percentage of MDVs and HDTs that remain in the national fleet reflects the longer service life of those vehicles, which makes it especially important to encourage early uptake of EVs in those vehicle categories.

SENSITIVITY ANALYSIS

We include two sensitivity cases to confirm the robustness of our results even if electricity rates increase or gas and diesel prices decrease. In the sensitivity case that evaluates low fossil fuel prices, we model a decrease in gas and diesel prices of 30% relative to the base case. In the sensitivity case for high electricity price, we assume approximately 40%, 18%, and 41% increases in per-kWh charging tariffs for LDVs, MDVs, and HDTs, respectively.

Figure 19 illustrates the effects of the two sensitivity cases on TCO for the six classes of vehicles.

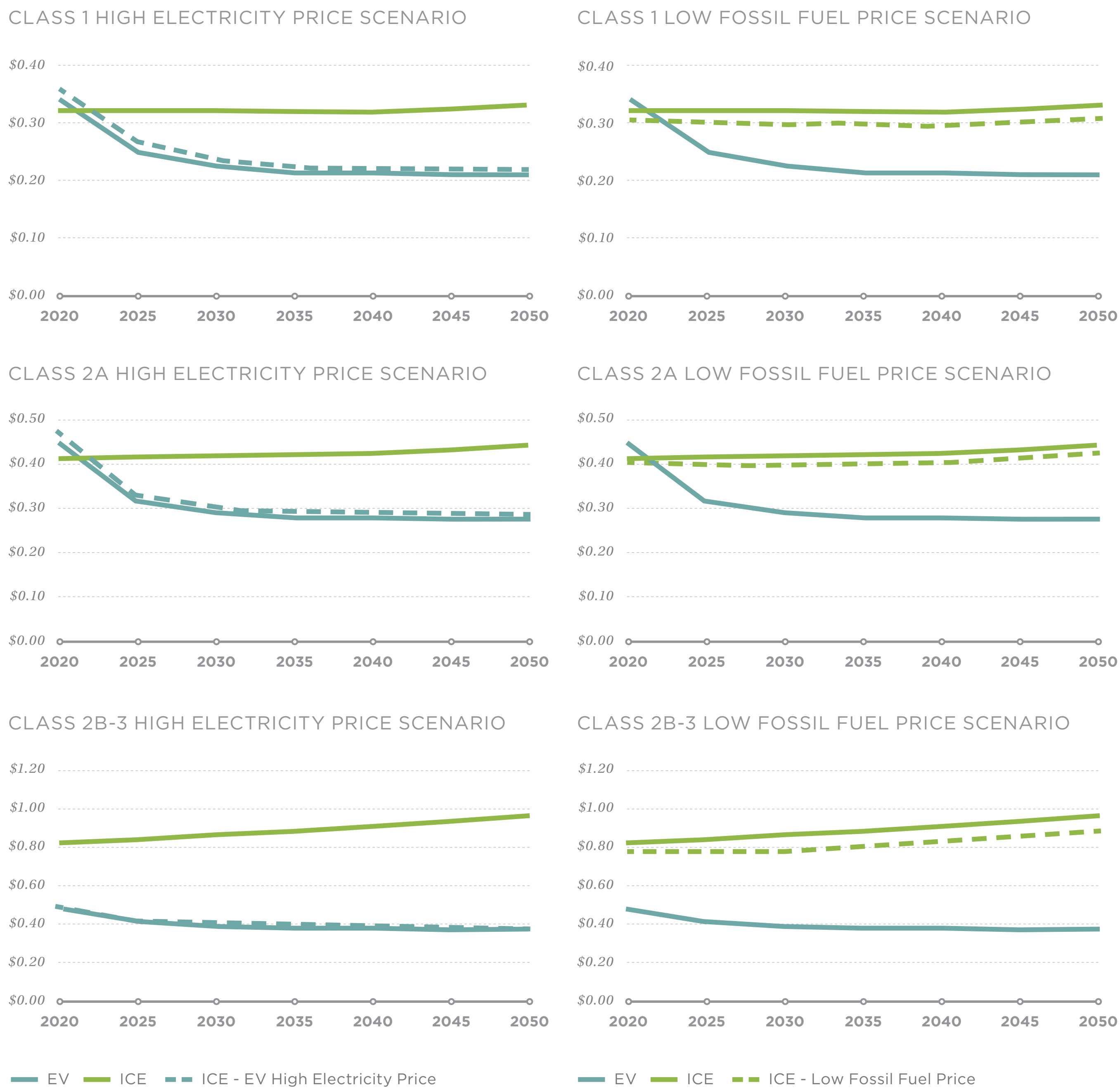


FIGURE 19.

Effects of sensitivity cases on TCO by vehicle class (coninued on next page)

FIGURE 19.

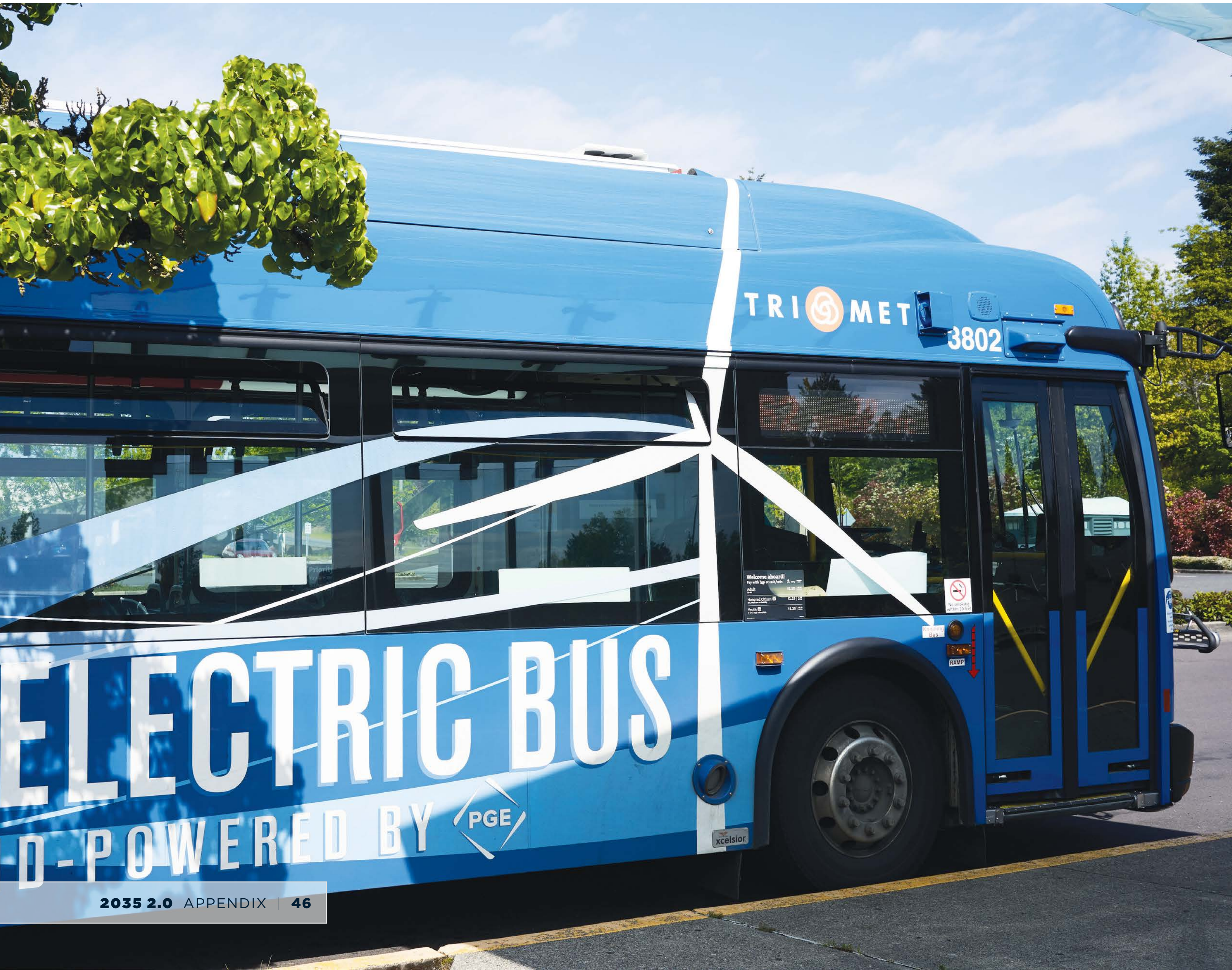
Effects of sensitivity cases on TCO by vehicle class (continued from previous page)

We find that the EV-adverse scenarios have only a small effect on their TCO competitiveness. The impact of the sensitivity cases on the TCO of comparative EV and ICE vehicles depends on the operational characteristics of the vehicle class. In either sensitivity case, lighter classes of vehicles experience a modest increase in TCO that delays parity by at most 1 to 2 years. For class 1 passenger vehicles, the sensitivity analyses find that higher electricity prices or low gasoline prices increase TCO by $0.01 and $0.02, respectively. For heavier vehicle classes, which have more annual VMTs, higher electricity rates or lower fossil fuel prices more strongly affect savings from fuel switching.

For class 7-8 tractors, we find that a 41% increase in electricity prices produces an $0.05 increase in TCO for EVs and that a maximum 30% decrease in diesel prices increases EV TCO by $0.12. Our analysis shows, however, that the TCO of medium- and heavy-duty EVs is already lower under these adverse economic scenarios. Furthermore, future decreases in capital costs resulting from improvements in battery storage economics will fully offset any increases in fuel expenses.

FLEET-LEVEL COST ESTIMATION

The TCO savings realized at the individual consumer level translate into economy-wide savings at the fleet level. **Figure 20** compares fleet-level costs by class under the DRIVE Clean and No New Policy scenarios.



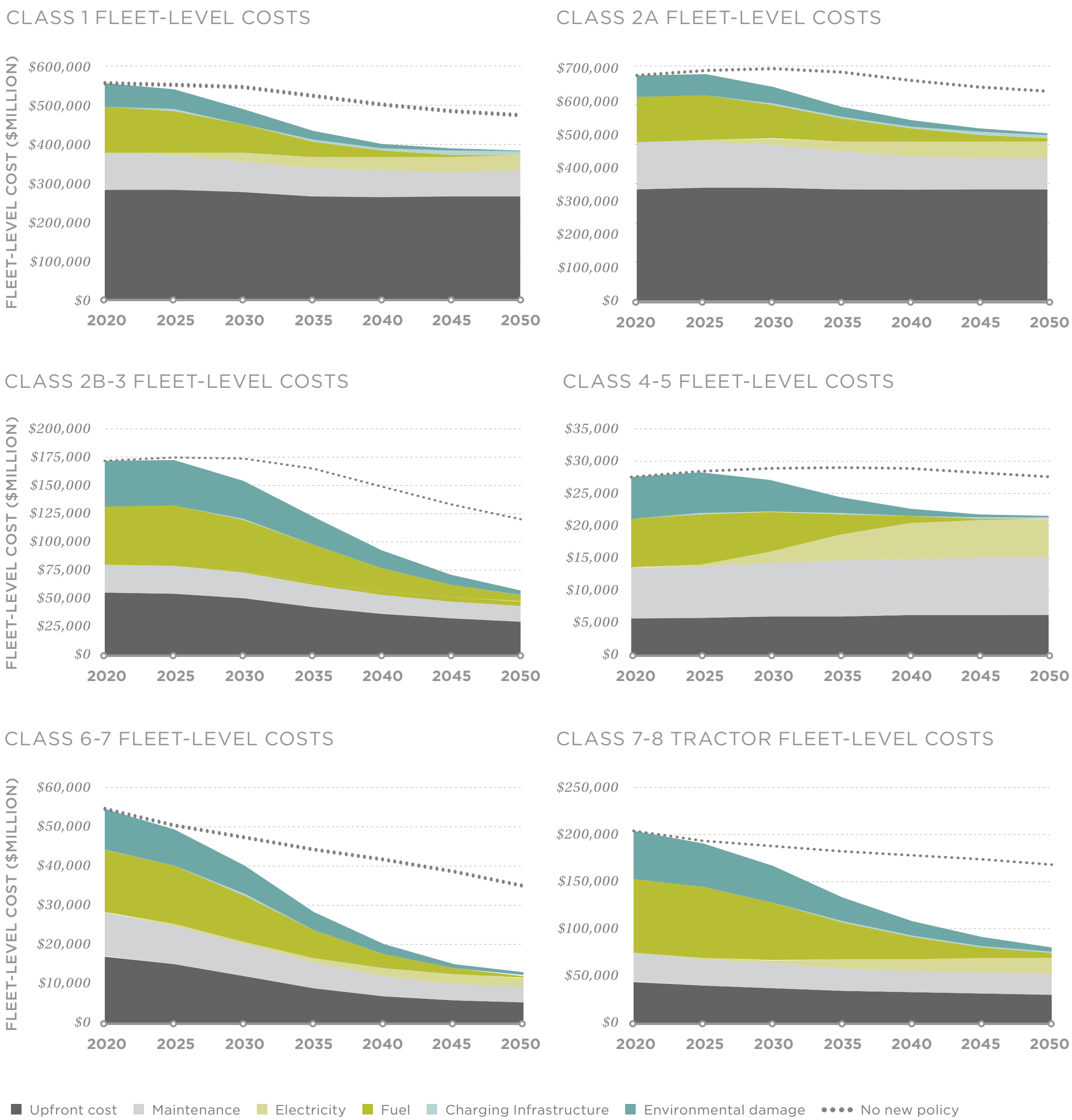


FIGURE 20.

National fleet-level costs by vehicle class under the No New Policy and DRIVE Clean scenarios

Including all vehicle classes, the savings under the DRIVE Clean scenario total $3.4 trillion, including the savings in health and environmental damages. Although some fleet-wide savings result from decreasing upfront and maintenance costs, those trends are offset partly by a naturally evolving increase in vehicle population during the study timeframe. Despite the increase in EV population, the DRIVE Clean scenario indicates savings across all classes from 2020 to 2050, including a 12%-13% reduction in total fleet costs for LDVs, 13%-30% for MDVs, and 24% for HDTs.

Across all classes, the largest savings—42% of the total—derive from fuel switching. The savings are greater for heavier vehicle classes having larger annual VMTs, such as class 6-7 vehicles and class 7-8 tractors. Applying the DRIVE Clean scenario, we observe a decrease in fuel costs of 31% for class 7-8 tractors compared to 27% for light-duty class 1 vehicles. For all classes, costs attributable to environmental damages decline 33%-50% under the DRIVE Clean scenario compared to the No New Policy scenario, as shown in **Figure 21**. LDVs contribute 54% of the total reductions, MDVs 22%, and HDTs the remaining 24%.

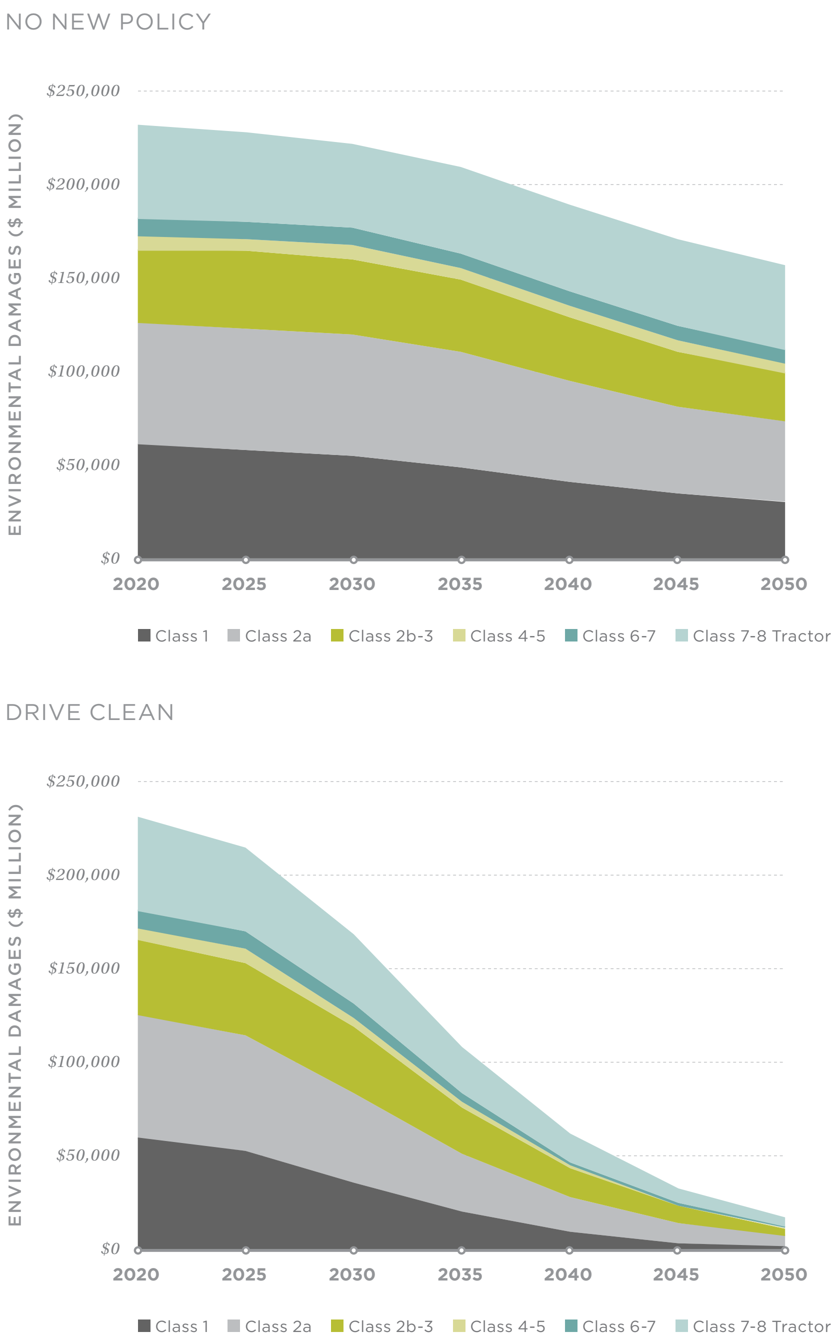


FIGURE 21.

Comparison of health and environmental damages under the No New Policy and DRIVE Clean scenarios

GRID IMPACTS

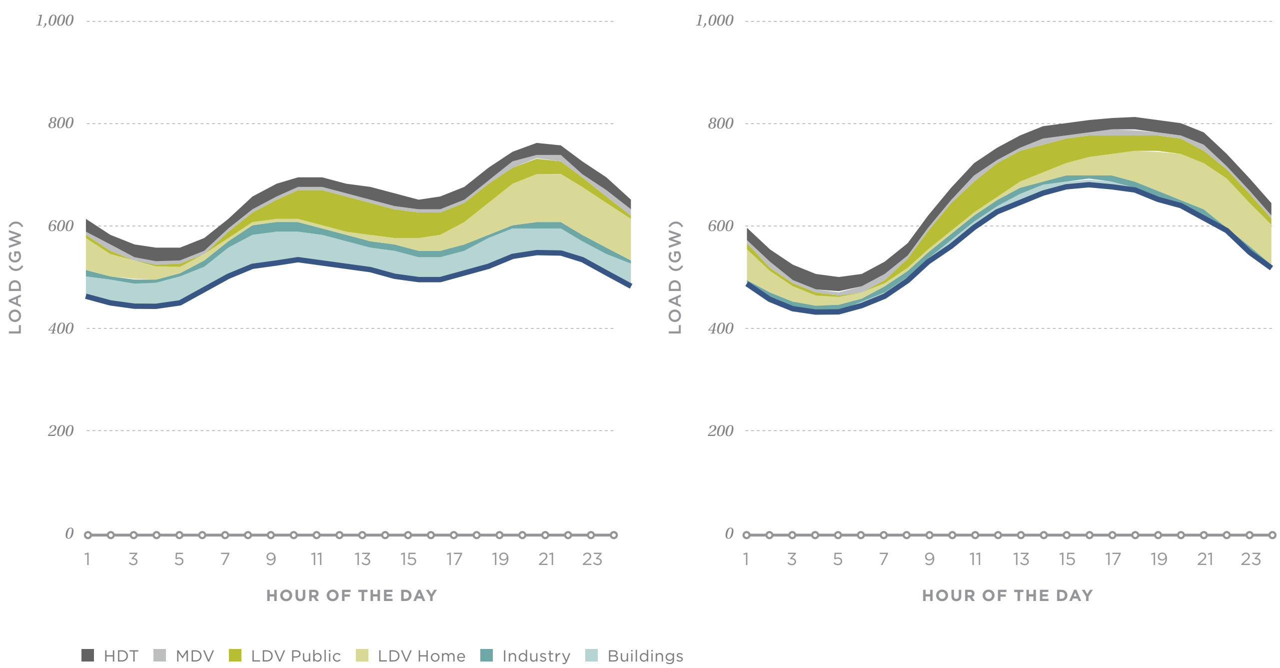
We evaluate effects on the electrical grid of increasing EV populations. We examine effects on system operations, load, and generation, the role of natural gas, the role of battery storage, the regional distribution of clean energy investments, and the potential of smart charging.

System Operations, Load, and Generation

System loads nationwide will increase significantly because of the projected electrification of the transportation, building, and industrial sectors. Electrification of transportation contributes more to load increases than does electrification of the building and industrial sectors, primarily because of the faster stock turnover rates. Load shapes vary significantly by sector and the use case within the sector. Most of the LDV home charging in our model occurs during evening/night hours, while most of the LDV public charging occurs during the day and evening. MDV and HDT charging occurs throughout the day and the load curve is largely flat. Building electrification load, which is mainly heating, peaks primarily in winter. Commercial building heating has the effect of shifting the building electrification load peak to the middle of the day in winter. Industrial electrification load is largely flat through all seasons and hours of the day. **Figure 22** shows the additional hourly electricity demand in 2035 due to electrification in the DRIVE Clean case.

FIGURE 22.

Average additional hourly electric load in 2035 under the DRIVE Clean scenario (left: January, right: July). All hours are EST.



To model the operation of a low-carbon power system, we examine hourly dispatch at the power plant level throughout the United States. ReEDS is used to assess capacity expansion during the study years, while PLEXOS is used to model hourly operations in 2035. Weather is a key factor in electricity demand—it affects both demands from buildings and the output of wind and solar generators. We incorporate seven years of weather data, from 2007 to 2013, to cover a range of probable conditions. In the future large amounts of solar and wind power will produce significant changes in daily supply and demand profiles. Even in the No New Policy case, solar and wind sources are expected to expand to 39% and 34%, respectively, of national electricity generation by 2035, with higher levels in some regions. The DRIVE Clean scenario pushes solar and wind generation up to 39% and 34%, respectively, of national electricity supply. Because solar is a daytime-only resource, California's current phenomenon known as the duck curve will be endemic to all power systems. The duck curve is so named because the shape of the load profile resembles the profile of a duck. The curve features low net demand during midday hours, followed by a large and rapid ramp-up to the net peak period in the early evening, when the sun fades as electricity demand does. The extent of the afternoon ramp-up and timing of the net peak depend on regional weather patterns and especially on air conditioning load as a percent of total demand. The outputs from wind and solar sources in a given region typically are not correlated, and sometimes can even be synergistic. In most regions, wind sources typically peak in the evening or nighttime, but have significant variability in hourly and daily output. During summer peak load periods (July/August), wind energy resources decrease significantly, while during winter peak load periods (December-February), solar energy resources decrease significantly. Regions that have an advantageous balance of wind and solar may show a less dramatic duck curve than do solar-dominated systems.

Utilizing large amounts of renewables can require some curtailment of wind and solar generation during periods of excess generation relative to demand. Although energy storage may absorb substantial amounts of the excess generation, saving it for use in hours of lower generation, a point comes when the long-run marginal cost of adding more storage outweighs the cost of wasting clean generation. It costs less, in short, to pay producers for their curtailed power than to install enough storage to eliminate curtailment. Our model includes the full annualized cost of wind and solar, including the costs of curtailment. Under the DRIVE Clean scenario, wind and solar are found to be reasonably synergistic at the national level, combining to provide around-the-clock supply on average. The lowest wind output is in the summer months (July and August), when the shortfall is made up by higher solar output and greater dispatch of gas generators. Similarly, in winter (December/February), when solar output drops significantly, wind generation and gas dispatch increase. Batteries can be charged during the day, then discharged for the evening peak load, reducing dispatch of gas generators. The use of batteries is most pronounced in summer months. Curtailment is highest in spring (March/May), when wind and solar generation increase while electricity demand for space cooling has not yet started. Curtailment is nearly absent in peak summer months (July and August), owing primarily to the high afternoon demand and a significant drop in wind generation.

ROLE OF NATURAL GAS

This study incorporates the novel strategy of using already built gas-fired power plants—sparingly—along with low-cost storage—to fill the gaps in wind and solar generation. Thanks to the broad availability of wind, solar, and other clean assets such as nuclear and hydropower, the gas-fired plants need operate infrequently and thus produce few emissions. ReEDS modeling retires gas plants only at the end of their technical life rather than for economic reasons; under the DRIVE Clean scenario ReEDS retains about 450 GW of gas capacity in 2035. Transferring that capacity to PLEXOS, which evaluates hourly operational feasibility throughout seven weather years, results in a maximum of 311 GW of gas capacity used in 2035. This amount is about 60% of the 540 GW of gas capacity currently operating in the United States. Because no new gas capacity is needed to meet electricity demands, this strategy creates significant cost savings while moving to a clean energy future. Gas is especially useful for periods of high net load such as summer afternoons (high demand and little wind generation) or winter (high demand and little solar generation). The overall load is smaller in winter than in summer. In the solar-heavy renewable energy configuration that we project, however, the overall renewable generation in winter drops significantly, resulting in a high net load. Based on seven years of weather data across the United States (2007-2013), PLEXOS found the hourly need for gas generation tends to be highest in both the peak summer (July/August) and winter (January-February) months. In the DRIVE Clean case for 2035, the highest gas dispatch in the seven weather years occurs in weather year 2010 on February 2 at 7 AM Eastern Time, at 311 GW, as shown in **Figure 23**. More than 70 GW of the natural gas capacity gets dispatched during less than 1% of the operating time, as shown in **Figure 24**.

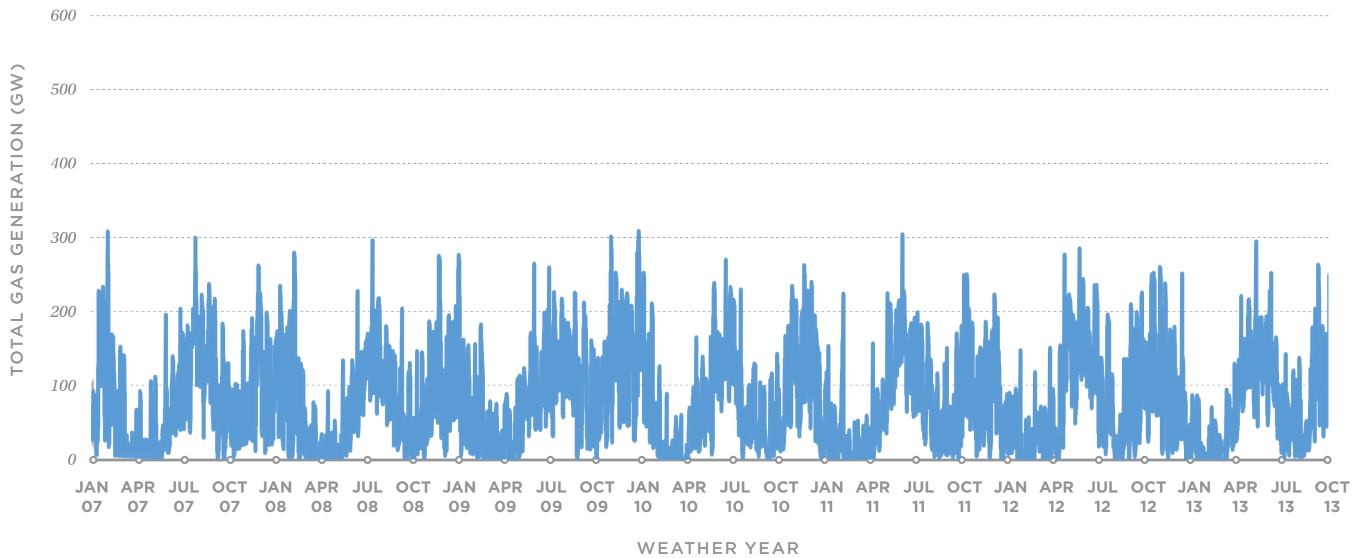


FIGURE 23.

Total gas generation in 2035 over seven weather years

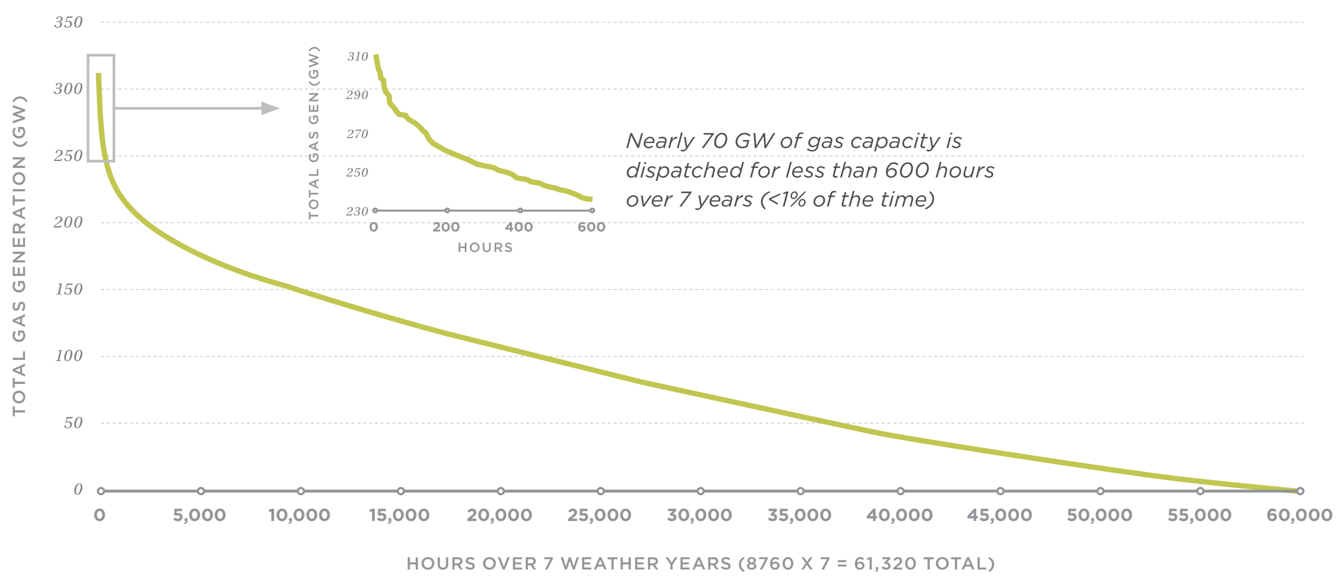


FIGURE 24.

Total gas generation duration curve in 2035 over seven weather years

ROLE OF BATTERY STORAGE

Batteries can provide the grid with diurnal balancing because they generally charge during the day and discharge during the evening and early morning. Batteries are crucial for meeting loads during evening and night hours, when most EV home charging occurs. We estimate that by 2035, 425 GW (~2600 GWh) of battery storage capacity will be required to operate the grid cost-effectively. More specifically, we find the need for 31 GW of 2-hour batteries, 70 GW of 4-hour batteries, 156 GW of 6-hour batteries, 160 GW of 8-hour batteries, and 9 GW of 10-hour batteries by 2035. The role of batteries is crucial in meeting the load during evening and night hours, particularly because most of the EV home charging load takes place during those hours. Batteries generally charge during the day and discharge during the evening and early morning and are critical for providing diurnal balancing to the grid. Their role in providing the seasonal balancing (e.g. shifting the excess renewable generation during spring months to high-demand summer months or low-RE winter months) is rather limited.

REGIONAL DISTRIBUTION OF CLEAN ENERGY INVESTMENTS

The quickly and steeply decreasing cost of wind and solar energy renders investments in renewable energy cost effective throughout the country, including in states that have significant coal and gas capacity. Those investments will provide significant job gains and opportunities during the transition from fossil fuels. **Figure 25** shows locations by state for investments in new renewable energy and storage capacities (2021-2035). **Table 8** summarizes the investments in new clean energy resources for the top 15 states under the DRIVE Clean scenario.

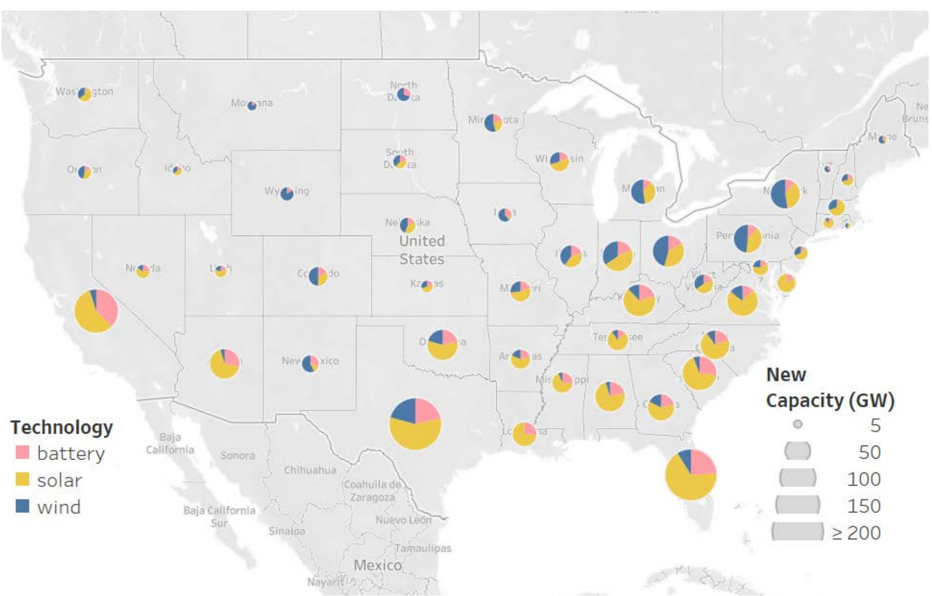


FIGURE 25.

Cumulative new renewable energy and storage capacity by state (2021-2035)

TABLE 8.

Investments in new clean energy resources by the top 15 states under the DRIVE Clean scenario (2021-2035 total)

STATE	NEW INVESTMENTS IN WIND, SOLAR, AND STORAGE (GW)	NEW INVESTMENTS IN WIND, SOLAR, AND STORAGE ($ BILLION, 2020 REAL)
Texas	242	277
Florida	194	221
California	140	168
New York	64	97
South Carolina	85	96
Ohio	72	88
Kentuky	75	85
Virginia	69	82
Indiana	67	79
Oklahoma	68	79
Arizona	64	76
Pennsylvania	57	74
Alabama	64	66
North Carolina	62	65
Georgia	51	61

All regions of the country could experience significant economic activity from deploying local renewable energy generation and storage capacity. The transition from fossil fuel generation, however, may disrupt the lives of some workers and communities that rely on jobs and tax revenue from fossil fuel production and power generation. Policies implemented to decarbonize the power sector should include measures to support transitions to a lower-carbon economy. Research suggests that wind and PV plants can be built close to many retiring coal plants, helping to provide new economic opportunities in affected communities (Gimon et al. 2021). Support for economic redevelopment and diversification beyond the clean energy industry also can help make a smooth transition from fossil fuels.

ROLE OF SMART CHARGING

EV charging load peaks (at about 150 GW nationally) in the evening at about 8-9 pm EST. The primary driver is LDV home charging (about 90 GW nationally). Although our simulations did not model EV smart charging, several other studies have shown that smart charging of EVs could offer significant grid benefits—particularly for managing the evening peak load, net load ramp ups after solar hours, and investments in the distribution system. There are three ways in which smart charging of EVs would benefit the system.

(a) The LDV home charging load could be delayed by 3 to 4 hours so the charging load does not coincide with the evening peak load. Most passenger cars already provide a range of 200 to 300 miles, which is significantly more than LDVs average in a day. Because the cars may still retain significant range when they arrive home in the evening, EV drivers may be willing to delay home charging.

(b) Charging of HDTs and MDVs could be shifted primarily to solar hours. Doing so would offer the possibility of signing long-term solar purchase agreements, which would provide nominally fixed and low charging costs and offer significant hedge against fluctuating oil prices.

(c) Smart charging of EVs that shifts the charging demand away from system peak hours could help with cost-effectively managing the distribution system upgrades that may be needed for meeting the overall demand for additional electricity. This potential benefit would arise because investments in distribution systems are determined primarily to meet peak load. Additional analysis is needed to assess in detail the role of smart charging and its economic benefits.

APPENDIX 4

MANUFACTURING CAPACITY AND COMMITMENT

This appendix describes the conditions necessary to support and further the production of EVs, including manufacturing the vehicles themselves, producing the batteries required for EV operation, and obtaining and processing the necessary raw materials.

ELECTRIC VEHICLE MANUFACTURING

Governments in the EU, China, India, Japan, Korea, and Canada all provide direct financial support for EV and battery manufacturing. The financial support typically is combined with other EV policies, such as emissions standards, limitations on ICE vehicles, and consumer purchase incentives.

In the United States, President Biden has proposed $174 billion dedicated to charging infrastructure, tax credits, federal procurement, consumer incentives, and other policy measures to expand domestic EV production and sales.[16] Global and domestic manufacturing supply chains already have begun to ramp up aggressively to meet new EV demands.

The federal government must structure its policies so that transportation decarbonization creates new American manufacturing jobs. Consumer incentives to purchase EVs will not, by themselves, effectively increase domestic employment. Policies that address only sales demand risk relying heavily on imported products, as is the case with solar cells. EV and battery manufacturing are at risk of following the same path, but there remain opportunities to seed substantial battery and EV manufacturing in the United States.[17] The United States needs an industrial policy on EV and battery manufacturing that addresses both supply and demand.[18] According to the ICCT, nearly three-quarters of EVs sold in the United States were produced in one region, suggesting

16 See Biden/Harris website. https://joebiden.com/made-in-america/ [last accessed 05/22/2021]

17 A related issue is that federal R&D spending is needed to provide domestic production of raw materials. See Energy Department Selects 15 Projects to Advance Critical Material Innovations. [last accessed 05/22/2021]

18 The U.S. is one of the few major auto powers that lacks a serious EV manufacturing strategy. See *Industry Week's* May 21, 2020 "Time for a Serious US Electric Vehicle Manufacturing Strategy." [last accessed 05/22/2021]

the necessity of a strong demand-side market strategy.[19]

United States-based manufacturers have announced plans to spend at least $34 billion investing in domestic EV and battery manufacturing. In the United States it takes 2 to 5 years to construct a large-scale vehicle manufacturing plant, from ground- breaking to production. Tesla is developing an electric pickup truck plant in Austin, Texas, at a site chosen in mid-2020 that will begin production in 2021 or 2022. Tesla's factories in development in Berlin and Shanghai are on similar two-year construction schedules. Ford announced in February 2021 that it will invest $29 billion in autonomous and electric vehicles through 2025.[20] Ford already has invested $700 million and broken ground for a new high-tech manufacturing center at its Rogue Complex in Michigan. The expansion is dedicated to its all-new, all-electric F-150 pickup truck, projected to come to market in mid-2022. The Lordstown Motor Corporation, which purchased a closed GM plant in Ohio in 2020, has 100,000 pre-orders for EVs, expects to produce 50,000 light trucks in 2022, and can scale production at that site to 600,000.[21] Meeting the goal of all EVs sold in America being American-made by 2030 will require establishing, in the next 10 years, about 26 to 30 EV manufacturing plants at a scale similar to Lordstown's Ohio plant.

GM will need many EV plants operating by 2030 to meet its ambition to sell only EVs by 2035.[22] Volkswagen has a recently converted Zwickau plant that will produce only its electric ID.3 brand and has plans for a new EV production plant in Tennessee (see note[19] above). The company hopes to make 75% of its new cars EVs by 2030. Fiat-Chrysler plans to launch more than 30 EV and hybrid products by 2022 and will invest heavily in electric vehicle manufacturing in the United States.

Along with building new manufacturing facilities, the required production can be achieved by converting existing vehicle manufacturing sites. Assuming the availability of batteries, converting such sites to EV production can happen faster than developing a greenfield site. Tesla purchased a closed vehicle manufacturing plant in Fremont, California, in 2010 and produced its first vehicle in 2012. In 2020 it employed 10,000 workers there producing 500,000 Teslas (NS Energy 2020).

Electric medium-duty vehicles and heavy-duty trucks present another opportunity to bolster U.S. manufacturing capability. More than 125

19 See ICCT's May 2018 "New study shows where the auto industry is primed for the transition to electric vehicles." [last accessed 05/22/2021]

20 See *Washington Post's* February 2021 "Auto industry peers into an electric future and sees bumps ahead" [last accessed 05/22/2021] and *Industry Week's* April 2021 "Ford's commitment to battery innovation is far from shocking." [last accessed 05/22/2021]

21 See YouTube video February 2021. "Electric Truck Series Part 1 - Lordstown Motors." [last accessed 05/22/2021]

22 GM already has extensive experience with EV manufacturing from its large market share of EVs in China. In late 2020 its Wuling brand Hongguang Mini became the top-selling EV in China. Sales of GM's Chevrolet Bolt in the United States doubled in the fourth quarter of 2020 from a year earlier.

zero-emission MDVs and HDTs are in production, development, or demonstration in the United States (Sharpe et al. 2020). Volvo has invested heavily in its electric Class 8 heavy-duty truck. Daimler has invested $20 million in a Detroit ePowertrain manufacturing facility. Dana, Cummins and Meritor are investing in manufacturing heavy-duty truck and bus components. Proterra, China's BYD, and others are producing electric buses in the United States. A parallel set of investments is occurring in domestic battery manufacturing.

Although the challenge of drastically ramping up American EV manufacturing may seem daunting, historical and international precedent supports the feasibility of the endeavor. China's explosive vehicle manufacturing growth demonstrates that government support is key to EV manufacturing. For example, in the nine years from 2000 to 2009, China ramped up its production of ICE vehicles from 2 million to almost 14 million and, for the first time, surpassed U.S. auto production. It began producing significant numbers of EVs only in 2013, but has invested nearly $60 billion in the industry, which now produces about 1.33 million passenger EVs (both battery-only and hybrid) (International Energy Administration 2020). China also produces 90% of the world's electric buses. The United States is not far behind, and a well-organized set of policy and financial supports can put the United States back in a leadership position.

A similar situation is occurring in the European Union. The EU has launched policy initiatives to ramp up sales of passenger EVs. Europe's global share of the electric vehicle market climbed sharply from an annual average of 3% in 2019 to about 8% in early 2020, surpassing even China in sales of electric and plug-in hybrid vehicles. Norway, where EVs make up 46% of the country's vehicle fleet, is the global leader in size of EV market share. Volkswagen is investing $37 billion globally in its EV program and has committed to sell 28 million electric cars by 2028. Similar stories are found in other parts of the world. In 2018, Japan launched a mandate to achieve 100% electric vehicle sales by 2030.[23] South Korea's EV market is forecast to grow by a compound annual rate of 19% between 2019 and 2025.[24] Given ambitious and thoughtful federal policy support, the United States also can build a thriving new domestic electric vehicle manufacturing industry.

23 See January 2021 "IHS Markit forecasts global EV sales to rise by 70% in 2021." [last accessed 05/22/2021]

24 See February 2020 Orion Market Research's "South Korea Electric Vehicle Market Size, Share & Trends Analysis Report... and forecast 2019-2025." [last accessed 05/22/2021]

BATTERY MANUFACTURING

The critical component of electric vehicles, batteries, requires a separate dedicated manufacturing capacity and supply chain. Global demand for lithium-ion batteries, which represent about 300 GWh today, will increase dramatically, particularly if the United States pursues an aggressive vehicle electrification strategy. Analysis of the current and projected battery manufacturing landscape suggests that global manufacturing capacity can ramp up to meet demand. Industry announcements for new and expanded battery manufacturing facilities promise more than 500 GWh in new global capacity by 2022 and nearly 1,000 GWh by 2025 (up from 95 GWh in 2019). Germany, which achieved a national EV market share of 17.5% in October 2020, has committed $1.1 billion to fund EU battery production. France developed an $800 million action plan to support the battery value chain. The planned expanded production of battery cells and packs far exceeds the needs of near-term electric vehicle mandates from around the world.

The United States has an opportunity to participate in the battery production race, partly because, while currently lagging other countries, it is not starting from zero. Current U.S. production of lithium-ion batteries is about 60 GWh, or approximately 13% of global production (Gul et al. 2020). BNEF projects that U.S. lithium-ion battery production will quadruple by 2025 (McKerracher et al. 2021). Numerous battery manufacturers are investing heavily in domestic production. LG Chem, for example, will invest more than $4.5 billion between now and 2025 in its U.S. business to bring annual domestic production capacity to more than 110 GWh. One of its battery plants, a joint venture with GM, involves $2.3 billion of investment in a 35-GWh plant in Ohio that is expected to open in 2022. Ford is making a $185 million investment in its new global battery research center, while Sila Nanotechnologies plans to build a factory in the United States to make the silicon anode materials to supply batteries for more than one million EVs annually. SK Innovation is completing work on $2.6 billion worth of U.S. battery manufacturing facilities, which will employ 1,000 workers by the end of 2021 and 2,600 by 2024, when they expect to produce batteries for more than 300,000 EVs annually. Tesla has several large battery manufacturing plants in operation or advanced development, while Novonix is producing synthetic graphite for battery cells at a factory in Tennessee.

Several factors encourage optimism that the United States, given strong policy support, can supply much of its own demand for EV batteries. First, economics strongly favor battery manufacturing near EV sales markets because batteries are heavy and expensive to transport. Labor, which is traditionally more costly in the United States, is only a small part of battery manufacturing costs. Those factors make the United States a competitive place to manufacture batteries if governmental policy drives an increase in EV demand and sales. Second, financial incentives to both buy and produce in America[25] can substantially increase U.S. lithium-ion battery production by 2030. Third, the United States has a technical lead in developing solid-state lithium batteries, which may offer lower costs and operational advantages over current lithium-ion batteries. Finally, the costs of manufacturing batteries are declining, partly because of U.S. technical leadership. According to RMI 2019, increasing investment in the lithium-ion supply chain will reduce the cost of new manufacturing capacity (on a per-GWh basis) by more than half from 2018 to 2023.

GLOBAL RAW MATERIALS AND PROCESSING

Benchmark Mineral Intelligence (2019) estimates that more than 2,000 GWh of battery capacity will be in the pipeline for 2028. Globally, raw material reserves are more than sufficient to support the transition to EVs (Greim et al. 2020). A concern regarding domestic EV manufacturing is access to a supply of (and capacity to process) raw materials. Currently, the United States depends largely on foreign sources for most of the 35 rare-earth elements needed for manufacturing batteries, wind turbines, and other clean energy technologies. Foreign sources also supply most of the other critical raw materials for batteries and motors, including lithium, graphite, and cobalt. Most analysts expect that raw material supplies, with the possible exception of lithium, will not be a constrained during the next 10 years. Still, efforts are underway to address ongoing lithium supplies and demand, and governments are planning numerous efforts to address longer-term supply risks for other minerals and elements.[26]

25 See January 2021 "Executive Order on ensuring the future is made in all of America by all of America's workers." [last accessed 05/22/2021]
26 See BNEF, Electric Vehicle Outlook 2020. [last accessed 05/22/2021]

The United States has a start on securing reliable sources of raw materials. California's Salton Sea presents an opportunity to create a new U.S. lithium industry. Lithium is found in high concentrations in the Salton Sea brine, and several ventures currently are experimenting with extraction methods. Other projects are underway to expand or develop domestic mining and processing capacity for lithium and other raw materials.[27] In 2020 U.S. agencies established a consortium to promote a domestic battery industry, citing the role the industry could play in consumer electronics and national defense. The United States is using the Defense Production Act to speed development of mines for extracting rare-earth elements. Congress included provisions to secure domestic and allied sources of strategic minerals and metals, including lithium, in the National Defense Authorization Act for fiscal year 2021.[28] In April of 2021, the U.S. Department of Energy launched a $30 million grant program to support increasing domestic supplies of rare-earth elements.

Recycling batteries is another way to secure raw materials. Some experts suggest a significant proportion (30%-40%) of demand for raw materials for new batteries can be met through recycling.[29] Multiple systems and processes are available to recover rare-earth metals from used batteries. China is the only country that has a policy focused on recycling vehicle batteries. China's largest EV manufacturer, BYD, has begun construction of a battery recycling plant in Shanghai. Other countries are pursuing recycling. A Belgian company has developed a smelting technology to recover battery metals, including cobalt. Redwood Materials, a startup developed by a former Tesla Chief Technology Officer, is recovering scrap metal left from the manufacture of EV batteries for use in new EV batteries.

The development of robust battery recycling programs will be especially important for the United States as it approaches high-volume EV manufacturing in 2030. More can and should be done to create a large-scale battery recycling industry in the United States. America can follow China's lead and impose battery recycling obligations on EV manufacturers; require battery products to be standardized for easy disassembly; and establish tracing systems for battery components.

27 For example, the Australian firm Ioneer is seeking permits to establish a lithium mine in Nevada to quadruple U.S. production. Another company, Piedmont Lithium Ltd., expects to begin producing lithium in North Carolina by 2023.

28 See December 2020 Metal Tech News, "Strategic metals firepower for Pentagon." [last accessed 05/22/2021]

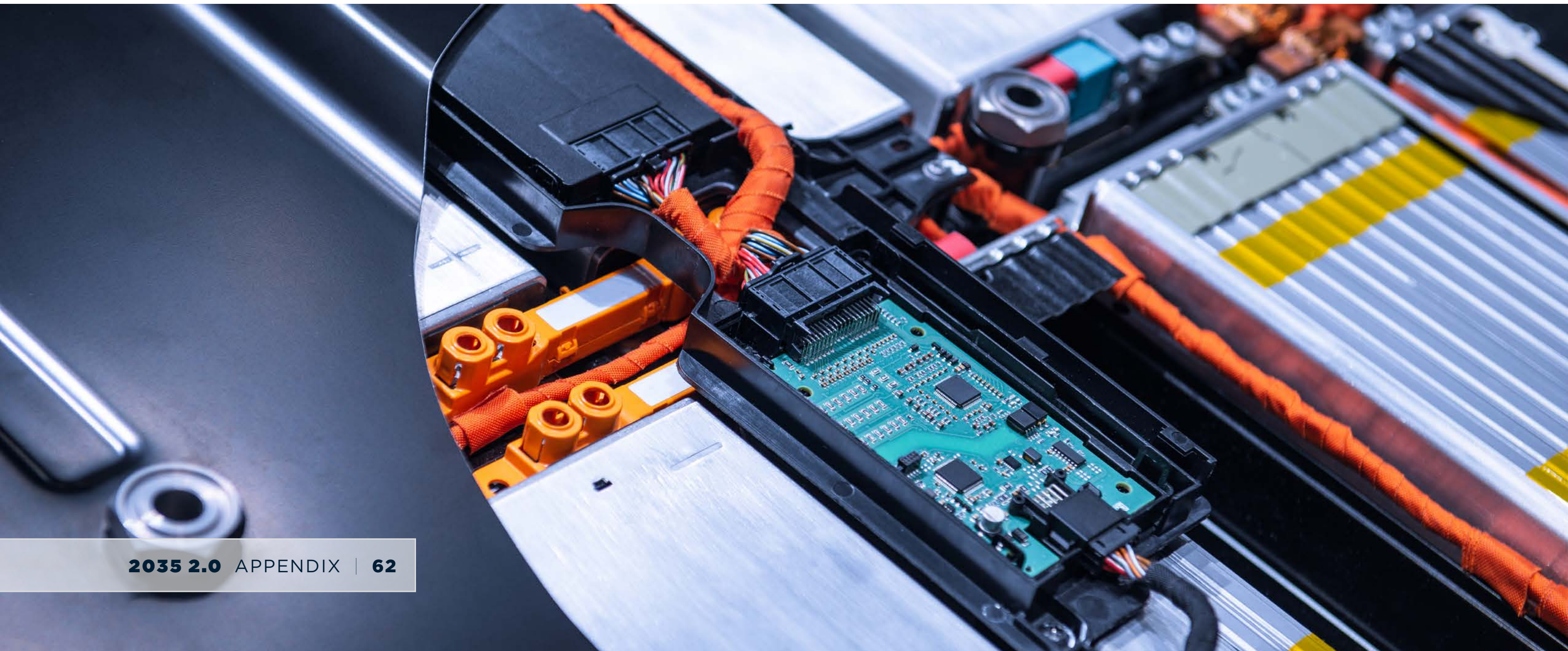
29 See Union of Concerned Scientists February 2021 fact sheet titled, "Electric vehicle batteries: Addressing questions about critical materials and recycling." [last accessed 05/22/2021]

APPENDIX 5

DISTRIBUTION SYSTEM INVESTMENTS

Although our analysis of the power sector considers the impacts of vehicle electrification on investment in new generation and transmission capacities, it does not consider impacts to distribution systems. Distribution grids will require upgrades to support increasing electric loads from vehicle charging. A supporting analysis from E3 evaluates investments in distribution systems required to support electrification (Cutter et al. 2021). This analysis considers impacts of light-duty electric vehicles only; additional work is needed to understand the impacts MDVs and HDTs, as well as other industry subsectors such as buildings, will have on the distribution system.

This analysis estimates the U.S. national electric utility distribution upgrade costs that will be driven by EV charging for the No New Policy and DRIVE Clean (100% electrification of LDV sales by 2030) scenarios in the 2035 Report 2.0. We estimate costs for two categories of upgrades: primary distribution costs such as distribution transformers and feeder lines driven by coincident peak EV charging (coincident peak load); and secondary distribution costs such as lines connecting distribution transformers to homes, driven by the interconnection of EV chargers (connected load). Key drivers of distribution upgrade costs vary widely and are location-specific, making any nationwide estimate



necessarily approximate. For the DRIVE Clean scenario we estimate 2050 annual revenue requirements for distribution upgrades that range from $2.8 to $20 billion. Even at the high end, this is a fraction of the $162 billion of annual distribution revenue requirement projected for 2050 by the 2021 Annual Energy Outlook. Additionally, the added EV charging load would actually reduce average $/kWh distribution rates. The 2021 AEO projects a national average distribution cost of $0.03397/kWh based on retail sales of 4,748 TWh in 2050. The highest cost estimates of the E3 analysis add $20 billion in annual revenue requirement for the distribution system, and a total of 882 TWh of EV charging load. This results in an average distribution rate of $0.03221/kWh, a reduction of $0.0018/kWh or 5%. Furthermore, simple managed charging solutions such as TOU rates could reduce distribution costs by 50% or more. Figure 26 details the cumulative distribution system investment costs of the DRIVE Clean scenario for the four cases E3 analyzed. The CA DRP cases are a detailed evaluation of all forecasted needs on the distribution system, based on an approach developed for the California Distribution Resource Planning Proceeding. The Marginal Cost cases are based on a survey of marginal cost approaches commonly used to estimate load growth in various rate cases and proceedings throughout the U.S. High and low estimates are utilized for each case.

The full analysis is published as a standalone paper and can be accessed here.

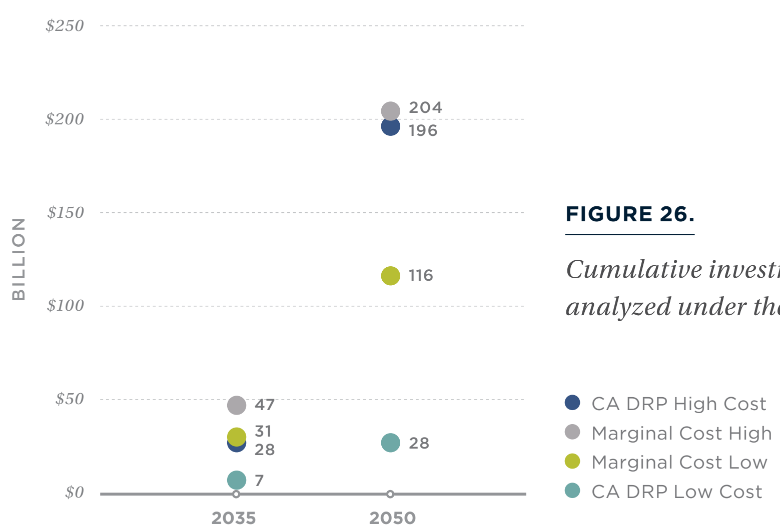


FIGURE 26.

Cumulative investment cost for four cases E3 analyzed under the DRIVE Clean Scenario

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