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Technology and Fuel Transition Scenarios to Low Greenhouse Gas Futures for Cars and Trucks in California to 2050

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Key Findings

- The savings to California from transitioning to zero-emission cars and trucks by 2050 is about $300 billion.
    - These savings result mostly from the cost of zero-emission vehicles (ZEVs) dropping close to or below the cost of gasoline and diesel vehicles; additional savings come from operational cost advantages.
    - Policies at the state and national level, as well as the success of ZEV manufacturers, will affect California's ability to achieve ZEV adoption targets and realize net economic benefits. However, even in the absence of ZEV-supportive policies, the global embrace of electric vehicles and the resulting cost reductions from innovation and scale economies will lead to substantial benefits and savings for California.
- We created several scenarios to examine future costs and benefits of reducing emissions from the transportation sector. The core scenario, "Low Carbon" (LC) reaches 100% ZEV sales by 2035 for light-duty vehicles and 2036 for trucks, with electric vehicles dominating. This is the lowest cost scenario, and the $300 billion savings estimates are from comparing it, over the 2025–2050 period, to a "Business as Usual" (BAU) scenario that has relatively low ZEV adoption rates.
    - In the first 6–8 years beginning in 2025, the LC scenario actually costs $25 billion more than the BAU scenario, because ZEVs still cost more than internal combustion engine vehicles (ICEVs). However, after this initial period, as ZEVs reach price parity with ICEVs and their operational costs remain lower, the LC scenario costs much less than the BAU scenario.
    - Cost parity, which is achieved in light-duty vehicles earlier than in trucks, could be achieved before 6–8 years, especially if battery costs drop faster than we assume in the LC and BAU scenarios. We address this in our sensitivity analysis.
- Through the rest of the 2020s, in the LC scenario, the annual investment cost requirements for vehicle charging and hydrogen refueling infrastructure will likely be large—even higher than the annual incremental costs of ZEV car and truck purchases (above the BAU scenario).
- The High Fuel Cell (HFC) scenario achieves the same ZEV targets as LC, but with more fuel cell vehicles and somewhat fewer electric vehicles. It achieves a similar CO2 reduction as LC, but at a somewhat higher cost.
- Our BAU with high biofuels (BAU-HB) has BAU levels of ZEV penetration and very high use of biofuels, reaching 100% of gasoline and diesel fuel by 2040. This would require a dramatic increase in ethanol or bio-gasoline, along with on-going high levels of renewable diesel (75% market penetration in 2024). The reductions in greenhouse gas emissions are much larger in the BAU-HB scenario than in the BAU scenario, but they are smaller than those in the LC scenario. This BAU-HB scenario is also more expensive than the LC scenario.

Executive Summary

This report addresses the transition of California's road transportation system to a very low carbon system by 2050, via ambitious targets for zero-emission vehicles (ZEVs), as well as reductions in the carbon intensity (and shifts in types) of energy used by vehicles. We consider a number of scenarios including: "low carbon" (LC, focused on ZEV uptake to meet targets), "delayed targets" (LC-delayed, with targets delayed about 5 years), "high biofuels" (HB, with low ZEV uptake), and "high fuel cell" (HFC, similar to LC but with more fuel cells and somewhat fewer battery electric vehicles). In the LC and HFC scenarios, transit bus sales are assumed to be 100% zero emission by 2030 and light duty vehicle sales by 2035 (following current California regulatory requirements), and truck sales by 2036 (following a contractual agreement between the state and OEMs) In the "delayed" scenario, 100% ZEV sales are not reached until 2040. The high biofuels case assumes much slower growth in ZEV sales, with growth in biofuels accounting for most of the decarbonization in the scenario.

The LC scenario is premised on meeting California's ambitious regulatory requirements, which may or may not stay in place. As of May 2025, the bus and light duty vehicle requirements (ACC-II and ACT) are still in place, but the Advanced Clean Fleet rule requiring many fleets to purchase 100% ZEVs by 2036 has been withdrawn. (An agreement with OEMs to sell 100% ZEVs starting in 2036 remains). The part of the rule related to in-state government fleets is still being implemented and the Advanced Clean Truck rule requiring 40-75% of truck sales (depending on vehicle size) is also still in place. Meanwhile, the Trump Administration and Republican Congress are actively seeking to prevent California's enforcement of its various ZEV regulations and also attempting to remove national vehicle purchase incentives. These actions will heavily influence vehicle sales and the likelihood of the LC scenario being realized.

The impacts of the LC and HFC scenario, with mid-2030s ZEV sales targets reached, include a near 100% ZEV stock of ZEV cars and trucks by 2050; a 95% or greater reduction in total vehicle well-to-wheel GHG emissions by 2050; and total costs for all vehicles and fuels far lower than in a business-as-usual (BAU) scenario with low penetration of ZEVs.

The net costs of this LC scenario are higher for the next 6-8 years, due to higher vehicle costs, but are negative thereafter to 2050. The charging and hydrogen refueling infrastructure investment costs for ZEVs, while included in total costs, amount to about $45 billion by 2035 in this LC scenario, which is more than the expected incremental costs of the vehicles. As a result, the estimated cost of CO_2 reduction is higher for 6-8 years, amounting to an average cost of CO_2 mitigation over this period of around $200/ton compared to a business-as-usual (low ZEV) case. But from that point on, beginning in the early 2030s, the cost of CO_2 reduction is negative – meaning that the LC scenario costs expended for vehicles, fuels, and infrastructure are lower than the costs in a BAU scenario. This remains true (and becomes more negative annually) out to 2050. Other findings include:

- The HFC (high fuel cell) version of the LC is somewhat more expensive than LC, but still provides significant net benefits, since the costs of fuel cells and hydrogen also drop considerably over time and with market growth.

- We estimate that in a "delayed" LC case where 100% ZEV sales are not reached until 2040, cumulative CO_2 emissions would be about 12% higher by 2050 than in the LC or HFC scenarios, and would lead to overall higher costs, since fewer lower-cost ZEVs (on a total cost of ownership basis) would be sold in the 2030s.

- The high biofuels case does not achieve as low a CO_2 level as LC, and would require high volumes of renewable gasoline (or vehicles that can run on 100% ethanol) along with already high volumes of renewable diesel, to come close. The BAU scenario is used for ZEVs in this scenario – with current ZEV market shares increasing only slowly over time and remaining below 30% (for LDVs) and 10% (for trucks).

As these scenarios indicate, the potential GHG and economic benefits of continued implementation of aggressive California ZEV targets are large. But achievement of these benefits requires on-going strong supporting policies, such as sales requirements and price incentives, at least during the period when ZEV purchase costs are higher than gasoline and diesel vehicles, and while consumers are still slowly embracing these new types of vehicles. Eventually, California's market growth (and an accompanying global commitment to ZEVs) could reduce vehicle prices and render the transition economically compelling to consumers regardless of policy. But if and when such a tipping point occurs is highly uncertain, and is probably at least 5 years away. The scenarios in this report quantify the climate and economic impacts of different transition timings and processes, exploring the implications of ZEV transition paths in California along with some biofuel-dominant alternatives. The ZEV pathway still appears the most promising, with large long-term net benefits to consumers and fleets.

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Glossary

ACF	Advanced Clean Fleets
AEO	Annual Energy Outlook (of the Energy Information Administration)
BAU	Business as Usual
BET	Battery Electric Truck
BEV	Battery Electric Vehicle
CAFÉ	Corporate Average Fuel Economy (standards)
CARB	California Air Resources Board
CCST	California Council on Science and Technology
CI	Carbon Intensity (typically CO_2e grams per megajoule of energy or similar energy unit)
CO_2e	Carbon Dioxide-Equivalent Emissions (including CH4 and N2O)
CNG	Compressed Natural Gas
DGE	Diesel Gallons Equivalent
DOE	U.S. Department of Energy
EATS	Engine After Treatment System
EV	Electric Vehicle
EDV	Electric Drive Vehicle (includes battery electric, plug-in hybrid and fuel cell)
EMFAC	Emissions Factors (California Air Resources Board emissions inventory model)
EPA	U.S. Environmental Protection Agency
FCV	Fuel Cell Vehicle
H_2	Hydrogen
HEFA	Hydro-Processed Esters and Fatty Acids
HDV	Heavy Duty Vehicle (including medium and heavy-duty trucks)
GE	Gasoline Equivalent
GGE	Gallons Gasoline Equivalent
GHG	Greenhouse Gases (same as CO_2e)
ICEV	Internal Combustion Engine Vehicle
LDV	Light Duty Vehicles
LNG	Liquefied Natural Gas
LCFS	Low Carbon Fuel Standard
NMNL	Nested Multinomial Logit Model
MPGGE	Miles Per Gallon Gasoline Equivalent
MHDV	Medium and Heavy Duty Vehicle
P80	Plug-in Hybrid Electric Vehicle with 80 Mile Electric Driving Range
P40	Plug-in Hybrid Electric Vehicle with 40 Mile Electric Driving Range
PHEV	Plug-in Hybrid Electric Vehicle
RGC	Reduced Generalized Cost
RNG	Renewable Natural Gas
TCO	Total Cost of Ownership

TTM	Transportation Transitions Model
VMT	Vehicle Miles Traveled
ZEV	Zero Emission Vehicle (and name of scenario in this study)
ZEV+B	Zero Emission Vehicle + Biofuels (name of scenario in this study)

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1. Extended Executive Summary

California has adopted ambitious targets for greenhouse gas (GHG) reduction, including a target of 80% reduction in energy-related CO_2 emissions by 2050 relative to 1990, a statutory target of 40% reduction by 2030, and an executive order calling for state-wide carbon neutrality by 2045. Perhaps most importantly for transportation, the state has extended and tightened its zero-emission vehicle (ZEV) sales requirements so that all transit bus sales must be ZEV by 2030, light-duty vehicle (LDV) sales by 2035, and all truck sales by 2036. As of April 2025, the recent events at the national level have not changed this picture.

In this study, we examine the costs and challenges of meeting these LDV and medium/heavy duty vehicles (MHDV) requirements, including steep ramp ups during the second half of this decade and first half of the 2030s. As of the publication of this paper, there are fewer than 60 months left until 2030. Just the rate of ramp up of vehicle production and infrastructure installation over this 5-year period is likely to be challenging, and require enormous investments. Encouraging consumers and fleets to shift purchase patterns to the numbers needed represents a similar challenge; this aspect has been covered in related papers but is less of a focus here. This report focuses on the pathways, requirements, and costs to bring about the rapid transition to ZEV sales by the mid-2030s, and to a net zero transportation system by 2045.

We present four market penetration scenarios for ZEV technologies and fuels into both LDVs and MHDVs (including trucks and buses) with the following key features:

- **The business as usual (BAU) scenario** reflects a continuation of past trends, *as though the current rules and targets were not in place.* This is different from our previous BAU (and many other) BAU scenarios, as it is hypothetical, and serves as a "continuation of the past" rather than "continuation of the present" case. It still serves as a base scenario to compare the policy driven scenarios to. In this scenario, we start from the 2024 levels of ZEV sales and alternative fuel use and increase these only very slowly into the future.

- **The Low Carbon (LC) scenario** reflects all of the current rules and policies in the state, notably the Advanced Clean Cars II rule, Advanced Clean Trucks rule, and Advanced Clean Fleets (though the latter is not necessary to reach the numbers of ZEV sales in the scenario). This scenario also estimates the amount of recharging and hydrogen refueling infrastructure that will be needed to serve these vehicles. Finally, it projects a plausible future for low-carbon fuels, given the remaining liquid fuels demand from the road sector, and policies such as (Low Carbon Fuel Standard) LCFS that will incentivize on-going uptake of such fuels.

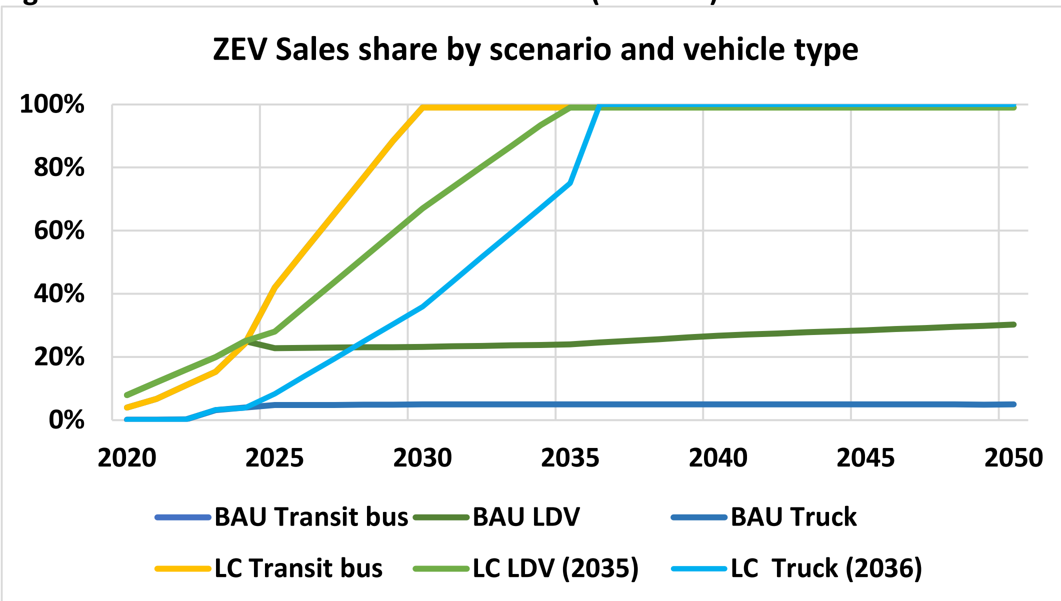
- **The High Fuel Cell (HFC) scenario** follows the same ZEV sales requirements as the LC scenario, but assumes a higher share of fuel cell vehicles than in that scenario. This varies by vehicle type; for example, for LDVs the 2040 share rises from 5% in the LC to 20% in the HFC, so battery electric vehicles still dominate. At the other extreme, for long-haul trucks the fuel cell rises from 50% in the LC to 75% in the HFC scenario. The liquid fuel transition in this scenario is no different from LC.

- **High biofuels BAU (BAU-HB) scenario:** Here we consider a future without strong ZEV penetration (BAU levels), and efforts to achieve low-carbon futures focus on replacing gasoline and diesel with low-carbon substitutes, such as bio-based diesel and ethanol and other bio-based gasoline fuels. These fuels reach 100% of the liquid fuel pool in California by 2050 or earlier (renewable diesel is already over 70% of the diesel pool as of early 2025).

The scenarios provide an opportunity to compare a world with and without current ZEV and low-carbon fuels policies, and two variants on the policy-driven world. A principal focus is cost – what will the vehicles, fuels, and infrastructure cost to consumers and to the public? Is one scenario more cost effective than another? We also consider the value of GHG emissions reductions in this context (or alternatively, the cost per ton implied by the costs of the scenarios and CO_2 avoided). Finally, we consider some variants of our main cases, such as "LC-delayed" and "HFC-delayed" cases, that show the difference in ZEV sales/stock ramp-ups, CO_2 emissions, and costs if the 100% ZEV sales targets were delayed to 2040, given a change in the policy environment or other factors. We also do sensitivity analysis on some of the cost/price assumptions we include in the scenarios, and their effects on overall scenario costs through 2050.

Figure ES-1 shows the sales fraction of ZEVs in our main cases: the BAU and LC (with HFC matching the LC for total ZEV sales shares). For LDVs, these scenarios reach a 100% ZEV sales share by 2035; for trucks, it is a weighted average of sales across truck classes, and reaches 100% in 2036. This reflects the original Advanced Clean Fleets target, but also reflects an on-going agreement between the state and major OEMs (CARB, 2023). In the BAU, ZEV truck sales remain below 5% into the future, while in the LC and HFC cases they reach 100% by 2036. For LDVs, the BAU ZEV sales stay near the current level, about 25%, while they reach 100% by 2035 in the LC and HFC cases. Public transit buses are kept the same in both scenarios, as it seems likely that buses will reach high ZEV sales percentages even without strict ZEV adoption targets.

Figure ES- 1. ZEV Sales Shares in BAU and LC (and HFC) Scenarios



Figures ES-2 and ES-3 show the ZEV ramp-ups in more detail for LDVs and trucks, including all three scenarios in each case.

ZEV Results

The core scenario in the study is the low-carbon (LC) scenario. It involves reaching 100% sales share of all ZEV buses by 2029, ZEV LDVs by 2035, and ZEV trucks by 2040. It requires very rapid increases in sales, year over year, for both LDVs and MHDVs (Table ES-1). The charging and hydrogen refueling infrastructure must also grow at this rapid rate and align with the growth of vehicle sales and stocks. A few key findings include:

- As an interim target, the 2030 requirements of around 66% ZEV sales for LDVs and 40% or more for trucks require annual sales of more than 1 million for LDVs and 50k for trucks, a much stronger growth than has occurred in the past 5 years. By 2030, the stock of ZEV LDVs will need to rise by about 3-fold, and trucks by nearly 10-fold.

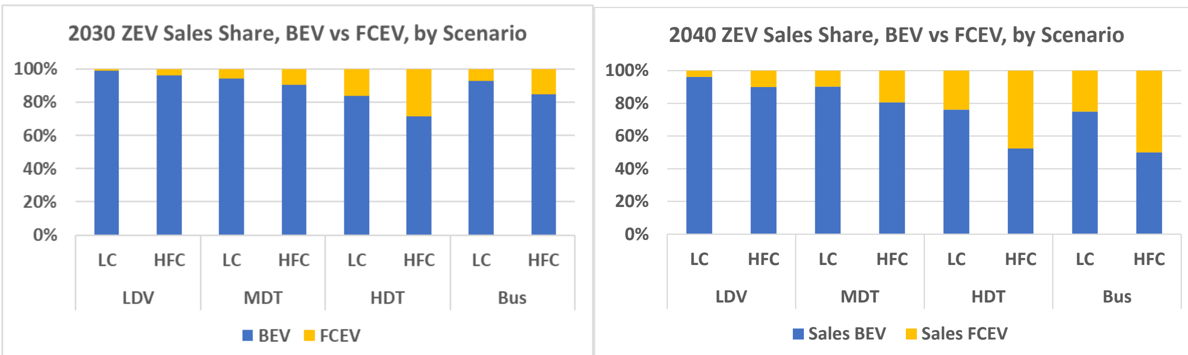
Table ES-1. Sales and Stocks of ZEVs by Vehicle Type and Year, LC scenario (thousands)

	Sales		Stock	
	2025	2030	2025	2030
LDV	460	1,100	2,200	6,100
All MHDVs	11	50	22	190
MDV	8.9	41	17	160
HDV	1.3	6.0	2.4	22
Transit bus	1.3	3.0	3.4	14

Note: Estimates shown to two significant digits.

- As shown in Figure ES-2 for 2030 and 2040, while battery electric vehicles dominate sales of LDVs in both scenarios, and are important for LMDVs, FCEVs also play an important role for these in LC, and account for more than half of HDVs and buses in the HFC scenario.

Figure ES-2. Sales Share of BEVs and FCEVs by Vehicle Type, Scenario and (in each figure) for Different Years

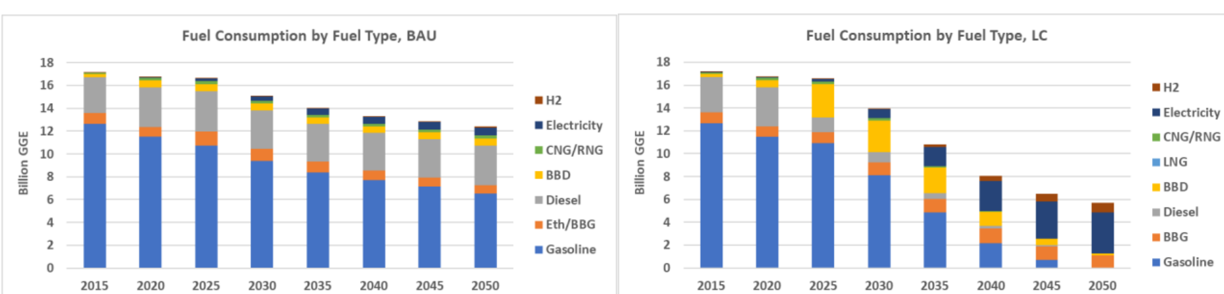


Both the LC and HFC scenario can achieve very low net CO_2e emissions, if the state succeeds to deeply decarbonize electricity production. Hydrogen used in transportation in the state is targeted to be 100% renewable (mostly electrolytic) under the ARCHES (Alliance for Renewable Clean Hydrogen Energy Systems) hub program.

Fuels Results

The uptake of ZEVs in the LC case dramatically changes the California energy mix over time, and compared to the BAU. Even in the BAU, the expected improved efficiency of vehicles over time reduces overall energy demand, but in the LC, the shift to electric and hydrogen vehicles reduces energy use dramatically, given that hydrogen fuel cells can be up to twice as efficient as ICEs and EVs up to 3x as efficient. By 2040, energy use is half of the 2025 level, and is nearly half electricity and hydrogen. By 2050, it is 80% electricity and hydrogen.

Figure ES-3. Energy Use in the BAU and LC Scenarios, to 2050

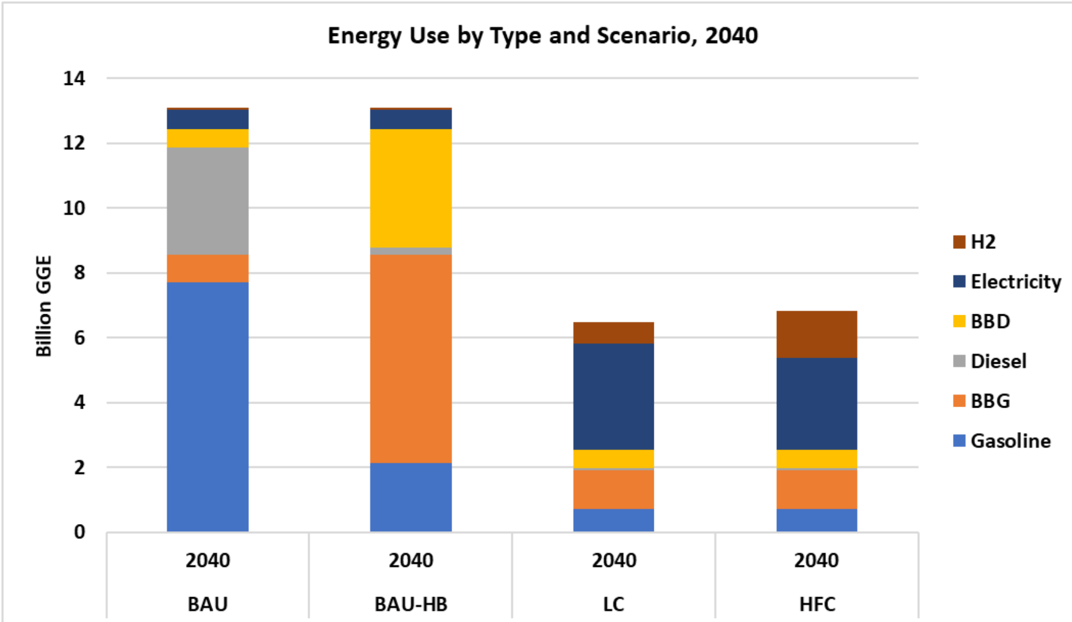


In the LC case, we also consider the effects of, and requirements for, decarbonizing the remaining non-electricity or hydrogen fuels in the road transportation system. These are mainly the liquid fuels (gasoline and diesel), and while in the BAU they maintain constant 2024 shares of blended biofuels, in the LC and HFC, we assume these are fully replaced by low-carbon biofuels by 2045. The diesel pool in California is already over 70% renewable diesel (as of November 2024). Gasoline has around 10% ethanol; for this to rise above 15%, it would likely have to be shifted to a drop-in fuel such as bio-gasoline. We assume this occurs over time.

We also consider a fourth case – the BAU with high biofuels (BAU-HB) case, which includes the BAU penetration of ZEVs, but with high blending of biofuels to achieve carbon intensity reductions. This could occur, for example, if the transition to ZEVs stalls, but the LCFS continues to push low-carbon fuels into the fuel mix. Comparing this high biofuels case (shown below in Figure ES-4, for 2040) with either the BAU or LC shown above, there is a huge difference between the scenarios in terms of biofuels demand. In the LC scenario, the strong transition to ZEVs precludes a major role for biofuels, which can replace gasoline and diesel with the relatively small overall quantity of about 3-4 billion gallons GE per year. In fact, the 2025 use of biodiesel is estimated to be close to 4 billion gallons GE, and thus is already at the maximum level needed; however, over time, the requirement for bio-based diesel would drop as that for bio-based gasoline would rise. In the high biofuels BAU however, biofuels reach over 10 billion gallons GE per year in 2040, around 3x higher. As this is just one state, if other states followed suit, the total biofuels demand could rise much higher. This would require a large volume of feedstocks such as corn or soy crops; we do not investigate the implications of this feedstock requirement here.

Figure ES-4 also shows the fuels shares in 2040 for the LC and HFC cases. In these cases, the use of biofuels is identical (and far lower than the BAU-HB case, but the use of hydrogen is about double the LC case, with a proportionately lower demand for electricity. This only includes end use energy, so does not include process energy such as electricity required to make hydrogen. However, there is an increase in end-use energy needed, since hydrogen fuel cell vehicles are less efficient than EVs.

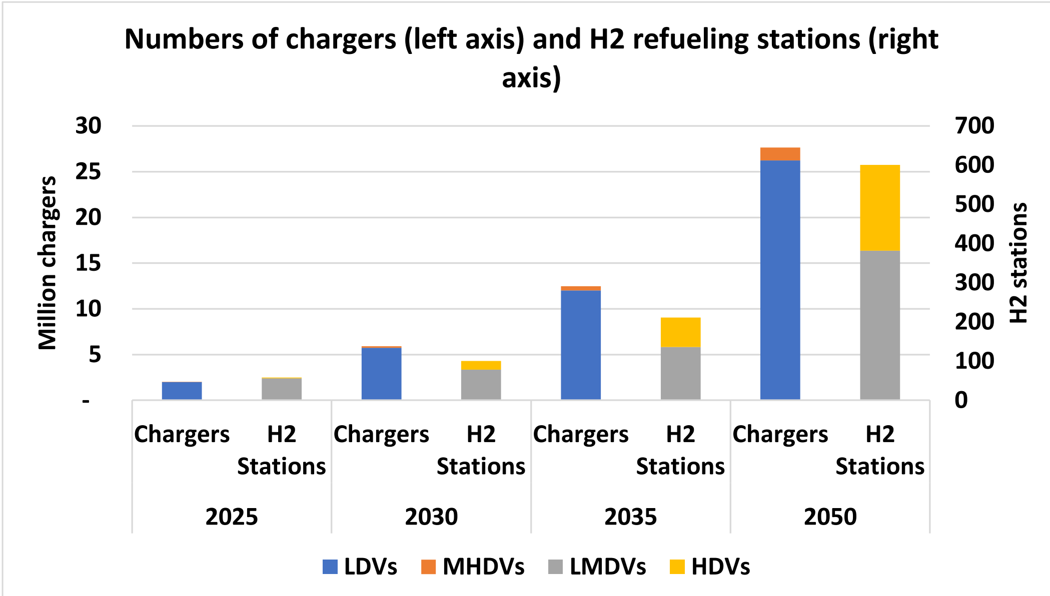
Figure ES-4. Energy Use in 2040 in the BAU, BAU with High Biofuels, LC and HFC Scenarios



ZEV Infrastructure Requirements

To support the large numbers of electric cars and trucks in the future (in the LC scenario) and relatively high numbers of fuel cell vehicles (in the HF scenario), charging and hydrogen refueling infrastructure will be needed. We have included this infrastructure in our scenarios, based on assumptions of how many chargers of different types, and how many H2 stations, will be needed to provide sufficient energy for the vehicles. It also takes into account the need for charging and station availability so drivers can find them as needed. In early years, there are more chargers and H2 stations than strictly needed, As the systems grow, they move toward equilibrium ratios of infrastructure to numbers of vehicles. This is covered in detail in the report; here we provide a summary of numbers and costs for the LC Scenario. The HFC is similar but with about 20% fewer chargers and 30% more HRS than in the LC.

Figure ES-5. Number of Chargers and H2 Refuelling Stations in LC Scenario



We do not attempt to estimate the specific investment needs for other infrastructure, such as electric power systems or "make ready" infrastructure, nor hydrogen production or distribution infrastructure, though the costs of these are to some degree reflected in the energy prices we use in the analysis. We do note that investments will be needed in order to maintain a well-connected electric transmission network for EVs, and (for a larger system) an open-access hydrogen pipeline network to support FCEVs. Such a system, while requiring considerable investment, would ultimately lead to lower levelized costs than a truck-delivery-based system.

Investment Costs

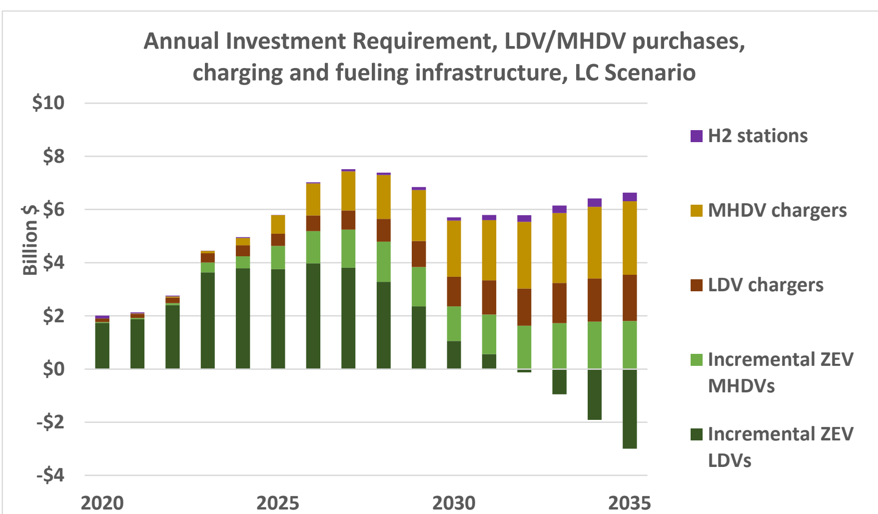
The costs of installing chargers and hydrogen refueling equipment are tracked; for chargers, this considers the types of chargers and the average installation cost of each type; this per-unit cost is very high for ultrafast chargers, though they are assumed to be used for many vehicles per day, so the numbers needed per vehicle are relatively low. The costs of hydrogen stations are a function of size (declining cost per unit capacity) and time (declining cost over time). These costs do not include any "make ready" costs, getting electricity to the plug, or costs of producing and moving hydrogen to stations.

For vehicle costs, we focus on the incremental purchase costs of electric and fuel cell vehicles over their base competitor, which is gasoline vehicles (for LDVs) and diesel trucks. This is broken down by size class, for better comparability.

The results are shown in Figure ES-6. As shown, costs are fairly flat through the pandemic years, then start to rise rapidly around 2023. They also are dominated by LDV incremental costs, as few ZEV trucks have been sold yet. Chargers matter but are mostly L2 home or work chargers, at relatively low cost. However, by 2025, ZEV trucks begin to matter, and the cost of providing infrastructure for them begins to appear as well. By 2028, the cost of chargers for cars and trucks together just about matches the incremental costs of purchasing the vehicles; by 2030 it clearly exceeds them, and truck chargers are the single most expensive investment category. This reflects the rapid growth in HDV Battery Electric Trucks (BETs), and the need for fast and ultra-fast chargers for these trucks. After about 2028, the incremental costs of LDV ZEVs starts to decline as purchase prices drop relative to gasoline vehicles; by 2033 these are net negative as they are projected to be less expensive than gasoline vehicles. But chargers must still be installed, and these costs continue to rise. The cost of H2 refueling stations becomes significant in the 2030s, but is small compared to charger costs. This is mainly due to much fewer FC cars and trucks than BEV cars and trucks, but also reflects lower installation H2 RFS construction than charger costs, *per vehicle served.*

The cumulative investment costs, 2020-2035, are shown to the right. These total nearly $90 billion and range from $2 billion for HRS to $26 billion for LDV incremental purchase costs. Notably chargers for LDVs and trucks combined are about $42 billion. In the HFC case (not shown), there are about twice as many HRS with an investment cost of $4 billion, along with about a $4 billion drop in charging infrastructure costs.

Figure ES-6. Annual Investment Requirements for Infrastructure and Vehicle Purchase (with total investment requirements, 2020-2035, in box on right)



Total investment to 2035

$2 B

$22 B

$20 B

$17 B

$26 B

The HFC case (not shown) has about 2x the investment costs for HFCs, and slightly higher costs for vehicle purchase, than the LC case. But this is mostly offset by lower BET and charger costs, with a net effect of only about 5% more expensive investments overall. After 2035, the investment costs mostly flatten and remain similar to 2035 year after year. The exception is LDV incremental costs, which decline and become more and more negative through 2040, by which year they more than offset all other investment costs.

However, this is only part of the story – apart from investment costs, there are the costs of operating vehicles and infrastructure. The full costs, including purchase and operating costs, are considered next.

Scenario Costs

What are the full, annual and cumulative costs of these scenarios into the future, and how do they compare with each other? Ultimately, the costs of the LC scenario from 2025 to 2050, for vehicle purchase and operating costs (including fuel costs), and aggregated across LDVs and trucks, are not significantly different than the costs of the BAU scenario. Costs are higher over the next few years then become lower, mainly due to energy cost savings from electric vehicles. But these higher and lower costs are in the tens of billions of dollars over a few years, compared to trillions of dollars spent overall on vehicles and fuels in California.

Figure ES-7 summarizes the differences over time between the LC scenario and the BAU. This includes LDVs, trucks and buses, and the purchase and infrastructure investment costs shown in the previous section. The annual operating costs, including maintenance and fuel costs, are now also added in. It is the lower fuel costs, particularly electricity for EVs, that causes the total cost to start to drop around 2028, and go negative around 2032. These savings finally outweigh the additional vehicle and infrastructure purchase costs and result in net societal savings into the future, vs a BAU with relatively few electric vehicles. Costs are somewhat higher, and take a little longer to pay back and go negative, in the HFC case.

Figure ES-7. Cost Differences Between LC and BAU Scenarios, by Year

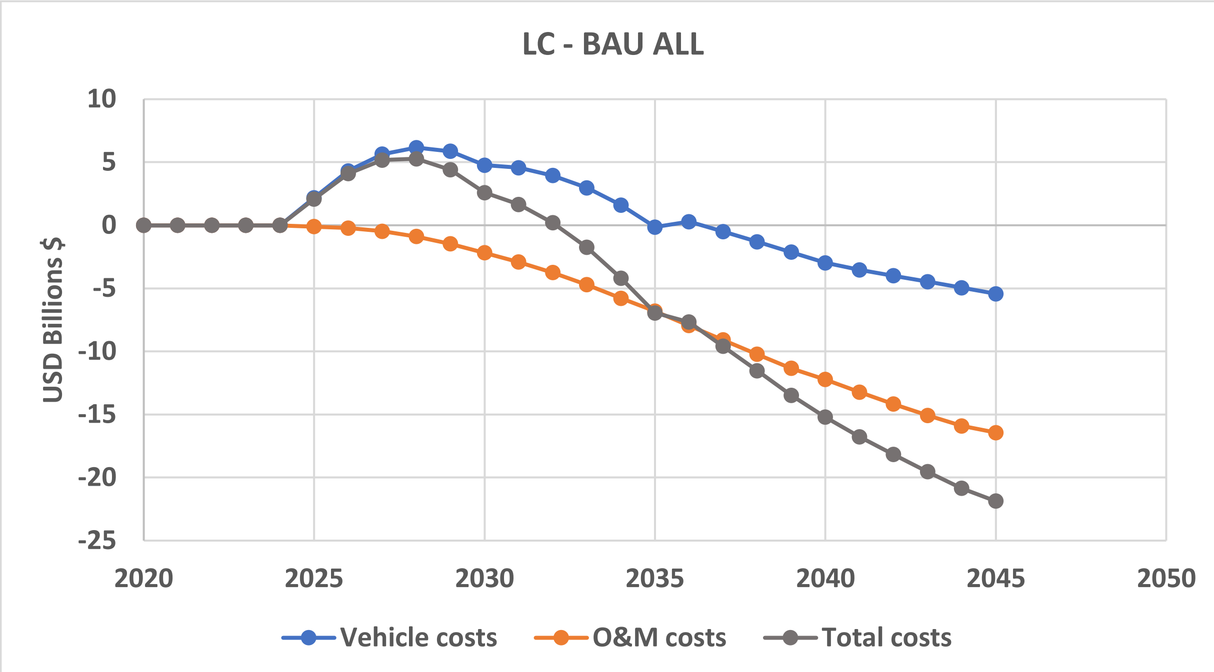
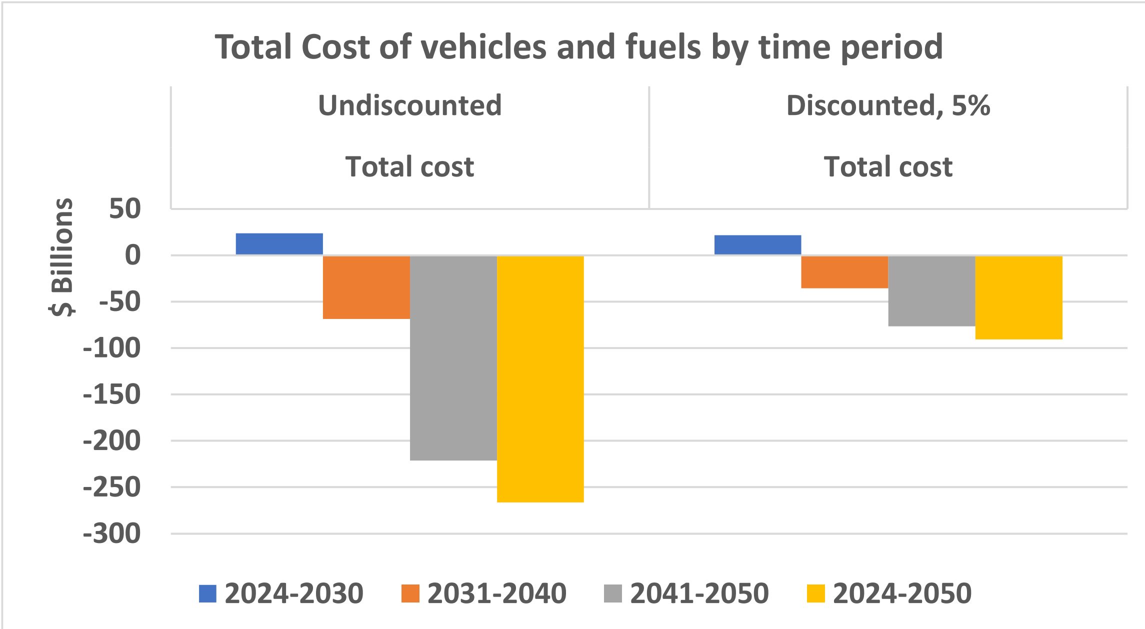


Figure ES-8 shows these costs over specific time periods, and also compares the undiscounted costs (as also shown above in Figure ES-7), with costs discounted at 5% per year into the future. In both cases these costs go negative between 2030 and 2035, and the savings are much larger than the costs out to 2050; but the totals are lower in the discounted case, since the further into the future they are calculated, the lower their importance and value relative to the undiscounted case. But they are still over $100 billion in total savings, compared to about $18 billion in net additional costs to 2030.

Figure ES-8. Total cost of vehicles and fuels by time period, with and without time discounting



Finally, considering the CO_2-equivalent emissions reduced in these scenarios (taking into account vehicle and upstream emissions), the LC scenario cuts CO_2e over the 2024-2050 period by nearly half (from 4.0 down to 2.1 gigatonnes) over the time frame; it also reaches near zero net CO_2 in the 2040-205 time frame (Figure ES-9). Comparing these to the costs estimated above and estimating the cost per tonne CO_2 reduction (Figure ES-10), the cost per tonne in the first 6 or so years is around $200/tonne, and thereafter becomes negative (since there are net savings). The exact amount of negative cost by time period varies, but it is strongly negative across the entire 2024-2050 time frame (yellow bar) in both the undiscounted and discounted cost cases.

Figure ES-9. Cumulative CO_2 Emissions and Cost Per Ton by Scenario

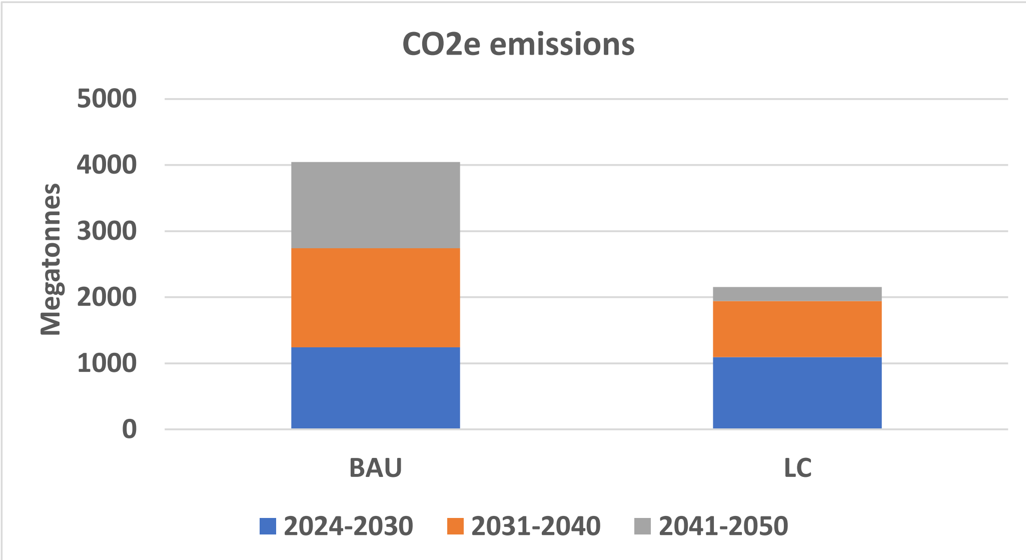
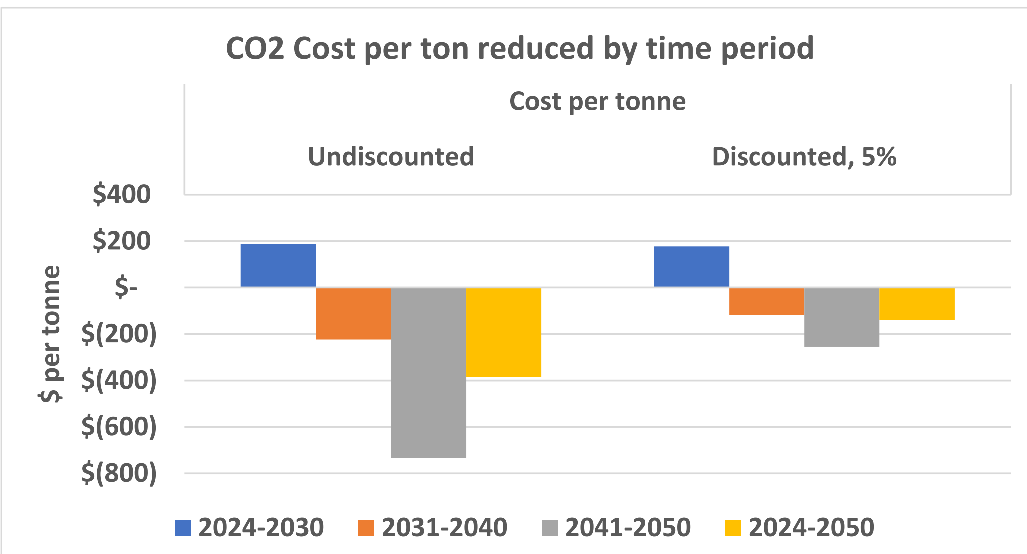


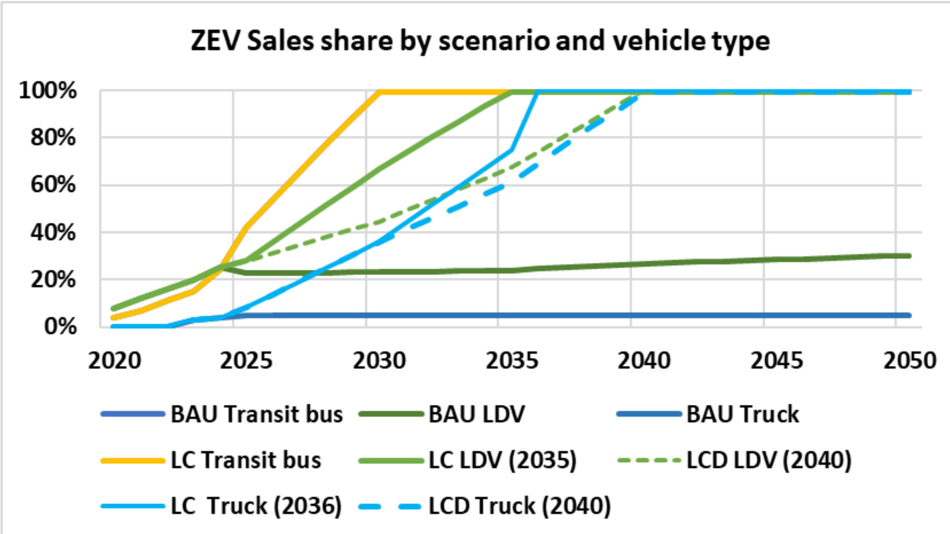
Figure ES-10. CO_2 Cost Per Ton Reduced by Time Period, with and without Discounting



Effects of Delaying the 100% ZEV Sales Date to 2040

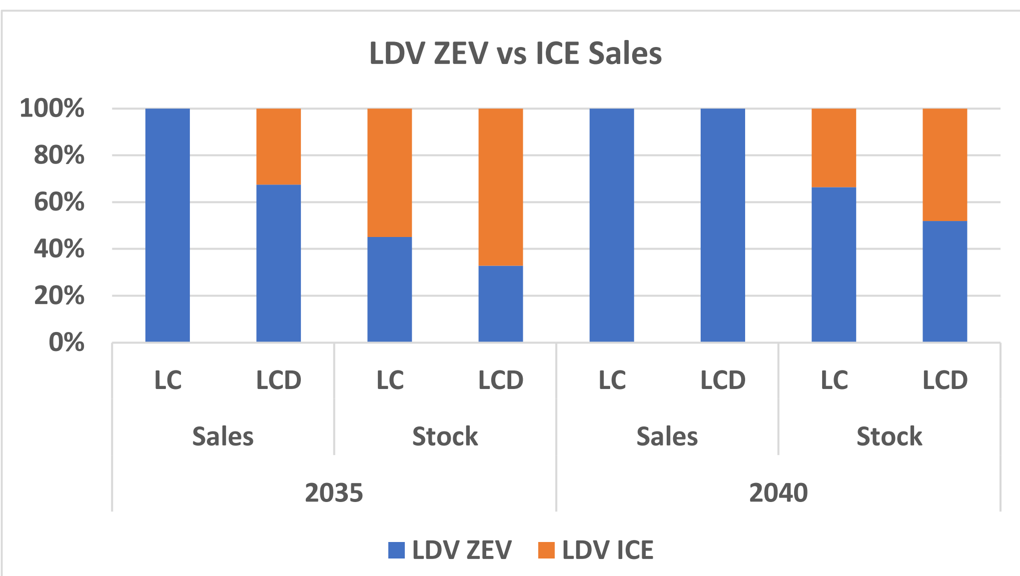
As described above, we assume in our main LC and HFC scenarios that the California targets for adoption of ZEV light-duty and heavy-duty vehicles are met, namely the CARB rules that 100% ZEV LDV sales must occur by 2025, and 100% truck sales by 2036. However, if for any reason these targets were detailed, it is possible to consider what this means for the stock of ZEVs, CO_2 emissions, and costs. Here we consider a "side case" where the rate of ZEV adoption slows and reaches 100% only by 2040. It is reflected by the dotted line in Figure ES-11 below.

Figure ES-11. ZEV Sales Shares with "Delayed" Cases, Reaching 100% by 2040



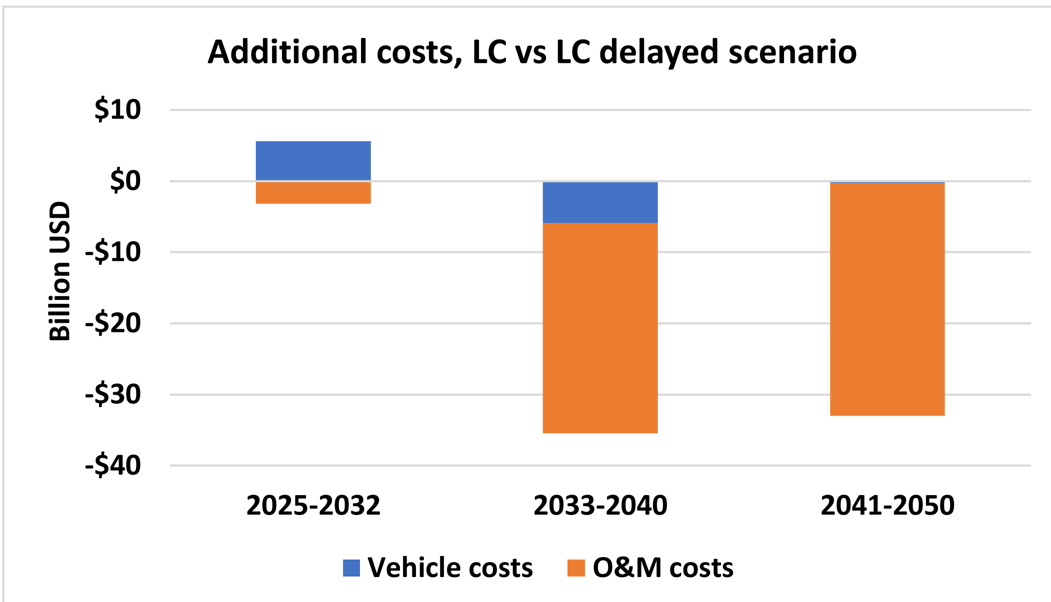
The market shares of light-duty ZEVs in the LC vs LC-delayed (LCD) scenarios, for both sales and stocks, and in 2035 and 2040, are shown in Figure ES-12 below. The LCD catches up with LC by 2040 in terms of sales, but lags behind in ZEV stock by about 12% in 2040. It closes the gap to about 8% in 2045 (not shown). The effect of the delay on MHDVs is slightly lower. The combined effect of the delay for LDVs and MHDVs on cumulative GHGs between 2025 and 2050 is about a 12% increase.

Figure ES-12. LDV ZEV Sales and Stock Shares for LC and LC-delayed (LCD) Scenarios, in 2035 and 2040



The cost differences between the LC and LCD scenarios are similar in type (but not scale) to those between the LC and BAU scenarios. As shown in Figure ES-13, the additional costs (and savings, when negative) of the LC scenario over the LCD scenario are summarized in three time frames. The delayed implementation (LCD) saves a small amount of money through 2032 (blue positive bar), from lower expenditures on ZEV purchases, though it is more expensive regarding O&M costs. The net effect during this period is about $4 billion in higher costs for the LC vs LC delayed. But after 2032, the LC saves over $35 billion out to 2040, and another $30+ billion to 2050—over $60 billion overall. Compared to the BAU (not shown here), the LC can save $300 billion, whereas the LCD saves only about $240 billion.

Figure ES-13. LC scenario Costs Minus LC-Delayed Costs, by Cost Type (LDVs and MHDVs)



Sensitivity Analysis of Vehicle and Fuel Prices

The costs of each scenario vary substantially depending on a range of assumptions about technologies and fuels, particularly future petroleum, hydrogen, and biofuel prices. We explore this through a sensitivity analysis. We summarize some of the differences in Table ES-2 below.

As shown in the table, with a 25% lower future cost for hydrogen and electricity, compared to the LC scenario, the results are an earlier breakeven year, lower "excess" cost until the breakeven point, and much higher cost savings out to 2050 after the breakeven point. With a 25% higher cost for hydrogen and electricity, the inverse occurs, with a 2 year delay in reaching breakeven costs, about 50% higher costs to that point, and a reduction in over 50% in cost savings after that point. Though the cost savings are still over 3 times higher than the excess cost before the breakeven point.

Table ES-2. Effects of 25% Lower and Higher Hydrogen and Electricity Costs on Overall Scenario Costs

	Cross over	Excess LC cost	LC cost savings
Scenario	(year)	(billions$)	(billions$)
All vehicle costs, LC - BAU			
Base case	2032	25.4	292
Low ZEV fuel cost	2030	18.1	447
High ZEV fuel cost	2034	40.3	144

Takeaways From These Scenarios

Overall, the LC Scenario reaches 100% ZEV stock penetration by 2045 at a long-term cost well below zero, even with significant discounting of future cash flows. However, in the near term (through 2030 or so), net costs may be substantial. Specific findings include:

- ZEVs are likely to provide long-term savings to consumers, but there are significant up-front investment costs. Given higher vehicle purchase costs for ZEVs over the next 5-10 years, policy incentives or mandates may be needed to grow these markets. Vehicle purchase costs are approximately $40 billion higher in the LC and $45 billion higher in the HFC scenario than in the BAU scenario, over the 2025–2030+ timeframe (up to the break-even year). The extent to which subsidies would be needed to offset these higher costs will depend on operating cost savings, which are considerable; they will also depend on non-cost factors affecting household and fleet interest in buying the vehicles, such as driving range. Several of our separate reports consider the full set of factors influencing vehicle choices by households and fleets, and estimates costs and market shares (e.g. Zhao et al, 2025, Burke et al, 2024).

- A principal difference between the LC and HFC scenarios is the assumed success and estimated competitiveness of hydrogen fuel cell cars and trucks, which play a much larger role in HFC. This depends on the assumption that fuel cell and hydrogen costs come down substantially over this period, which in turn depends on a strong rollout of these systems, which is not assured. This also depends heavily on how much their competition – batteries – improves over the next 5-10 years. Strong battery improvement could help resolve some issues with BEVs, such as driving range and recharging time. In particular, if battery technology advances sufficiently to allow penetration into longer-range truck applications, that could fundamentally change the expected vehicle portfolio and reduce the need for fuel cell trucks.

- Delaying ZEV adoption in these scenarios, with a slower ramp up and reaching 100% ZEV sales in 2040 rather than the mid-2030's, would generate a significant increase in CO_2 over the 25 year time from (2025-2050). It would also cost money, since the savings from ZEVs would be delayed. The net savings from a "delayed" scenario, 2025-2050, is significantly lower than in the LC and HFC scenarios that hit the mid 2030's 100% ZEV targets; though delaying the ZEV ramp up does help reduce the up-front costs of the transition.

- Biofuels could be used to help speed CO_2 reductions in high ZEV scenarios by more rapidly removing fossil fuels from the remaining ICE vehicles. Within California, this is not expected to take much more biofuels than is already being used, if ZEV penetration occurs at the rate targeted by the state. If slower ZEV penetration occurs, more biofuels would be needed to accomplish a major CO_2 reduction (though still unlikely to achieve the full elimination of GHG emissions, well-to-wheels, as can be achieved with ZEVs). In any case, reliance on biofuels in a world without strong ZEV adoption would require a large quantity of such fuels - about 5x more than needed in the LC case. And if a similar "low ZEV, high biofuel" strategy was followed at the US level, perhaps an additional 10x more biofuels would be needed to achieve the same outcome as this scenario does in California. This number only gets larger if one expands the strategy to other countries.

More work is needed to better understand how costs may change over time (such as a function of vehicle production volumes and learning), and the level and types of policy support that may be needed depending on how the future unfolds.

2. Introduction and Background

This study examines advanced vehicle and fuel technologies that could enable a transition to low carbon futures in California in the on-road sector, through 2050. We focus on zero-emission vehicle (ZEV) technologies, namely battery electric vehicles (BEVs) and fuel cell vehicles (FCEVs), using low carbon electricity and hydrogen fuel to reduce greenhouse gases (GHGs) to near-zero levels. We also consider low-carbon fuels for internal combustion engine (ICE) vehicles. We create various scenarios of market penetration for BEVs and FCEVs in the light-duty vehicle markets as well as medium- and heavy-duty trucks and buses, to estimate the resulting vehicle stocks, GHG reductions, changes in fuel use, and costs of the vehicles and fuels relative to scenarios without these. This is the third such paper we have produced on this topic, with our Technology Transition Model (TTM), with previous papers in 2019 and 2021. We compare some of our results to these previous efforts to understand how the situation is changing, and how our projections (such as the cost of transitioning) are evolving.

California has adopted very ambitious targets and accompanying regulations for both light-duty vehicles (LDVs) and medium- and heavy-duty vehicles (MHDVs) in order to meet the state's air quality and climate change goals. These regulations include mandates for vehicles sales, fleet purchases, and overall stock of zero-emission vehicles (ZEVs) in fleets. The market penetration scenarios attempt to match the requirements of these various regulations. We assume all sales requirements are met (such as annual vehicle percent sales requirements), but do not exceed these annual levels. We do not put any particular constraints on meeting 100% ZEV stocks for LDVs or MHDVs, but these follow sales to become strongly ZEV dominated over time.

The study uses the UC Davis Transportation Transitions Model (TTM) which is a stock turnover model with inputs such as vehicle stock, vehicle miles traveled (VMT), vehicle fuel economy, fuel carbon intensities, vehicle and fuel costs, and outputs such as resulting vehicle stock, fuel use, GHGs, and costs. Prior studies have used this model to understand the effects of advanced vehicle and fuel technologies in California (Brown et. al. 2021, Fulton et. al. 2019) and in the entire US (Wang 2023).

The present analysis includes two major changes to the earlier California TTM. The previous TTM version included high initial ZEV costs for the 2020 timeframe and assumed these costs would be substantially reduced by 2025 due to significant ZEV market penetration resulting in reductions in component costs. While LDV ZEVs saw substantial market penetration, MDHV ZEVs had essentially no sales into 2024. We reevaluated our present and projected vehicle costs for both LDV and MDHV ZEVs, and the costs for MDHV ZEVs are much higher in the 2025-2030 timeframes. Second, the latest California regulations include more aggressive sales and fleet purchase requirements, effectively requiring 100% ZEV market shares of sales by 2035 for LDVS and by 2036 for MDHVs. Our current main scenarios reflect those changes, resulting in a much faster transition in the overall fleet stock than we assumed in previous reports.

3. Methodology and Key Assumptions

General Approach

Since vehicles can have different characteristics, the TTM disaggregates LDVs into two categories and MDHVs into eight categories (see Table 1). This approach allows the model to calculate the GHG emissions, costs, and fuel use of each vehicle type separately. The model then tracks vehicle sales, stock turnover, resulting annual stocks of vehicles by vintage and travel per vehicle, total travel, average efficiency, energy use, and CO_2 emissions. We also estimate the costs of vehicle purchases, maintenance, and energy costs. In this analysis, we have added in a separate analysis related to the needed investment in infrastructure (such as charging and hydrogen refueling stations). All of these variables are included in the spreadsheet model. More details on the model structure are available in Fulton et al (2019), along with results from that previous California TTM transition scenarios report.

Table 1. Vehicle Categories and Their Definitions

Vehicle Category	Subcategory	Definition
Light-Duty Vehicles	Cars	Passenger cars
	Light-duty trucks	Vehicles with a gross vehicle weight < 8500 lbs., used primarily for transporting property
Medium- and Heavy-Duty Vehicles	Long-haul trucks	Heavy-duty trucks that generally travel > 250 mile/day and do not return to base every night
	Short-haul trucks	Heavy-duty trucks that generally travel < 250 mile/day and return to base every night
	Heavy-duty vocational trucks	Heavy-duty trucks that carry equipment or materials rather than cargo (e.g. refuse or mixers)
	Medium-duty vocational trucks	Medium-duty trucks that do not transport cargo (e.g. utility truck)
	Medium-duty urban trucks	Medium-duty trucks operating on urban drive cycles that generally transport cargo (e.g. delivery box truck)
	Urban buses	Transit buses operating primarily on urban drive cycles
	Other buses	Coaches operating primarily on highway drive cycles
	Heavy-duty pickups and vans	Pickup trucks or vans with gross vehicle weight > 8500 lbs. and < 14,000 lbs.

We created four scenarios of ZEV market penetration to compare the resulting GHG emissions, fuel use, and costs. The scenarios specify the sales shares for each vehicle and technology type (e.g. BEV car, diesel long haul truck, FCEV transit bus, etc.). The scenarios are briefly described below.

- Business-as-usual (BAU): Specified sales shares assuming no significant climate change policies for ZEVs go into effect.
- Low Carbon (LC): Very aggressive ZEV market penetration to meet the California regulations.
- High Fuel Cell (HFC): ZEV market penetration identical to the LC scenario but fuel cell market penetration is significantly higher than in the LC scenario.
- BAU with High biofuels (BAU-HB): Market penetration similar to the BAU scenario with high update of low-carbon liquid fuels.

Many of the key technology assumptions and projections used in these scenarios are described in our accompanying technology documentation report (Fulton et al, 2019), but key assumptions are also described in sections below.

Table 2 shows the key inputs and outputs for the TTM. Each vehicle type and technology (e.g. fuel cell long-haul trucks, gasoline cars, or battery electric transit buses) has inputs on a per vehicle or per unit energy basis. The inputs may vary for each year such that ZEV capital costs decrease over time, vehicle fuel economy increases over time, electricity carbon intensities decrease over time, etc. The output parameters are given for the entire fleet for each vehicle type and technology year by year.

Table 2. Key Inputs and Outputs in the TTM

Model Inputs	**Model Outputs**
Vehicle sales shares	Fuel consumption
Vehicle fuel economy	Vehicle sales by year
Vehicle capital cost	Vehicle stock by technology type
Vehicle survival rate	Total VMT
Vehicle miles traveled	GHG emissions
Vehicle maintenance cost	Vehicle costs
Initial vehicle stocks	Fuel costs
Fuel cost	
Fuel carbon intensity	

Scenario Development

The four model scenarios (BAU, LC, HFC, BAU-HB) were created to project technology sales shares (and subsequent total sales, stocks, energy use, etc.) under different policy sets and market conditions. In our BAU, we assume a counterfactual case without strong ZEV mandate directives, and relatively flat or slow growth in ZEVs beyond current (2025) levels to 2050. In the LC and HFC scenarios, we include the actual policies that mandate ZEV sales and purchases, one with a near total dominance of BEVs (LC), and the other with considerable numbers of fuel cell vehicles (HFC). Finally, we consider a scenario where ZEVs play a much smaller part than in the LC or HFC scenarios and where biomass based fuels increase to replace fossil fuels in the ICE vehicles. Although the California Air Resources Board (CARB) has approved several policies mandating the sales and purchases of ZEVs, the BAU does not reflect these policies in order to act as a better baseline to compare results both with and without these policies. CARB's approved policies vary in which entities are affected (OEMs through sales or fleets through purchases or overall stock of ZEVs) and in which vehicle types are regulated (LDVs, MDHVs, drayage trucks, transit buses). The TTM advanced scenarios (LC and HFC) are created to meet the sales requirements of these policies. In general, the LDV and truck scenarios are best thought of as "what if" specifications of market penetration used to understand potential effects and costs of new technologies and fuels entering the marketplace.

The following paragraphs briefly describe the various CARB ZEV related policies.

Advanced Clean Trucks Rule

In 2018 CARB approved the Innovative Clean Transit (ICT) regulation (CARB 2018). The ICT requires:

- All new bus purchases must be ZEVs starting January 1, 2029.
- Agencies must submit a Zero-Emission Bus Rollout Plan with a goal of full transition to zero-emission buses by 2040.

In 2022 CARB adopted the Advanced Clean Cars II (ACC II) regulation (CARB 2022). The regulation sets percentage sales requirements for OEMs which rise to 35% in 2026 and reach 100% in 2035.

In 2021 CARB approved the Advanced Clean Truck (ACT) regulation (CARB 2021). The ACT sets a ZEV sales percentage schedule which OEMs must meet in selling trucks in California. CARB set various modifiers to that schedule such that OEMs have some flexibility in meeting the requirements. The ACT sales schedule is shown in Table 3.

Table 3. Truck ZEV Sales Percentage Requirements Based on the ACT Regulation

Model Year	Class 2b-3	Class 4-8 Straight Trucks	Class 7-8 Tractors
2024	5	9	5
2025	7	11	7
2026	10	13	10
2027	15	20	15
2028	20	30	20
2029	25	40	25
2030	30	50	30
2031	35	55	35
2032	40	60	40
2033	45	65	40
2034	50	70	40
2035 and beyond	55	75	40

Advanced Clean Fleets Rule

In 2023 CARB approved the Advanced Clean Fleets (ACF) regulation (CARB 2023). This regulation has not been granted a waiver by EPA under the Clean Air Act and CARB is not enforcing this provision at this time (CARB 2025). However, major OEMs also signed an agreement with CARB to reach the 100% ZEV sales target by 2036, regardless of the enforcement of ACF, and this is still in effect (CARB 2023b).

In addition, CARB has indicated that the agency is exploring alternative policies to help OEMs achieve the targets, such as on-going and perhaps stronger fiscal incentives to fleets to purchase ZEVs. In any case, we continue to assume that this particular target is achieved in our LC and HFC scenarios, and describe details of the regulatory approach here, and assume sales track the targets in the ACF, as described below.

The ACF includes sections regulating state and local government agency fleets, drayage trucks, high priority and federal fleets, and OEMs. State and local fleets must purchase ZEVs according to the following schedule:

- Starting January 1, 2024, 50 percent of purchases in each calendar year.
- Starting January 1, 2027, 100 percent of purchases in each calendar year.

Drayage fleets must meet the following requirements:

- Beginning January 1, 2024, all drayage trucks registering must be ZEVs.
- Beginning January 1, 2025, any legacy drayage truck must not exceed its minimum useful life threshold.
- Beginning January 1, 2035, all drayage trucks must be ZEVs.

High priority fleets are defined to be fleets with ownership or control of more than 50 trucks or entities with greater than $50 million in total gross annual revenue. High priority and federal fleets must choose between:

- Adding only ZEVs to their fleet beginning in 2024.
- Opting-in to the flexibility option shown in Table 4.

Table 4. ACF ZEV Fleet Milestones by Vehicle Body Type and Year

	Percentage of fleet that must be ZEVs				
Group	10%	25%	50%	75%	100%
Box trucks, vans, 2-axle buses, light-duty package delivery vehicles yard tractor	2025	2028	2031	2033	2035 and beyond
Work trucks, day cab tractors, 3-axle buses	2027	2030	2033	2036	2039 and beyond
Sleeper cab tractors, specialty vehicles	2030	2033	2036	2039	2042 and beyond

The ACF includes various potential exemptions for fleets under specific circumstances. Finally, the ACF requires all OEM sales in year 2036 and after to be ZEVS. As noted above, this is an important aspect of the regulation that also exists as a separate agreement between the state and major truck OEMs, outside of the ACF.

BAU Scenario - LDVs

The BAU scenario does not assume any ZEV regulation in effect through 2050, but given the present market penetration of LDV ZEVs, the LDV ZEV sales shares reach modest values in that timeframe. The LDV vehicle types in the TTM include BEVs, FCEVs, and plug-in hybrids with either a 40 mile (P40) or 80 mile (P80) all electric range, and we recognize all three vehicle types as ZEVs. In 2020 the TTM BAU scenario specifies almost 8% market share for LDV ZEVs with 2% plug-in hybrids. The model assumes just over 21% LDV ZEVs by 2025 exceeding 30% in 2050. In 2050 20% of LDV ZEVs are BEVs with 10% plug-in hybrids for both cars and LD trucks. The BAU assumes essentially no fuel cell LDVs through 2050.

BAU Scenario - MDHVs

The truck BAU assumes very modest ZEV market penetration with only transit buses having ZEV market share above 5%. Long haul and short haul trucks have ZEV market shares of roughly 3% starting in 2025 and increasing to roughly 5% in 2050. MD delivery trucks, HD pickups, and MD vocational truck all reach sales shares of 5% ZEVs by 2050 while HD vocational and other buses reach 2%. All these vehicle types have minimal fuel cell market share. The major outlier for MDHVs in the BAU scenario is transit buses. Before the ICT rule, transit buses were expected to reach very high sales of ZEVs. We assume they reach 100% sales in 2030 and by 2050 BEV and FCEV buses have market shares of 87% and 13% respectively.

LC Scenario – LDVs

The LC scenario for LDVs is essentially identical for both cars and LD trucks. The ZEV market share reaches 28% by 2025, 67% by 2030, and 100% by 2035 in accordance with the ACC II regulation. The plug-in sales are dominated by P40s until 2035 when P80s overtake them ultimately reaching 15% by 2050. Sales shares of FCEVs rise very slowly reaching 2% by 2035 and 5% by 2050.

LC Scenario – MDHVs

Except for transit buses, the ZEV sales share of all MDHVs reach 75% in 2035 and 100% by 2036. We assume many fleets may wish to delay the purchase of ZEVs until only ZEVs are available; therefore, there is a significant jump between 2035 and 2036. Transit buses have the same sales shares as the BAU scenario reaching 100% in 2030. Each vehicle type has a different ratio of BEVs to FCEVs with some types (vocational and MD delivery) only reaching 15% FCEVs sales in 2050 and transit buses and long haul trucks reaching 25% and 33% FCEVs respectively in 2050.

HFC Scenario – LDVs

The intent of the HFC scenarios is to explore the possibility of significantly higher FCEVs sales. FCEV sales are highly dependent on several factors such as FCEV cost, hydrogen cost, and availability of hydrogen fueling infrastructure. Presently FCEV costs are higher than BEV costs, hydrogen is extremely expensive, and there are very few hydrogen fueling stations, particularly for trucks. Depending on near- to mid-term state and federal actions, these barriers could be reduced significantly. In California the ARCHES Hydrogen Hub plans to vastly increase the hydrogen supply and work with OEMs and fleets to increase the demand. If these projects are successful, the FCEV market share could increase markedly (ARCHES, 2025).

The HFC scenario for LDVs has the identical ZEV and plug-in vehicle market share each year as the LC scenario. The only difference is the ratio of BEV to FCEV sales shares. FCEVs reach 10% in 2040 and 17.5% in 2050.

HFC Scenario – MDHVs

The HFC scenario for MDHVs also has identical ZEV market share each year as the LC scenario. The FCEV sales shares increase in 2050 from a minimum of 30% for HD vocational trucks to 50% for most vehicle types and 66% for long haul trucks. The California ARCHES Hydrogen Hub (ARCHES 2025) plans to vastly increase the supply of clean hydrogen in the state, and work with OEMs and fleets to increase fuel cell truck and thus hydrogen demand. Their targets include 5000 FC trucks and 50 MHDV refueling stations in operation by 2030. If these targets are met, markets for FC vehicles and hydrogen could continue to increase rapidly after 2030.

BAU-HB Scenario
The BAU-HB scenario has the identical vehicle sales shares as the BAU scenario. The only difference is that the biomass based fuel blends are same as those assumed in the LC and HFC scenarios.

Appendix A shows the market share for all 10 vehicle types for each of the three scenarios.

Other Key Inputs and Assumptions

Fuel Economy
The TTM uses vehicle fuel economy and VMT to calculate the fuel use per year for each vehicle type and technology. The fuel economy for future years is determined using the Advisor dynamic vehicle simulation program (Burke and Zhao 2015) tying the results to present EMFAC or published values for diesel and gasoline vehicles. The Advisor model uses inputs for vehicle weight, rolling resistance, frontal area, and drag coefficient to determine the road load. Vehicles are then modeled with engine maps and transmission efficiencies for diesel or gasoline vehicles, battery characteristics and motor/controller efficiencies for battery electric vehicles, and fuel cell characteristics and motor/controller efficiencies for fuel cell vehicles. Estimates were made for the changes in these input parameters over time such that fuel economies for all vehicle types and technologies improve through 2050.

Using input drive cycles, the Advisor program calculates the fuel use for the drive cycle distance. The miles per unit of fuel is then converted to gallons of gasoline equivalent (GGE) and input to the TTM. Natural gas vehicles were not modeled using the Advisor program. The present fuel economy for natural gas vehicles was compared to the fuel economy for gasoline LDVs or diesel vehicles. This ratio was kept constant over time through 2050. The fuel economy for each vehicle category and technology is shown in Appendix C.

Vehicle Costs

Vehicle costs for the present year, 2025, were taken from published values of commercial vehicles where available. For some ZEV trucks there are no available commercial vehicles. In those cases, we used the procedure for projecting vehicles costs outlined below.

Future year projections were calculated by summing the various major component costs for each vehicle. More detail can be found in an earlier research report (Zhao 2024). Costs are reduced over time via rising production volumes and learning. We assume a reasonable market growth outside California to help achieve this; thus the same per-vehicle cost assumptions are used in all of our scenarios. The component costs considered for each vehicle technology are the following:

ICE vehicle

- Glider
- Engine
- Transmission
- Engine after treatment system (EATS)
- Battery (for hybrid vehicles)

Battery electric vehicle

- Glider
- Battery
- Motor/controller

Fuel cell vehicle

- Glider
- Fuel cell
- Hydrogen storage
- Motor/controller
- Battery

The battery, fuel cell, hydrogen storage, and motor/controller costs are all parameterized using equations of the form

$$\text{Component cost} = (\$/\text{unit}) * \text{units}$$

where the units are $/kWh, $/kW, $/kgH2, $/kW for batteries, fuel cell, hydrogen storage, and motor/controllers respectively. The $/unit parameterization values all decrease with time. The values used are given in Table 5 (5a and 5b).

Table 5a. Values for MDHV Component Parameterization

	Battery	Fuel cell	Hydrogen storage	Motor/controller
Year	$/kWh	$/kW	$/kg H2	$/kW
2025	200	225	800	56
2030	175	169	400	42
2035	150	127	350	32
2040	125	95	300	24
2045	120	90	280	20
2050	115	88	270	18

Table 65b. Values for LDV Component Parameterization

	Battery	Fuel cell	Hydrogen storage	Motor/controller
Year	$/kWh	$/kW	$/kg H2	$/kW
2025	133	166	800	30
2030	110	141	400	26
2035	91	127	350	23
2040	76	95	300	20
2045	74	90	250	17
2050	72	88	200	15

The dynamic vehicle simulation program, Advisor, was used to derive the battery capacity, fuel cell power, hydrogen storage kgs, and motor/controller power for each vehicle and technology combination through 2050.

The battery unit cost ($/kWh) represents the cost for a battery cell. The cell must be integrated into a pack and the pack must be integrated into the vehicle before sale. These two integration costs must be added to the battery cell cost. We assume this integration factor decreases over time starting from 1.4 in 2025 down to 1.12 in 2050.

We include an oversize factor for both batteries and hydrogen storage in MDHVs. This oversize factor is a correction to the energy calculation to account for accessory loads, road grades, and other factors that increase the required vehicle power, and hence energy, over the given drive cycle. We estimate the oversize factor to be 1.38. All component costs include a markup factor of 1.35 representing the profit margin of the manufacturer or distributor. Vehicle costs do not include any taxes and are shown in Appendix B.

Fuel Costs

Fuel prices in the TTM are taken from projections of prices in California. The prices used do not include taxes or any policy incentives such as the Low Carbon Fuel Standard, and the prices are input into the TTM in units of $/GGE. All prices are shown in Table 7.

Gasoline and diesel prices

Gasoline and diesel prices are taken from the California Energy Commission's 2023 Integrated Energy Policy Report (IEPR) (CEC 2023). The price for gasoline and diesel fuel rise gradually to roughly $5/GGE and $5/DGE respectively including taxes. We subtract state and local sales tax, state excise tax, and federal excise tax (totaling $0.94 for diesel and $0.88 for gasoline) from the prices and convert diesel prices to $/GGE.

Electricity prices
We take electricity prices from the CEC's California Energy Demand 2024 Demand Forecast Electricity Rate Forecast (CEC 2024) and from estimates of public charging. The CEC forecast includes both residential and commercial rates. The residential rate rises from $0.24/kWh in 2020 to about $0.32/kWh in 2025. The projection rises very slightly to roughly $0.325/kWh in 2045. Commercial rates rise from $0.21/kWh in 2020 to $0.27/kWh in 2025 and stay constant through 2040. Public charging rates can vary significantly from below $0.40/kWh to over $0.60/kWh. We take the public charging rate to be $0.50/kWh.

For LDVs we assume the average car charges mostly at home at the residential rate, but LDVs will occasionally charge at public chargers when necessary. We assume roughly 80% of all BEV charging occurs at home (Qmerit 2025). We then take the price of LDV electricity as the weighted average of residential and public charging. For fleet vehicles, we use the commercial rate for vehicle charging.

Long haul trucks are expected to charge mostly from truck stops. We assume that truck stop charging will be rather high in the near-term and decrease through 2050. We use the public charging cost for 2025 and linearly decrease this value to the commercial cost in 2050.

Hydrogen prices
The price of hydrogen to the transportation end user results from costs along the supply chain (production, storage, distribution, station-related costs) and from various market forces that, for example in California, have recently resulted in quite high hydrogen prices. We assume that prices (without taxes or subsidies) return to a more cost-based level by 2030, which is on the order of $10/kg to vehicles. This relates to various recent papers we have published on this topic (Fulton et al, 2024a and b). Even this price, though still much higher than gasoline (given hydrogen's similar energy density per kg as gasoline per gallon), depends on market expansion and competition which is assumed to happen as the market expands such as from ARCHES, CEC and other investments. The price then continues to fall toward a long-run level of about $6/kg by 2045. The actual end-use price is likely to be lower given incentive programs such as LCFS and other state and national programs. These should help the market to expand in line with our LC and possibly HFC scenarios. We do not assume different hydrogen prices in these scenarios.

Biomass based diesel and gasoline prices
Various biofuels (ethanol, biodiesel, renewable diesel, sustainable aviation fuel) have different costs of production, though their final prices also depend on market size and production location. We use fairly simplifying assumptions for this study for biomass based gasoline and biomass based diesel sold in California. These are as follows and do not include taxes or subsidies such as the LCFS:

- Biodiesel/RD (2025) price in the near term, through 2030: $5.00/gal (or about $4.40 per GGE), compared to regular diesel which is estimated to be around $3.50. Beyond 2030, and out to 2050: prices are assumed to stay flat since expected small reductions in technology cost are offset by higher feedstock prices. However, these do get relatively cheaper than gasoline and diesel prices, since these prices experience a slow rise to 2050 based on EIA projections.

- Ethanol/Biogasoline (the current price of ethanol as blended with gasoline is assumed to be $4.00 per gallon. However, since it is near the blend limit in California, in a scenario eventually moving to high biofuel blends, nearly all growth will have to be in the form of biogasoline. For 2025, we assume biogasoline is (or would be) $0.50/gal higher cost than renewable diesel due to refinery configurations. Though with large volume production this cost difference could drop, we assume that this $0.50/gal difference remains into the future as refineries continue to be configured more for biodiesel and biojet (kerosene) fuels.

Overall, our price projections are shown in Table 7.

Table 7. Fuel Prices in $/GGE for LDVs and MDHVs through 2050

Fuel	2020	2025	2030	2035	2040	2045	2050
Gasoline Blend	3.02	3.45	3.58	3.72	3.85	3.99	4.12
Gasoline	3.00	3.45	3.58	3.72	3.85	3.99	4.12
Ethanol/Biogasoline	3.27	3.45	3.58	3.72	3.85	3.99	4.12
Diesel Blend	3.26	3.26	3.32	3.38	3.45	3.51	3.57
Diesel	3.26	3.26	3.32	3.38	3.45	3.51	3.57
Biodiesel/Ren Diesel	3.97	3.26	3.32	3.38	3.45	3.51	3.57
CNG	2.03	1.91	1.79	1.95	2.24	2.50	2.80
Electricity							
LDV	8.05	12.08	12.08	12.08	12.08	12.08	12.08
Fleet depot	7.05	9.06	9.06	9.06	9.06	9.06	9.06
Truck stop	17.10	17.10	15.49	13.88	12.28	10.67	9.06
H2	16.00	25.00	10.00	8.50	7.00	6.00	6.00

Carbon Intensity of Fuels

For biofuels, we start with the average carbon intensity of fuels in CA as reported by LCFS and assume this policy incentivizes on-going reductions in this average CI. Separating the biofuel components from blends with gasoline, but averaging their pathways, the current estimates vary somewhat around an average of 40 g/MJ for biodiesel/renewable diesel, and 65 g/MJ for ethanol. The blend levels in 2025 are close to 15% ethanol per liter of gasoline and nearly 80% bio/renewable diesel per liter of diesel fuel (i.e. only 20% petroleum diesel). In our low-carbon, high biofuels scenarios these blends reach close to 100% by 2040, with ethanol being replaced by a drop-in biogasoline that has no blend limit. Renewable diesel, already at over 70%, completely displaces both traditional biodiesel (fatty acid methyl ester) and petroleum diesel, probably by 2030 or even sooner.

Table 8. Fuel/Pathway Carbon Intensity Scores Currently and in 2040

Fuel/pathway	2025	2040
Biodiesel/RD	40	30
Ethanol	66	50
Biogasoline	45	35
Electricity	50	10
Hydrogen	60	15

Table 9. Carbon Intensity of Fuels in gCO_2e/GGE and Blend Percentages for Biofuels Through 2050

Fuel	2020	2025	2030	2035	2040	2045	2050
Gasoline Blend	11916	11568	11412	10908	9596	7675	4633
Gasoline	12185	12185	12185	12185	12185	12185	12185
Ethanol/Biogasoline	8349	6023	5745	5467	5189	4911	4633
Diesel Blend	11264	6912	6358	5782	5182	4559	3475
Diesel	12229	12229	12229	12229	12229	12229	12229
Biodiesel/Ren Diesel	5791	4633	4401	4170	3938	3706	3475
CNG	7453	7302	6830	6199	5570	4774	4911
Electricity	10031	8228	6316	4404	2491	579	579
Hydrogen	6413	6413	5099	3786	2472	1158	1158
Ethanol Blend %	7%	10%	12%	19%	37%	62%	100%
Biodiesel Blend%	15%	70%	75%	80%	85%	90%	100%

NOTE: 1 GGE is roughly 115.8 MJ.

As shown in Table 9, the carbon intensity can be described, with some notes, as follows:

- Biodiesel/RD (2025) = 40 g/MJ, steady improvement to 30 g/MJ by 2050; this is just the BD/RD components and when blended with petroleum diesel is higher (but is already 80% of the diesel pool in 2025)
- Ethanol/Biogasoline (2025) = 55 g/MJ, currently mainly from corn ethanol; steady improvement to 35 g/MJ in 2040; mostly or all biogasoline, slightly higher CI than renewable diesel
- Blended fuels reflected a weighted average of these CI scores with those of petroleum diesel and gasoline, which remain near 100 g/MJ. In the high biofuels case, these fuels reach near 100% so their CIs become the pool CIs over time
- Electricity is currently about 50% renewable with an average of around 80 g/MJ, though when adjusted by vehicle efficiency is much lower in effective terms (CARB 2023c). This

reaches 100% renewable in 2040 with a CI near zero; set at 10 to account for some emissions in the supply chain and from infrastructure construction

- Hydrogen currently about half renewable (excepting refining use), rising to 100% by 2030 under ARCHES plans; the 60 g/MJ drops close to that for electricity by 2040 at 15 g/MJ

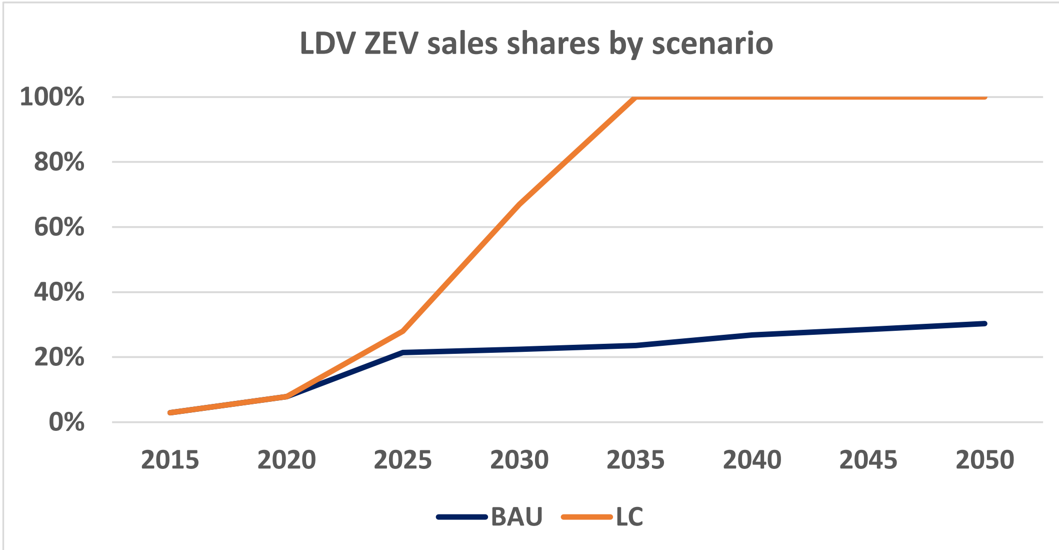
4. Detailed Results

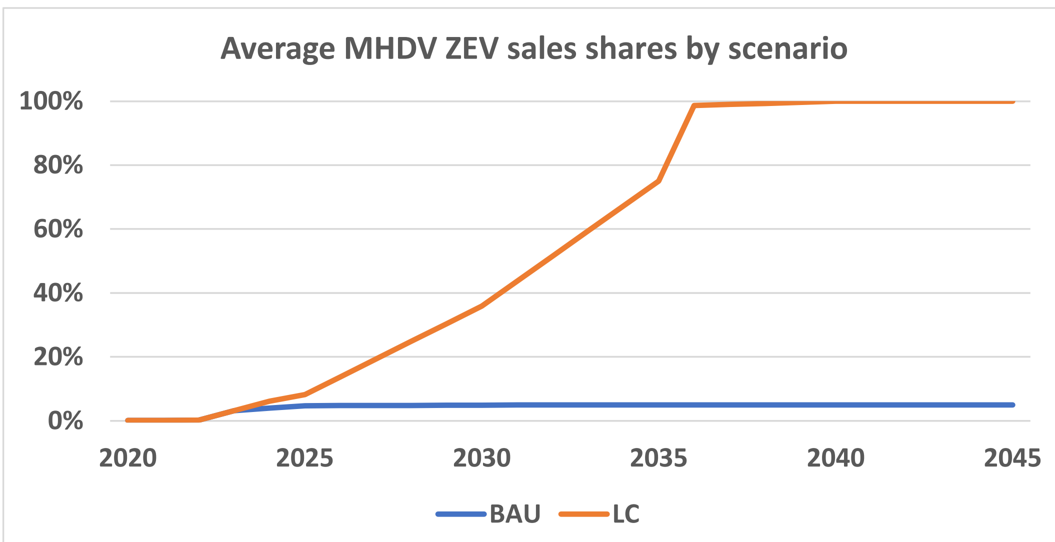
LDV and HDV Market Shares

As described above, our market share projections of ZEVs (cars, trucks and buses) are heavily governed by the California policies and ZEV sales requirements. We utilized our vehicle choice models and our own judgement to produce estimates and variations between electric vehicle and hydrogen vehicle sales shares in the two relevant scenarios. These are also adjusted by a range of assumptions, such as improvements in vehicle costs over time. We also made adjustments to market shares to ensure that the LC and HFC scenarios have good separation, to better understand how these two futures could be different in terms of energy use, CO_2 emissions, costs, etc.

Figure 1 shows the market share for LDVs and MHDVs for the BAU and LC scenario (and also for HFC since the total ZEV shares are the same as for the LC). In the BAU scenario, average ZEV LDV sales rise slowly from about 20% in 2020 to 30% by 2050. Truck sales shares are steady into the future at about 4-5%. In the LC scenario LDVs reach 100% sales share in 2035, and the share of ZEV trucks reaches 75% in 2035, and then shoots up to 100% in 2036, as per the CARB agreement with OEMs described above.

Figure 1. ZEV Market Shares Over Time for LDVs and MHDVs in the BAU and Low-Carbon Scenarios





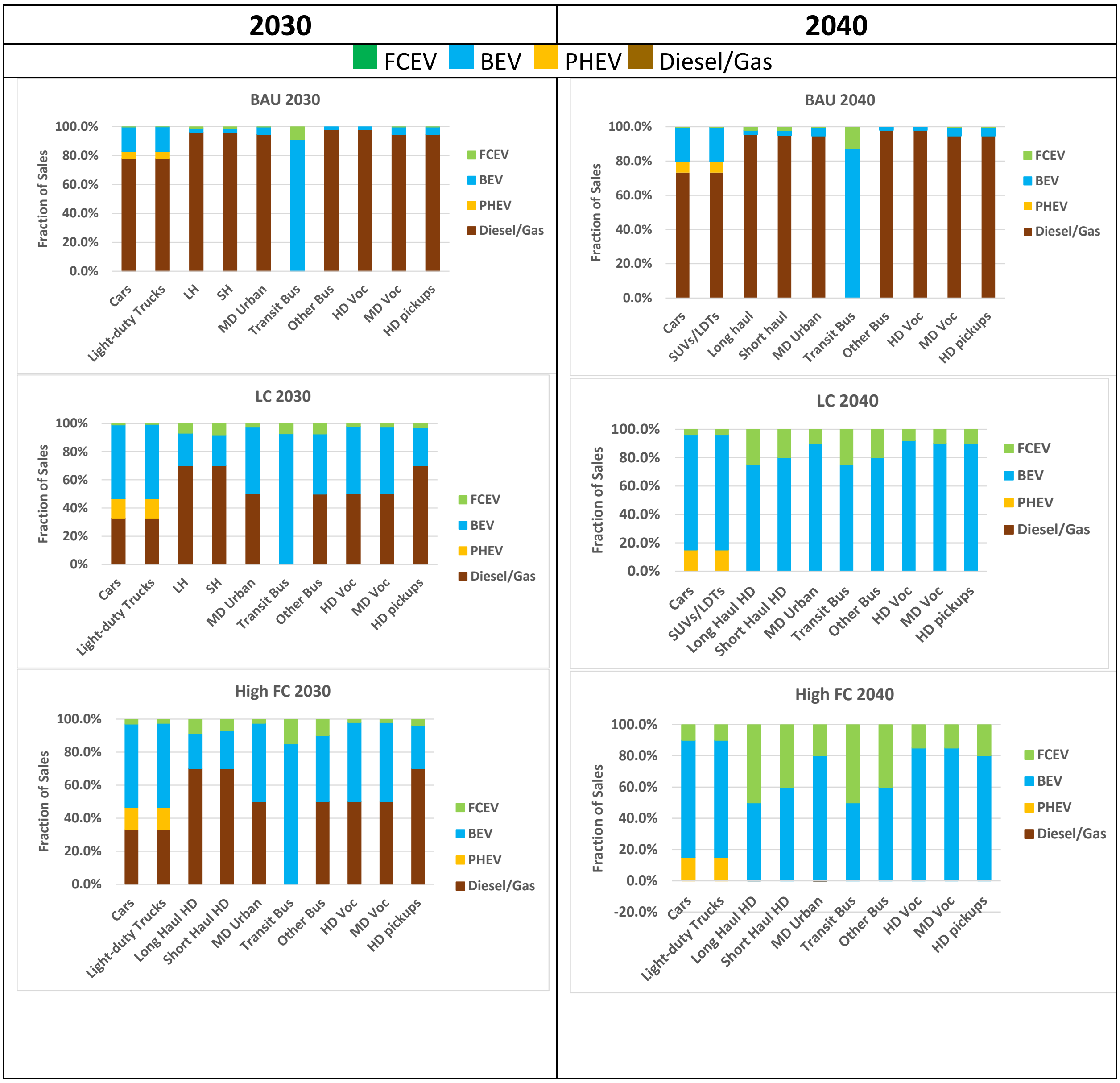
Note: for MHDVs, the ACT has different ramp-up rates for different vehicle types; figure shows the average across all truck types.

Figure 2 shows the 2030 and 2040 percentages of vehicle sales by technology type for each of the 10 vehicle types, for the BAU, ZEV, and ZEV+B scenarios. The BEV and Fuel Cell vehicle sales shares sum to the total ZEV shares shown in Figure 1. The 2030 and even 2040 shares of ZEVs in the BAU are very low, with the major exception of transit buses. This reflects an expectation that BEV transit buses are on track to very high levels, with good economic competitiveness and strong commitments from public and other transit bus agencies.

In the LC scenario, ZEV (and near-ZEV, [i.e. PHEV]) LDVs achieve a 100% market share by 2035, with BEVs taking more than 80% share relative to PHEVs. For trucks, as they approach 100%

ZEV sales shares by 2036, the share of ZEVs taken by hydrogen fuel cell vehicles increases somewhat but varies considerably by vehicle type. In 2030 it is typically quite low, except for heavy duty trucks and transit buses. It is somewhat higher for most vehicle types in 2040. In the HFC scenario FCEV shares are significantly higher, reaching 50% market share for HD long haul trucks and transit buses by 2040 and 20-40% shares for most other vehicle types, except only about 10% for LDVs.

Figure 2. Market Share by Vehicle Type in 2030 and 2040 in Each of the Scenarios
(HEV, hybrid electric vehicle; CNG, compressed natural gas; FCEV, fuel cell electric vehicle)

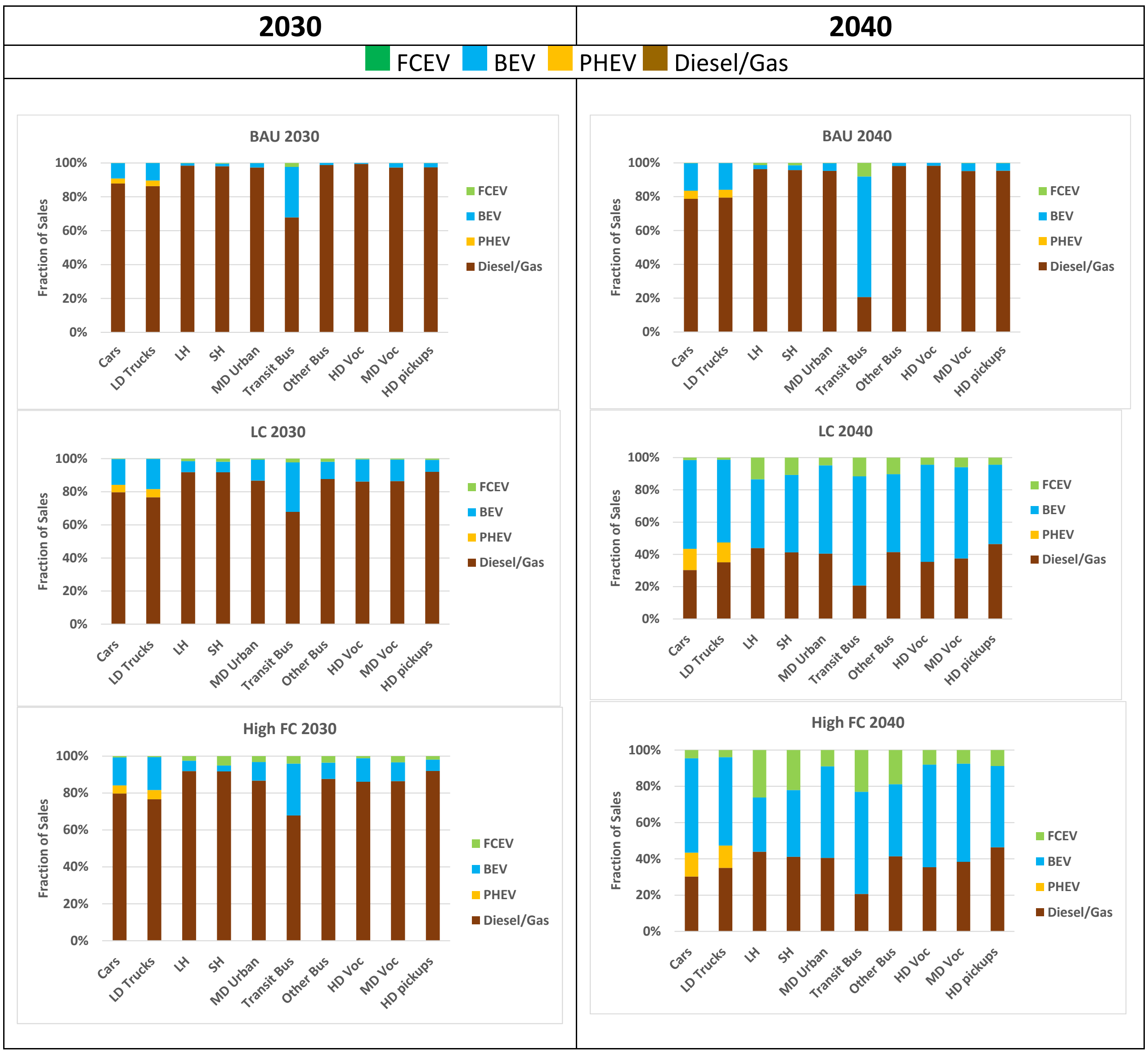


(Abbreviations: LH, long-haul, SH, short-haul; MD, medium duty; HD, heavy duty; Voc, vocational; FCEV, fuel cell electric vehicle; PHEV, plug-in hybrid vehicle; BEV, battery electric vehicle; HEV, hybrid electric vehicle; NG, natural gas; LD, light-duty; LH, long-haul trucks; SH, short-haul trucks; MD, medium-duty; HD, heavy duty; Voc, vocational)

Fleet Stock

The total stock of vehicles, resulting from the sales and turnover and removal of retired vehicles, is shown in Figure 3. The lag time between sales of new technologies and their increase in the stock is evident, but by 2040 in the LC and HFC scenarios, the transition to ZEVs is well underway, reaching over 50% of the stock for all vehicle types, and 80% for transit buses. By 2050 (not shown), the transition reaches over 90% for all vehicle types.

Figure 3. Stock Share by Vehicle Type in 2030 and 2040 in Each of the Scenarios
(HEV, hybrid electric vehicle; CNG, compressed natural gas; FCEV, fuel cell electric vehicle)

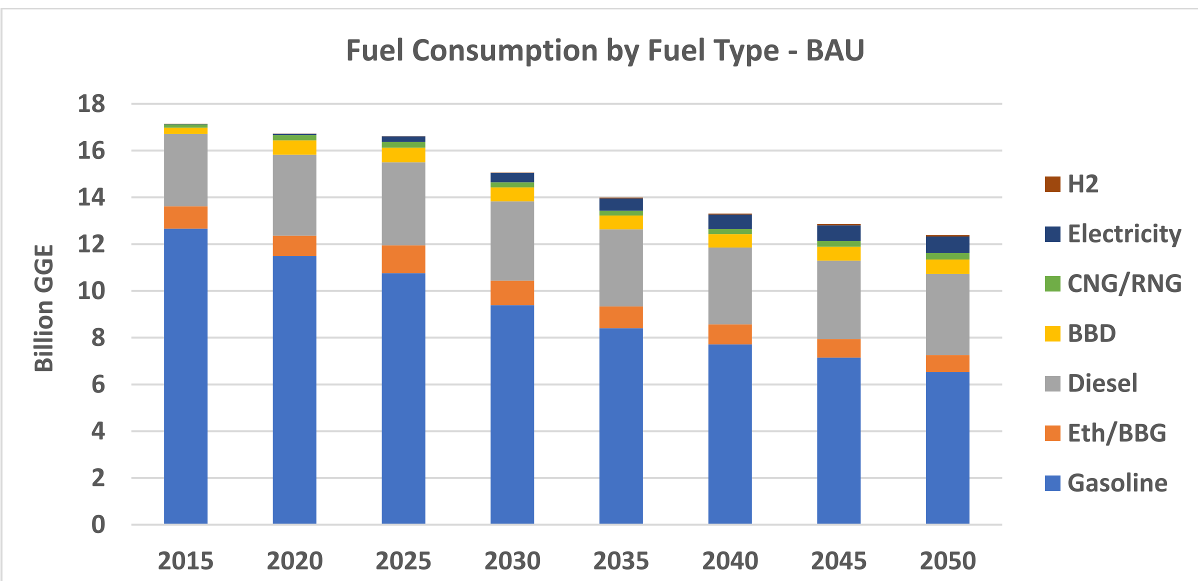


Fuel Consumption by Fuel Type

Figure 4 shows the LDV plus MDHV fuel consumption for the BAU and LC scenarios by fuel type every five years from 2015 through 2050. Even though VMT increases over time, the BAU fuel consumption decreases due to vehicle fuel efficiency. The percentage of biomass based diesel and biomass based gasoline remains constant through 2050; consequently, these fuels only contribute a modest amount. The natural gas sales shares are zero in later years except for medium-duty delivery trucks, other buses, and vocational trucks; therefore, the natural gas contribution is small. ZEV sales shares are low for all MHDVs except transit buses, and ZEVs show modest sales for LDVs in later years. In addition, the vast majority of ZEVs are BEVs, so electricity dominates over hydrogen usage, but electricity consumption remains small.

The LC scenario shows a large reduction in fuel use due to the high market share of ZEVs and their high fuel efficiency. The fuel usage in 2050 is roughly one third of the usage in 2015. Over time, biomass based fuels increase their contribution until 2050 when 100% of liquid fuels are biomass based fuels. The contribution of electricity and hydrogen dominates fuel usage by 2045 and especially in 2050. Electricity represents roughly 62% of all fuel usage.

Figure 4. LDV plus MDHV Fuel Consumption by Fuel Type for the BAU and LC Scenarios as a Function of Year



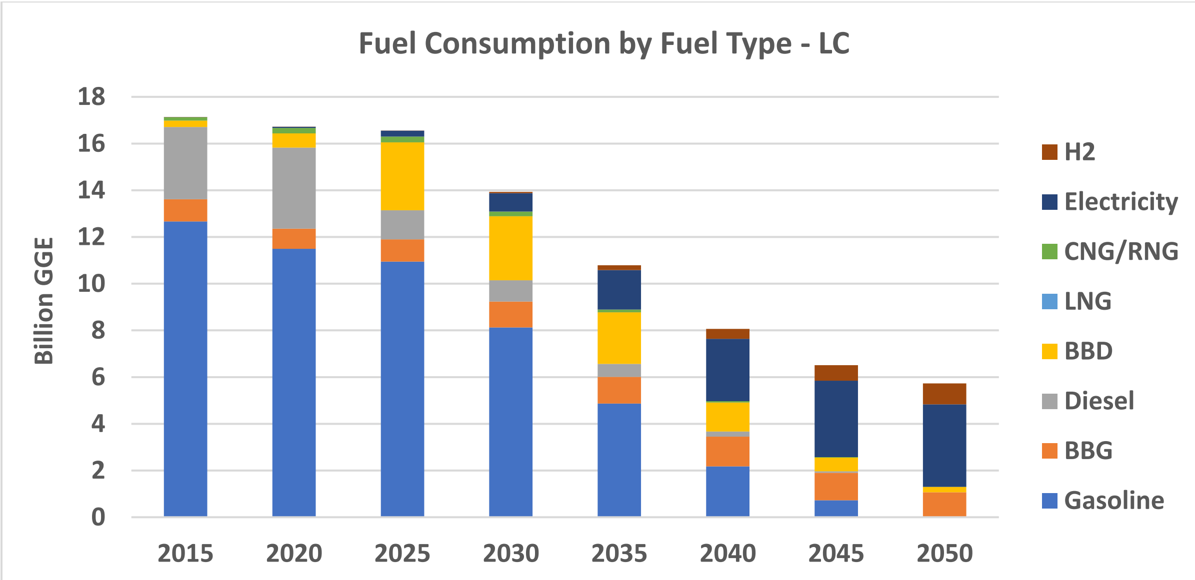
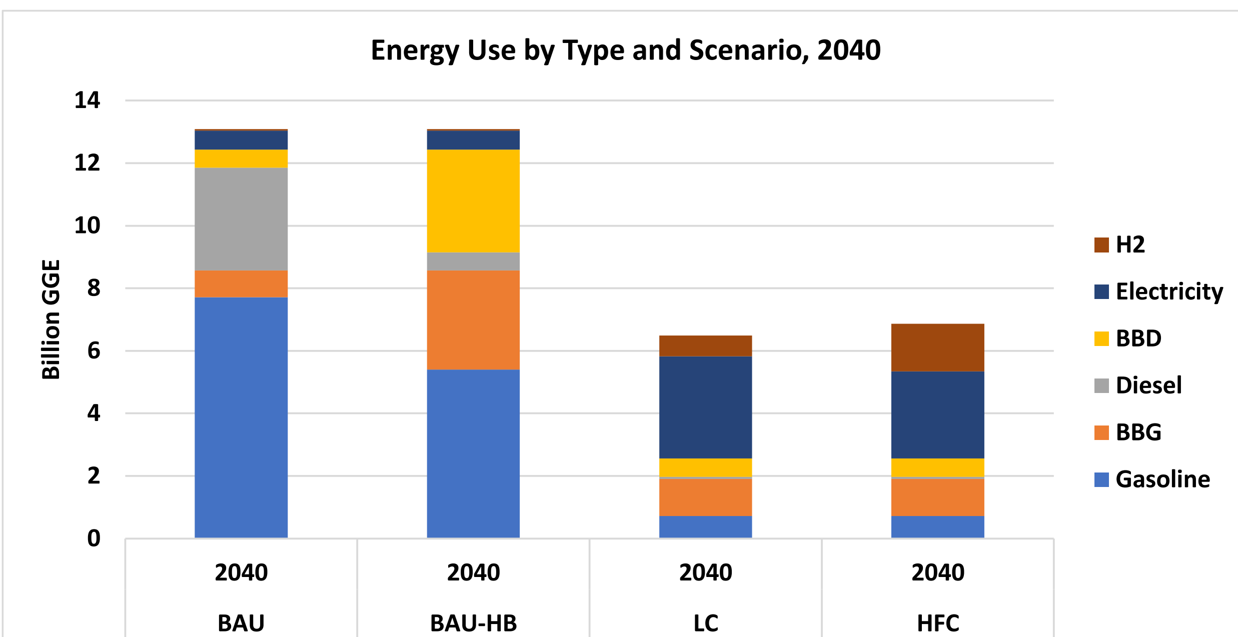


Figure 5 shows the energy usage in 2040 by fuel type for each scenario. The BAU scenarios use roughly twice as much fuel as the LC and HFC scenarios. The BAU scenario is dominated by diesel and gasoline with small amounts of biomass based fuels. The BAU-HB includes large contributions of biomass based fuels. The LC and HFC scenarios are rather similar with the HFC scenario having slightly higher fuel usage due to the somewhat lower fuel efficiency of FCEVs compared to BEVs. In both scenarios electricity and hydrogen dominate the overall fuel usage; however, the HFC scenario has significantly more hydrogen.

Figure 5. Energy Use in 2040 by Fuel Type for Each Scenario



GHG Emissions

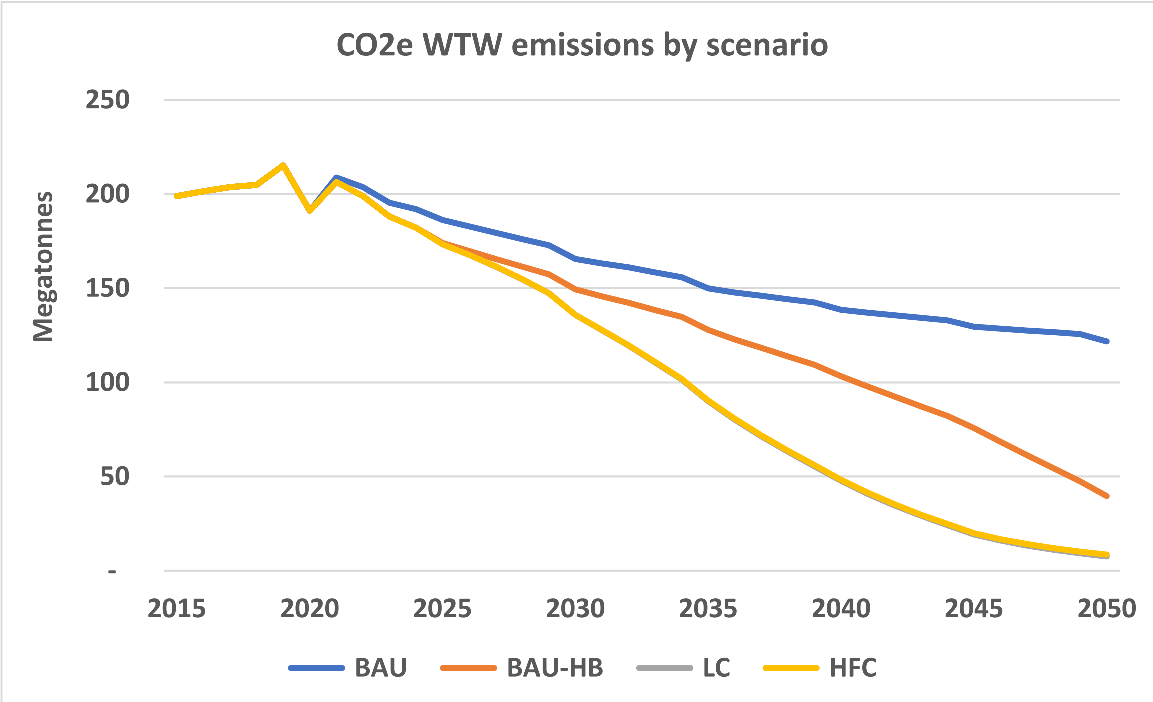
The primary reason to mandate ZEV LDV and MHDV sales and purchases is to reduce greenhouse gas (GHG) emissions. The combination of higher vehicle efficiencies and lower fuel carbon intensities can produce extremely low GHG emissions from ZEV fleets. Over time the vehicle miles traveled (VMT) for both LDVs and MHDVs increases, and every scenario has identical VMT growth. Table 10 shows the reduction in GHG emissions between 2015 and 205o for each scenario.

Table 10. GHG Reductions in 2050 from 2015 Values for Each Scenario

Scenario	GHG Reduction in 2050 from 2015
BAU	38.8%
LC	96.2%
HFC	95.7%
BAU-HB	80.1%

Figure 6 shows the reduction in GHG emissions for each scenario over time. The BAU scenario shows a GHG reduction of almost 39% in 2050 vs 2015, due to both significant increases in vehicle fuel economy and the modest market penetration of ZEVs in LDVS. The LC and HFC scenarios reduce GHG emissions by roughly 96% in 2050. Although these scenarios utilize large amounts of electricity and hydrogen, their contribution to GHG emissions is extremely small because battery electric and fuel cell vehicles have very high fuel economy and the fuels are produced from renewable sources and have very low carbon intensities in later years. The BAU-HB case (BAU but with high biofuels) has a must slower decline rate in total CO_2e than the ZEV scenarios, but still achieves an 80% reduction in 2050 vs 2015, due to a declining carbon intensity rate in ethanol, renewable gasoline, and renewable diesel, over time. However, its faster drop toward 2050 would likely flatline at that point since the fuels have reached 100% liquid market share and may be near their ultimate CI levels.

Figure 6. Reduction in GHG Well-to-Wheel CO_2e Emissions for Each Scenario Over Time



Scenario Cost Comparisons

As described above, in addition to the technology and fuel projections, this study estimates a range of costs. These include the capital and operating costs for LDVs and MDHVs by vehicle and technology type each year through 2050, along with fuel and infrastructure costs. We do not account for the operating costs for vehicles past 2050. All costs are given in real ($2025) dollars, Vehicle capital costs are allocated entirely to the purchase year. We do not discount costs in the main results, but we show a variant with discounted costs.

The following figures (Figures 7-10) compare the capital (vehicle purchase) and operating (fuel and maintenance) costs between scenarios on a year by year basis. The figures show the difference between the two scenarios each year. The blue curves show the difference between the vehicles' capital costs. The orange curves show the difference between the operating costs. Finally, the grey curves show the difference between the total costs. The LC and HFC scenarios are compared to the BAU scenario. A positive value indicates that the LC or HFC scenario is more expensive than the BAU scenario. A negative value indicates that the LC or HFC scenario is less expensive than the BAU scenario.

The shape of all the curves in these figures is similar. Initially ZEV vehicles cost more than conventional vehicles, so the cost difference is positive. As ZEV market penetration increases, the vehicle cost difference grows. ZEV costs decline over time as volume sales grow and the vehicle production learning curve decreases the costs, and eventually the vehicle cost difference reaches a maximum. Afterwards, the vehicle cost difference declines enough that total costs also decline, even with rising sales.

Since ZEV LDVs have significantly higher fuel economy than conventional LDVs, their fuel cost is smaller than conventional vehicles. In addition, their maintenance costs are lower. The total operating costs for ZEV LDVs are then less than for conventional vehicles, and the operating cost difference is negative starting in 2025 and grows more negative with time. The total cost difference for LDVs is initially dominated by the vehicle cost difference and starts off positive (i.e. LC or HFC scenario is more expensive). Eventually, the combination of the decreasing vehicle cost difference and the negative operating cost difference drives the total cost difference negative.

The MDHV cost curves are somewhat different than the LDV curves. The vehicle cost difference initially grows and eventually reaches a peak, but the cost difference never decreases below zero such that the LC and HFC vehicle costs are always greater than the BAU costs. The cost difference starts to decrease in the early 2030s, but there is a slight increase in 2036. This increase is caused by the assumption that fleets will delay their ramp up in purchases to 100% ZEV purchases in 2036 and only purchase 75% of vehicles as ZEVs in 2035. The sudden significant increase in ZEV sales between 2035 and 2036 drives the cost difference higher. The MDHV operating cost difference initially starts positive and eventually decreases to negative values. While MDHVs have a higher fuel economy than conventional vehicles, the costs of electricity and hydrogen are not always low enough to create lower fuel costs. This issue is especially true for fuel cell long haul trucks. Their fuel economy is only marginally better than diesel long haul trucks, and hydrogen is particularly expensive in early years. Fuel cell long haul trucks contribute significantly to the overall MDHV fuel usage since long haul trucks have low fuel economies and very high VMT and the long haul application has higher fuel cell sales shares than any other application. Eventually the operating cost difference becomes negative, and combined with the decreasing vehicle cost difference, the overall cost difference becomes negative.

Figure 7, Figure 8, and Figure 9 show the cost difference between the LC and BAU scenarios for LDVs, MDHVs, and all vehicles respectively. Figure 10 shows the cost difference between the HFC and BAU scenarios for and all vehicles. In all cases, the savings from ZEVs in terms of O&M costs, especially energy costs, begin immediately and eventually outweigh higher vehicle purchase costs to lead to net lower costs, but this happens much sooner for LDVs than for MDHDs.

In the HFC, with a higher purchase share of fuel cell vehicles and use of hydrogen, costs are somewhat higher than in the LC, but overall the LC and HFC cost curves are similar in the context of total costs and savings. The HFC cost differences are slightly greater for both vehicles and operating costs due to the higher stock of fuel cell vehicles, whose capital costs are higher than BEVs, and whose use of more expensive hydrogen is greater.

Figure 7. Cost Difference Between the LC and BAU Scenarios for LDVs

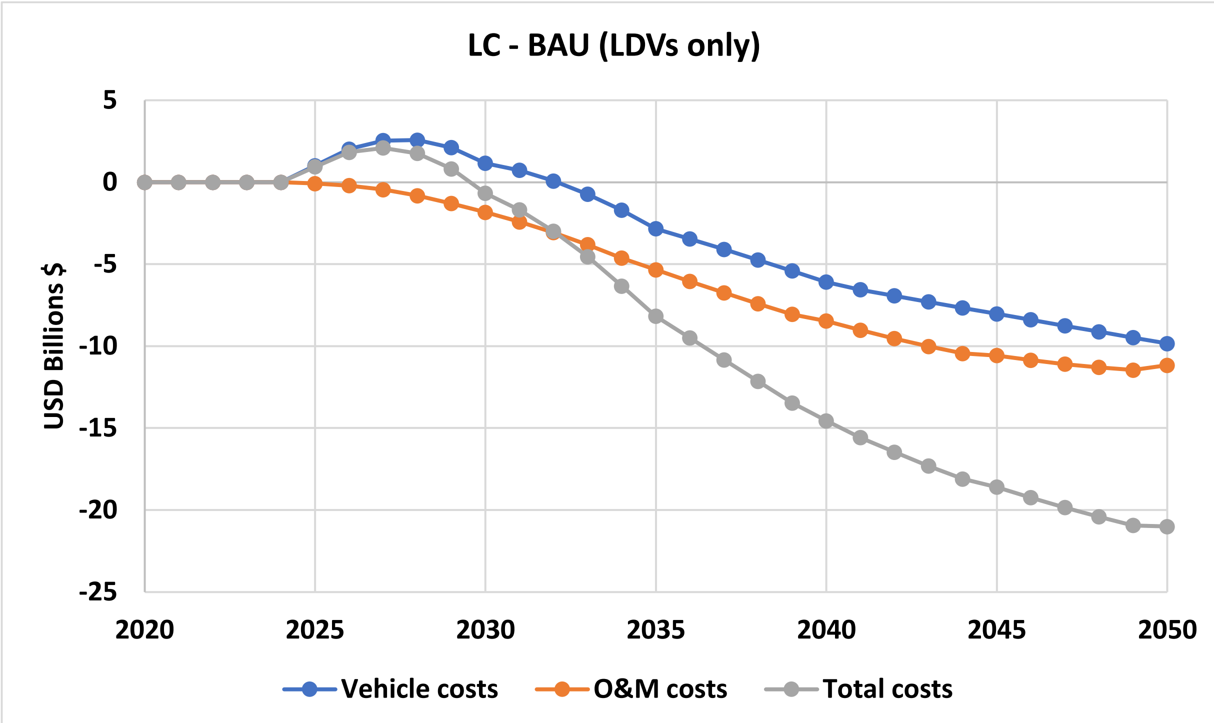


Figure 8. Cost Difference Between the LC and BAU Scenarios for MDHVs

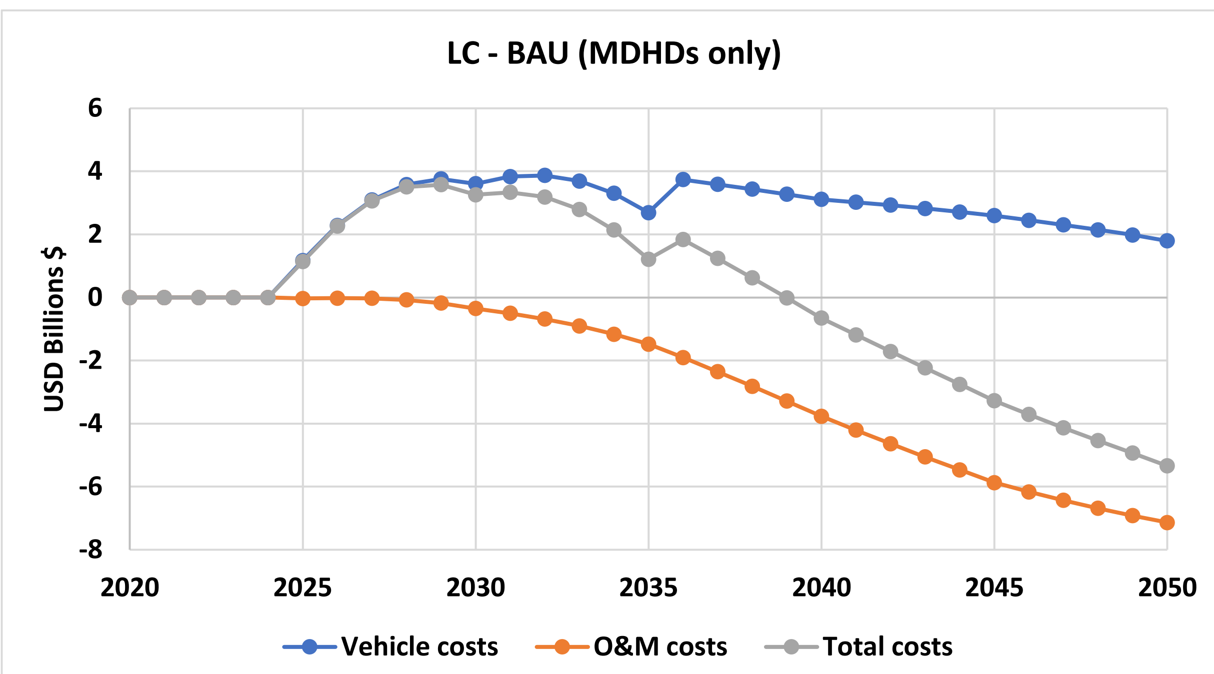


Figure 9. Cost Difference Between the LC and BAU Scenarios for All Vehicles

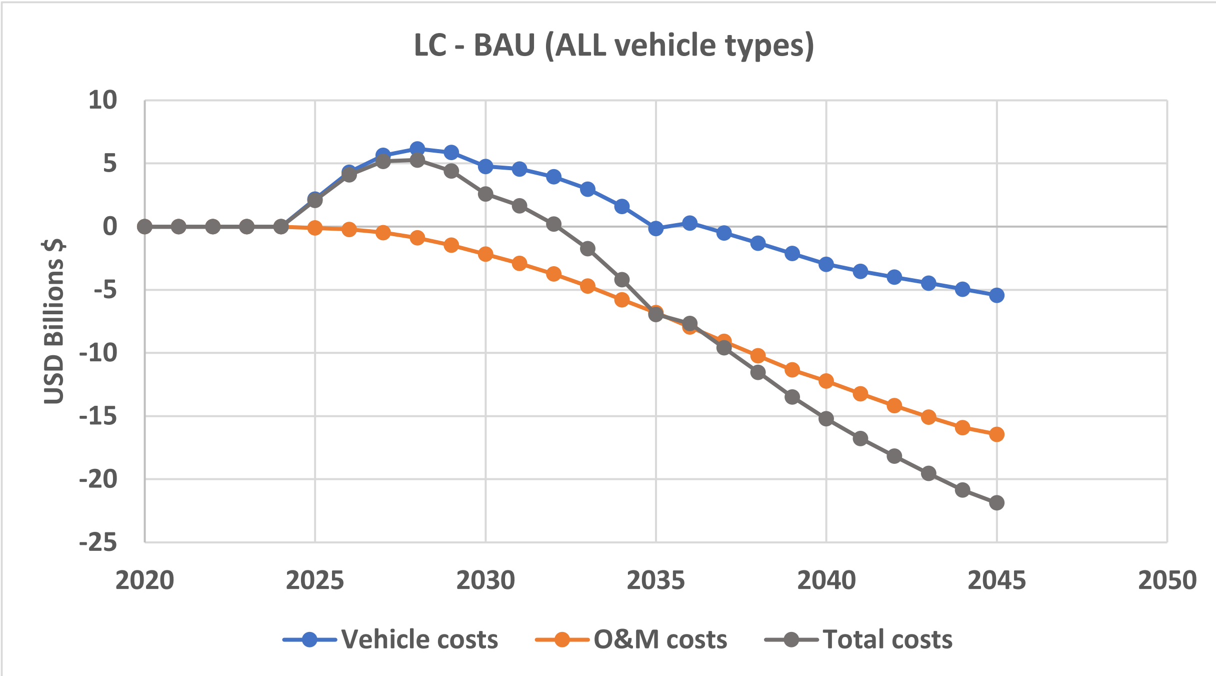
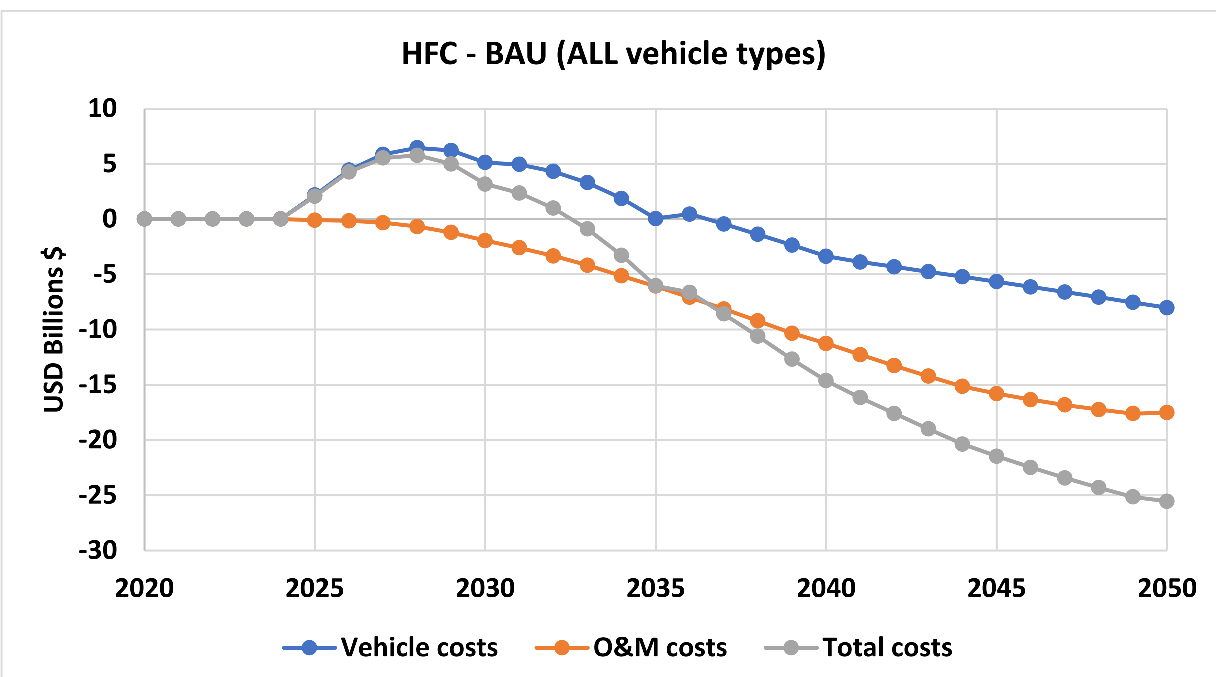


Figure 10. Cost Difference Between the HFC and BAU Scenarios for All Vehicles



Sensitivity Analysis of Vehicle and Fuel Prices and Costs

In creating the cost difference curves, we recognize that there is uncertainty in several of the inputs. In particular, the cost of electricity and hydrogen could vary significantly over time. Presently, hydrogen is rather expensive, and assumptions on reducing the cost at the pump to be similar to gasoline on an energy basis may be optimistic. To meet the vehicle demand for electricity, utilities must make major upgrades to their infrastructure over the next couple of decades. Such upgrades could increase the cost of electricity over our projections.

We assume that LDV ZEV costs will decrease to be similar to ICEs shortly after 2030. We do not project such cost reductions for MDHD ZEVs. In fact, our model assumes ZETs remain more expensive than diesel trucks out to 2050. LDVs have much larger volume sales than trucks, and this difference is likely to result in slower cost reductions of ZETs compared to LDV ZEVs. Nevertheless, our assumptions on ZET cost reductions could be too pessimistic.

Given these uncertainties, we performed sensitivity analyses on the cost of electricity, hydrogen, and ZET capital costs. We created two scenarios of ZEV fuel cost increasing (High ZEV fuel costs) and decreasing (Low ZEV fuel costs) the cost of electricity and hydrogen by 25% starting in 2030. For ZETs we considered a single sensitivity scenario decreasing all truck capital costs to be equal to the diesel truck cost in 2040. After 2040, ZET costs decrease modestly out to 2050.

The cost difference curves for the LC – BAU for these sensitivities have a similar shape to those shown above. The ZEV scenario costs increase above the BAU costs starting in 2025 but eventually fall below the BAU costs such that the cost difference becomes negative. Table 11 compares the base LC – BAU case with the three sensitivity cases showing the year the LC scenario becomes less expensive than the base case (cross over year), the excess cost for the LC scenario before that cross over year, and the savings for the LC case after the cross over year through 2050.

The cross over years do not vary significantly, but there is considerable difference in the excess costs and cost savings. As expected, the low ZEV fuel cost scenario cross over before the base case, has lower excess costs, and has higher cost savings. In the high ZEV fuel cost scenario, the reverse is true (i.e. later cross over, higher excess cost, and lower cost savings). We compared the low ZET capital cost scenario with the base case for MDHD vehicles. The crossover year for the low ZET capital cost scenario is earlier than the base case while the excess cost and cost savings are lower and higher respectively.

Table 11. Comparison of the Base LC minus BAU Case, with the Three Sensitivity Cases

	Cross over	**Excess LC cost**	**LC cost savings**
Scenario	(year)	(billions$)	(billions$)
All vehicle costs, LC - BAU			
Base case	2032	25.4	292
Low ZEV fuel cost	2030	18.1	447
High ZEV fuel cost	2034	40.3	144
MDHD costs LC – BAU			
Base case	2039	33.2	34.5
Low ZET capital cost	2036	28.2	72.5

5. Charging Infrastructure Requirements and Costs

This section covers the charging infrastructure requirements and investment costs for medium and heavy-duty vehicles. This was a special project for this paper and represents a new type of cost broken out in detail. The investment costs presented here are used to develop the full levelized cost of charging and refueling, that were included in the full set of costs presented above; however, the investment costs presented here are just one part of those levelized costs; the up-front capital investment. This does not include the day-to-day operating costs of refueling. It is helpful, however, to know what types and levels of investment may be needed for this infrastructure in the future, relative to the projections and scenarios for the numbers of light and heavy-duty vehicles.

As we do throughout this report, we focus on two main scenarios: the LC with high electrification and EV adoption rates, and the HFC, with somewhat lower EV adoption rates and somewhat higher fuel cell adoption, and thus higher hydrogen refueling infrastructure costs. We present the Charger results in detail, for trucks and then LDVs, and then cover the hydrogen infrastructure costs. Finally, we show all these investment costs together, along with vehicle investment costs (in the form of purchase costs to consumers).

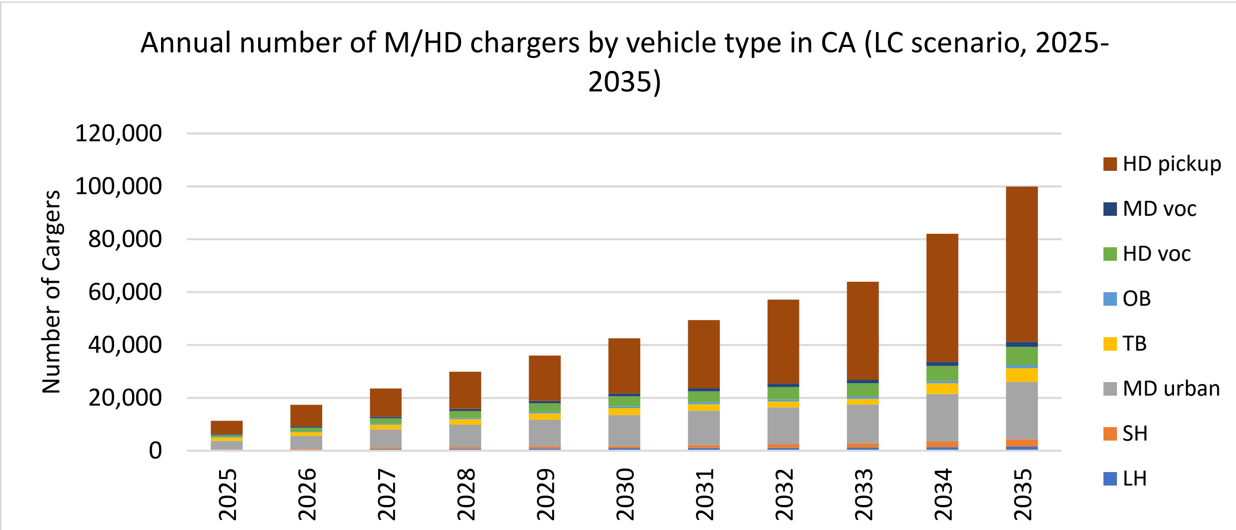
For chargers, we undertook two separate, detailed studies of the typical numbers and power levels of chargers used by different types of vehicles, separated by home or base charging and on-the-road charging with commercial chargers. The detailed assumptions by vehicle type, charging situation, and future year are included in two separate papers: one for LDV charging (Yang et al, 2024) and one for MHDV charging (Yang et al, 2025). While these papers provide the detailed methodologies used, we summarize the approach and results here.

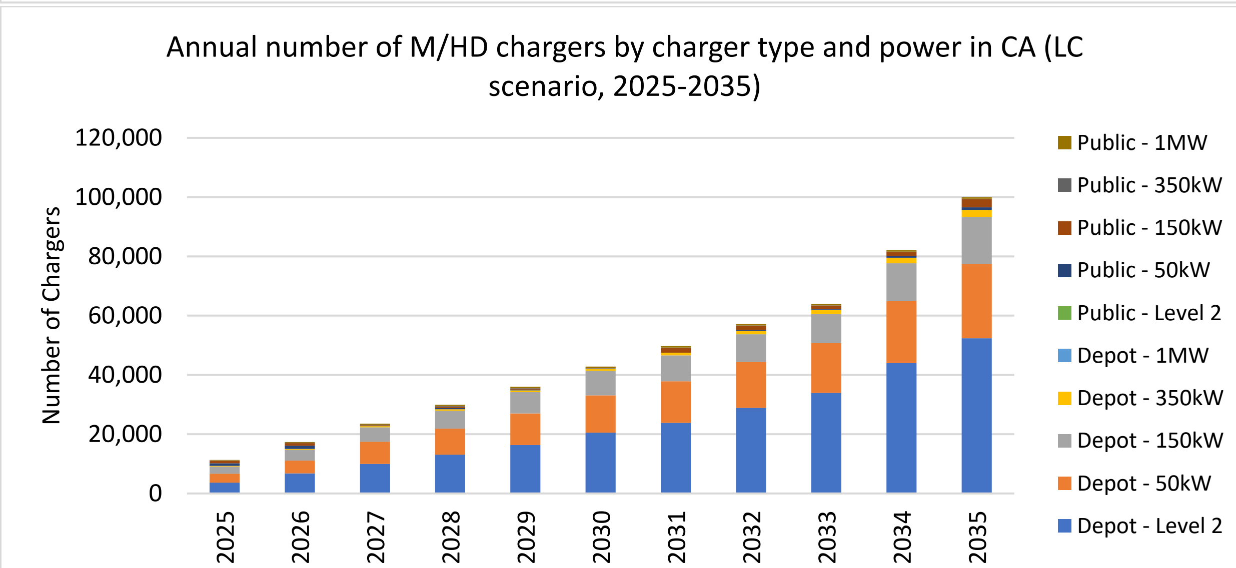
MHDV Charger Requirements

In the LC scenario, the annual number of MHD chargers will steadily increase and reach about 42 thousand/year in 2030. From a charger-count perspective, many chargers will be used for heavy-duty pickup trucks (HD pickup, Class 2b) and medium-duty urban trucks (MD, Classes 4 to 6). In terms of the types of chargers and charger power levels, many MHD chargers are expected to be for depot Level 2, 50kW, or 150kW in California.

Figure 11. Projected Number of Chargers Needed by Vehicle Type

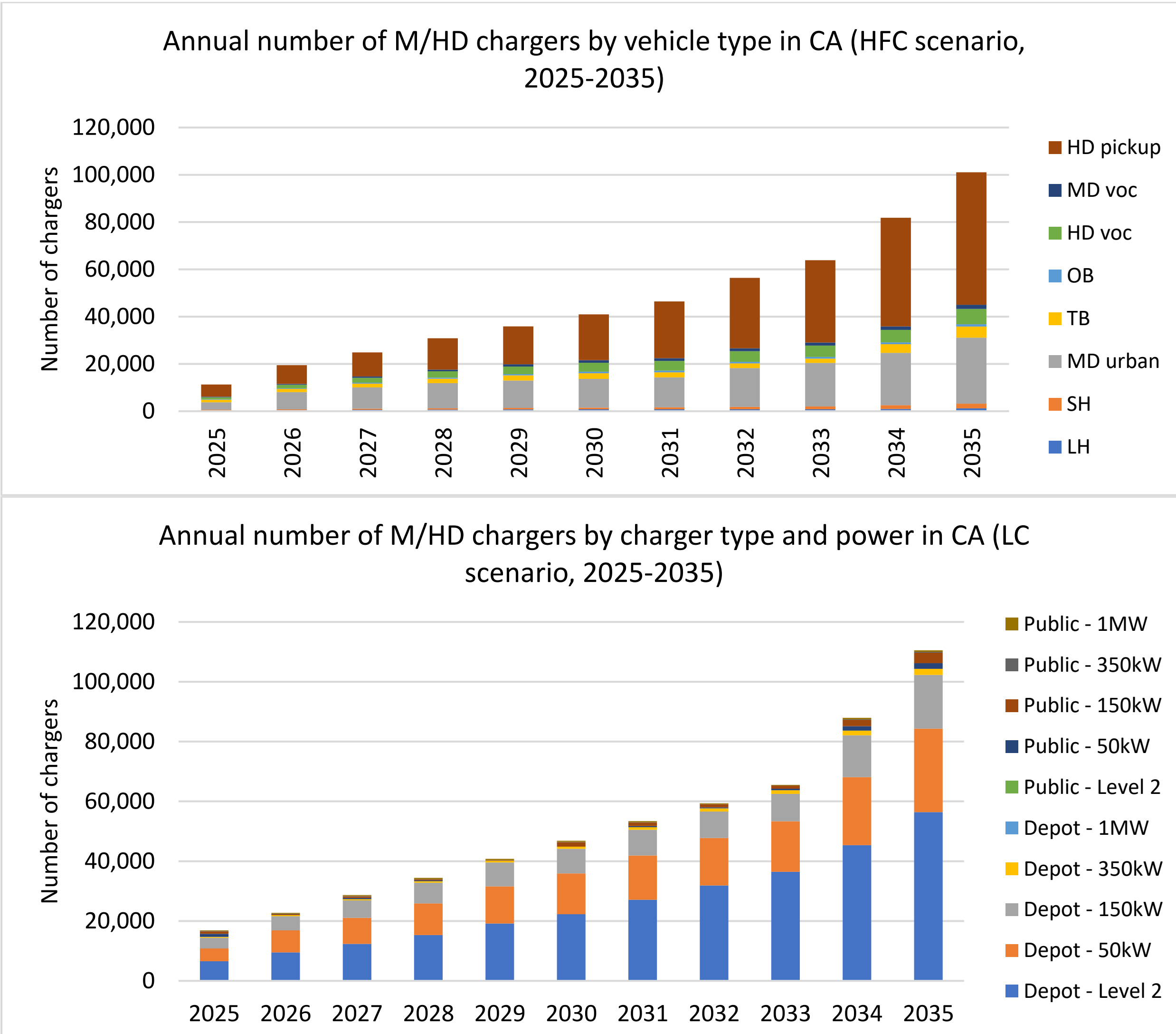
(Figure 11a) and by charger type and power level (Figure 11b), LC Scenario.





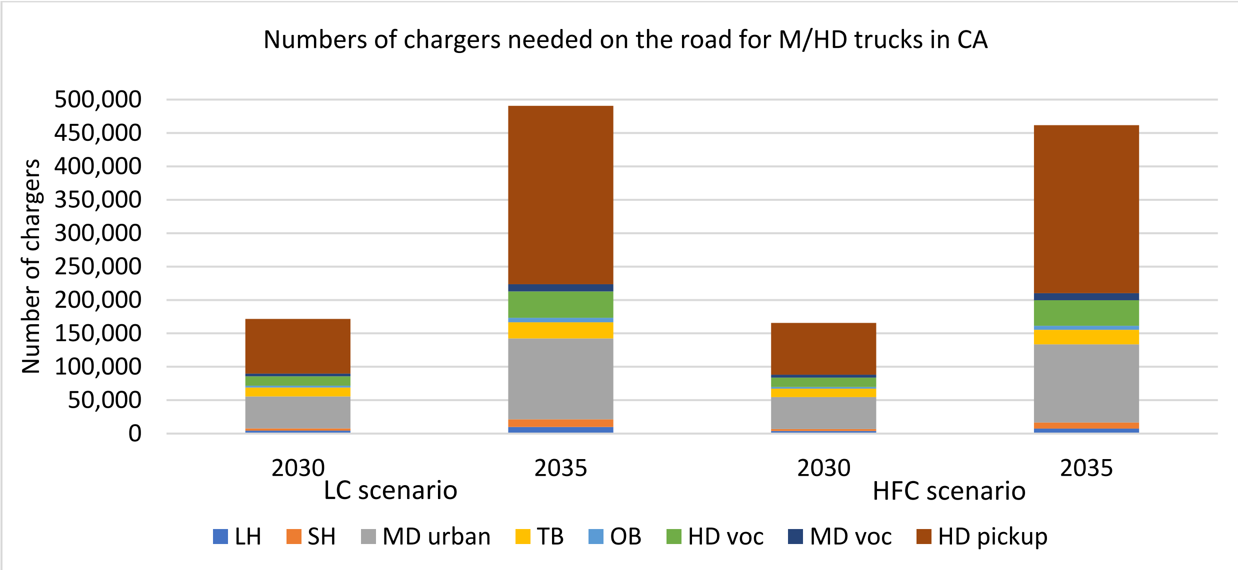
The MHD charging infrastructure needs can be affected by the composition of different zero-emission vehicle choices for the MHD sector. As shown in Figure 12, in the HFC scenario, the number of MHD battery electric trucks is slightly lower than in LC (Figure 11). (These two scenarios are also compared in Figure 13). The annual number of MHD chargers will steadily increase and reach about 41 thousand/year in 2030. Just like the distribution in the LC scenario, many chargers will be used for heavy-duty pickup trucks (HD pickup, Class 2b) and medium-duty urban trucks (MD, Classes 4 to 6) from a charger-count perspective and most of the MHD chargers are expected to be for depot Level 2, 50kW, or 150kW in California.

Figure 12. Projected Number of Chargers Needed by Vehicle Type
(Figure 12a) and by charger type and power level (Figure 12b), LC-HFC Scenario.



As shown in Figure 13, in the LC scenario, the total number of M/HD chargers needed on the road will reach nearly 172 thousand by 2030 and increase to nearly 491 thousand by 2035. For the High Fuel Cell scenario, the cumulative number of MHD chargers will reach about 166 thousand by 2030 and increase to 462 thousand by 2035. From a charger-count perspective, estimations of charging needs in both scenarios in 2030 to support the electrification of Class 2b trucks through Class 8 trucks are slightly higher than estimations in reviewed studies (i.e., a total of 112 thousand to 155 thousand chargers needed by 2030). This may be caused by different sets of assumptions, such as truck type composition, charging type, and power composition, as well as electric truck stock projections across all studies.

Figure 13. Numbers of Chargers Needed on the Road for MHD Trucks in CA in 2030 and 2035, LC and HFC Scenarios

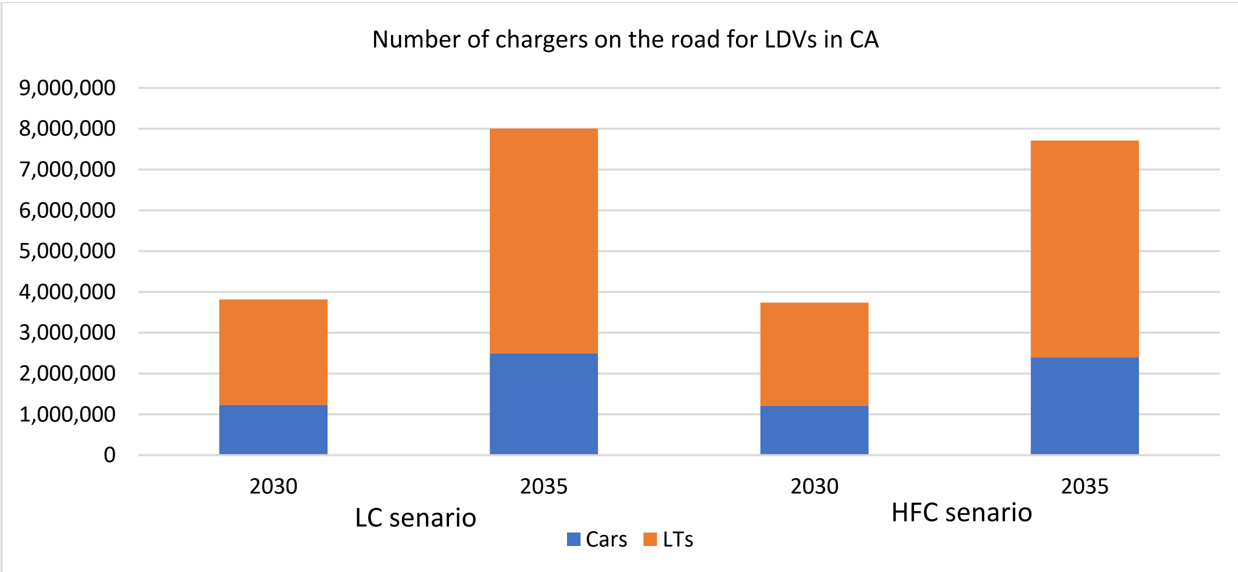


LDV Charger Requirements

In another more detailed paper (Yang et al, 2024), the authors reviewed the charging infrastructure needs and associated investment needs for LDVs in the U.S. to 2030. The paper finds that the average charger-to-vehicle ratio from reviewed studies is about 0.77 chargers per vehicle through 2030 and the average investment cost for charging infrastructure is about $1673 per vehicle through 2030. This paper uses these two findings as the assumption for estimating the charging infrastructure needs for California.

As shown in Figure 14, it is estimated that the cumulative number of chargers needed for LDV charging by 2030 in the LC and High Fuel Cell scenarios is about 3.8 and 3.7 million, respectively. These estimates could increase to 8.0 and 7.7 million by 2035, respectively.

Figure 14. Number of Charges Needed on the Road for LDVs (Cars and Light Trucks) in CA



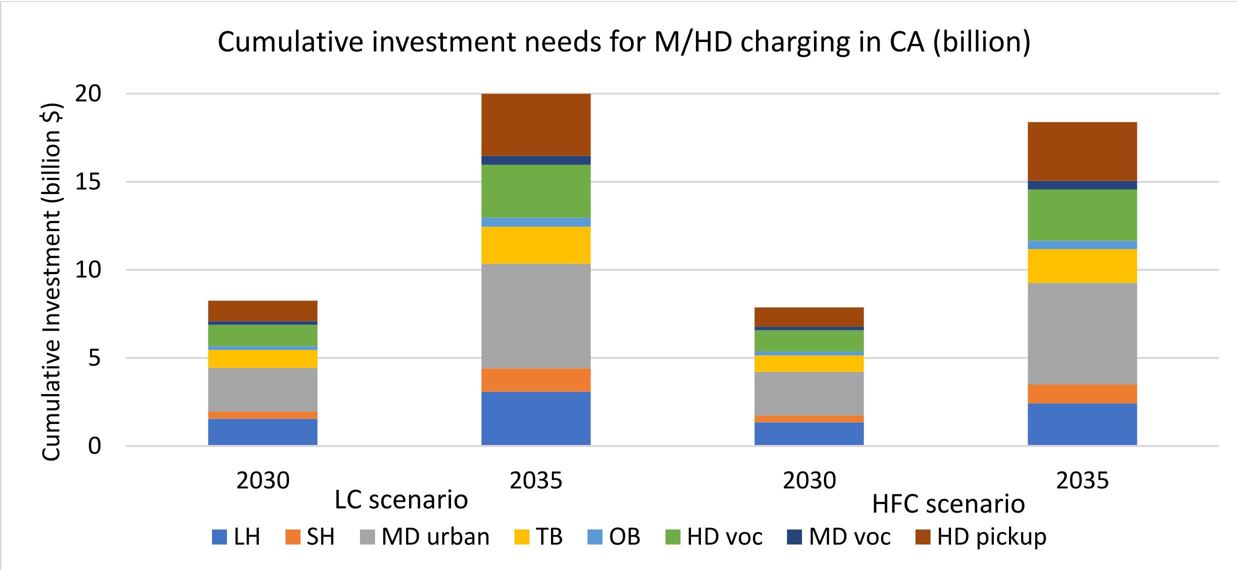
MHD Charger Investment Needs

In general, the investment need for MHD charging infrastructure for the LC scenario is higher than that for the High Fuel Cell scenario (Figure 15). For example, the annual investment needed for MHD chargers can reach about $1.85 billion/year in 2030 in California. The cumulative investment needs for MHD charging will be about $8.2 billion through 2030, supporting 198 thousand battery-electric MHD in California in 2030. Such cumulative investment needs can increase to $20.0 billion through 2035, supporting 578 thousand battery-electric vehicles in California in the "Low Carbon" scenario in 2035.

For the High Fuel Cell scenario, the annual associated investment needs for MHD charging are about $1.74 billion/year in 2030. The cumulative investment needs will add up to about $7.9 billion through 2030 and $18.4 billion through 2035, supporting 190 thousand and 537 thousand battery-electric MHD in California, respectively. All investment estimates are in net present value, assuming a 5 percent discount rate.

It is noted that the cumulative charging investment estimates include investment costs for chargers that are installed to replace existing chargers that have been used for 10 years. This report assumes a 10-year lifetime for all chargers.

Figure 15. Cumulative Investment Needs for MHD Charging in CA

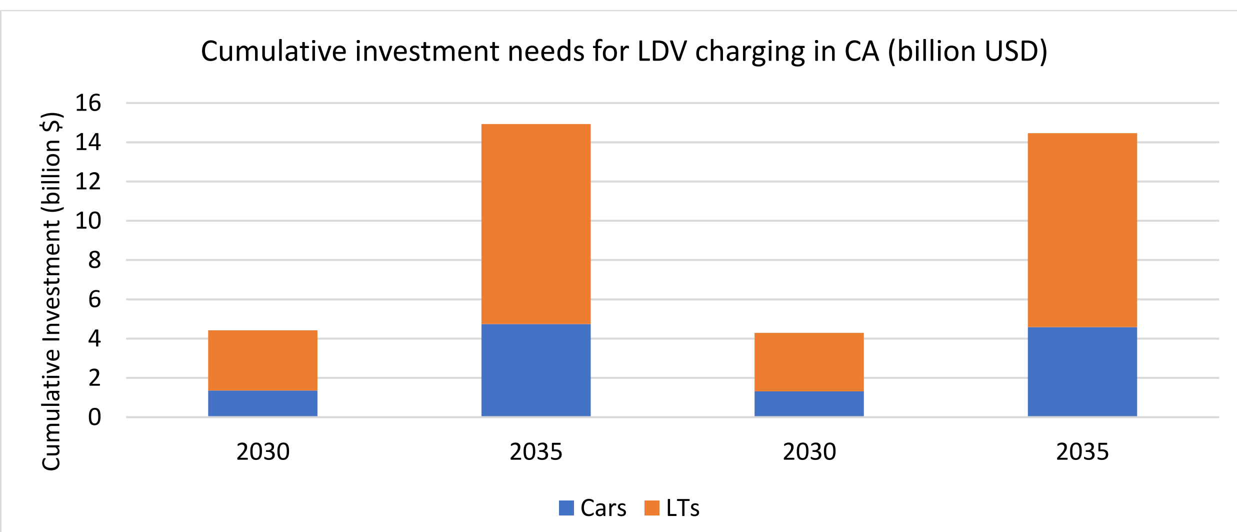


LDV Charger Investment Needs

As shown in Figure 16, for light-duty vehicle charging, the charging investment cost in the LC scenario and High Fuel Cell scenario is about $4.4 and $4.3 billion in net present value by 2030. These estimates are likely to increase to $14.9 and $14.5 billion in net present value by 2035, respectively. All investment estimates include investment costs that are used to installed chargers to replace obsolete chargers. These investment needs are in net present value, assuming a 5 percent discount rate.

While the number of chargers needed for LDVs in both scenarios is significantly higher than that for MHDVs, the charging investment needs for LDVs and MHDVs will be relatively close in the same scenario by 2030. Yet by 2035, the charging infrastructure investment for H/HDVs is visibly higher than that for LDVs in the same scenario.

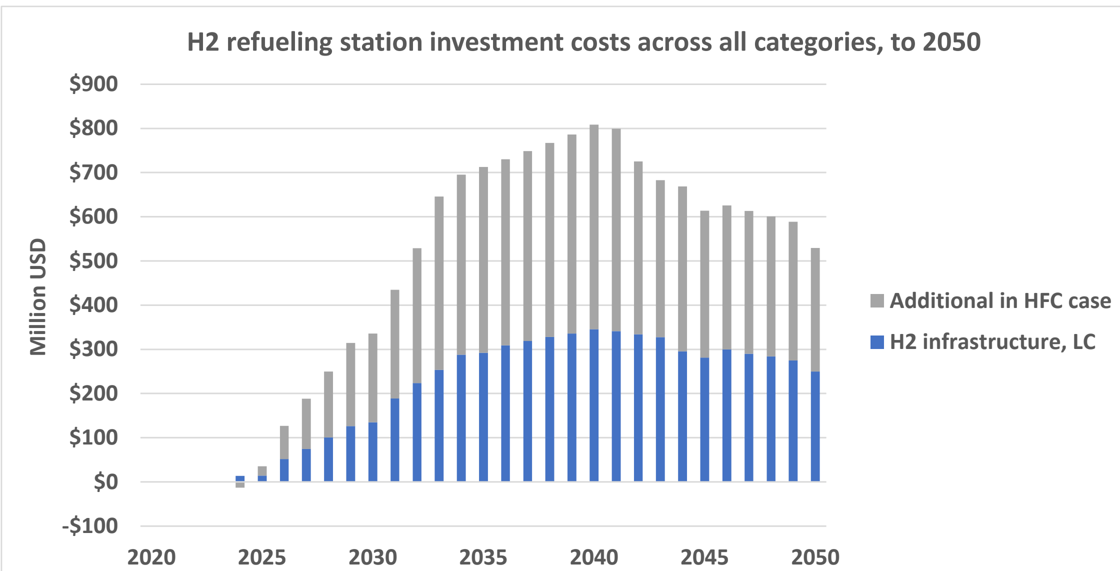
Figure 16. Cumulative Investment Needs for LDV Charging in CA



Hydrogen Refueling Station Investment Needs

For the fuel cell vehicles in these scenarios, station construction costs (and thus investment needs) have been assessed in several recent UCD studies. Figure 17shows that the investment costs peak around 2040 at about $350 million per year in the LC scenario, and $800 million per year in the HFC, with around double the number of fuel cell cars and trucks as in the LC. The current scenarios reflect some adjustments in the numbers of vehicles and stations per vehicle (or vehicles per station), with a general reduction in the projected number of stations needed to support vehicles, given somewhat larger stations than previously projected, and higher utilization rates for those stations than has historically been the case, especially for LDV stations.

Figure 17. Hydrogen Refuelling Station Investment Costs by Scenario (including LDV and HDV stations)

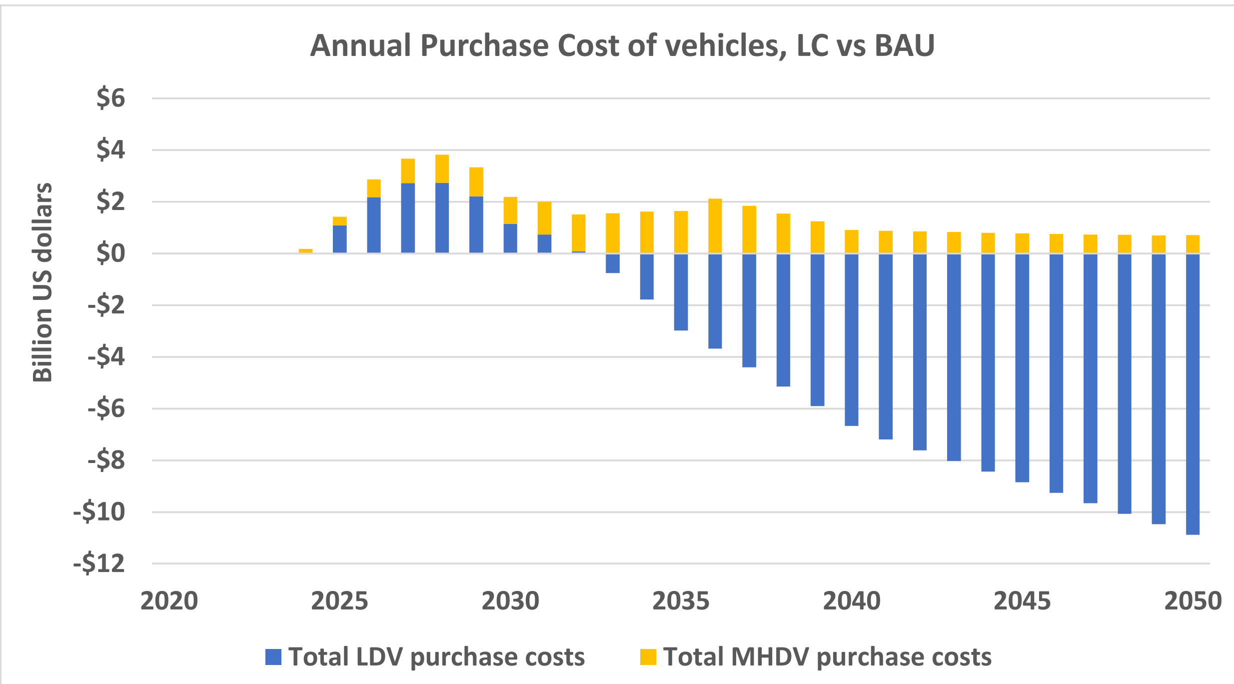


New Vehicle Purchase Costs

In addition to the investment needs reported above for chargers and hydrogen refueling stations, we also consider the upfront "investment" costs of ZEVs. These are the purchase costs borne by customers and represent investment costs in much the same way as do up-front costs for constructing and installing charging and HRS equipment, but with one major difference. For vehicle purchase, only the incremental cost of ZEVs over baseline ICE versions is included, whereas the full cost of refueling/recharging equipment is included above. For vehicle purchase we subtract the avoided cost of ICE vehicles not purchased since only this increment represents additional cost. For refueling/recharging equipment, it is not as clear that there is such a direct avoided cost, since it is not clear how much equivalent gasoline/diesel equipment would have been built in a BAU type scenario (given its widespread availability already and somewhat declining market demand), and also because the investments may be made by different entities and so there is no direct savings to those making the investments.

The annual investment costs for the LC scenario (incremental costs over the BAU) are shown in Figure 18. These reach about $4B per year in the late 2020s then decline, with LDV costs dropping below zero in the early 2030s. In other words, on average, the cost of purchasing BEVs, FCEVs and PHEVs becomes less than that of the gasoline and diesel vehicles they replace. And these become strongly negative by 2035. For trucks and buses, these costs never quite drop to zero, given the price assumptions used in our main scenarios (described in the previous section).

Figure 18. Annual Purchase Cost of Vehicles, LC vs BAU



Total Investment Needs by Scenario

Adding together the estimated and projected investment needs from the types reported above (including chargers and hydrogen refueling stations, as well as vehicle purchase investment (incremental costs) of ZEVs, the combined picture is shown for the LC and HFC scenarios in and Figure 19 and Figure 20 below. Their total cost projections are pretty similar, with only a small reduction in vehicle purchase costs in LC relative to HFC, and a small increase in charging infrastructure costs in the LC. These are mostly offsetting, but are charges to different stakeholders (vehicle buyers vs station/charging infrastructure providers).
In both LC and HFC, while the vehicle purchase costs are larger than the infrastructure up-front costs through the late 2020s, after this time the LDV purchase costs start to decline toward zero, and the result is the infrastructure investment costs are higher than vehicle costs by about

2030 and beyond. The on-going reductions in LDV costs (and increasing savings) eventually makes the overall total investment cost near zero by the mid-2040s. However, the costs for charging infrastructure remain high and fairly constant into the future. This takes into account both the growth in EVs and the need to eventually replace chargers with new ones (we assume a 10-year life for chargers).

In comparison (as shown above), the investment costs for hydrogen refueling stations are relatively small, given the small number of fuel cell vehicles in the LC scenario, and the modest station cost on a per-vehicle basis. For example, a $3 million LDV hydrogen station with a capacity of 2000 kg/day should be able to serve about 3000 LDVs, or a capital cost of $1000 per car. This is lower than typical charger costs, given the need for home charging and some public charging per vehicle. Even in the HFC, with about twice the costs for building H2 stations, these costs are small compared to chargers. However, the savings from lower vehicle purchase costs also decreases, leading to a similar overall outcome. On the other hand, the operating costs of HRS are high compared to that for chargers. Those operating costs are not reflected here, but show up in the hydrogen fuel price estimates used for our broader life-cycle cost and societal cost calculations.

Figure 19. Investment Costs Across All Categories, LC Scenario

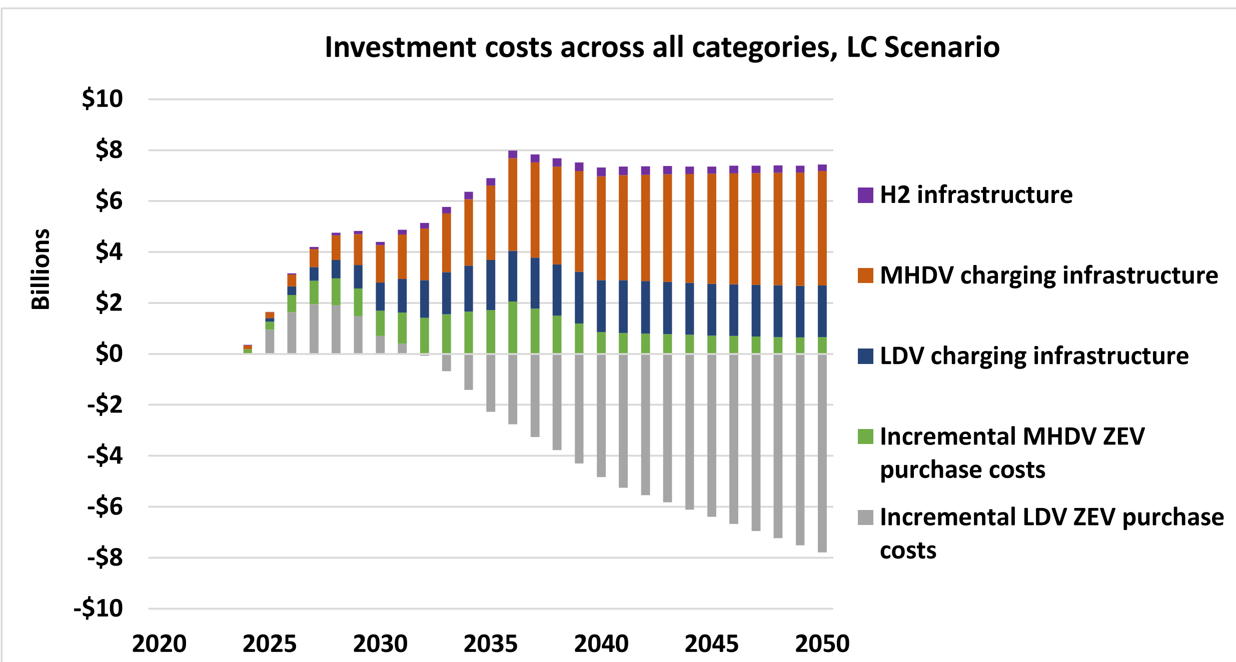
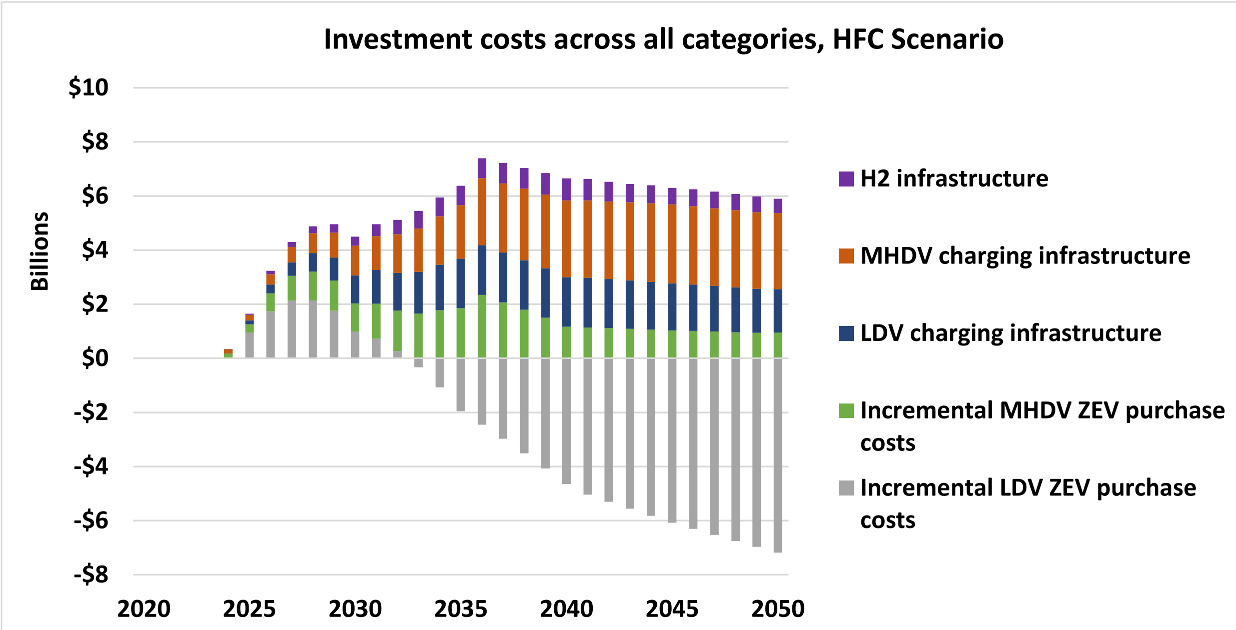


Figure 20. Investment Costs Across All Categories, HFC Scenario



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7. Appendices

Appendix A. Market Share

The following tables show the percentage sales for cars and light-duty trucks for the three scenarios BAU, LC, and HFC.

Table A-1. Cars BAU Scenario

	2020	2025	2030	2035	2040	2045	2050
ICE	87.6%	68.3%	68.8%	69.0%	67.2%	65.5%	63.7%
DSL	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	4.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
P40	2.0%	4.0%	2.0%	0.0%	0.0%	0.0%	0.0%
P80	0.0%	1.5%	3.0%	4.8%	6.5%	8.3%	10.0%
EV	5.7%	20.0%	20.0%	20.0%	20.0%	20.0%	20.0%
FC	0.1%	0.2%	0.2%	0.3%	0.3%	0.3%	0.3%

Table A-2. Light-Duty Trucks BAU Scenario

	2020	2025	2030	2035	2040	2045	2050
ICE	87.6%	72.6%	71.8%	70.5%	67.3%	65.6%	63.8%
DSL	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	4.0%	6.0%	6.0%	6.0%	6.0%	6.0%	6.0%
P40	2.0%	4.0%	2.0%	0.0%	0.0%	0.0%	0.0%
P80	0.0%	1.5%	3.0%	4.8%	6.5%	8.3%	10.0%
EV	5.7%	15.8%	17.1%	18.6%	20.1%	20.1%	20.1%
FC	0.1%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%

Table A-3. Cars LC Scenario

	2020	2025	2030	2035	2040	2045	2050
ICE	87.6%	67.0%	28.0%	0.0%	0.0%	0.0%	0.0%
DSL	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	4.0%	5.0%	5.0%	0.0%	0.0%	0.0%	0.0%
P40	2.0%	5.0%	8.6%	5.0%	0.0%	0.0%	0.0%
P80	0.0%	1.0%	5.0%	15.0%	15.0%	15.0%	15.0%
EV	5.7%	21.7%	52.5%	78.0%	81.3%	80.0%	80.0%
FC	0.1%	0.3%	0.9%	2.0%	3.8%	5.0%	5.0%

Table A-4. Light-Duty Trucks LC Scenario

	2020	2025	2030	2035	2040	2045	2050
ICE	87.6%	67.0%	28.0%	0.0%	0.0%	0.0%	0.0%
DSL	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	4.0%	5.0%	5.0%	0.0%	0.0%	0.0%	0.0%
P40	2.0%	5.0%	8.6%	5.0%	0.0%	0.0%	0.0%
P80	0.0%	1.0%	5.0%	15.0%	15.0%	15.0%	15.0%
EV	5.7%	21.9%	52.9%	78.0%	81.3%	80.0%	80.0%
FC	0.1%	0.1%	0.5%	2.0%	3.8%	5.0%	5.0%

Table A-5. Cars HFC Scenario

	2020	2025	2030	2035	2040	2045	2050
ICE	87.6%	67.0%	28.0%	0.0%	0.0%	0.0%	0.0%
DSL	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	4.0%	5.0%	5.0%	0.0%	0.0%	0.0%	0.0%
P40	2.0%	5.0%	8.6%	5.0%	0.0%	0.0%	0.0%
P80	0.0%	1.0%	5.0%	15.0%	15.0%	15.0%	15.0%
EV	5.7%	21.6%	50.4%	74.0%	75.0%	71.5%	67.5%
FC	0.1%	0.4%	3.0%	6.0%	10.0%	13.5%	17.5%

Table A-6. Light-Duty Trucks HFC Scenario

	2020	2025	2030	2035	2040	2045	2050
ICE	87.6%	67.0%	28.0%	0.0%	0.0%	0.0%	0.0%
DSL	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
HEV	4.0%	5.0%	5.0%	0.0%	0.0%	0.0%	0.0%
P40	2.0%	5.0%	8.6%	5.0%	0.0%	0.0%	0.0%
P80	0.0%	1.0%	5.0%	15.0%	15.0%	15.0%	15.0%
EV	5.7%	21.9%	51.0%	74.0%	75.0%	71.5%	67.5%
FC	0.1%	0.1%	2.4%	6.0%	10.0%	13.5%	17.5%

ICE – Internal combustion engine
DSL - Diesel
CNG – Compressed natural gas vehicle
HEV - Hybrid
P40 - Plug-in 40 mile range
P80 - Plug-in 80 mile range
EV - Battery electric
FC - Fuel Cell

The following tables show the percentage sales for all truck types for the three scenarios – BAU, LC, and HFC.

Table A-7. Long Haul BAU Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	99.9%	97.1%	96.1%	94.7%	92.9%	87.0%	79.2%
Hybrid	0.1%	0.1%	0.1%	0.5%	2.3%	8.2%	16.0%
CNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Fuel Cell	0.0%	0.0%	1.0%	2.0%	2.0%	2.0%	2.0%
BEV	0.0%	2.8%	2.8%	2.8%	2.8%	2.8%	2.8%

Table A-8. Short Haul BAU Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	100.0%	96.3%	95.4%	94.7%	94.7%	94.7%	94.7%
Hybrid	0.0%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
CNG SI	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Fuel Cell	0.0%	0.4%	1.3%	2.0%	2.0%	2.0%	2.0%
BEV	0.0%	3.0%	3.0%	3.0%	3.0%	3.0%	3.0%

Table A-9. Medium-Duty Urban BAU Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	69.1%	65.0%	59.8%	46.2%	41.6%	36.6%	35.2%
Gasoline	15.0%	13.0%	13.0%	13.0%	13.0%	13.0%	13.0%
Hybrid	0.8%	2.9%	7.9%	14.0%	20.9%	25.7%	28.1%
CNG	15.0%	13.8%	14.0%	21.5%	19.2%	19.3%	18.3%
Fuel Cell	0.0%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
BEV	0.1%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%

Table A-10. Urban Buses BAU Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	25.6%	22.00%	0.0%	0.0%	0.0%	0.0%	0.0%
Hybrid	15.4%	5.00%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG SI	45.0%	31.00%	0.0%	0.0%	0.0%	0.0%	0.0%
Fuel Cell	0.1%	1.90%	9.0%	10.7%	12.6%	12.6%	12.6%
BEV	4.0%	40.10%	91.0%	89.3%	87.4%	87.4%	87.4%
Gasoline	10.0%	0.00%	0.0%	0.0%	0.0%	0.0%	0.0%

Table A-11. Other Buses BAU Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	79.3%	83.4%	78.3%	75.9%	63.2%	52.7%	45.9%
Hybrid	0.1%	0.2%	0.3%	0.9%	2.6%	6.3%	10.7%
CNG SI	0.6%	0.9%	4.4%	16.2%	32.2%	39.1%	41.4%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BEV	0.0%	0.5%	2.0%	2.0%	2.0%	2.0%	2.0%
Gasoline	20%	15.0%	15.0%	5.0%	0.0%	0.0%	0.0%

Table A-12. Heavy-Duty Vocational BAU Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	99.3%	98.2%	95.0%	93.1%	84.9%	72.1%	52.5%
Hybrid	0.1%	0.3%	0.8%	2.1%	4.4%	9.6%	24.3%
CNG SI	0.7%	1.1%	2.2%	2.8%	8.7%	16.2%	21.2%
Fuel Cell	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BEV	0.0%	0.5%	2.0%	2.0%	2.0%	2.0%	2.0%

Table A-13. Medium-Duty Vocational BAU Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	99.1%	89.6%	71.3%	56.1%	47.8%	44.4%	42.5%
Hybrid	0.6%	3.5%	16.3%	23.4%	27.0%	26.4%	25.0%
CNG SI	0.3%	1.6%	7.1%	15.2%	19.9%	24.0%	27.2%
Fuel Cell	0.0%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
BEV	0.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%

Table

Table A-14. HD Pick-Ups and Vans BAU Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	57.3%	50.2%	45.5%	42.7%	40.8%	40.2%	40.5%
Gasoline	35.0%	32.0%	32.0%	32.0%	32.0%	32.0%	32.0%
Hybrid	7.6%	12.5%	17.2%	20.0%	21.9%	22.5%	22.2%
CNG	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Fuel Cell	0.0%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
BEV	0.1%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%

Table A-15. Long Haul LC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	99.9%	93.00%	70.00%	25.00%	0.00%	0.00%	0.00%
Hybrid	0.1%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
CNG CI	0.0%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fuel Cell	0.0%	0.00%	5.00%	20.00%	25.00%	25.00%	25.00%
BEV	0.0%	7.00%	25.00%	55.00%	75.00%	75.00%	75.00%

Table A-16. Short Haul LC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	99.8%	93.00%	70.00%	25.00%	0.00%	0.00%	0.00%
Hybrid	0.1%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
CNG SI	0.0%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fuel Cell	0.0%	0.00%	4.00%	12.50%	20.00%	20.00%	20.00%
BEV	0.1%	7.00%	26.00%	62.50%	80.00%	80.00%	80.00%

Table A-17. Medium-Duty Urban LC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	69.1%	65.00%	37.20%	25.00%	0.00%	0.00%	0.00%
Gasoline	15.0%	7.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Hybrid	0.8%	3.00%	7.80%	0.00%	0.00%	0.00%	0.00%
CNG	15.0%	14.00%	5.00%	0.00%	0.00%	0.00%	0.00%
Fuel Cell	0.0%	0.00%	2.50%	5.00%	10.00%	10.00%	10.00%
BEV	0.1%	11.00%	47.50%	70.00%	90.00%	90.00%	90.00%

Table A-18. Urban Buses LC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	25.6%	22.00%	0.0%	0.0%	0.0%	0.0%	0.0%
Hybrid	15.4%	5.00%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG SI	45.0%	31.00%	0.0%	0.0%	0.0%	0.0%	0.0%
Fuel Cell	0.1%	3.00%	7.3%	15.0%	25.0%	25.0%	25.0%
BEV	4.0%	39.00%	92.8%	85.0%	75.0%	75.0%	75.0%
Gasoline	10.0%	0.00%	0.0%	0.0%	0.0%	0.0%	0.0%

Table A-19. Other Buses LC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	79.2%	78.10%	45.59%	25.00%	0.00%	0.00%	0.00%
Hybrid	0.1%	0.0%	0.0%	0%	0%	0%	0%
CNG SI	0.6%	0.9%	4.4%	0%	0%	0%	0%
Fuel Cell	0.0%	0.0%	7.3%	12.0%	20.0%	20.0%	20.0%
BEV	0.1%	11.0%	42.7%	63.0%	80.0%	80.0%	80.0%
Gasoline	20%	10.0%	0.0%	0.0%	0%	0%	0%

Table A-20. Heavy-Duty Vocational LC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	99.2%	87.90%	50.00%	25.00%	0.00%	0.00%	0.00%
Hybrid	0.1%	0.0%	0.0%	0%	0%	0%	0%
CNG SI	0.7%	1.1%	0.0%	0%	0%	0%	0%
Fuel Cell	0.0%	0.0%	2.0%	5.0%	8.0%	10.0%	10.0%
BEV	0.1%	11.0%	48.0%	70.0%	92%	90%	90%

Table A-21. Medium-Duty Vocational LC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	99.0%	83.9%	40.00%	25.00%	0.00%	0.00%	0.00%
Hybrid	0.6%	3.48%	5.00%	0.00%	0.00%	0.00%	0.00%
CNG SI	0.3%	1.61%	5.00%	0.00%	0.00%	0.00%	0.00%
Fuel Cell	0.0%	0.00%	2.50%	5.00%	10.00%	10.00%	10.00%
BEV	0.1%	11.00%	47.50%	70.00%	90.00%	90.00%	90.00%

Table A-22. HD Pick-Ups and Vans LC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	57.3%	50.00%	35.00%	15.00%	0.00%	0.00%	0.00%
Gasoline	35.0%	32.00%	25.00%	10.00%	0.00%	0.00%	0.00%
Hybrid	7.6%	11.00%	10.00%	0.00%	0.00%	0.00%	0.00%
CNG	0.0%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fuel Cell	0.0%	0.00%	2.00%	4.00%	10.00%	20.00%	20.00%
BEV	0.1%	7.00%	28.00%	71.00%	90.00%	80.00%	80.00%

Table A-23. Long Haul HFC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	99.9%	93.00%	70.00%	25.00%	0.00%	0.00%	0.00%
Hybrid	0.1%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
CNG SI	0.0%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fuel Cell	0.0%	0.00%	9.00%	37.50%	50.00%	50.00%	50.00%
BEV	0.0%	7.00%	21.00%	37.50%	50.00%	50.00%	50.00%

Table A-24. Short Haul HFC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	99.8%	93.00%	70.00%	25.00%	0.00%	0.00%	0.00%
Hybrid	0.1%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
CNG SI	0.0%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fuel Cell	0.0%	0.00%	7.00%	30.00%	40.00%	40.00%	40.00%
BEV	0.1%	7.00%	23.00%	45.00%	60.00%	60.00%	60.00%

Table A-25. Medium-Duty Urban HFC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	69.1%	65.00%	37.00%	25.00%	0.00%	0.00%	0.00%
Gasoline	15.0%	7.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Hybrid	0.8%	3.00%	8.00%	0.00%	0.00%	0.00%	0.00%
CNG	15.0%	14.00%	5.00%	0.00%	0.00%	0.00%	0.00%
Fuel Cell	0.0%	0.00%	2.50%	10.00%	20.00%	20.00%	20.00%
BEV	0.1%	11.00%	47.50%	65.00%	80.00%	80.00%	80.00%

Table A-26. Urban Buses HFC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	25.6%	22.00%	0.0%	0.0%	0.0%	0.0%	0.0%
Hybrid	15.4%	5.00%	0.0%	0.0%	0.0%	0.0%	0.0%
CNG SI	45.0%	31.00%	0.0%	0.0%	0.0%	0.0%	0.0%
Fuel Cell	0.1%	4.30%	15.00%	30.00%	50.00%	50.00%	50.00%
BEV	4.0%	37.70%	85.00%	70.00%	50.00%	50.00%	50.00%

Table A-27. Other Buses UFC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	79.2%	78.10%	45.59%	25.00%	0.00%	0.00%	0.00%
Hybrid	0.1%	0.0%	0.0%	0%	0%	0%	0%
CNG SI	0.6%	0.9%	4.4%	0%	0%	0%	0%
Fuel Cell	0.0%	0.0%	10.0%	20.0%	40.0%	40.0%	40.0%
BEV	0.1%	11.0%	40.0%	55.0%	60.0%	60.0%	60.0%
Gasoline	20%	10.0%	0.0%	0.0%	0%	0%	0%

Table A-28. Heavy-Duty Vocational HFC Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	99.2%	87.90%	50.00%	25.00%	0.00%	0.00%	0.00%
Hybrid	0.1%	0.0%	0.0%	0%	0%	0%	0%
CNG SI	0.7%	1.1%	0.0%	0%	0%	0%	0%
Fuel Cell	0.0%	0.0%	2.0%	10.0%	15.0%	20.0%	20.0%
BEV	0.1%	11.0%	48.0%	65.0%	85.0%	80%	80%

Table A-29. Medium-Duty Vocational ZEV+B Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	99.0%	83.4%	40.0%	25.0%	0.0%	0.0%	0.0%
Hybrid	0.6%	3.48%	5.00%	0.00%	0.00%	0.00%	0.00%
CNG SI	0.3%	1.61%	5.00%	0.00%	0.00%	0.00%	0.00%
Fuel Cell	0.0%	0.55%	2.0%	10.0%	15.0%	20.0%	20.0%
BEV	0.1%	11.00%	48.0%	65.0%	85.0%	80%	80%

Table A-30. HD Pick-Ups and Vans ZEV+B Scenario

	2020	2025	2030	2035	2040	2045	2050
Diesel	57.3%	50.00%	35.00%	15.00%	0.00%	0.00%	0.00%
Gasoline	35.0%	32.00%	25.00%	10.00%	0.00%	0.00%	0.00%
Hybrid	7.6%	11.00%	10.00%	0.00%	0.00%	0.00%	0.00%
CNG	0.0%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Fuel Cell	0.0%	0.00%	4.00%	8.00%	20.00%	40.00%	40.00%
BEV	0.1%	7.00%	26.00%	67.00%	80.00%	60.00%	60.00%

Appendix B. Vehicle Cost

Costs are in 2025 dollars.

Table B-1. Cars

	2020	2025	2030	2035	2040	2045	2050
ICE	31,710	32,667	33,790	34,168	34,547	35,049	35,551
DSL	34,010	34,967	36,090	36,468	36,847	37,349	37,851
CNG	35,476	36,329	37,347	37,635	37,923	38,372	38,821
HEV	36,112	35,553	34,818	34,853	35,083	35,350	35,733
P40	35,109	34,456	33,562	33,448	33,530	33,877	34,227
P80	39,796	37,808	35,373	34,925	34,696	35,042	35,391
EV	51,844	45,417	35,818	32,203	30,102	28,892	27,683

Table B-2. Light-Duty Trucks

	2020	2025	2030	2035	2040	2045	2050
ICE	38,797	39,859	41,122	41,593	42,065	42,686	43,307
DSL	42,247	43,309	44,572	45,043	45,515	46,136	46,757
CNG	45,703	46,586	47,669	47,987	48,305	48,844	49,382
HEV	44,775	44,029	42,957	42,953	43,146	43,532	43,804
P40	43,386	42,218	40,952	40,779	40,806	41,037	41,386
P80	50,115	47,228	43,741	43,069	42,632	42,855	43,196
EV	59,142	52,279	42,368	38,623	36,522	35,468	34,411
FC	104,623	74,634	54,291	44,523	38,859	38,218	38,039

ICE – Internal combustion engine
DSL - Diesel
CNG – Compressed natural gas vehicle
HEV - Hybrid
P40 - Plug-in 40 mile range
P80 - Plug-in 80 mile range
EV - Battery electric
FC - Fuel Cell

Table B-3. Long Haul Trucks

	2020	2025	2030	2035	2040	2045	2050
Diesel	172088	180001	187800	189381	190963	192544	194125
Hybrid	195788	198331	198600	198381	197563	198484	199405
CNG SI	235657	242713	244291	239268	234479	229907	225536
Fuel Cell	500000	500000	332045	233972	202809	196731	193397
BEV	600000	600000	422164	330111	321053	310000	300000

Table B-4. Short Haul Trucks

	2020	2025	2030	2035	2040	2045	2050
Diesel	153723	160000	165538	166985	168432	169880	171327
Hybrid	180412	178330	176338	175985	175032	175820	176607
CNG SI	203292	209663	209881	205532	201375	197393	193574
Fuel Cell	456871	500000	303564	193851	167536	165226	162821
BEV	286291	450000	286802	203760	198357	190000	185000

Table B-5. Medium-Duty Urban Trucks

	2020	2025	2030	2035	2040	2045	2050
Diesel	80000	80000	81000	82000	83000	84000	85000
Gasoline	50194	51322	52449	52729	53010	53291	53572
Hybrid	80323	79745	79528	79284	78872	79135	79397
CNG	90650	91146	91684	91216	90789	90399	90047
Fuel Cell	300000	300000	187078	117980	90613	86000	83000
BEV	300000	300000	167269	101161	99674	95000	91000

Table B-6. Urban Buses

	2020	2025	2030	2035	2040	2045	2050
Diesel	476867	536000	602412	602412	602412	602412	602412
Hybrid	500567	562639	632352	632352	632352	632352	632352
CNG SI	530312	598135	672246	672246	672246	672246	672246
Fuel Cell	742360	914000	713242	614362	589812	585000	580000
BEV	628246	810000	679049	614551	603528	600000	595000

Table B-7. Other Buses

	2020	2025	2030	2035	2040	2045	2050
Diesel	133221	135000	136276	136617	136958	137299	137640
Hybrid	162121	157880	149476	147657	145098	144559	144020
CNG SI	139653	139973	140334	139824	139356	138925	138532
Fuel Cell	340000	340000	264776	227725	205190	128931	125469
BEV	322000	322000	217862	166570	161414	131977	129918

Table B-8. Heavy-Duty Vocational Trucks

	2020	2025	2030	2035	2040	2045	2050
Diesel	296413	300000	302840	303734	304628	305522	306415
Hybrid	314422	315350	311251	311006	310252	310436	310623
CNG SI	315506	319325	322348	323300	324251	325202	326153
Fuel Cell	829000	829000	538602	395570	369086	360000	350000
BEV	600000	600000	427450	342463	335738	325000	300000

Table B-9. Medium-Duty Vocational Trucks

	2020	2025	2030	2035	2040	2045	2050
Diesel	144716	147000	148135	148591	149047	149502	149958
Hybrid	156722	159196	160425	160918	161412	161905	162399
CNG SI	150449	150422	150446	150058	149711	149401	149129
Fuel Cell	360000	360000	270230	226015	205014	185000	175000
BEV	323000	323000	228933	182601	175517	167000	160000

Table B-10. HD Pick-Ups and Vans

	2020	2025	2030	2035	2040	2045	2050
Diesel	56000	56000	57000	58000	59000	60000	61000
Gasoline	52358	52956	55171	55729	56287	56845	57403
Hybrid	66888	65655	66827	68000	69172	70345	71517
CNG	61858	61981	63745	63874	64025	64196	64386
Fuel Cell	212757	212757	137039	98237	73799	68000	62000
BEV	135760	135760	85710	61059	58110	57000	56000

Appendix C. Fuel Economy Tables

All fuel economy is in units of miles per gallon gasoline equivalent (mpgge).

Table C-1. Car Fuel Economy

	2020	2025	2030	2035	2040	2045	2050
ICE	30.7	33.2	35.7	38.2	40.7	43.2	45.7
DSL	43.9	45.7	47.7	49.7	52.0	54.4	54.4
CNG	37.6	39.7	42.2	44.1	46.3	48.6	48.6
HEV	53.4	55.7	58.1	60.2	62.5	64.9	64.9
P40-gas	52.4	54.6	56.9	58.9	61.0	63.3	63.3
P40-elec	161.7	163.8	166.0	166.8	167.7	168.6	168.6
P80-gas	48.6	48.7	48.7	49.9	51.2	52.5	52.5
P80-elec	163.0	166.3	169.7	169.6	169.6	169.6	169.6
EV	137.0	144.2	152.3	153.5	154.7	155.9	155.9
FC	67.6	71.3	75.4	76.6	77.9	79.3	79.3

Table C-2. Light Trucks Fuel Economy

	2020	2025	2030	2035	2040	2045	2050
ICE	22.4	23.6	24.9	26.1	27.4	28.6	29.9
DSL	34.7	35.3	35.9	37.0	38.2	39.6	39.6
CNG	29.7	30.7	31.7	32.8	34.0	35.3	35.3
HEV	41.2	40.9	40.7	42.0	43.5	45.0	45.0
P40-gas	40.7	40.5	40.3	41.6	43.0	44.5	44.5
P40-elec	139.0	140.0	141.0	141.3	141.5	141.7	141.7
P80-gas	37.4	35.4	33.6	34.3	35.1	35.9	35.9
P80-elec	113.3	108.5	104.1	104.7	105.2	105.8	105.8
EV	104.6	103.6	102.6	103.2	103.7	104.3	104.3
FC	47.1	48.7	50.3	51.1	51.8	52.6	52.6

Table C-3. Long Haul Fuel Economy

	2020	2025	2030	2035	2040	2045	2050
Diesel	5.96	7.36	7.88	8.21	8.58	8.98	9.42
Hybrid	6.27	7.74	8.27	8.62	9.01	9.43	9.90
CNG SI	5.30	6.69	7.16	7.47	7.81	8.17	8.57
Fuel Cell	7.15	8.83	9.45	9.86	10.30	10.78	11.31
BEV	15.81	16.30	16.79	17.22	17.66	18.11	18.58

Table C-4. Short Haul Fuel Economy

	2020	2025	2030	2035	2040	2045	2050
Diesel	5.20	6.25	6.53	6.77	7.02	7.30	7.60
Hybrid	5.47	6.87	7.83	8.12	8.43	8.76	9.13
CNG SI	4.62	5.68	5.94	6.15	6.39	6.64	6.91
Fuel Cell	10.92	13.12	13.71	14.21	14.75	15.34	15.96
BEV	16.64	19.99	20.89	21.66	22.48	23.37	24.33

Table C-5. Medium Duty Delivery Fuel Economy

	2020	2025	2030	2035	2040	2045	2050
Diesel	7.89	9.32	9.66	9.99	10.35	10.74	11.14
Gasoline	7.13	7.99	8.25	8.53	8.81	9.12	9.45
Hybrid	10.52	13.97	15.46	15.98	16.56	17.18	17.83
CNG	9.20	9.45	9.70	9.95	10.20	10.45	10.70
Fuel Cell	16.58	19.57	20.29	20.98	21.74	22.55	23.40
BEV	30.00	35.41	36.71	37.95	39.33	40.80	42.34

Table C-6. Urban Bus Fuel Economy

	2020	2025	2030	2035	2040	2045	2050
Diesel	4.20	4.91	5.13	5.30	5.48	5.68	5.89
Gasoline	4.20	4.91	5.13	5.30	5.48	5.68	5.89
Hybrid	5.17	5.91	6.17	6.38	6.60	6.84	7.09
CNG	3.73	4.47	4.66	4.81	4.98	5.17	5.35
Fuel Cell	9.23	10.81	11.29	11.65	12.06	12.49	12.95
BEV	13.43	15.72	16.42	16.95	17.55	18.16	18.84

Table C-7. Other Bus Fuel Economy

	2020	2025	2030	2035	2040	2045	2050
Diesel	6.63	7.82	8.11	8.39	8.69	9.01	9.35
Hybrid	6.98	11.74	12.98	13.42	13.90	14.41	14.97
CNG SI	7.62	8.54	8.82	9.11	9.42	9.74	10.09
Fuel Cell	14.58	17.21	17.85	18.45	19.10	19.83	20.58
BEV	21.21	25.04	25.96	26.84	27.79	28.84	29.94

Table C-8. Heavy-Duty Vocational Fuel Economy

	2020	2025	2030	2035	2040	2045	2050
Diesel	4.03	4.72	4.92	5.09	5.26	5.45	5.65
Hybrid	5.38	6.29	6.54	6.77	7.00	7.24	7.52
CNG SI	3.58	4.20	4.37	4.52	4.68	4.85	5.02
Fuel Cell	8.87	10.38	10.82	11.19	11.58	11.99	12.43
BEV	12.90	15.09	15.74	16.28	16.84	17.43	18.08

Table C-9. Medium-Duty Vocational Fuel Economy

	2020	2025	2030	2035	2040	2045	2050
Diesel	7.61	9.33	9.80	10.16	10.54	10.96	11.40
Hybrid	11.71	14.35	15.68	16.24	16.87	17.53	18.23
CNG SI	6.77	8.29	8.71	9.03	9.37	9.73	10.13
Fuel Cell	15.99	19.59	20.58	21.32	22.14	23.01	23.94
BEV	28.93	35.45	37.25	38.59	40.06	41.63	43.30

Table C-10. Heavy-Duty Pick-Up Trucks and Vans Fuel Economy

	2020	2025	2030	2035	2040	2045	2050
Diesel	17.93	20.01	22.85	23.75	24.72	25.78	26.93
Gasoline	16.32	18.21	20.80	21.61	22.49	23.46	24.50
Hybrid	26.90	30.02	34.28	35.63	37.08	38.68	40.39
CNG	16.32	18.21	20.80	21.61	22.49	23.46	24.50
Fuel Cell	39.46	44.02	50.28	52.25	54.38	56.72	59.24
BEV	68.15	76.04	86.84	90.25	93.93	97.98	102.33

Appendix D. Vehicle Retention Rates

Vehicle retention rates are required to calculate stock turnover from year to year. Retention rates are defined as the fraction of vehicles of a given age that remain in the fleet the following year. Retention rates vary across vehicle types, but we assume constant rates for different technology types within the same vehicle type. The MDHV retention rates are based on CARB's Vision 2.0, and the LDV rates are based on results from a recent CARB study (Jacobsen 2023). Table D-1 shows retention rates for two vehicle types, long haul trucks and cars.

Table D-1. Vehicle Retention Rate Assumptions for LH Trucks and Cars

Age	LH trucks	Cars
1	1.00	1
2	0.98	0.98
3	0.95	0.99
4	0.98	0.995
5	0.97	0.98
6	0.97	0.97
7	0.97	0.975
8	0.97	0.96
9	0.97	0.96
10	0.97	0.93
11	0.98	0.92
12	0.95	0.91
13	0.95	0.9
14	0.93	0.895
15	0.92	0.87
16	0.90	0.86
17	0.93	0.84
18	0.91	0.83
19	0.89	0.82
20	0.88	0.81
20+	0.88	0.86

Appendix E. Vehicle Miles Traveled

The average annual VMT per vehicle for each vehicle type is taken from CARB's Vision 2.0 model. The VMT is a function of vehicle age with the miles traveled decreasing each year. Earlier versions of the TTM included lower VMT for battery electric and fuel cell vehicles compared to conventional vehicles due to expected limited range. The present version assumes all vehicle technologies have the same VMT.

Table E-1. VMT in the First Year for Each Vehicle Type

Vehicle Type	VMT (thousand miles)
Cars	15,300
Light-duty Trucks	15,300
Heavy-duty Pickups and Vans	16,813
Medium-duty Urban	25,539
Transit Bus	18,657
Other Bus	23,763
Medium-duty Vocational	5,893
Heavy-duty Vocational	17,544
Short-Haul Heavy-duty	44,795
Long-Haul Heavy-duty	81,041

In order to calibrate the TTM with on-road data, the diesel and gasoline fuel use output from the model was compared to the fuel use from CARB's Scoping Plan (CARB 2022). A VMT correction factor modifies the TTM vehicle VMT to align fuel use between the model and the Scoping Plan data. The correction factor increases model VMT by 2% for LDVs and by 8% for MDHVs.