Princeton's Net-Zero America study
Annex C: Transport and Buildings Sector Transitions

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1 Introduction

Final energy demands in every sector over time and by region of the country are among the inputs used by the RIO model to determine the energy-supply technology mix over time that meets the 2050 target for net-zero emissions at least total energy-system cost, subject to other exogenous constraints that vary from one net-zero pathway to another. Final energy demands, including for transportation and buildings sectors, are developed using the EnergyPATHWAYS scenario tool, as discussed in Annex A [1]. Here we provide underlying input assumptions and intermediate results used to estimate final-energy demand in transportation and buildings sectors at each model time step.

The starting point for EnergyPATHWAYS calculations is projected demands for energy-services by region and over time across the entire modeling period. Energy-service demands are the same for all of our modeled net-zero pathways and are based on energy-service demands projected in the Reference case of the *Annual Energy Outlook 2019* [2]. The mix of technologies that use final energy to deliver the energy-service demands is exogenously specified in the form of assumptions about the fraction of different types of technologies entering service for the first time in any given year. For example, in the case of light-duty cars, the proportions of new sales in every modeled time step that are internal combustion engine vehicles (ICEV), battery electric vehicles (EV), and hydrogen fuel cell electric vehicles (FCEV) are specified. Each stock unit has an assumed useful lifetime, at the end of which the stock unit is replaced by a new unit of a type consistent with the exogenously defined proportions of different types of new sales for that year. EnergyPATHWAYS tracks the compositions of technology stocks by type of unit, vintage, and geographic performance. An example of the relevance of the latter is heat pumps for meeting building space conditioning demand. Performance varies from one region to another due to differing climates.

The Evolved Energy Research modeling team's considerable experience in modeling technology evolutions to achieve net-zero emissions targets was relied upon in developing assumptions about the likely needed change over time in technology mixes to achieve net-zero emissions targets. Additionally, to provide insight on the assumed technology penetration rates, two scenarios were run with different technology adoption rates. These correspond to the demand-side technology evolutions represented by the E+ and E- pathways.

Total final energy demand by type of energy carrier and region for each time step is then calculated based on the mix of technologies in the stock in that time step and the technology-specific efficiencies in converting final energy into energy services.

2 Transportation Sector

Road vehicles and airplanes account for most of the final-energy demand in transportation.

2.1 Road transportation

2.1.1 Energy-service demands, technology mixes, and final-energy use

Figure 1 shows energy-service demands (vehicle-miles per year) assumed for light-, medium-, and heavy-duty vehicles. Service demands stay roughly constant for light-duty trucks, but service-demands for light-duty autos and medium- and heavy-duty trucks all grow over time.

EnergyPATHWAYS tracks ten different types of road vehicles, each with its own assumed efficiency in converting final energy into energy-services over time (Table 1). New vehicles of all types entering service in a given time step are assumed to be more efficient than new vehicles entering service in the prior time step, with the average rate of efficiency improvement from

2020 to 2050 as shown in Table 1. By tracking technology vintages (and associated energy efficiencies) EnergyPATHWAYS determines the average efficiency for each vehicle type within the stock of vehicles operating in a given year serving the same duty level. The average efficiency by vehicle type, combined with the exogenously assumed fraction of that type of vehicle in the total vehicle fleet at that duty level and the total number of vehicles of all types at that duty level (determined from total energy-service demand and assumed amount of demand delivered by individual vehicles), is used to determine the total final energy needed for all vehicles of that type in that year.

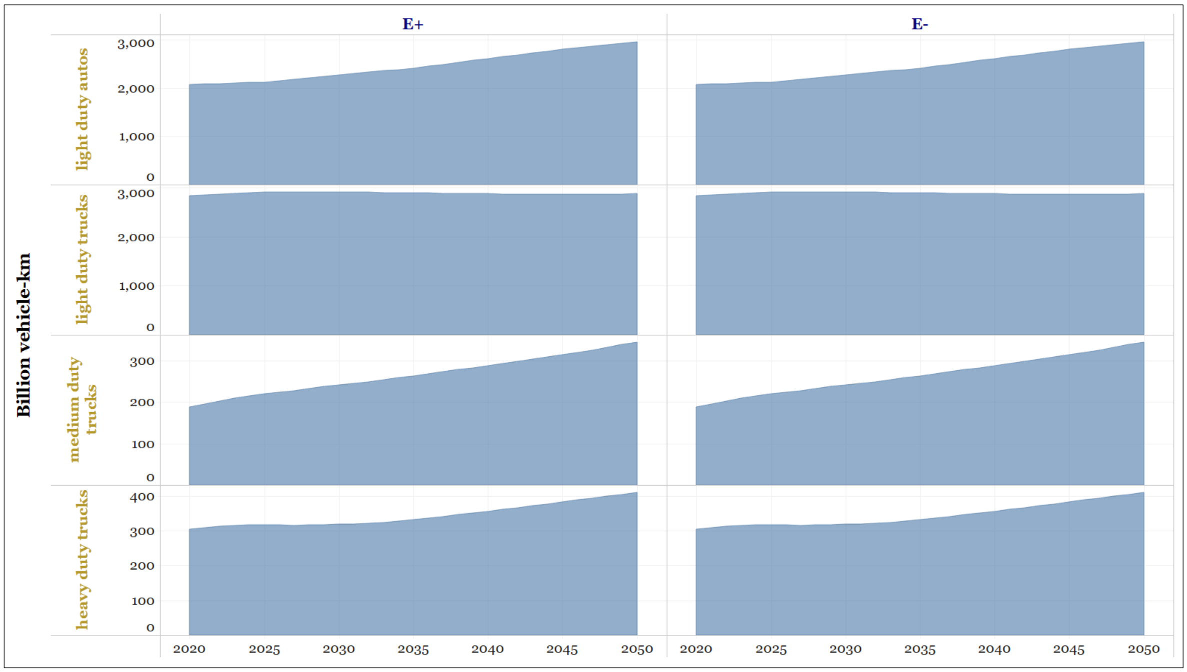

Figure 1. Energy-service demands for light-, medium-, and heavy-duty road vehicles. All modeled net-zero emissions pathways assume these same energy-service demands.

The average decline rates in energy use per vehicle-km in Table 1 reflect aggressive improvements over the 30-year transition period relative to historical rates of efficiency gains. To illustrate this point, we note that the highest average efficiency gain historically over any 30-yr period for light-duty cars, light-duty trucks, and heavy-duty trucks has been 1.7%/y (1973 – 2003), 1.9%/y (1970 – 2000), and 0.7%/y (1973 – 2003), respectively [3].

Figure 2 (left panel) shows the assumed fraction of new vehicle sales in the E+ and E- scenarios over time for light-duty cars, light-duty trucks, medium-duty trucks, and heavy-duty trucks. By 2030 in the E+ scenario, the fraction of new vehicle sales that are electric-drive vehicles (EV or FC) exceeds 60% for light-duty cars and exceeds 30% for the other vehicle-duty categories. By 2050, 100% of new sales of all vehicles are electric-drive vehicles. The penetration of electric-drive vehicles in the E- scenario is much slower, reaching 85% to 90% by 2050. ICEVs account for the remaining 10% to 15%.

Figure 2 (right panel) shows the evolution in vehicle populations by type within each duty-class resulting from the assumed sales fractions in the left panel and the initial distribution of vehicle types by age. The distribution of vehicle types and distribution of vintages of vehicles within each type in the initial modeled year (2020) are based on the *Annual Energy Outlook* reference case projections [2], as described in [4]. To allow for a realistic initial 2020 distribution of stock across vintages, this distribution is endogenously determined by starting the stock-turnover modeling in the year 2000. (This same approach is used to determine initial 2020 distribution of vintages for most demand-side technologies.)

Table 1. Modeled final-energy use per vehicle-km for road vehicles.

		MJ_{HHV}/vehicle-km		Avg. decline
Light-duty vehicles		**2020**	**2050**	**%/y**
	Gasoline car	2.74	1.98	0.92
	Gasoline truck	4.00	2.84	0.97
	Electric car (long-range)	0.82	0.56	1.03
	Electric truck (long-range)	1.26	1.03	0.63
Medium-duty vehicles				
	Diesel	7.51	5.72	0.8
	Battery electric vehicle	4.67	3.66	0.72
	Hydrogen fuel-cell vehicle	1.35	1.03	0.8
Heavy-duty vehicles				
	IC (Diesel) engine vehicle	14.17	10.5	0.86
	Battery electric vehicle	7.76	5.51	0.97
	Hydrogen fuel-cell vehicle	7.8	6.83	0.42

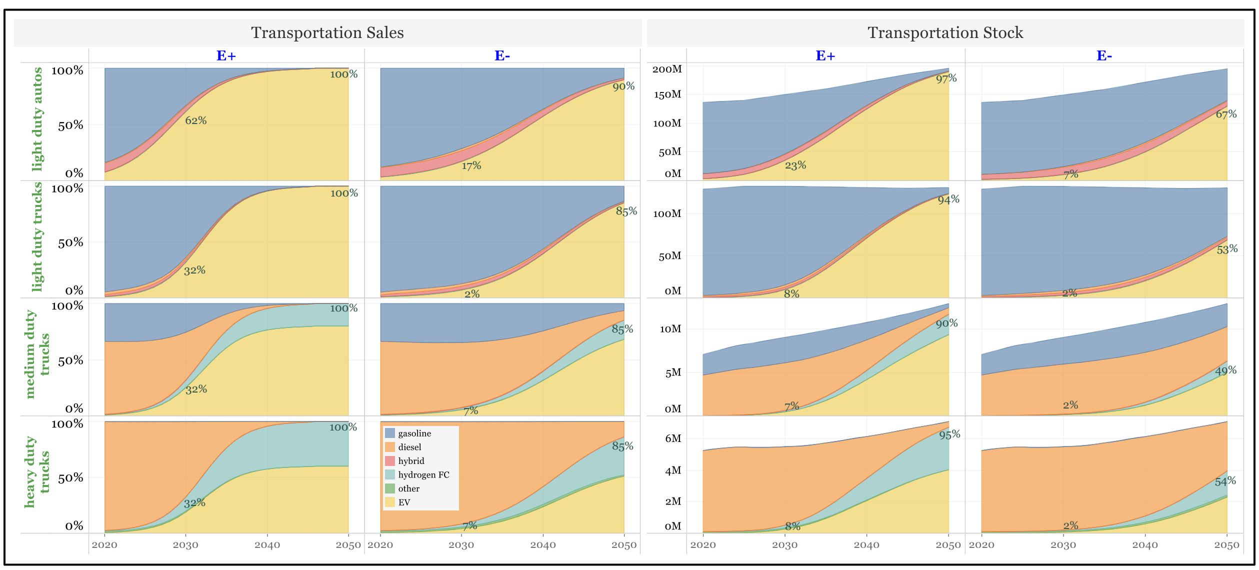

Figure 2. Left panel shows exogenously assumed fractions of new sales for different vehicle types within each vehicle-duty category for the E+ and E- pathways. Right panel shows resulting distribution of vehicle types within the total operating stock for each class of technology. Values superimposed on the graph at 2030 and 2050 indicate the fraction of new vehicle sales in those years that are electric drive train vehicles (BEVs and FCEVs).

An error, discovered during post-processing of EnergyPathways model outputs, caused EnergyPathways to incorrectly report state-level LDV and HDV stocks. (National level results were correctly reported, as were national and state level MDV stocks.) The LDV and HDV reporting errors did not cause incorrect modeling of the transportation sector at the national level, but required alternative downscaling methodologies to be used to estimate the distribution of LDV and HDV stocks across states. As a result, while national level LDV and HDV stocks are reported (at the [NZA website]) for six different vehicle types (battery electric [EV], gasoline, hybrid, diesel, hydrogen and other), state-level LDV and HDV stocks are reported for only two vehicle types each: "EV" and "all other" for LDVs and "fuel cell" and "all other" for HDVs. To be consistent with state-level LDV and HDV reporting, state-level MDV values from EnergyPathways are also reported in two categories, "EV" and a consolidated "all other". The national level stocks of LDV and HDV in Figure 2 were downscaled to the state level using different methods. As just noted, the reported state-level MDV stocks are those estimated by the EnergyPathways model.

For LDVs, the fraction of the national battery electric vehicles (EV) stock present in each state in 2020 was assumed to be the same as the fractions of actual 2020 state EV registrations reported by the DOE Alternative Fuel Data Center [5]. In 2050, the fractions of the national EV stock present in each state were assumed to be the same as the actual 2019 distribution of *all* light-duty vehicles across states, as reported by the Federal Highway Administration [6]. For 2030 and 2040, the state-level EV fractions are determined by interpolation as follows, where $EV\%_{US,20xx}$ refers to the national fraction of LDVs that are EV in year 2030 or 2040 (as in Figure 2), and $EV\%_{state,20xx}$ are the corresponding fraction for a state of LDV stocks that are EVs:

$$EV\%_{state,20xx} = EV\%_{state,2020} + \left\{ \left(EV\%_{state,2050} - EV\%_{state,2020} \right) \cdot \frac{\left(EV\%_{US,20xx} - EV\%_{US,2020} \right)}{\left(EV\%_{US,2050} - EV\%_{US,2020} \right)} \right\}$$

Figure 3 for E+ and Figure 4 for E- show the resulting number of EVs by state each decade.

A similar, though not identical, approach as for LDVs was adopted for HDVs. The fraction of the national HDV stock apportioned to each state was assumed for 2020 to be the same as reported in the EPA MOVES database [7], and this fractional distribution across states was assumed to stay constant through 2050. For each year in the transition, the fraction of a state's HDV stock that is hydrogen fuel cell powered was assumed to be the same as the modeled national fraction of fuel cell HDVs.

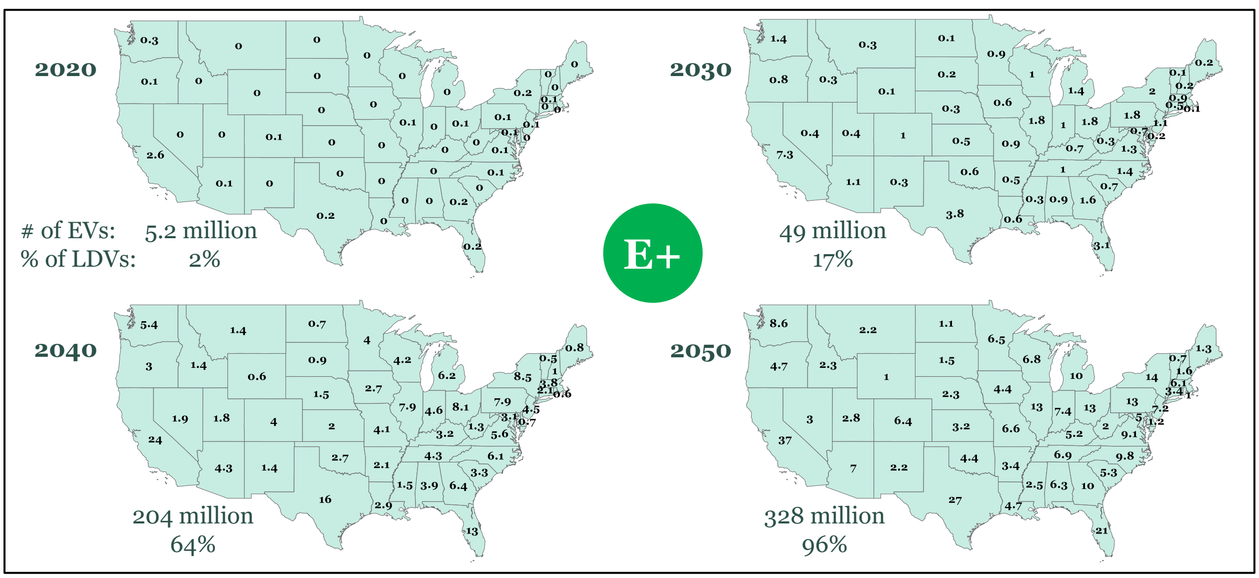

Figure 3. Number of light-duty electric vehicles (millions) by state in E+ scenario from 2020 to 2050. Also shown are national total number of EVs and the fraction of the light-duty vehicle fleet this represents.

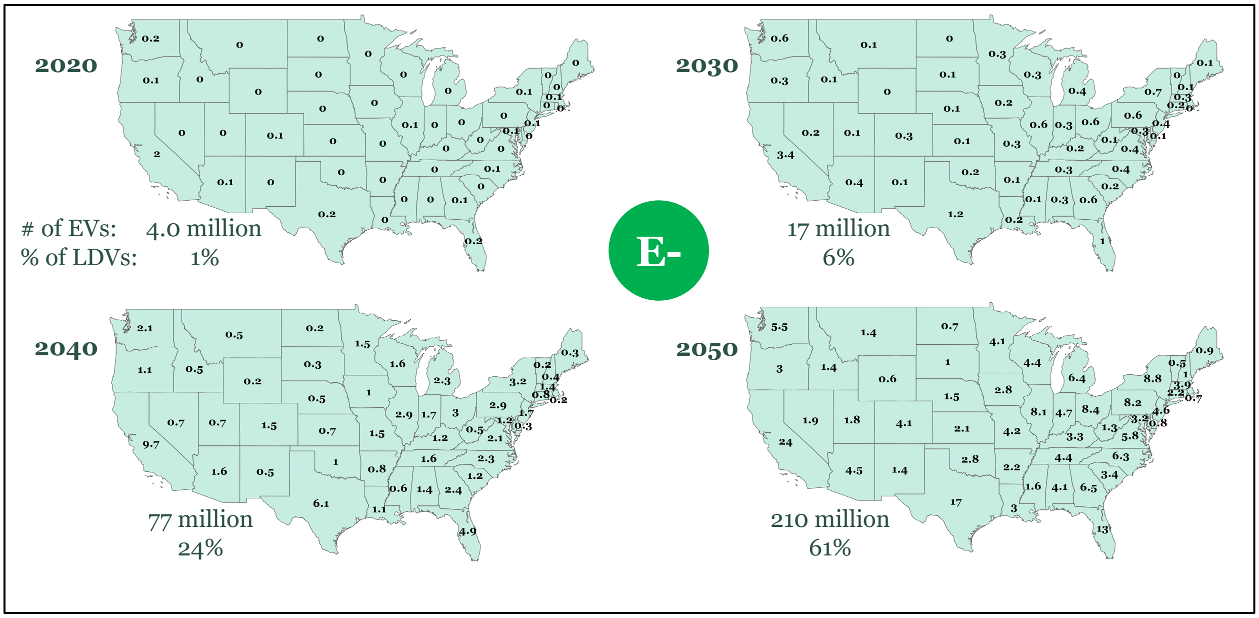

Figure 4. Number of light-duty electric vehicles (millions) by state in E- scenario from 2020 to 2050. Also shown are national total number of EVs and the fraction of the light-duty vehicle fleet this represents.

Figure 5 shows transportation final-energy demands by transport mode nation-wide that result from the EnergyPATHWAYS analysis described above. Results are shown for REF, as well as E+ and E- scenarios.

In the REF ("no new policies") scenario final-energy demand initially declines, with most of the decline due to light-duty vehicle efficiency improvements mandated by corporate average fuel economy (CAFÉ) standards. Those standards are slated to expire in 2025, but demographic momentum continues the decline in light-duty vehicle energy demands for about a decade thereafter before an increasing demand for energy services (Figure 1) begins to more than offset the improving fleet-average efficiency. Meanwhile, energy-service demands for other transportation modes also grow over time, and efficiency improvements in most modes are insufficient to prevent some additional growth in final-energy demands. Demand in 2050 for the sector as a whole is about 92% of the 2020 level.

In the E+ and E- scenarios, final-energy demand in 2050 is 49% and 62% of the 2020 level, respectively, with reductions in energy use for every mode of transport except aviation. In the case of aviation, efficiency improvements just offset growing passenger travel demands, and final-energy demand varies little over the course of the transition. In the case of light-, medium-, and heavy-duty vehicles, final-energy demand falls as a result of incremental efficiency improvements in gasoline and diesel ICEVs (Table 1), but the far larger reason for the decline is the replacement over time of large numbers of ICEVs by far-more-efficient electric drive vehicles (BEV or FCEV). The declines in final-energy use are especially dramatic for light-duty vehicles.

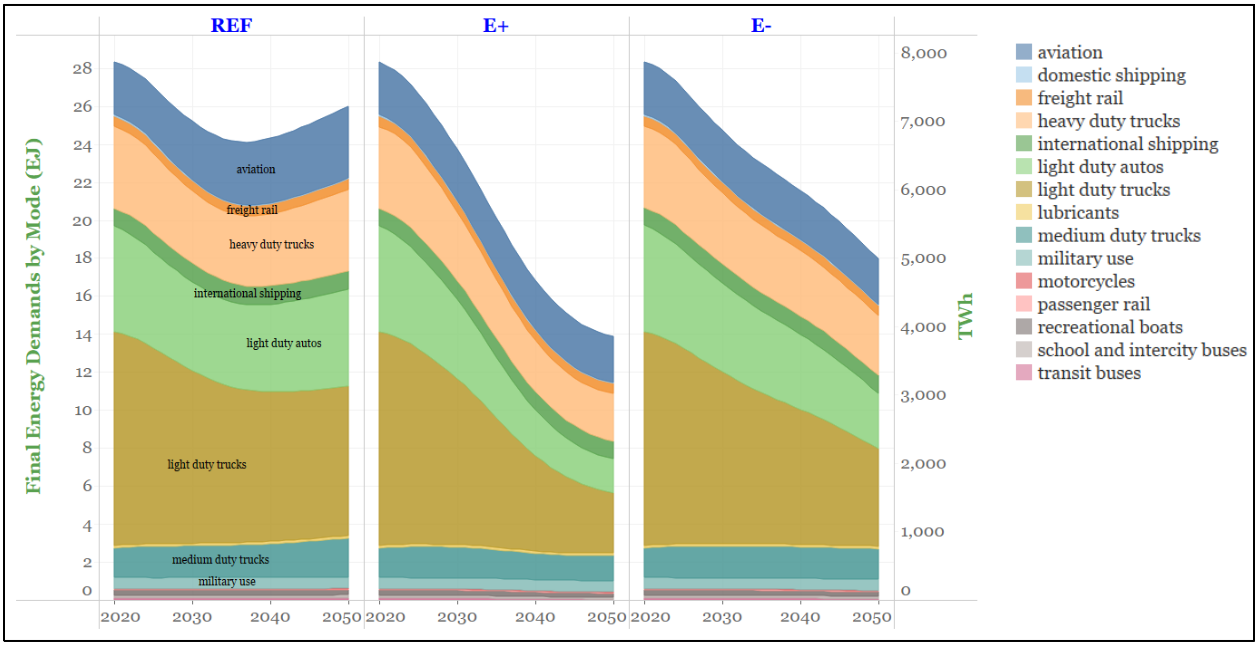

Figure 5. Final-energy demands in transportation by transport mode for REF, E+, and E- pathways.

2.1.2 Road-transport vehicle costs

Vehicle costs are key input assumptions for modeling total energy-system costs for the net-zero transition. The input costs assumed in the NZA modeling are based on reflect well-regarded projections of EV costs available at the time [8], adjusted to ensure consistency across vehicle types (see Appendix). Electric LDV costs have been falling in recent years due largely to battery cost reductions, and the model assumes costs reductions will continue, with cost parity reached with conventional ICEVs around 2030 in the case of light-duty vehicles (Figure 6). Cost premiums for medium and heavy-duty trucks are assumed to decline more slowly over time (Figure 7). Consistent with these higher first-cost differentials and larger relative battery sizes, these fleets transition to electric or hydrogen fuel-cell power more slowly than the light-duty fleets (Figure 2, right panel). We note, however, that significant uncertainty exists in the rate at which HDVs in particular could transition to BEV or FCEV. Because many HDVs drive far more miles annually than passenger vehicles, the operational savings that can come from BEV or FCEV is greater. This may result in delayed, but ultimately faster turnover than in the LDV sectors as businesses take advantage of a lower total cost of ownership. Nevertheless, even under the assumptions made here, penetration of the alternative drive trains into medium- and heavy-duty truck stocks is significant by 2050 because of the imperative the model has to reach net-zero emissions economy-wide by that year and the difficulty of scaling low-carbon drop-in-replacement liquid fuels to the level of liquid fossil fuel use today.

The cost of batteries for EVs has continued its rapid decline since the NZA modeling was completed, and more recent projections [e.g., 9, 10, 11] suggest that the incremental costs of EVs relative to ICEVs are currently falling more rapidly than assumed for the NZA modeling.

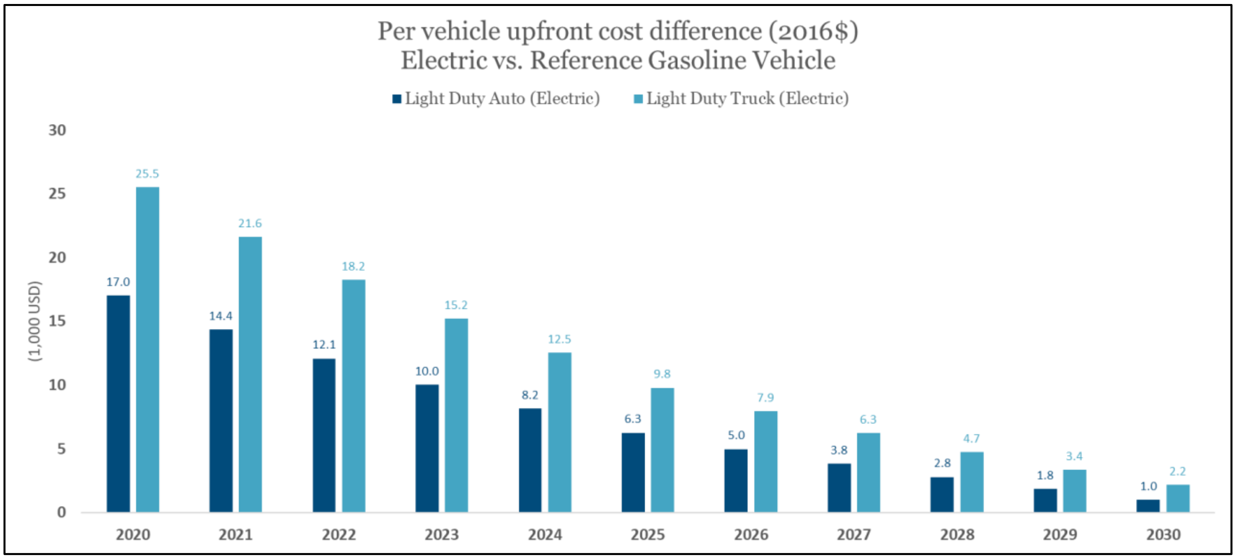

Figure 6. Upfront cost premiums for electric vs. gasoline light duty vehicles fall through 2020s, reaching close to parity by 2030

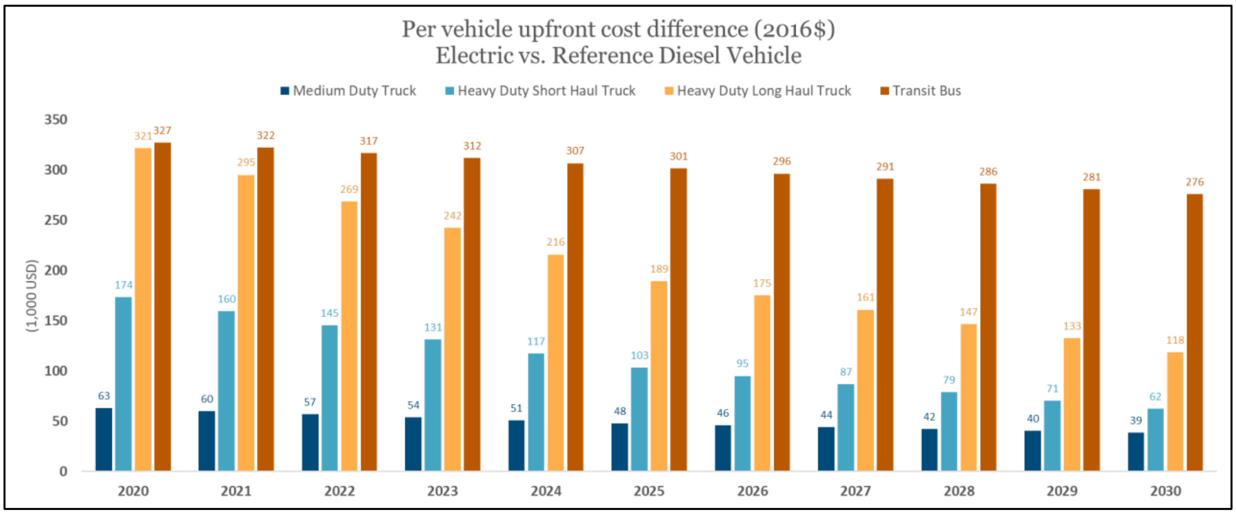

Figure 7. Upfront cost premiums for medium and heavy-duty electric trucks and transit buses.

2.1.3 EV-charger estimates

The estimated number of public EV charging plugs needed over time by state to support projected fleets of light-duty EVs are shown in Figure 8 for the E+ scenario and in Figure 9 for the E- scenario, along with the capital investments needed to install these. The state totals for number of plugs include both Level 2 and DC fast chargers (DCFC) and are based on the stocks of EVs in the state (Figure 3 and Figure 4) and estimates of the required number of charging plugs per 1,000 EVs in regions of differing population densities (Table 2). The number of EVs in a state that operate in regions categorized as city, town, and rural (as in Table 2), was assumed to be directly proportional to the fraction of that state's population living in urbanized areas, urban clusters, and rural areas, respectively, as reported in the 2010 US census [12]. To calculate the investment requirements for charging stations, we assumed costs for DCFC chargers of $25,000 per plug, and for L2 chargers we assumed $1,600 and $4,000 per plug for residential and commercial applications, respectively [13].

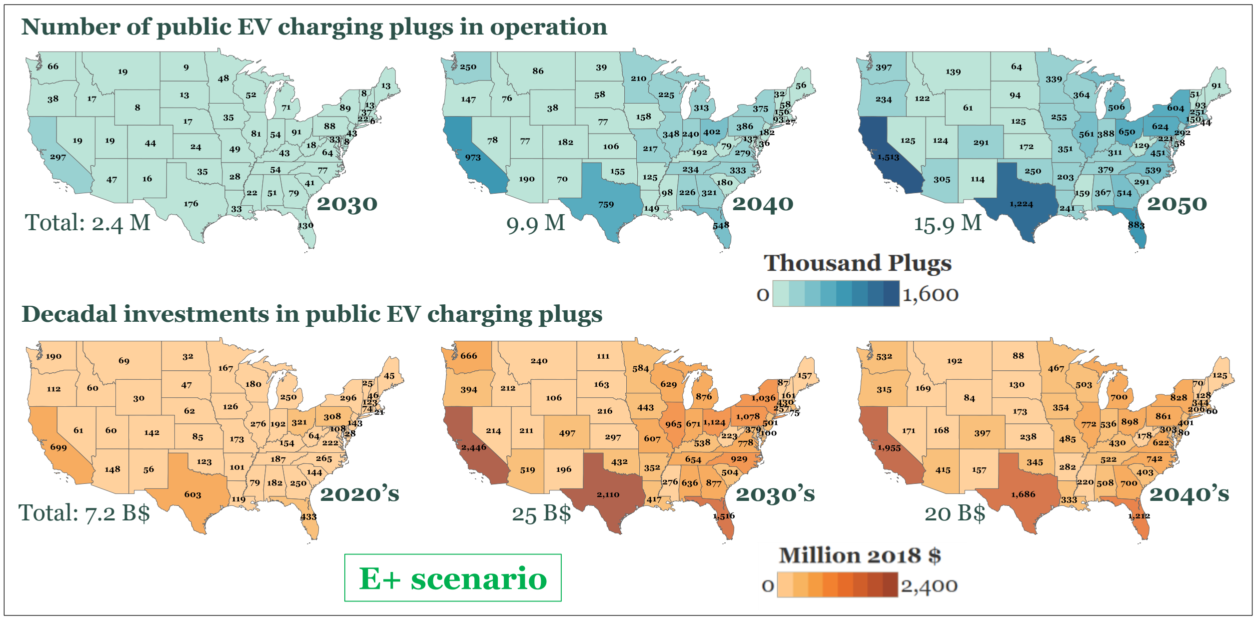

Figure 8. Number of public EV charging plugs (top) and decadal investments in public EV charging plugs (bottom) in the E+ scenario.

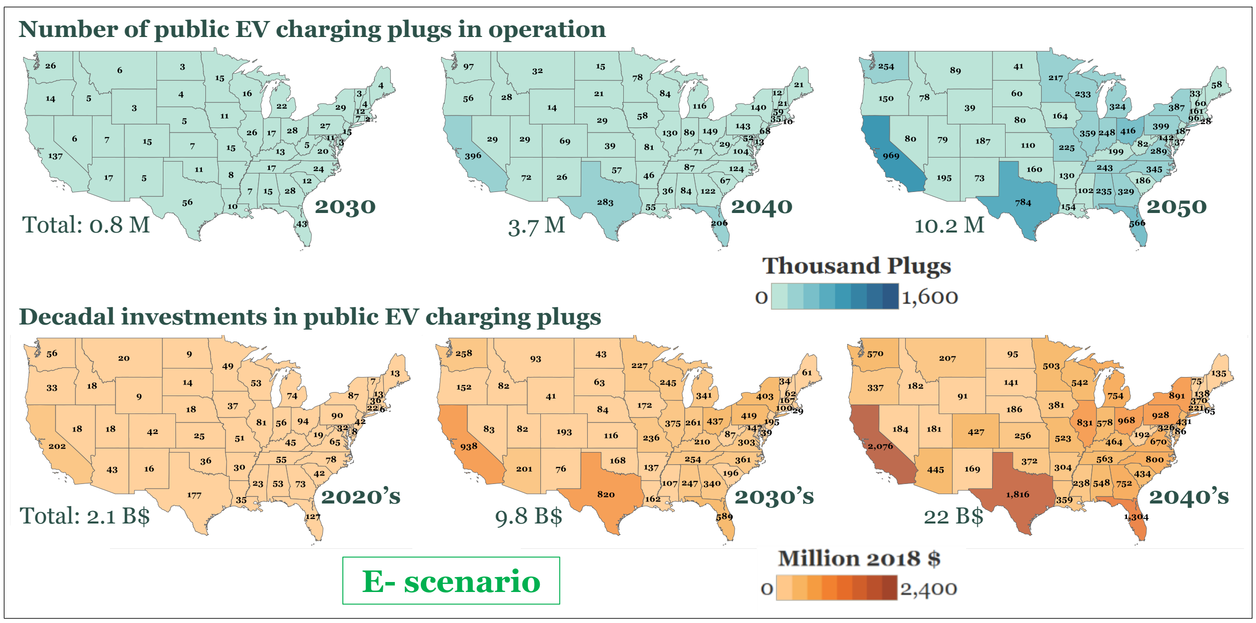

Figure 9. Number of public EV charging plugs (top) and decadal investments in public EV charging plugs (bottom) in the E- scenario.

Table 2. Public charging plugs per thousand EVs [13].

	city	town	rural
DCFC	1.5	2.2	3.1
L2	36	54	79

2.2 Aviation

Demand for air travel is assumed to grow about 2% per year from 2020 to 2050 (Figure 10), but reductions in energy-use per seat-km of 2.6% per year (Table 3) result in final-energy demand for aviation in 2050 being 12% lower than in 2020. The energy-intensity decline rate of 2.6%/yr is more than double the decline rate in the REF scenario. And, for perspective, energy use per seat-km has decreased about 1%/yr since 2010 (excluding impacts due to the Covid pandemic), and EIA's latest *Annual Energy Outlook* projects a continuation of this pace on average to 2050 in its reference scenario [14].

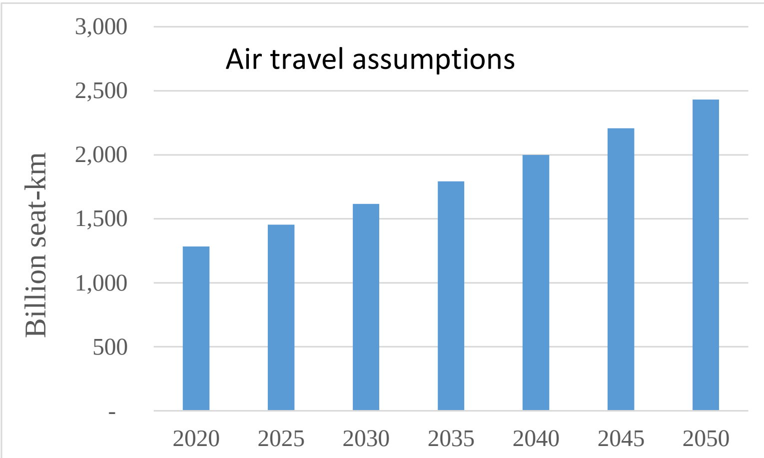

Figure 10. Assumed energy-service demands for aviation sector.

Table 3. Modeled final-energy use per seat-km for air travel.

	MJ_{HHV}/seat-km	
	REF	**E+, E-**
2020	2.19	2.19
2030	1.94	1.71
2040	1.74	1.32
2050	1.59	1.02
%/yr decline, 2020 - 2050	1.1%	2.6%

3 Buildings Sector

3.1 Residential

Major residential energy-service demands in 2020 and 2050 are shown in Table 4. Space heating service demands decline during the transition despite assumed growth in population and conditioned floor space because of tightening building shells and an assumed continuing decline in heating degree days over time – a trend that began in the late 1970s [15]. Air conditioning service demands nearly double during the transition in part due to an increasing number of cooling degree days, continuing a trend that also dates to the late 1970s [16]. Lighting demands increase by a third. Most other service demands grow modestly or remain relatively constant.

Space-heating accounts for the largest share of residential final-energy use today. The amount of energy used is a function of the technologies adopted to deliver the services. Using an approach analogous to that described in Section 2.1.1 for determining the mix of vehicle technology types in the vehicle fleet, Figure 11 shows the mix of residential space heating, as well as water heating and cooking technologies, through the transition to 2050. The left panel shows the exogenously-assumed fraction of new sales of different technologies, and the right panel shows the resulting number of units in the full stock of technologies.

Table 4. Residential energy-service demands

	2020	2050	Change, 2020 to 2050
Space heating (delivered useful energy 10^{15} BTU/yr)	4.08	3.71	-0.31 %/y
Water heating (delivered useful energy 10^{15} BTU/yr)	1.23	1.34	0.29 %/y
Air conditioning (delivered useful energy 10^{15} BTU/yr)	2.21	3.95	2.62 %/y
Cooking (delivered useful energy 10^{12} BTU/yr)	870	940	0.36 %/y
Lighting (10^{15} lumen-hours/yr)	3.95	5.27	1.11 %/y
Refrigeration (volume cooled, 10^{9} cubic-feet)*	3.06	3.06	-
Dishwashing (10^{9} cycles)*	20.2	20.2	-

* Projected demands for refrigeration and dishwashing services were erroneously input as fixed values across the full 30-year modeling period when the EnergyPATHWAYS models were originally set up for the Net-Zero America modeling. In reality, some increase in these services are expected over time. If the error had been corrected prior to completion of the modeling, final-energy demands for the commercial sector would be slightly higher than indicated in this Annex, but the overall conclusions from the modeling work would not be impacted.

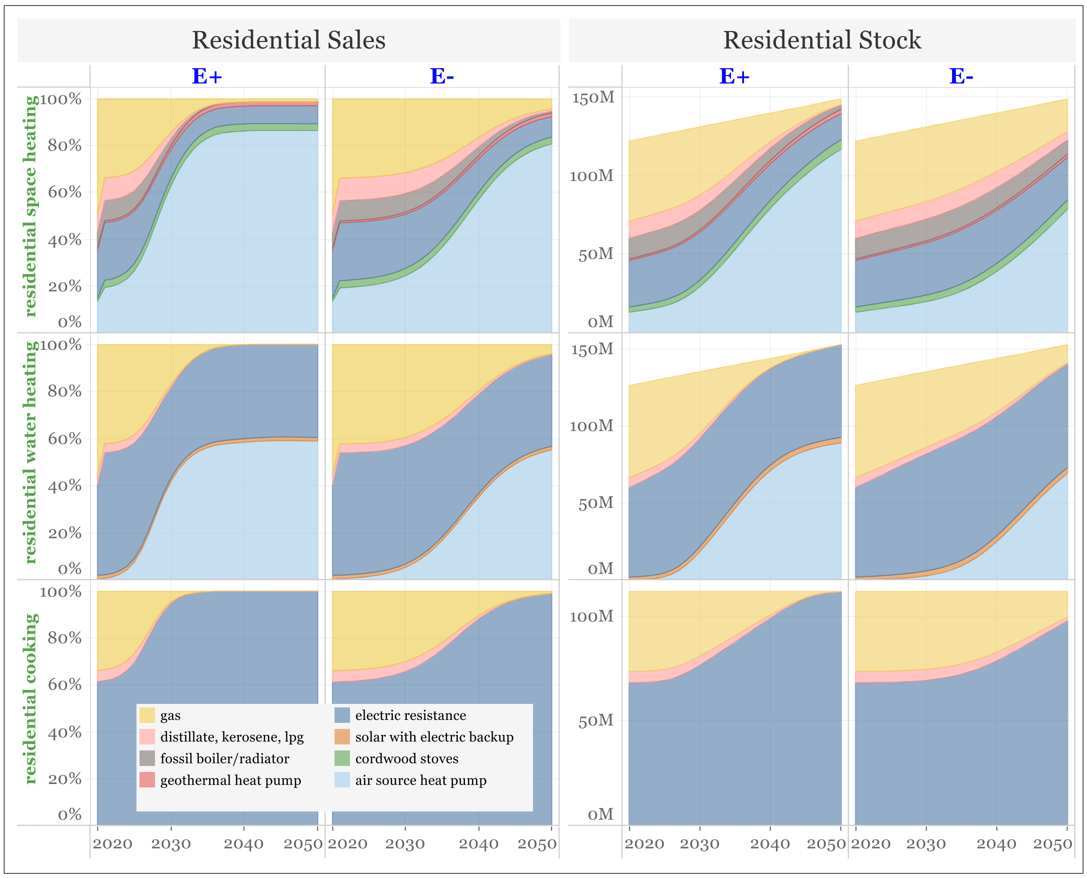

Figure 11. Exogenously assumed residential sector sales of heating and cooking units (left panel) and resulting stocks of same (right panel).

For space heating, air-source heat pumps grow to dominate new sales in both the E+ and E- scenarios. The fraction of the stock of heating units that are heat pumps varies significantly by climate zone, with heat pumps being more common in regions with less severe winter temperatures (Figure 12). Stocks of electric heating units by state are shown in Figure 13 for heat-pump heaters and Figure 14 for resistance heaters. New sales of water heaters are also dominated by electric models: heat pumps gain market share at the expense of gas heaters, but electric resistance heaters are generally retained in colder climates and so maintain a relatively constant share of new sales through the transition period (Figure 11). Induction cook stoves are 100% of new sales by 2035 in E+ and by 2050 in E-.

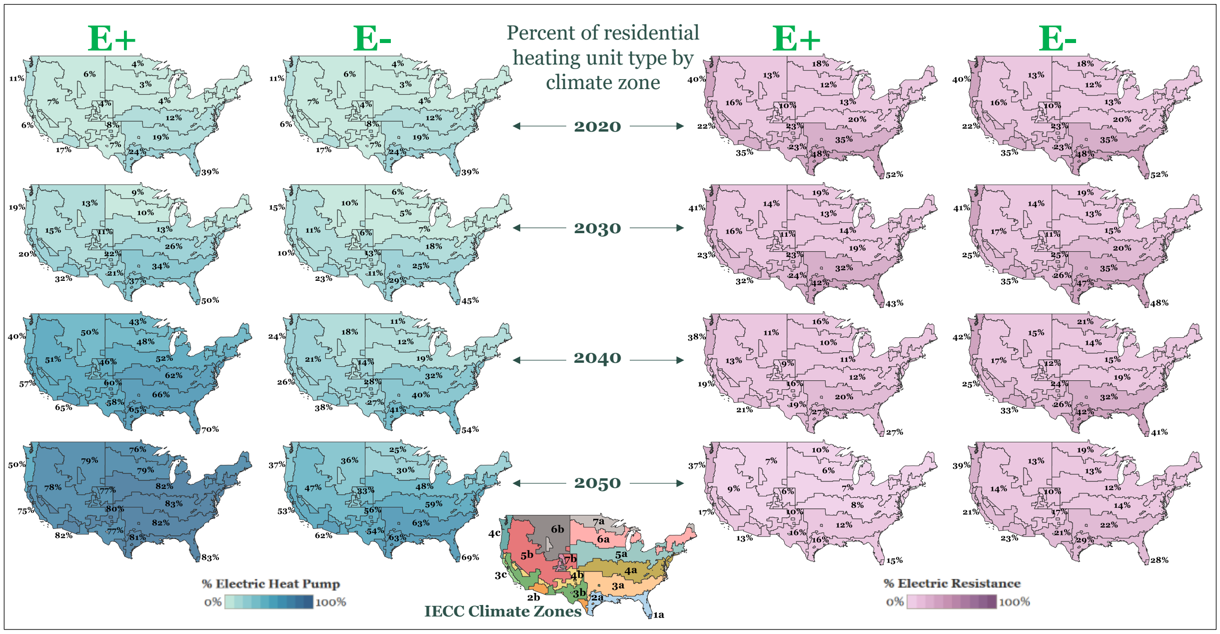

Figure 12. Electric home heating grows significantly through the transition to 2050, but adopted technologies varies by climate zone [17]: heat pumps favored in climate regions with warmer winters, and resistance heaters maintaining larger shares in colder regions.

Converting final energy into heated space and water using electric heat pumps is considerably more efficient than using electric resistance or gas-fired options. With assumed technology efficiencies shown in Table 5 and the distribution of stocks of equipment described above, residential final-energy demand falls by about 45% from 2020 to 2050 in the E+ scenario and by 34% in the E- scenario (Figure 15). Electricity's contribution to final energy increases only modestly in absolute terms through the transition period in E+ and E-, despite the increased use of electric heat pumps for space and water heating. Increases in efficiencies of other electricity using technologies (lighting, appliances, and plug loads) offsets much of the additional electricity used for heating.

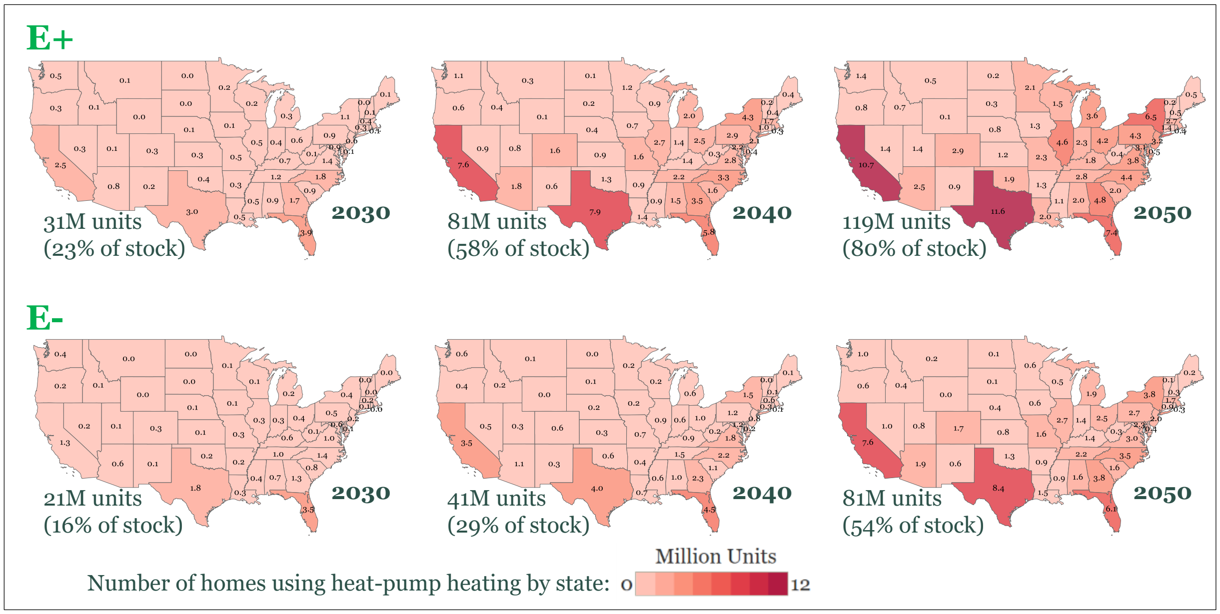

Figure 13. Number of residential heat-pump space heating units by state in E+ and E- scenario from 2030 to 2050. Nationally, residential heat pumps grow from ~10% of the space heating stock in 2020 up to 80% (E+) or 54% (E-) by 2050.

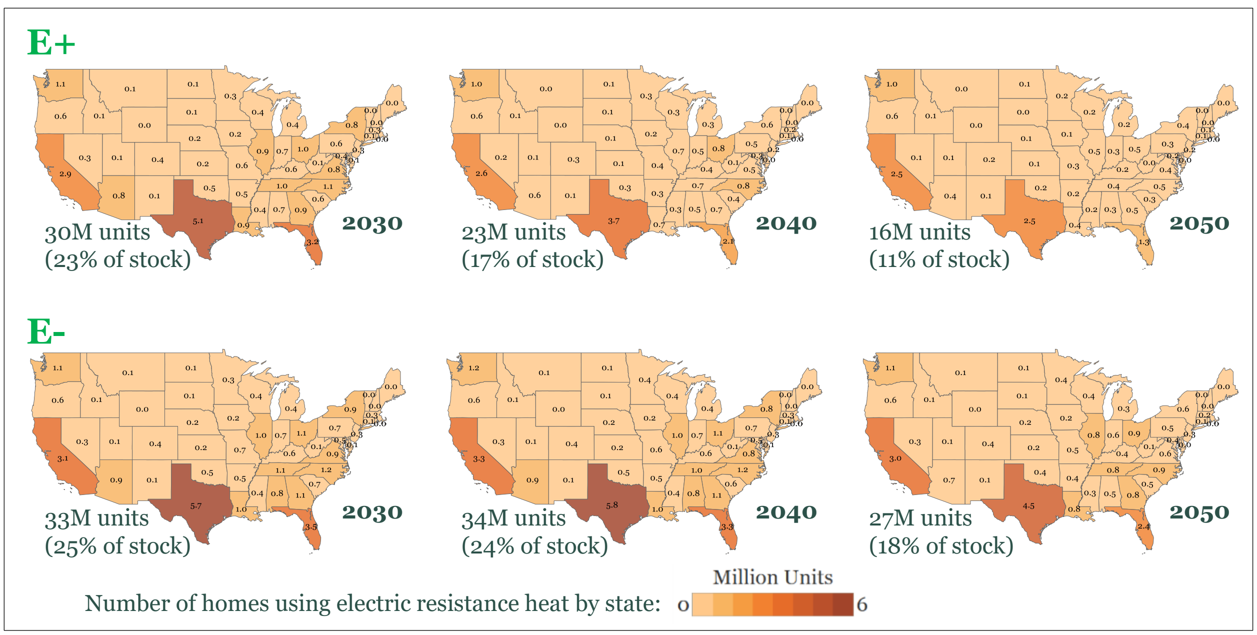

Figure 14. Number of residential electric resistance units by state in E+ and E- scenario from 2030 to 2050. Nationally, residential electric resistance units decline from ~25% of the space heating stock in 2020 to 11% (E+) or 18% (E-) by 2050.

*Table 5. Assumed efficiencies of residential space- and water-heating technologies in 2020 and 2050.**

		MJuseful/MJfinal energy		Average rise, 2020 – 2050
Space heating		**2020**	**2050**	
	Cordwood stoves	71%	82%	3.8 %/y
	Ductless mini-split heat pump**	297%	287%	- 0.1 %/y
	Air source electric heat pump	241%	376%	9.2 %/y
	Electric furnace	99%	99%	-
	Electric unit heaters	98%	98%	-
	Natural gas furnace	80%	90%	12 %/y
	Natural gas heat pump	116%	116%	-
Water heating				
	Gas fired	62%	62%	-
	Electric resistance	92%	95%	0.1 %/y
	Electric heat pump	304%	373%	0.7 %/y

* Heat-pump efficiencies vary with regional climate – efficiencies are lower where ambient temperatures are lower. The values in this table are nationally averaged efficiencies (expressed on a higher heating values basis).
** National average efficiency for ductless mini-split heat pumps is lower in 2050 than in 2020 because of greater use of this technology in colder regions in 2050 than in 2020.

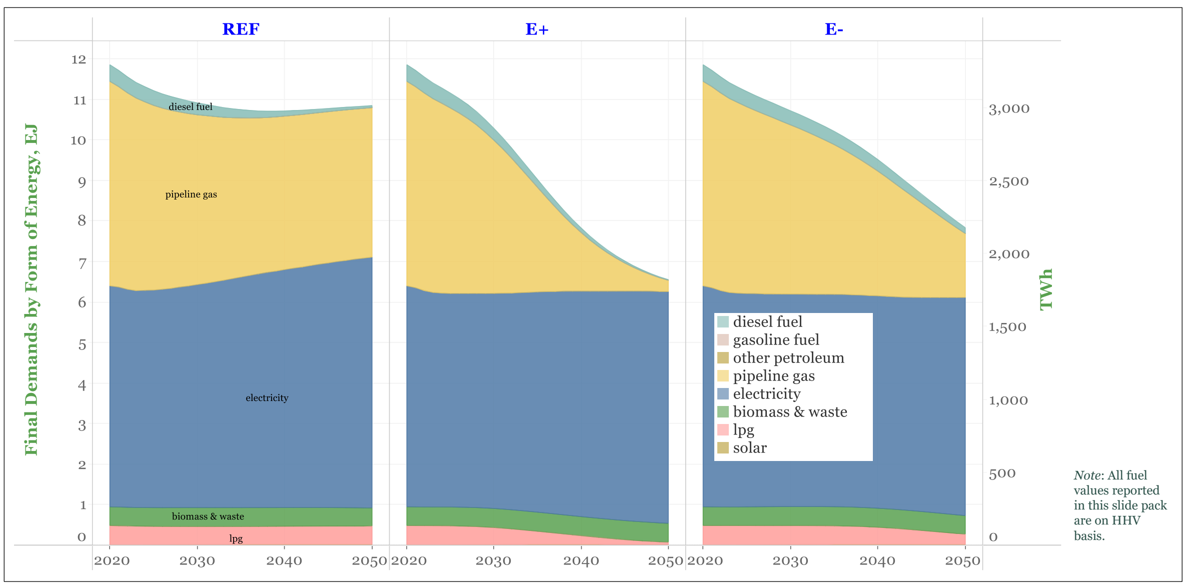

Figure 15. Final-energy demands in the residential sector for REF, E+, and E- pathways. In the latter two pathways, the use of natural gas and LPG fall dramatically by 2050 as they are replaced by electricity used in heat pumps, which deliver the same energy services as gas, but much more efficiently.

An idea of the overall decline in residential-sector energy intensity (final energy per unit of energy service delivered) can be gleaned from Table 6, which shows weighted-average energy intensities for delivering some key residential energy services. The annual average decline rates through the transition of 3.4%/yr (for E-) and 6%/yr (for E+) represent historically unprecedented rates of change. The most rapid rate of reduction in residential final-energy intensity observed in the past over an extended time period was 1.1%/yr from 1970 to 1985 [18].

Table 6. Energy-intensities in the residential-sector subcategories – weighted-averages across technologies in subcategories.

	E+			E-		
	MJ_{final}/MJ_{useful}		**%/yr decline 2020 – 2050**	**MJ_{final}/MJ_{useful}**		**%/yr decline 2020 – 2050**
	2020	**2050**		**2020**	**2020**	
Space heating	1.15	0.39	6.5%	1.15	0.65	2.6%
Water heating	1.37	0.58	4.5%	1.37	0.74	2.9%
Air conditioning	0.31	0.18	2.4%	0.31	0.18	2.5%
Cooking	2.04	1.43	1.4%	2.04	1.67	0.8%
All above combined	0.95	0.34	6.0%	0.95	0.47	3.4%

3.2 Commercial

Major energy-service demands assumed for the commercial buildings sector are shown in Table 7. All rise over time as the economy grows.

Space-heating accounts for a significant share of commercial final-energy use today, and the energy used for this is a function of the technologies adopted to deliver the services. Using an approach analogous to that described in Section 2.1.1 for determining the mix of vehicle technology types in the vehicle fleet, Figure 16 shows the mix of commercial space heating, as well as water heating and cooking technologies, through the transition to 2050. The left panel shows the exogenously-assumed fraction of new sales of different technologies, and the right panel shows the resulting stocks of technologies, expressed in terms of energy services delivered. For space and water heating, the rate of air-source heat pump penetrations into new sales is comparable to those in Figure 11 for the residential sector, but unlike in the residential sector, cooking is not fully electrified in the commercial sector in either E+ or E- scenarios by 2050.

As in the residential sector, total final-energy demands in the commercial sector fall from 2020 to 2050 (Figure 17), with natural gas and LPG use declining especially dramatically. Electricity use in absolute terms grows by 25% (in E-) to 40% (in E+): unlike in the residential sector, in the commercial sector the added electricity used for heating is not offset by efficiency improvements in other electricity uses. However, commercial-sector energy intensity (final energy per unit of energy service delivered) overall does decline through the transition, as suggested in Table 8 showing weighted-average energy intensities for delivery of some key commercial energy services. The average annual decline rates through the transition shown there, 2.1%/yr for E- and 2.7%/yr for E+, represent rapid change by comparison to the most rapid rate of reduction in commercial final-energy intensity observed in the past over an extended time period: 0.6%/yr from 2000 to 2011 [18].

Table 7. Commercial sector energy-service demands.

	2020	**2050**	**Change, 2020 to 2050**
Space heating (delivered useful energy, 10^{12} BTU/yr)	1,359	1,381	0.05 %/y
Water heating (delivered useful energy, 10^{12} BTU/yr)	504	655	1.00 %/y
Air conditioning (delivered useful energy, 10^{12} BTU/yr)	1,842	2,032	0.34 %/y
Cooking (delivered useful energy, 10^{12} BTU/yr)	165	218	1.08 %/y
Lighting (10^9 lumen-hours/yr)	1,257	1,698	1.17 %/y
Refrigeration (delivered useful energy, 10^{12} BTU/yr)	1,771	2,338	1.07 %/y
Ventilation (volume ventilated, 10^{15} cubic foot)	146	202	1.26 %/y

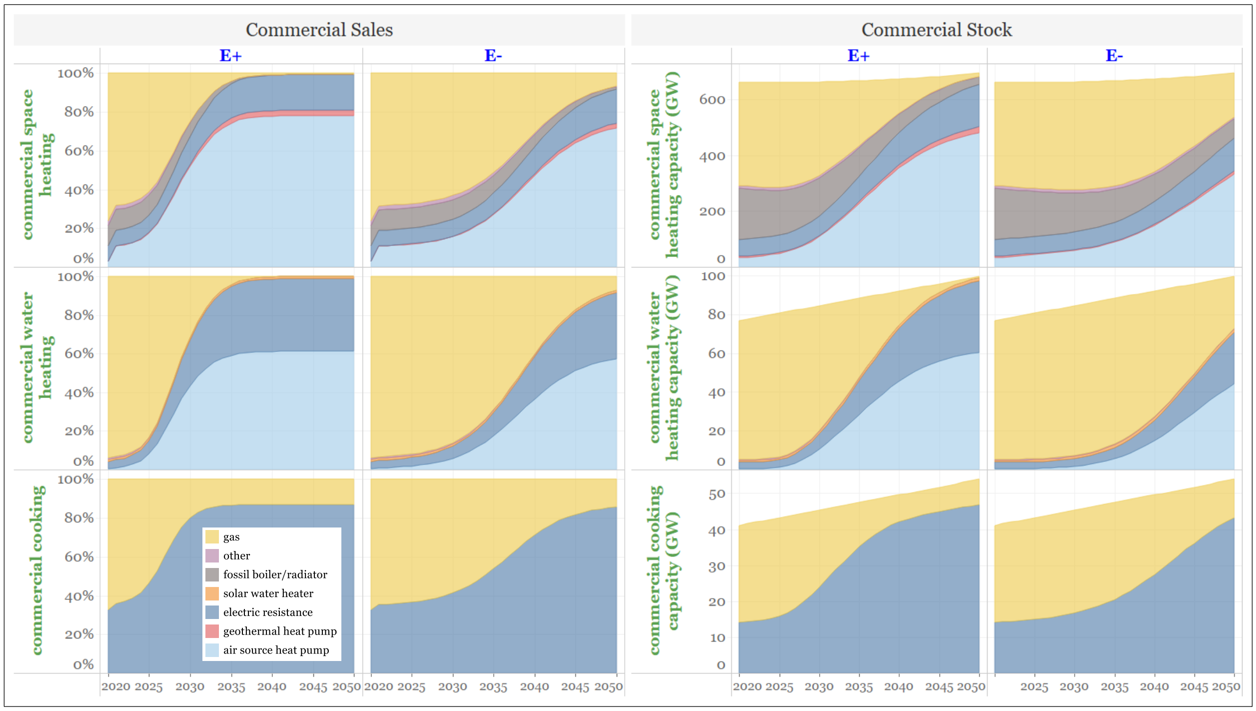

Figure 16. Exogenously assumed commercial sector percentage of new sales by heating and cooking technology (left panel) and resulting capacities for energy-services deliveries by technology type (right panel).

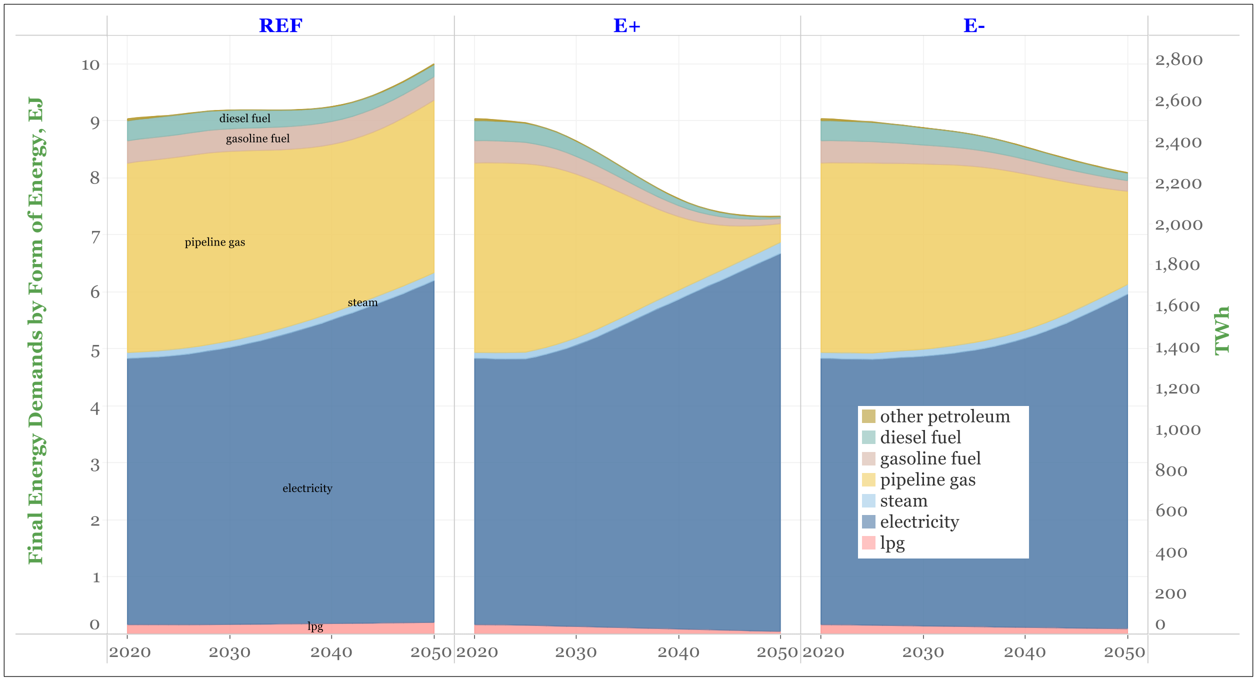

Figure 17. Final-energy demands in the commercial sector for REF, E+, and E- pathways. In the latter two pathways, the use of natural gas and LPG fall dramatically by 2050 as they are replaced by electricity used in heat pumps, which deliver the same energy services as gas, but much more efficiently.

Table 8. Energy-intensities in the commercial-sector subcategories (weighted-averages across technologies in each subcategory).

	E+			**E-**		
	MJ_{final}/MJ_{useful}		**%/yr decline 2020 – 2050**	**MJ_{final}/MJ_{useful}**		**%/yr decline 2020 – 2050**
	2020	**2050**		**2020**	**2020**	
Space heating	1.20	0.44	5.7 %	1.20	0.72	2.3 %
Water heating	1.23	0.57	3.8 %	1.23	0.75	2.1 %
Air conditioning	0.29	0.20	1.6 %	0.29	0.20	1.6 %
Cooking	1.92	1.43	1.2 %	1.92	1.49	1.0 %
Refrigeration	0.35	0.31	0.5 %	0.35	0.31	0.5 %
All above combined	0.66	0.36	2.7 %	0.66	0.40	2.1 %

Appendix: Estimating vehicle costs

To address concerns with using vehicle cost estimates from different sources that may not be directly comparable with each other, for example due to different specific weight and/or powertrain-size definitions between studies for vehicles of the same duty-class, a process of benchmarking and scaling for vehicle size was carried out to isolate the cost impact of changes in powertrain, the main distinguishing characteristic of each vehicle.

All duty-classes of vehicles share the same battery and hydrogen fuel cell cost assumptions, which were based on several then-current sources. Battery costs were based on an extension of the average of projections to 2030 by BloombergNEF [19] and ICCT [20] (Figure 18). A rapid slowing in cost declines was assumed after 2030, ultimately ending at $60/kWh in 2040 and then remaining flat through 2050. Fuel cell costs are based on projections to 2030 for zero-emission heavy-duty vehicles [21] (Table 9). Values from 2030 to 2050 decline by 12% and are pegged to cost reductions estimated elsewhere for battery cost declines.

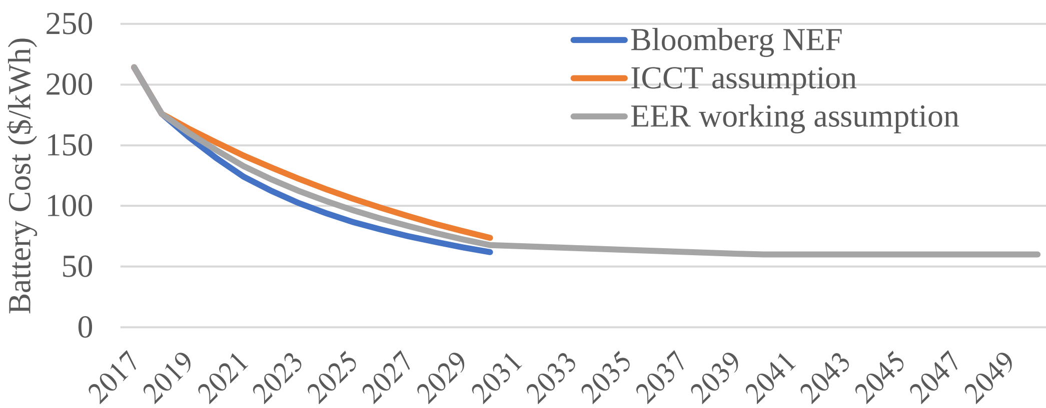

Figure 18. Battery cost projections (line labeled "EER working assumption") used for vehicle cost projections.

Table 9 Fuel cell vehicle component cost breakdown from page 26 of [21].

Component	**2015**	**2020**	**2025**	**2030**	**2050**
Electric motor, $/kW	22	18	16	14	14
Fuel cell system, $/kW	240	166	89	59	52
H_2 tank cost, $/kWh	33	23	21	19	19
Auxiliaries, $/kW	38	34	31	28	25

Light duty vehicle costs are based [20], specifically Table 3 in that report, which lists electric vehicle component costs from various studies. Costs are broken down into four components: powertrain, battery, other direct costs, and indirect costs. Each component in the table has been scaled to better reflect the average vehicle sold in the U.S. today, which is $29.5k for a light duty auto and $38.6k for a light duty truck. Separate scaling is used for weight of the vehicle and for drivetrain horsepower, both of which are reported in the modeling underlying the *Annual Energy Outlook* Reference case [22]. With this scaling, the EV cost is consistent with that for the modeled ICEV. The resulting light duty vehicle cost projections are shown in Figure 19 and show a cross-over point for light duty cars in 2028 and for light duty trucks in 2029. The crossover point for trucks is slightly longer due to larger battery sizes. The battery size of light-duty cars is assumed to start at 60 kWh and increase to 65 kWh by 2040. For light-duty trucks, the battery size starts at 90 kWh and increases to 100 kWh. After 2030, electric vehicles stay slightly cheaper than ICE vehicles on a capital cost basis through 2050.

For medium- and heavy-duty vehicles, cost projections in [21] form the scaffolding for the analysis, and the cost of components are updated using Table 9 above. Vehicle costs are divided into a glider cost and a series of additional cost categories that relate to drivetrain and fuel storage. In every case careful calibration ensures comparable trucks are costed between the various drivetrain options. For example, for electric trucks, only battery electric vehicles without dynamic induction or overhead catenary lines are considered, and thus these additional cost components are ignored. Battery sizes of 250 kWh for medium-duty trucks and 1,200 kWh for heavy duty trucks are assumed. Hydrogen tanks sizes of 500 kWh for medium-duty fuel cell trucks 2,920 kWh for heavy-duty fuel cell trucks are assumed. In the case of heavy-duty trucks, the cost of trailers is excluded, because this is assumed to be the same for ICEVs and the alternatives. Trailer costs are frequently included in some estimates as a component of HDV costs, including in [21], so careful examination of source material was necessary. The resulting assumed costs for medium and heavy-duty vehicles are shown in Figure 20 and Figure 21, respectively. Costs for diesel-fueled trucks in both duty-classes have discernable cost advantages over the alternative powertrain options before 2030, but only a small first-cost advantage after 2030.

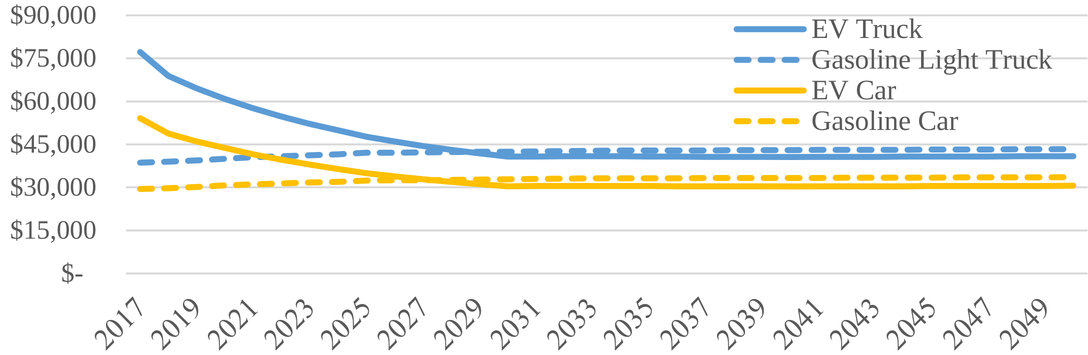

Figure 19. Light-duty car and light-duty truck cost projections.

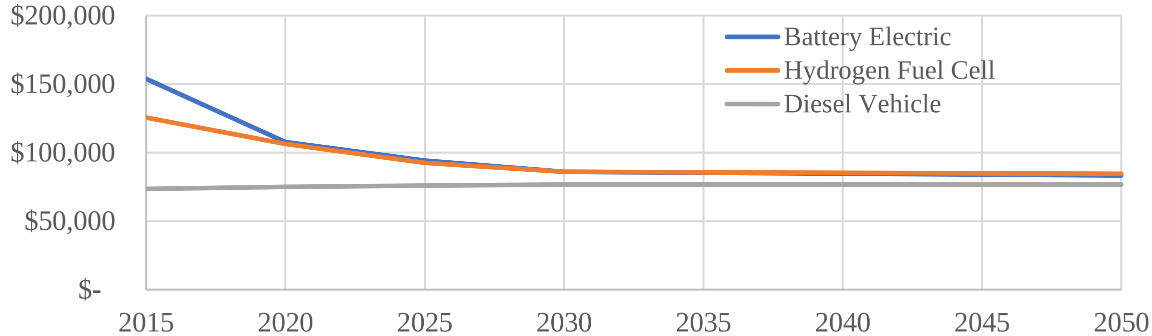

Figure 20 Modeled medium-duty vehicle cost.

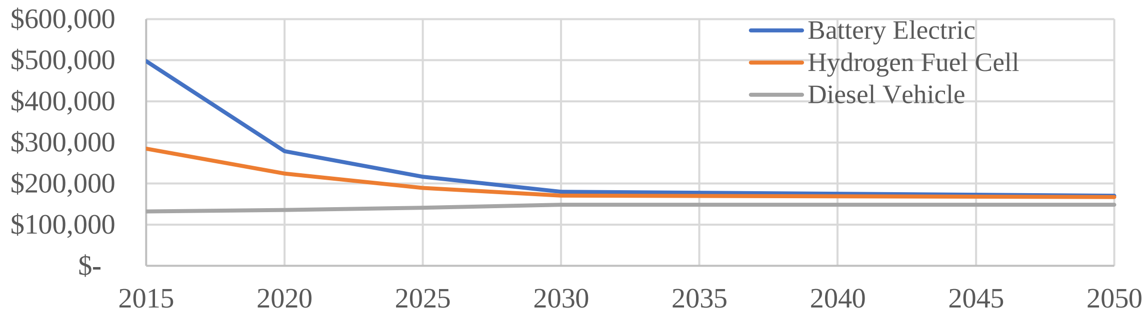

Figure 21. Modeled heavy-duty vehicle cost.

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