Technical Review of:

Medium and Heavy-Duty Electrification Costs for MY 2027- 2030

Final Report

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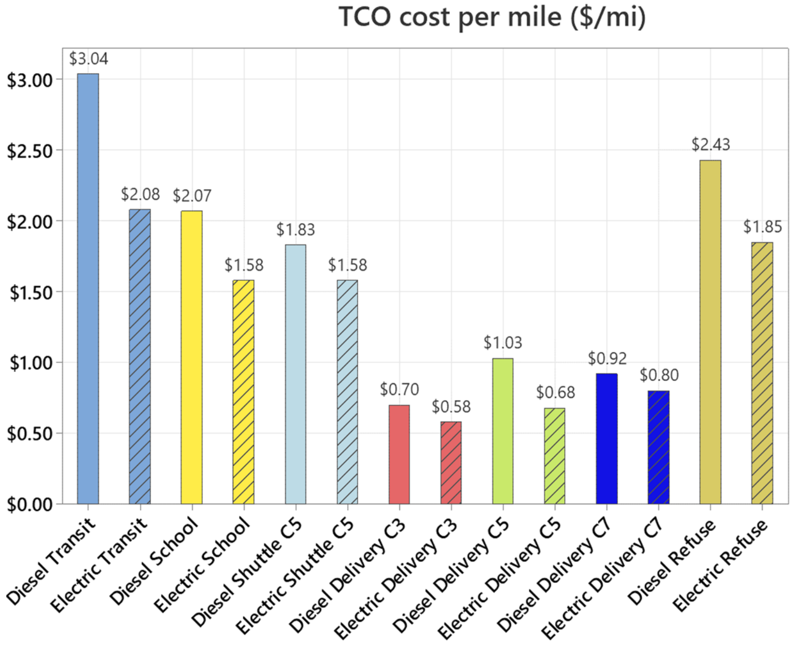
Abstract: Medium- and Heavy-Duty Electrification Cost Evaluation

This report evaluates the cost of electrifying vehicles in several medium- and heavy-duty market segments such as class 8 transit and class 7 school buses, class 3-7 shuttles & delivery vehicles, and class 8 Refuse haulers, whose use patterns are concentrated in urban areas. Emissions from diesel vehicles in these categories are significant sources of pollutants that are damaging to human health and the environment, including particulate matter, nitrogen oxides, and greenhouse gases. Greenhouse gas and NOx regulations will continue to become stricter, with the next milestones planned to take effect in 2024 and 2027. To accomplish these targets, engine, aftertreatment, and transmission technology will be developed that improves fuel economy and reduces emissions, adding costs to the ICE system. At the same time, battery, motor, and power electronics costs are decreasing more rapidly than predictions made in the past decade. This report evaluates the incremental costs at each of these milestones and compile a comprehensive total cost of ownership for a vehicle purchased in 2027. When considering vehicle purchase price alone (no amortization of costs), EV's are favored in all categories except shuttle buses in 2027 and favored in all categories in TCO when purchased in 2027. The TCO analysis shows that in the cases where EVs have higher upfront costs, total cost parity is achieved within 2 years of vehicle purchase, summarized in the below table. Charging costs were sourced from available literature detailing the installation cost as well as the hardware costs. The average published cost in literature for chargers of each power level were used in the TCO analyses for each class.

Class	Segment	Batt. Size	Purchase	Operating	Total Cost	TCO Parity
		kWh	% Cost Reduction of EV vs ICE			Year
Class 8	Transit Bus	400	0.8	49.5	31.6	2
Class 7	School Bus	60	12.4	26.5	23.7	1
Class 5	Shuttle Bus	200	0.2	15.9	13.7	3
Class 3	Delivery Van	100	0.7	31.2	16.9	3
Class 5	Delivery Truck	150	12.4	52.0	34.0	1
Class 7	Delivery Truck	100	9.4	14.3	12.7	4
Class 8	Refuse Hauler	200	7.3	35.6	23.9	1



EDF - Medium- and Heavy-Duty Electrification Cost Evaluation			
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Revision Summary

Date	Version	Change Description
11/18/2021	1.0	Preliminary Release - Draft
12/8/2021	1.1	Updated figures, sections, and links
12/14/2021	1.2	Updated TCO figures & calculations
01/13/2022	1.3	Revisions based on EDF comments, updated tables
02/02/2022	1.4	Further revisions based on comments, figures and tables updated

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Glossary

ADAS	-	Advanced Driver Assistance Systems
AWD	-	All Wheel Drive
BEV	-	Battery Electric Vehicle
BISG	-	Belt Integrated Starter Generator
BNEF	-	Bloomberg New Energy Finance
CAFE	-	Corporate Average Fuel Economy
GHG	-	Green House Gas
DI	-	Direct Injection
EHC	-	Electrically Heated Catalyst
EPA	-	Environmental Protection Agency
GCTP	-	Gravimetric Cell To Pack ratio (weight of the cells/weight of the battery pack)
HVAC	-	Heating Ventilation and Air-Conditioning
ICCT	-	International Council on Clean Transportation
ICE	-	Internal Combustion Engine
LFP	-	Lithium Ferro (Iron) Phosphate
NMC	-	Nickel Manganese Cobalt
NCA	-	Nickel Cobalt Aluminum
NHTSA	-	National Highway Traffic Safety Administration
NVH	-	Noise Vibration Harshness
OEM	-	Original Equipment Manufacturer
PM	-	Permanent Magnet
SAFE	-	Safer Affordable Fuel-Efficient Vehicles Rule
TM	-	Thermally Modulated

VCTP - Volumetric Cell To Pack ratio (volume of the cells/volume of the battery pack)

VVT - Variable Valve Timing

WLTP - Worldwide Harmonized Light Vehicle Test Procedure

YOY - Year on Year

Executive Summary

Emissions from diesel trucks and buses in all classes, particularly those used in urban areas, contribute to pollution that is damaging to both human health and the environment. Nitrogen oxides (NOx) emissions contribute to smog, and particulate emissions and other pollutants in diesel exhaust contribute to poor health outcomes. Additionally, greenhouse gas emissions contribute to climate change and are the subject of regulatory scrutiny. Delivery, box and stake trucks, and shuttle vehicles in class 3-7 segments, as well as class 8 transit and class 7 school buses, are a significant part of the medium- and heavy-duty market. These vehicles and their use tend to be concentrated in cities where average trip distances are short and the health and pollution effects are of most concern, making these categories logical targets for early electrification deployment.

The goal of this work is to evaluate the electrification of several medium- and heavy-duty market segments to develop projected incremental costs and total cost of ownership (TCO) for electric vehicles (BEV) in 2027-2030 for these vehicles. These costs are compared to equivalent ICE vehicles meeting the EPA Greenhouse Gas Phase 1 and 2 rules, as well as California Low NOx regulations in the California Omnibus HD NOx rule. Through these costing exercises, the approximate timeframe of EV cost parity with their ICE counterparts can be identified, and the viability of electrification in the selected MD/HD market segments can be determined for the 2027-2030 timeframe.

This study focuses on existing fleets with infrastructure (excluding chargers) already owned by the fleet operator, eliminating the need for any major changes. The study assumes EV market penetration levels such that higher costs associated with low production rates do not affect the adoption of EVs, matching predictions of increased EV availability and production. Model year 2027 is chosen to support regulation development and match the timeline of the possible adoption of these regulations in MY2027, including the costs of diesel powertrain advancements required to meet anticipated regulations in that time frame, such as tighter NOx standards.

While many sources point to substantial health and welfare benefits associated with the deployment of EVs, particularly in the HD market segments, these benefits are not considered nor included in the current analysis. This work focuses exclusively on the direct financial costs and savings related to vehicle ownership.

Prior work in the area supported by MJ Bradley and Associates identified the key market segments of the MD/HD market ripe for electrification, as well as the associated battery capacities chosen for this study [1]. The market segments, weight classes, and projected battery capacities used in this study for each class evaluated are summarized in Table 1. Battery capacities listed below are sized to cover an approximately average trip distance for each class and were derived from the MJ Bradley work and others. For example, the school bus segment is significantly lower in this report compared to the MJ Bradley report, owing to the generally short trip distance a majority of school buses travel in a day, as well as their ability to recharge mid-day during school hours.

Table 1: MD/HD market segments included in analysis.

Market Segment	Weight Class	Battery Capacity (kW-h)
Transit Bus	Class 8	400
School Bus	Class 7	60
Shuttle Bus	Class 3-5	100
Delivery and Service Van, Box and Stake Truck	Class 3	100
Short Haul Delivery, Service, Box, and Stake Truck	Class 6-7	150
Short Haul Delivery and Service Van, Box and Stake Truck	Class 4-5	100
Refuse Hauler	Class 8	200

Incremental costs were determined by identifying the major components in a diesel-powered vehicle that would be eliminated in an EV, as well as identifying components that must be added to a vehicle for electrification. Literature reviews of ICE and EV component costs were conducted to determine the current and future projections of costs in the MD/HD vehicle markets, accounting for developments in technology expected in the EV market and improvements to diesel engines, aftertreatment systems, and transmissions to meet increasingly stringent regulations in 2024 and 2027. Figure 1 shows the incremental costs (ICE delete vs. EV add) in 2021, 2024, and 2027.

The general trend across all categories and classes evaluated, point to the decreasing upfront cost of electrification compared to traditional ICE powertrains. Only Class 3 Shuttles show any cost increase of EV's over ICE vehicles in 2027, with an incremental cost of $3,214. Electrification costs drop between 26-30% by 2024, and 42-44% in 2027. Due to the large portion of the EV costs being driven by battery costs, batteries are the primary source of this reduction, projected to fall from $123/kW-h in 2021 to $68/kW-h in 2027. Table 2 shows the battery and other EV component cost decrease in 2027 compared to 2021. Motors, inverters, and other power electronics are projected to decrease in cost as well due to the increased ubiquity of manufacturing, use, and advancements in technology.

Cost of Reference BEV and Diesel Powertrains

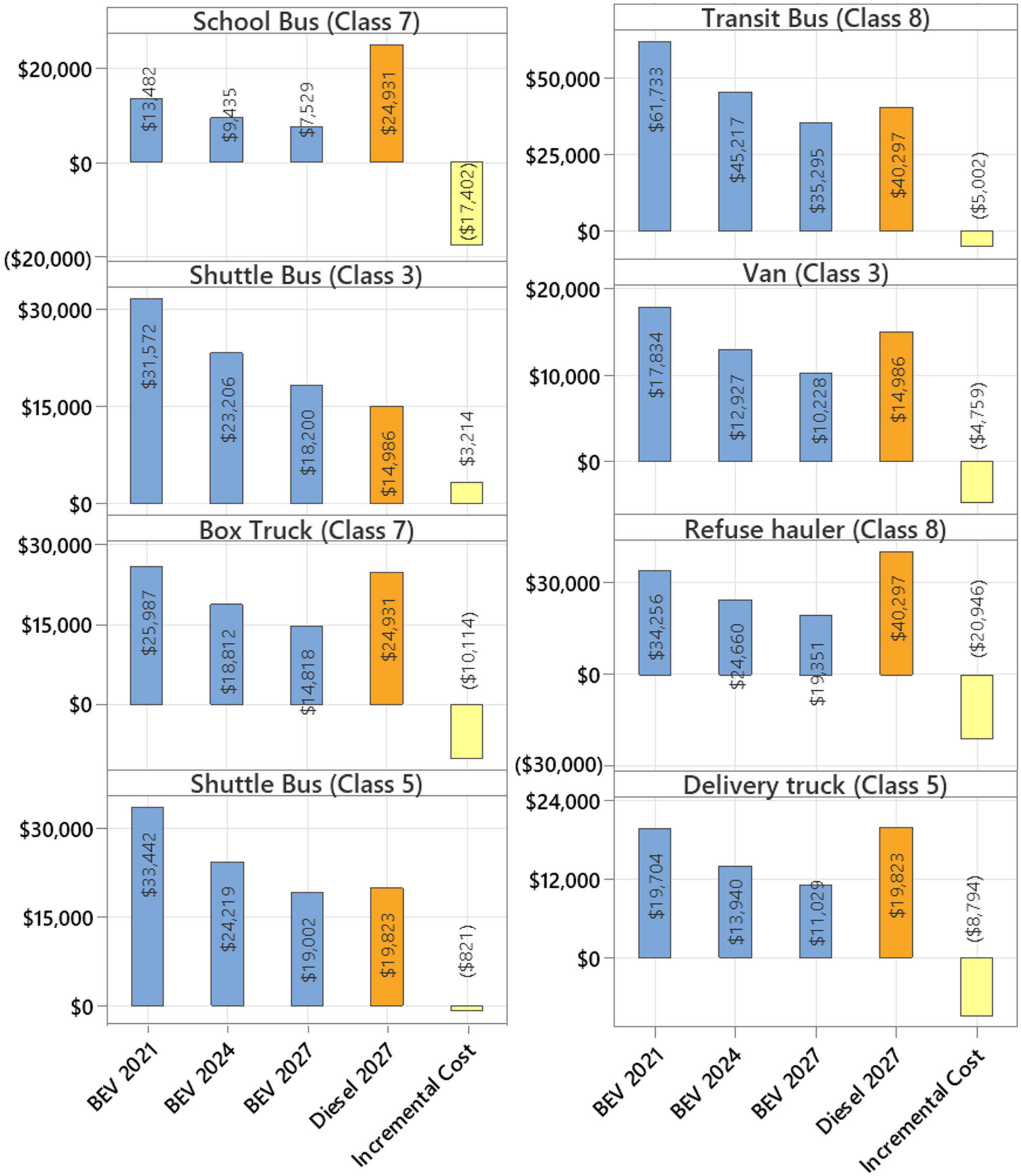


Figure 1: Incremental costs of electrification of MD/HD vehicles. Blue bars are EV powertrain (add) costs in 2021, 2024, and 2027, orange bars are ICE powertrain (delete) costs in 2027, and the yellow bars are incremental costs of the BEV in 2027 (negative value implies that an electric powertrain is cheaper than diesel in 2027)

Table 2: EV Component costs decrease from 2021 to 2027.

EV Component Costs 2027 vs 2021	
Batteries	-45%
Motors	-65%
Power Electronics	-19%

The total cost of ownership was determined for all financial aspects of ownership, including vehicle purchase cost of ICE or EV, fuel, or energy costs, charging or fueling infrastructure costs, maintenance costs, and vehicle mid-life refresh if applicable. Indirect costs or benefits outside of costs directly borne by the vehicle purchaser were not considered in this analysis, including the pollution and climate benefits associated with the deployment of zero-emission vehicles. The incremental costs derived in Figure 1 were used as a basis to determine the difference in the purchase price of a certain class of vehicle, as the study assumes economies of scale in the manufacturing and production of EVs.

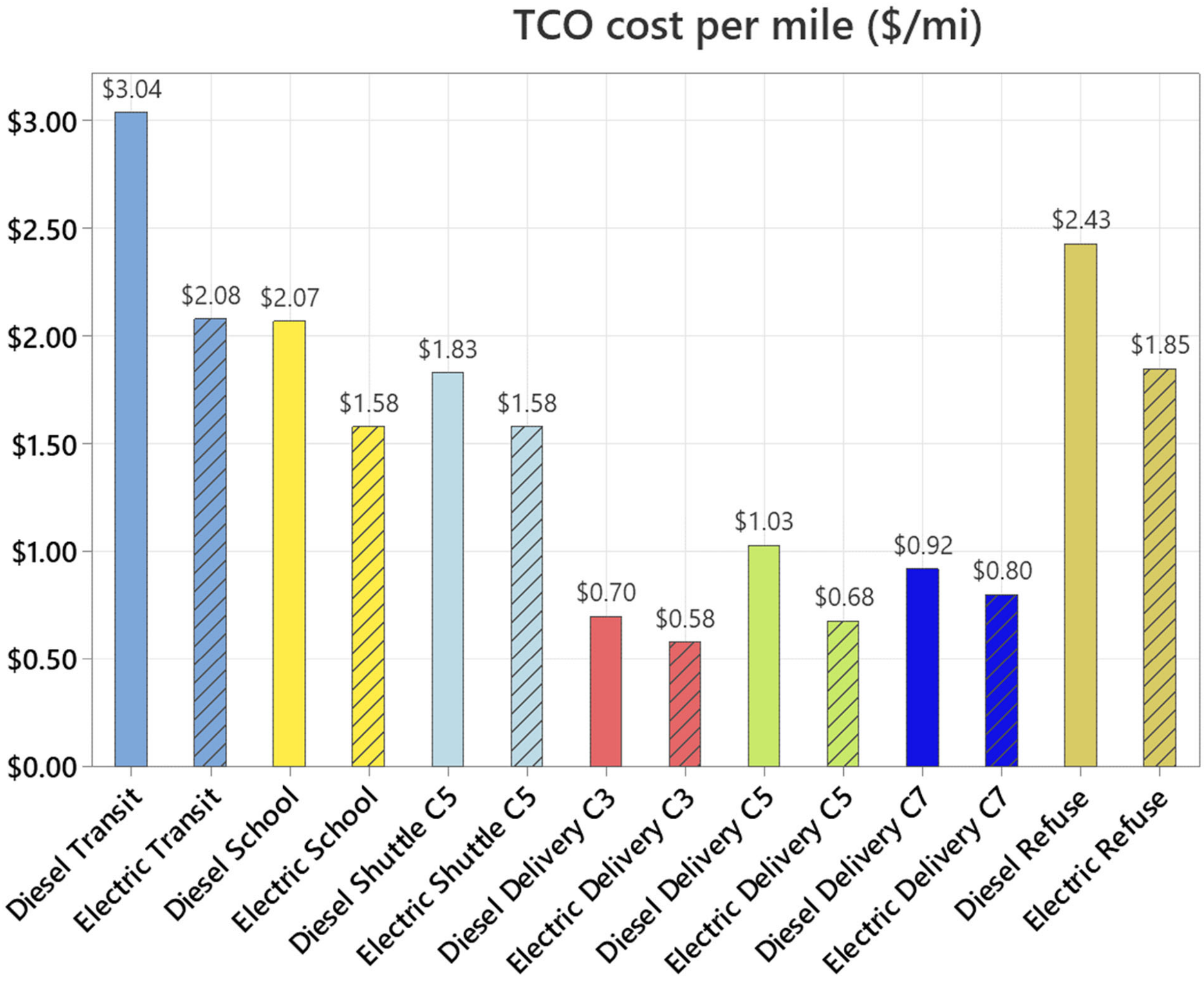
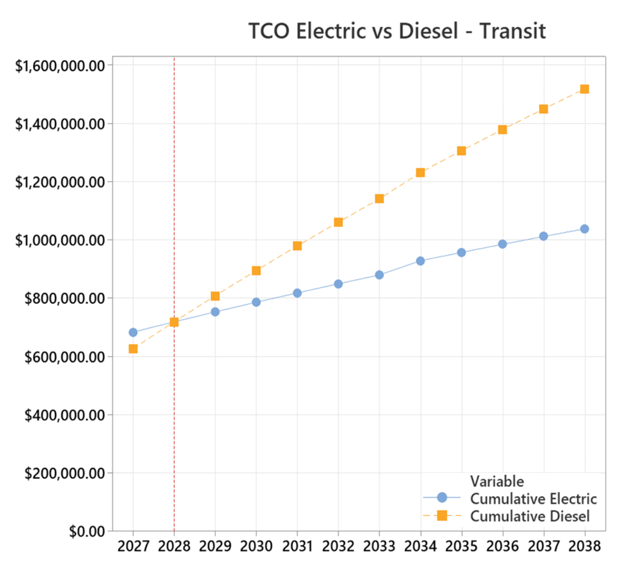
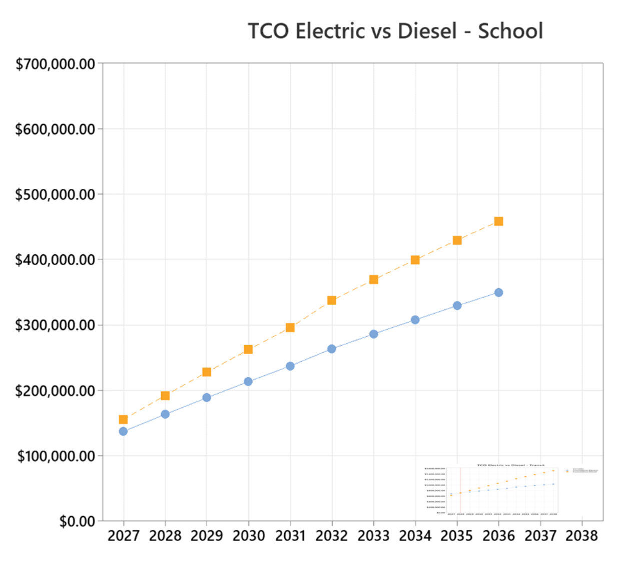
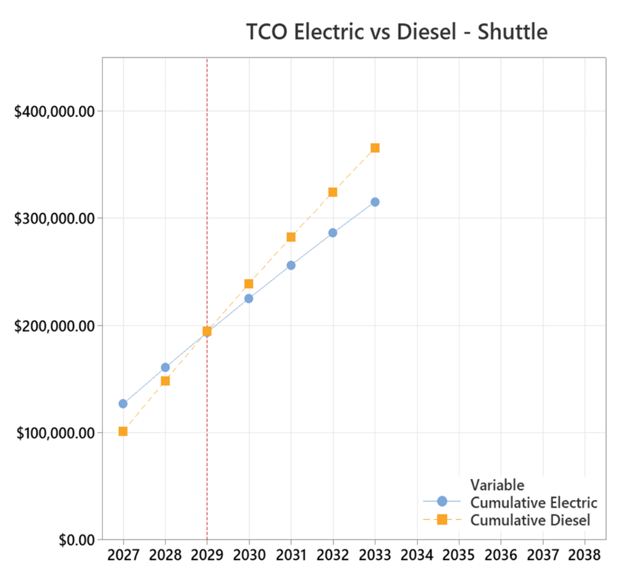


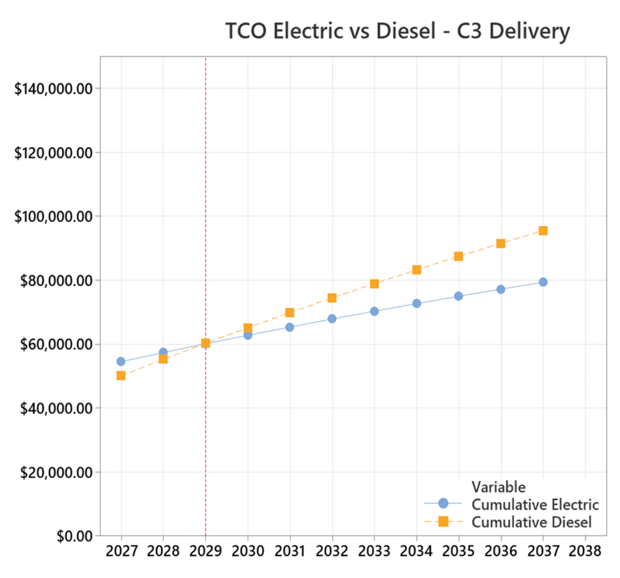
Figure 2: Total cost of ownership per mile in 2027 of all vehicle classes studied.

Figure 2 shows the cost per mile of all financial aspects of ownership of each class for a vehicle purchased in 2027. The striped bars show the electric vehicle costs. In all classes, EV costs are less than ICE costs over the life of the vehicle, as maintenance and energy costs are significantly lower for EVs than ICE vehicles. This overcomes the difference in costs associated with charging infrastructure and vehicle costs that can make initial investment costs of EVs higher than ICE vehicles. Plotting cumulative TCO over time shows the time to parity for each vehicle class.









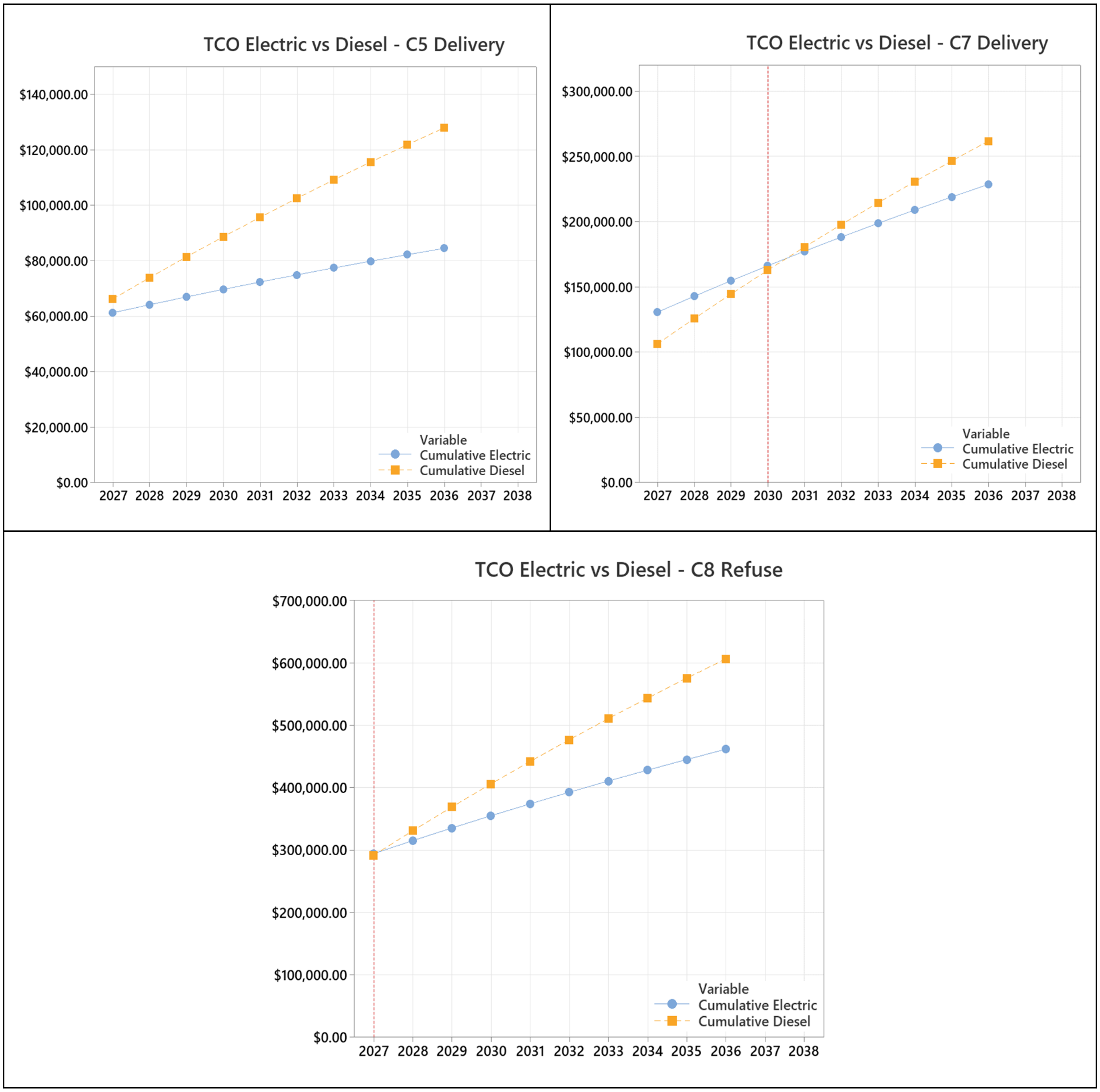


Figure 3: Cumulative TCO for all categories in the study. Vertical lines show the time to parity for classes where initial EV costs are higher than ICE.

Figure 3 shows the cumulative cost of all financial aspects of ownership of each class from 2027 to 2038. In all categories but Transit, Shuttle, and Class 7 delivery, cost parity is immediate given a 2027 purchase date. Transit reaches parity in the second year of operation, while the Shuttle and Class 7 Delivery categories reach parity in the third year of operation. The result is driven by the relatively higher cost of charging infrastructure when compared to the vehicle costs of these categories. A summary of the time to reach parity for each TCO is shown in Table 3.

Table 3: Year to parity for the cumulative cost of ownership for each class studied.

Cumulative TCO Parity Reached – 2027 Purchase	
Market Segment	**Parity Reached**
Class 8 Transit Bus	2028
Class 7 School Bus	Immediate
Class 5 Shuttle Bus	2029
Class 8 Refuse Truck	Immediate
Class 7 Delivery	2030
Class 5 Delivery	Immediate
Class 3 Delivery	2029

Charging infrastructure is a potential significant capital expense when transitioning a fleet to EVs. For the reference case TCO analysis, the depot charger and vehicle on-board charger were sized to charge a vehicle in 4 hours, assuming one charger per vehicle. The costs associated with the chargers examined in the study are shown in Figure 4. Charging costs were taken from literature sources detailing the installation cost as well as the hardware costs. The average published cost in literature for chargers of each power level was used in the TCO analysis. Charger costs are assumed constant in the costing timeframe presented. A detailed study of future charger costs was not conducted and optimizing charger utilization was not considered since they were outside the scope of this study. This results in fairly conservative estimates of charger costs in this study. Increasing charger availability, advancing technology, and optimized charging strategies could all reduce the infrastructure costs in the future, further reducing the TCO for BEVs presented in the report.

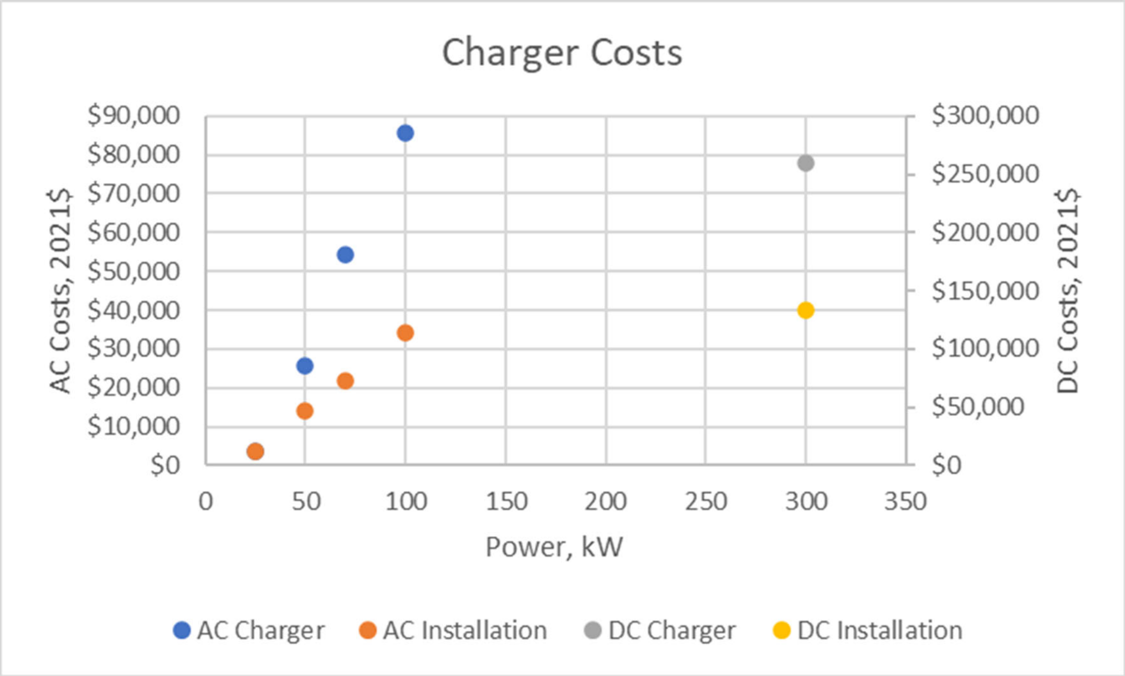


Figure 4: Charger and charger installation costs used in the study.

Sensitivities in the costing analyses are presented for both the incremental and total costs of ownership. For the incremental costs, these sensitivities are based on technology developments and options that may change the costs of both EV and ICE vehicles. The primary sensitivities for ICE vehicles are the possibilities of mild and full hybridization. Mild hybridization increases the hardware costs of diesel vehicles for start-stop functionality. Full hybridization includes the addition of a PMSM drive motor and small battery pack, as well as hardware costs associated with an optimized engine for hybrid functions. For EVs, the base assumption is an NMC battery pack, but lithium iron phosphate packs are cheaper and well suited to the large form factor of heavy-duty vehicles. Additionally, convergence in light- and heavy-duty motor design and production is expected to bring motor costs down, and this provides another sensitivity in the costs analysis of EVs. Once these sensitivities are considered in the incremental costs, all vehicle classes studied show a case where electrification provides a strong cost advantage over the equivalent ICE vehicle, as shown in Figure 5, even considering the conservative estimates of charger costs which ignore future developments in charger technology and adoption.

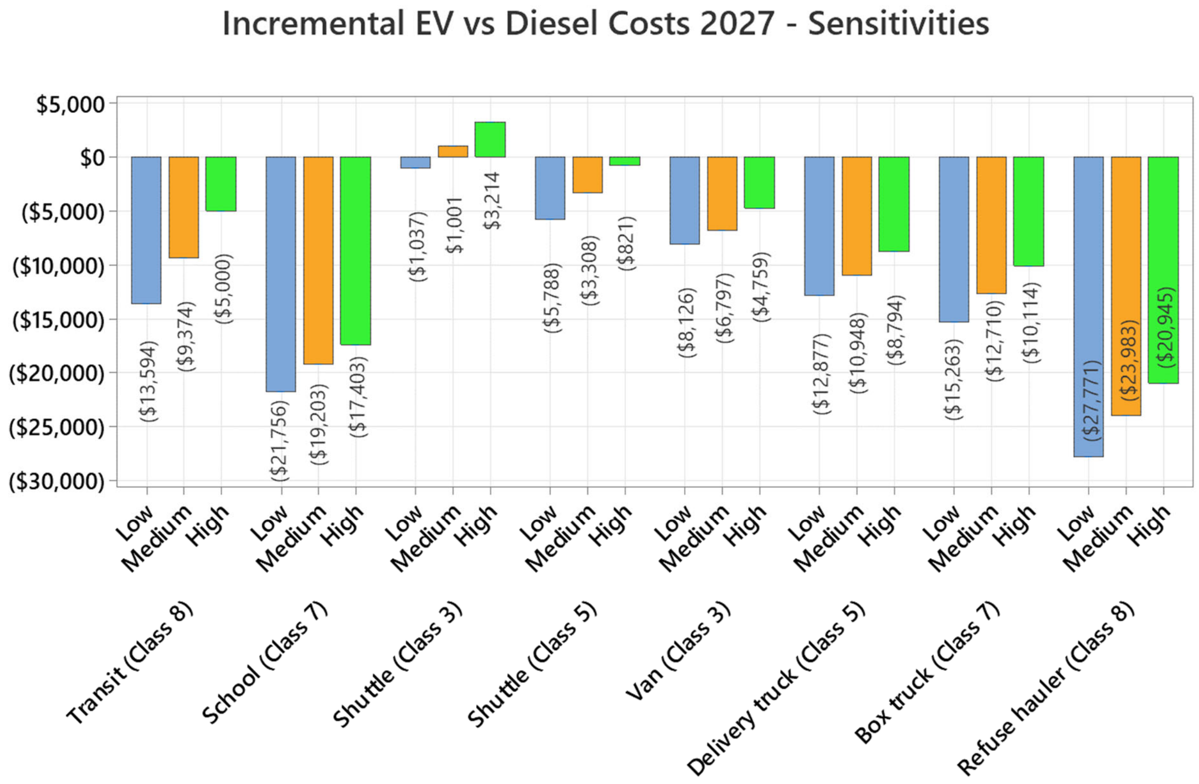


Figure 5: Incremental costs ranges after sensitivities are applied to the costs of an ICE powertrain vs an EV powertrain.

For the TCO analyses, sensitivities are more dependent on costs external to the vehicle such as fuel or energy costs, maintenance, and infrastructure choices. The best and worst-case scenarios of these factors, as well as vehicle costs, were analyzed in addition to a reference case to obtain a more complete picture of the costs associated with electric vehicle ownership. For some factors such as energy prices, a low case assumption for diesel vehicles would likely coincide with low costs for electricity for BEVs. In other cases such as vehicle costs, there is little connection between the two sets of assumptions. The low and high cases are intended to bound the operating costs of each vehicle. Figure 6 shows the results of the TCO sensitivity analysis on a cost-per-mile basis.

In both the upfront incremental costs and total cost of ownership, cost parity is achievable in all of these vehicle classes within the first three years of operation for the reference cases. Incremental costs differences in powertrain, emissions, and transmission equipment for diesel ICE vehicles compared to EVs favor EV adoption between 2024 and 2027 in nearly all cases based on the current trends and available forecasts. Because infrastructure costs are significant relative to the vehicle and operating costs in Class 3-5 shuttles, and lifetimes are shorter than other vehicles, the added expense of fast charging has an outsized effect on these TCO cases.

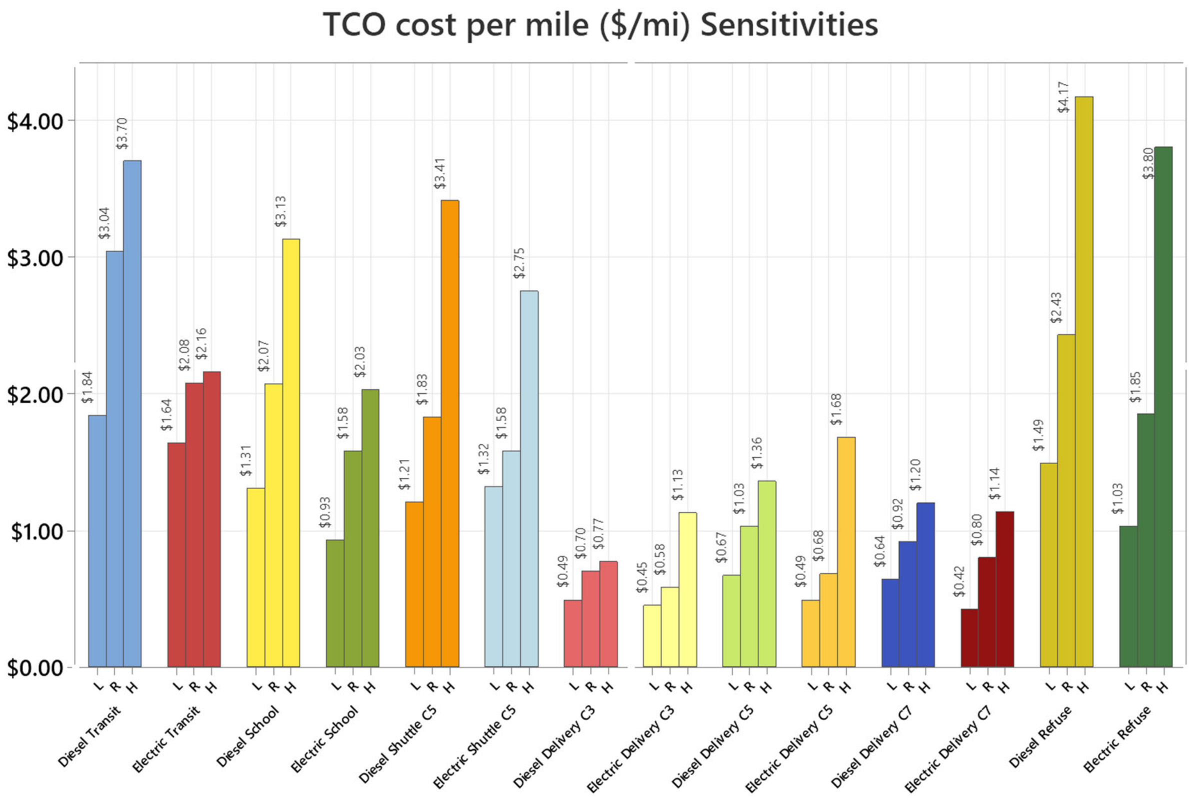


Figure 6: Sensitivities applied to each category costed for TCO per mile.

Vehicle cost is not the only consideration that goes into fleet purchase planning, as charging infrastructure will add upfront costs and operational costs which can be significant over the lifetime of the vehicle, which can be over a decade. In each TCO case studied, EVs show a cost advantage over the life of the vehicle at or near the purchase time, with savings increasing throughout the vehicle’s life. Planning and active charging management can increase these savings even more as an investment in charging is optimized across the fleet for its specific needs. The charging infrastructure cost is considered as an upfront cost for this analysis and financing of these costs is not evaluated. The impact of financing is assumed to be the same between the different types of vehicles from a fleet owner's perspective and therefore is not included. Additionally, incentives and tax rebates may also be available for the fleet owner to cover some portion of the upfront costs and weren’t considered.

There are many external benefits to EV adoption, including environmental benefits through the reduction of PM and NOx emissions, as well as the reduction in noise in congested environments. While these benefits are not included in this analysis, they may improve the case for EV adoption. Also not considered in this analysis are government-based incentives, subsidies, or policies that can offset or outright reduce the costs of EV adoption. These policies can only further drive investment in EV adoption, increasing the overall market penetration and economies of scale for EV components.

As with any developing technology, there are challenges associated with the widespread adoption of EVs. Batteries and motors currently rely on expensive and volatilely priced rare-earth metals for the permanent magnets and the battery cells. Some have argued that widespread EV adoption could strain these currently fragile supply chains and could offset the cost benefits seen in EV adoption without advancements or changes in technology pathways. Several current, emerging, and future technologies are presented that can alleviate this pressure and minimize reliance on these metals, including battery chemistries that minimize or eliminate the use of lithium, and motors that reduce or eliminate rare-earth permanent magnet use. Further work is underway developing battery production methods that increase the cycles that a battery can experience while maintaining its charge capacity. The analysis timeframe of 2027-2030 mitigates the effect of any near-term supply constraints as well as the effects of disruptive future technologies.

The categories in this study are not the only candidates viable for electrification in 2027 but were chosen as available evidence points to these MD/HD classes being the most viable. The results in this study show that broader adoption across the MD/HD market is possible and should be examined in future work.

Overall, typical worries with electric cars concern supply chains, materials, and price escalations. Assuming current availability continues and no continued development of technologies including cost reduction in EV parts, cost parity is achievable in both purchase costs and TCO. Developing technologies further drive the attractiveness of EV adoption for fleet customers, minimizing the reliance on rare-earth and expensive metals in the EV powertrain. There are no technical impediments to EV adoption in these classes with the technology available in 2021, and this will only continue to improve as technologies and production mature with the increasing adoption of EVs.

1.0 Introduction

Medium and heavy vehicles comprise less than 10% of the US vehicle fleet but account for 23% of the greenhouse gas emissions as shown in Figure 7 [2]. Since a large portion of MDHD vehicles are powered by diesel engines, they account for almost 60% of the total NOx and particulate emissions [2]. Hence electrification of the MDHD fleet will result in not only a significant reduction in greenhouse car emissions but also a marked improvement in air quality. It is important to understand the present and future (2021-2027) trajectory of electrification technologies and costs to have the right regulatory framework to accelerate the transition of the US MDHD fleet to BEVs. The transition to BEVs is not only important to mitigate the effects of climate change and improve air quality to reduce healthcare costs but also maintain the technology leadership and competitiveness of the US economy as many of the world's developed economies have announced deadlines to transition away from using fossil fuel for transportation.

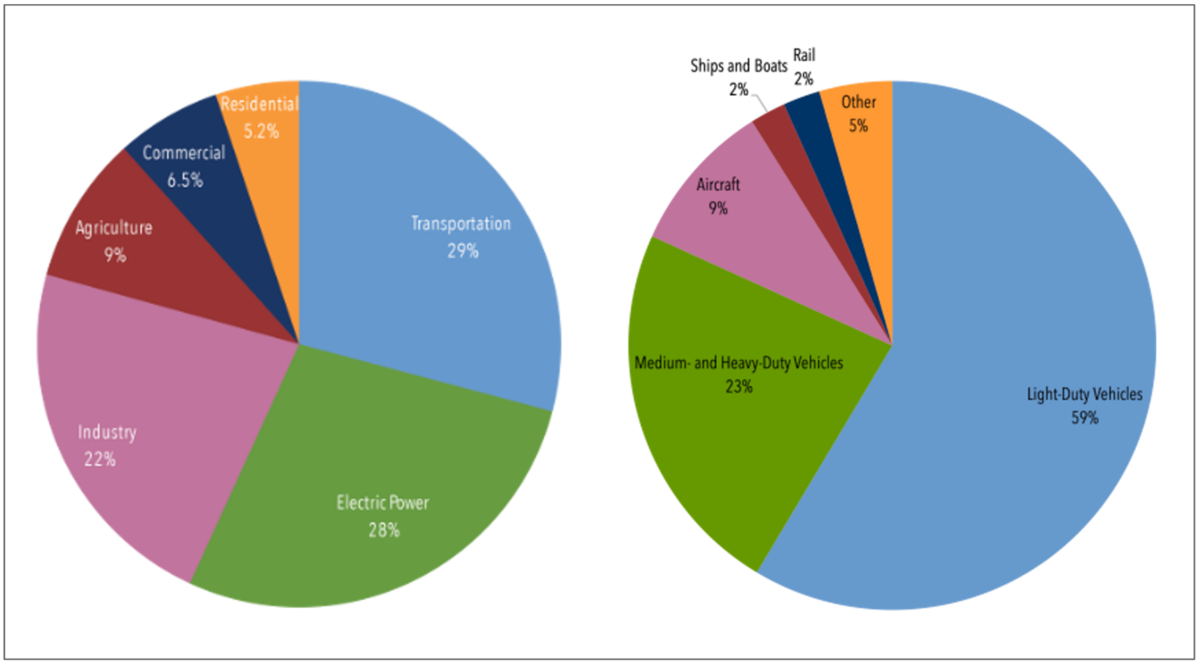


Figure 7: Factors contributing to the US total and US transportation-related CO_2 Emissions (2019 data). Source US EPA [2]

Emissions from the transportation sector contribute significantly to air pollution and the negative health effects that accompany it. More than 20,000 Americans die prematurely every year as a result of pollution from highway vehicles [3]. The health burden from vehicles in the heavy-duty categories such as trucks and buses is substantial, causing adverse health impacts in utero, in infants and children, in adults, and in the elderly. Those that live close to roads, highways, ports, distribution centers, freight depots, and other sources of truck pollution are subject to the greatest harm [4] [5] [6] [7] [8]. Additionally, NOx and PM emissions from the medium- and heavy-duty fleet are currently responsible for up to 4,550 premature deaths, 4,290 hospital visits, and 2.7 million incidents of exacerbated respiratory conditions and lost or restricted workdays annually. The monetized cost of these public health impacts from the medium- and heavy-duty fleet are estimated to exceed $53 billion annually [9] [10].

Battery prices have fallen by 88% in the last decade with cell cost per kWh falling under $100/ kWh for NMC chemistry in 2020 [11]. The increasing energy density, innovative cell form factor, and pack construction of cheaper (more than 20% when compared to NMC) and significantly more durable LFP chemistry has made it suitable for all but the highest range MDHD applications. Several motor technologies that do not use rare earth metals have matured and entered production. With the rapidly increasing manufacturing scale of electrification components (batteries, motors, power electronics) and increased automation of battery pack and motor manufacturing, the cost of electric powertrains is falling rapidly, significantly outpacing projections made as late as 2017. Unlike ICE powertrains, there can be significant sharing of components – cell modules, motors, and inverters between light-duty and MDHD applications giving significantly higher manufacturing scales and cost savings. Some of these cost savings are yet to be realized due to the manufacturing of most current MDHD applications being extremely small-scale, low automation using custom components. Given the state of technology summarized above, most of the MDHD fleet is ready for electrification.

It is also important to understand the contribution of various factors to the cost of owning and operating a BEV for different MDHD applications over the entire life of the vehicle. It is important to provide the right legislative framework and incentives to encourage not only BEV manufacture and purchase but also infrastructure development. This study quantifies the purchase price in 2021, 2024, and 2027, and the total cost of ownership ($/mile over the life of the vehicle) of representative battery electric vehicles from class 3 to 8 (listed in Table 4) purchased in 2027. An effort is made to assess the various factors (sensitivities) which will affect these costs and quantify their effects.

For every major market segment from classes 3 to 8, the paper defines a representative battery electric vehicle (Table 4) whose battery pack is sized based on vehicles usage statistics [12] and power output based on MDHD component sizing presented by Argonne National Labs [13] and specified by EDF for this work. A vehicle is divided into subsystems grouped into four categories (outlined in Figure 8) for calculating vehicle manufacturing cost: components that are only present in an ICE vehicle, components common to ICE and BEV, components that are only present in a BEV, and components that are modified when switching from an ICE to BEV architecture. All cost inputs for the analysis are derived from peer-reviewed journals, industry analysis reports, and teardown studies. Increase in cost of a diesel ICE powertrain from 2021 to 2027 due to fuel economy improvements required to meet the Phase II greenhouse gas rule and the 2027 California ARB low NOx rule are taken from the regulatory impact analyses [14] [15]. For calculation of the TCO, purchase price, fueling infrastructure cost (charger/ fuel depot operation), energy costs (diesel/ electricity), and maintenance are considered. The TCO of a BEV is compared to an ICE purchased in 2027 over the life of the vehicle using a discount rate of 3%.

Table 4: Representative vehicles used for TCO analysis

Market Segment	Weight Class	Battery Capacity (kW-h)
Transit Bus	Class 8	400
School Bus	Class 7	60
Shuttle Bus	Class 3-5	200
Delivery and Service Van, Box and Stake Truck	Class 3	100
Short Haul Delivery, Service, Box, and Stake Truck	Class 6-7	150
Short Haul Delivery and Service Van, Box and Stake Truck	Class 4-5	100
Refuse Hauler	Class 8	200

These categories represent vehicles that are typically operated along fixed routes and return to a home base daily. They are typically operated by fleet owners with the infrastructure to manage maintenance and charging. These features make these categories logical targets for electrification.

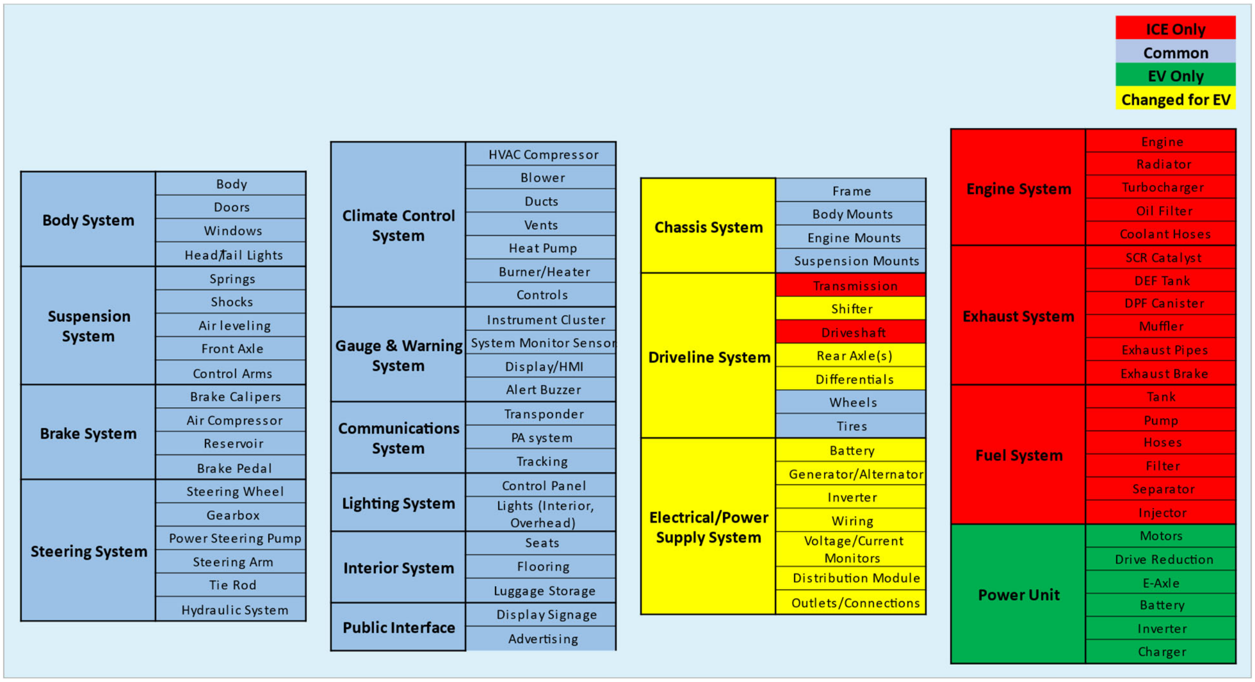


Figure 8: Comparison of the BOM for an ICE vehicle and BEV used for new vehicle cost analysis

The report summarizes the present state of the art and future trajectory of technology in battery, traction motor, and power electronics. The technology review is guided by the following questions – Are there technologies that will:

1) Significantly reduce the direct manufacturing cost and total cost of ownership of battery electric vehicles from 2021 to 2027 and beyond?
2) Mitigate increase in commodity prices or supply chain issues due to geopolitical or other factors of raw materials (like rare earth metals, copper, Cobalt, etc.) that might negatively affect the cost of a BEV derailing electrification of the US MDHD fleet?

The study found that the purchase price parity for almost all classes and vehicle use cases analyzed will be reached between 2024 and 2027. The only exception is class 3 delivery vans and shuttle busses that have low-cost gasoline or diesel engines that are based on light-duty applications. Due to the substantially lower fuel and maintenance cost of BEVs, the TCO advantage of the BEV widens over the life of the vehicle. For battery-electric vehicles, charging infrastructure represents a significant upfront cost that is dependent on fleet size, vehicle use patterns (uptime and charging time available, miles traveled per day), sharing of charging infrastructure between different fleets, etc. There are several technologies in the battery, traction motor, power electronics that can significantly reduce the cost of an electric vehicle from 2021 to 2027. There are also several alternative battery and motor technologies that the industry can take in the event of an increase in the commodity price of raw materials or supply issues due to geopolitical or other factors and continue its trajectory of reducing the cost of electrification.

2.0 Methodology

2.1 ICE Components

To determine the costs of the components that would be replaced or not present on an EV, a list of components related to an ICE vehicle was created and the parts to be eliminated were identified as seen in Figure 8. Of these, the primary drivers of cost were found to be the engine, transmission, and aftertreatment systems. Each of these is costed independently based on the vehicle segment, as well as required improvements for each to meet anticipated regulations in 2027. The engine is the prime mover of the vehicle and is the primary driver of fuel economy, power output, and emissions. Emissions control for the engine may consist of waste heat recovery devices, exhaust gas recirculation (EGR), and various combustion control systems built into the injectors, pistons, turbocharger, or otherwise.

The exhaust stream of the engine is routed to the aftertreatment system where further emissions control or cleanup occurs. This system commonly consists of a diesel particulate filter (DPF), selective catalytic reduction catalyst (SCR), and diesel oxidation catalyst (DOC). The aftertreatment system directly acts on emissions components that can cause pollution, such as PM, NOx, CO, and unburnt hydrocarbons.

The rotational power from the engine is sent to the transmission, which adjusts gear ratios for the required speed and torque of the vehicle. Transmissions may be automatic or manual, or an automated-manual with the number of gear ratios ranging from 6 to 18, depending on the application. Proper calibration and selection of forward ratios can improve fuel mileage in an ICE vehicle. This section examines the base technologies and advancements required to meet emissions regulations for the 2024 and 2027 GHG regulations, as well as the 2027 California Low NOx requirements.

The base costs for the engine portion of the delete package are derived from power levels as shown in Figure 2.2-4 of the 2019 Argonne National Labs report, copied in Figure 9 [16]. This figure, adjusted to reflect the value in 2021 USD, is used as the base engine and aftertreatment costs in the costing exercises. The base engine hardware is considered mostly mature and no significant cost reduction through optimization or improvements are anticipated. Most of the cost increments are for the engines to meet emissions standards put forward by EPA and ARB.

To achieve anticipated emissions standards, various engine systems are expected to change. These include overall engine developments such as downsizing, waste heat reduction, and down speeding. Inside the engine, systems such as injectors, piston shapes, and valves may increase in complexity to achieve higher efficiency. Advanced exhaust gas recirculation systems, turbocharging, and engine control systems will also help achieve lower emissions and higher efficiency. The tables below outline the various parts and systems that will increase cost in a base heavy-duty engine in 2027 [17] [18] [19] [20] [21].

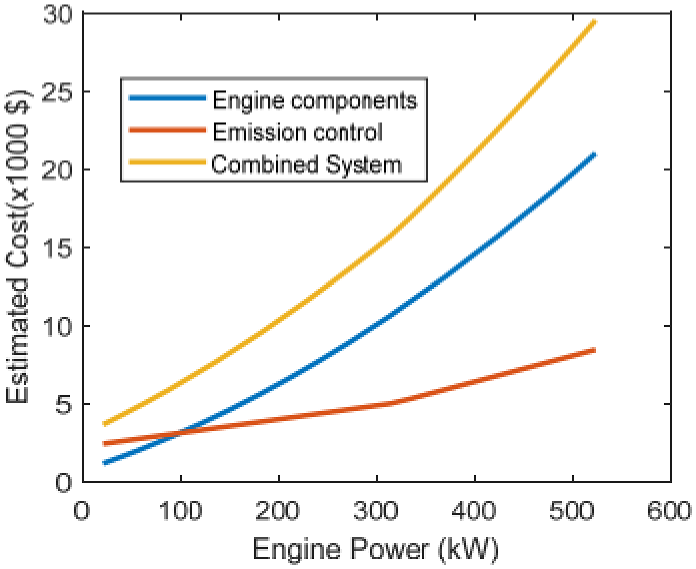


Figure 9: Estimated cost of diesel systems as a function of engine power, Figure 2.2-4 [16]

Table 5, Table 6, and Table 7 show the engine costs incurred for each regulation for the various engines examined.

Table 5: Engine costs incurred to meet 2024 and 2027 GHG rules for diesel engines in classes 3-6

Engine Component	2024 Cost: GHG Phase 1	2027 Cost: GHG Phase 2
	2021$	2021$
Valve Actuation	$188.78	$203.91
Cylinder Head	$11.86	$11.86
Turbocharger	$18.88	$20.15
EGR Cooler	$3.54	$3.54
Water Pump	$95.57	$100.77
Oil Pump	$4.72	$4.72
Fuel Pump	$4.72	$4.72
Fuel Rail	$13.04	$13.04
Fuel Injector	$15.41	$16.60
Piston	$2.36	$3.56
Valve Train	$115.00	$120.92
Model Based Controls	$37.76	$48.61
Incremental Costs per Regulation	**$511.64**	**$40.76**

Table 6: Engine costs incurred to meet 2024 and 2027 GHG rules for diesel engines in classes 7-8

Engine Component	2024 Cost: GHG Phase 1	2027 Cost: GHG Phase 2
	2021$	2021$
Valve Actuation	$188.78	$202.94
Cylinder Head	$7.08	$7.08
Turbocharger	$18.88	$20.06
EGR Cooler	$3.54	$3.54
Water Pump	$95.57	$100.29
Oil Pump	$4.72	$4.72
Fuel Pump	$4.72	$4.72
Fuel Rail	$10.62	$10.62
Fuel Injector	$11.80	$11.80
Piston	$2.36	$3.54
Valve Train	$86.13	$90.85
Model Based Controls	$37.76	$48.37
Incremental Costs per Regulation	**$471.95**	**$36.58**

Table 7: Engine costs incurred to meet 2027 Low NOx rules.

Engine Size	Cost to meet 2027 Low NOx
9L Heavy Duty (Class 8 Engines)	$2,200.97
Up to 7L Heavy Duty (All others)	$1,419.45

These costs were added to the base engine and transmission cost taken from Figure 9 to determine the reference cost of a diesel powertrain in 2021, 2024, and 2027.

2.2 Aftertreatment

Aftertreatment systems serve to remove emissions and pollutants from the engine's exhaust stream. Three primary aftertreatment systems are in use on heavy-duty diesel engines today: diesel particulate filter (DPF), selective catalytic reduction (SCR), and diesel oxidation catalyst (DOC). These serve to remove particulate matter (PM), NOx, CO, and hydrocarbons from the exhaust stream. Aftertreatment systems can effectively reduce emissions of non-CO2 pollutants below regulatory thresholds and will be a source of increased costs on ICE vehicles as emissions standards tighten.

Improvements to these systems may take the form of integration, backpressure reduction by reducing the wall thickness of DPF, reduced NOx emissions by improving SCR cell density, and reduced urea consumption during transients. These improvements, coupled with the engine improvements discussed previously, can help improve efficiency and emissions performance and contribute to the costs listed. For the costing exercise, Figure 9 was used for the base aftertreatment costs, with the additional costs in Table 8 added for the 2024 and 2027 model year costs.

Table 8: Aftertreatment costs incurred to meet each emissions regulation target compared to 2021 base aftertreatment.

Aftertreatment Component	2024 Cost: GHG Phase 1	2027 Cost: GHG Phase 2	2027 Cost: CARB
	2021$	**2021$**	**2021$**
SCR, Dosing, DPF - Vocational HHD	$16.52	$17.70	
Low NOx Aftertreatment Improvements			$2,262.35
Incremental Costs per Regulation	**$16.52**	**$1.18**	**$2,262.35**

2.3 Transmissions

Transmissions help maintain efficiency by keeping the engine in its most efficient operating range at all speeds and loads. Optimization of the number of forward speeds, as well as the drive ratio, can increase transmission cost. Automated manual and fully automatic transmissions can implement advanced controls to optimize efficiency better than a driver can with a manual transmission. Other implementations such as a dual-clutch transmission (DCT) or automated manual transmission can increase shift speed and reduce losses through a torque converter, improving efficiencies. The costs of the base transmission as well as advancements to reduce friction and optimize the transmission system for better efficiency and reduced emissions are shown in Table 9.

Table 9: Transmission costs incurred to meet each emissions regulation target compared to 2021 base transmission [22] [23] [24].

Transmission Component	2024 Cost: GHG Phase 1	2027 Cost: GHG Phase 2	2027 Cost: CARB
	2021$	**2021$**	**2021$**
Base Cost – Class 7-8 Heavy Duty	$15,628.00		
Base Cost – School Bus	$7,676.82		
Base Cost – Shuttle and Class 3-5	$2,600.00		
Improvements for Emissions (Class 7-8)		$2,200.72	

2.4 Hybridization

Hybridization is a form of partial electrification where some energy is provided by a system other than the consumable fuel, such as a rechargeable battery. There are multiple levels of hybridization that can be implemented, from mild to full hybridization. All energy supplementation by hybridization can reduce fuel consumption, directly reducing CO2 emissions from the vehicle. Hybridization is not required to meet more stringent emissions and fuel economy regulations, but it is an option that can save fuel and be attractive to fleet operators. Thus, it is considered as a sensitivity to the base engine costs in this work.

Mild hybridization may take the form of a belt-driven starter-generator that shuts the engine off when not needed, and starts the engine when power is required again. Some engine power may be supplemented by the ISG in this situation, but very minimal power is available from the motor and battery.

Emissions and fuel consumption are fairly low for a diesel engine at idle, but mild hybridization can still offer some improvement.

More expensive and fully hybridized drivetrains contain a larger, more powerful electric motor integrated into the drivetrain, typically as part of the transmission. This motor-generator unit can provide launch assist torque, fully electric operation, or regenerative braking for power generation. These full hybrid systems also require a battery for storing the energy harvested from the system and providing sufficient range for some full-electric operation. To convert the battery power to useable power by the motor, an inverter is required as well. Full hybrid drivetrains are complex and cost-adding systems that can greatly improve fuel economy, reduce carbon dioxide emissions, and improve performance.

Regenerative braking in a hybrid reduces the wear on brakes, by recovering mechanical energy through the motor-generator and converting it to electrical energy for the battery. This process eliminates the mechanical energy waste that turns vehicle kinetic energy into heat and reduces stress on many vehicle components. This in turn increases fuel efficiency and can reduce maintenance expenses to a degree.

Two sensitivities were applied to the base cost of an ICE drivetrain: mild hybridization and full hybridization. These two levels were selected as sensitivities as they represent significant investments in equipment on a vehicle to meet more stringent fuel economy and emissions standards compared to the minor variations of some components of an engine or aftertreatment system. Variations in the full hybridization cost can come from the power level of the motor(s) and the battery capacity selected. For this study, electrification power was set at 50% of ICE power. While this may vary depending on the application, motor costs are a lower contributor than battery costs and have a minor effect on the incremental cost of hybridization. Hybrid battery packs were sized to be 10% of the specified size for the full electric vehicle. Mild hybridization creates a moderate cost ICE package, and full hybridization creates the high-cost ICE package. It is worth noting that the advancement in electrification also reduces the future hybridization costs for ICE-based powertrains. Costs of the motor and battery are the same as used for electrification costs, discussed in the next section.

2.5 Electrification Costs

Figure 10 illustrates the main components of an electric vehicle and Table 10 summarizes the electrification costs used in the study.

The common components required to achieve vehicle electrification include the traction motor, inverter, battery (typically in pack form), and other power electronics such as an on-board charger and the DC-DC converter. In addition, a thermal management system is required to provide cooling to the components, similar to the thermal management system of an ICE vehicle.

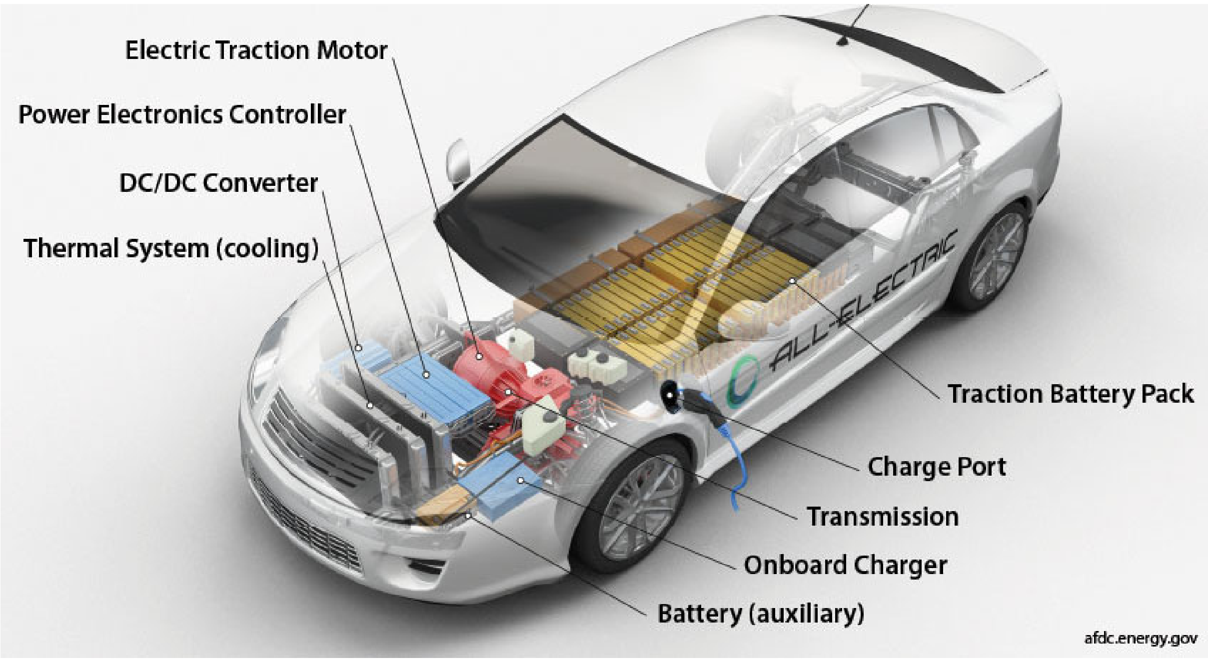


Figure 10: Components of a Battery Electric Vehicle (Source NREL)

The traction motor is typically an induction or permanent-magnet based AC motor operating at high voltages and frequencies for torque and speed control. The motor is the prime mover of the vehicle, and EVs may contain 1-4 of these motors depending on the drivetrain layout. Some vehicles utilize a single motor for driving a single axle, while others may employ one motor per axle or wheel or a combination of layouts.

To store the energy necessary for driving the vehicle, EVs utilize a battery pack. The battery pack consists of many small battery cells connected in both series and parallel to create a battery of the necessary voltage and capacity for the vehicle's requirements. Batteries may use a variety of chemistries but typically rely on Lithium-based formulations, though research is underway on other chemistries. NMC and LFP cathode chemistries are considered for this report. Several advanced battery technologies discussed in Section 3.1 are not used for projected costs, although these advanced battery technologies have the potential to significantly reduce cell and pack costs. Hence the costs used in this study are conservative.

The inverter takes the DC power output from the battery and turns it into AC power for the motor, at a specific frequency and amplitude required for the driver's requested torque and speed. The inverter controls the output of the motor and subsequently the vehicle's behavior. Under regenerative braking, the inverter handles electrical power flow in the opposite direction, taking power from the vehicle's traction motor and sending it back to the battery pack to recover some electrical energy from the vehicle's kinetic energy.

The power electronics of the vehicle provide auxiliary functions, such as a DC-DC converter for converting the high battery voltage to the common 12V used by many auxiliary vehicle systems. The onboard charger takes the AC power from a charger and converts it to usable DC power for charging the battery.

In the incremental "add cost" case, three situations were analyzed for electrification costs. A high-cost electrification package includes an NMC battery chemistry and heavy-duty specific motors. The lowest cost option consists of LFP battery chemistry and light-duty-based motors. A moderate-cost option was created that includes HD motors and LFP batteries. All cases used to create the electrification incremental costs assume an onboard charger sized for a 4-hour depot charge for the battery capacity in each class. The assumptions used in TCO are discussed in Section 2.6.3.

Some production medium and heavy-duty vehicles employ a single ratio reduction gearbox while others employ a two-speed gearbox. Some suppliers like Eaton are working on multispeed (4 speed) transmission for medium and heavy-duty vehicles. Roush believes that in the future most MDHD BEVs will employ a single-speed gearbox in the interest of cost, complexity, and reliability. In this report, only a single-speed gearbox was considered in EV drivetrains.

Table 10 summarizes the higher and lower unit cost of electrification components in 2021, 2024, and 2027.

Table 10: Summary Table of Electrification Component Cost

Component	Decription/ Assumption	Unit Cost ($/kW, $/kWh)		
		2021	2024	2027
Batteries	High – NMC	$123.40	$90.20	$68.40
	Low – Lithium Iron Phosphate (LFP)	$107.45	$78.54	$59.56
Motor	High - Low volume low speed high torque (ANL)	$18.35	$8.64	$6.48
	Low - Mass produced, light duty based Munro and associates teardown study 2020	$4.02	$3.62	$3.25
Inverter	Based on 2020 Model Y (SiC MOSFET) Munro and associates teardown study 2020	$3.65	$3.28	$2.96
DC-DC Converter	Lutsey & Nicholas 2019 [25]	$55.94	$50.35	$45.31
On board Charger	Lustey & Nicholas 2019 [25]	$55.94	$50.35	$45.31

2.6 Total Cost of Ownership

The total cost of ownership analysis in this study was conducted to account for all of the financial aspects of ownership of an ICE or EV. Only tangible financial aspects of ownership related directly to the vehicle were considered: purchase price, maintenance, energy, and infrastructure. Costs not included were staffing and labor, scrap or resale, taxes, grants, subsidies, or intangible benefits such as healthcare costs or environmental costs related to emissions or fuels. Staffing and labor costs, scrappage, and resale are not expected to change significantly between the two types of vehicles. Subsidies were not included to ascertain the costs are derived from a non-supported framework. As a consequence, the results of our analysis show that subsidies are not an essential portion of cost reduction or EV favorability in the 2027-2030 timeframe. The inclusion of subsidies for the consumer may accelerate the adoption and penetration of EVs but is not necessary for achieving cost parity.

Three cases were developed for TCO: Reference, Low, and High. The reference case provides approximately a median prediction for all costs associated with the vehicle with a 2027 purchase timeframe. For the ICE powertrain, this includes mild hybridization on top of the base diesel, while the EV powertrain assumes heavy-duty specific motors and an LFP battery pack. Literature sources were chosen for vehicle mileage, lifespan, energy costs, charger costs, and maintenance. These provide a middle-of-the-road approach to viewing TCO and should approximate expected costs in the future for vehicles.

The Low and High cases attempt to set bounds on the TCO by considering the best-case scenario and worst-case scenario for costs, respectively. The Low scenario assumes the lowest cost of energy, lowest purchase price, lowest vehicle mileage, lowest maintenance costs, highest fuel economy, and low-cost charging infrastructure in the EV cases. The High scenario assumes the opposite: High purchase price, high vehicle mileage, high maintenance, and energy costs, and expensive DC chargers. While it is unlikely that all of these situations combine to meet the high and low-cost scenarios, they do serve as bounds on the TCO analysis.

2.6.1 Common TCO Considerations

Common to both vehicle types are vehicle lifespan, daily mileage, and annual mileage. These were held constant between ICE and EV calculations to provide a direct comparison of the overall costs as well as costs per mile. The reference, low, and high lifespans and mileages used in the analysis are shown in Table 11 [26] [27] [28] [29] [15] [30] [31] [32] [33].

Table 11: Vehicle lifespans used in the TCO analysis.

Vehicle Lifetimes						
Vehicle Type	**Low Mileage**	**Reference Mileage**	**High Mileage**	**Low Years**	**Reference Years**	**High Years**
Transit – Class 8	331,200	500,000	652,836	12	12	12
School Bus – Class 7	221,120	221,120	425,000	10	10	10
Shuttle – Class 5	100,000	200,000	200,000	7	7	7
Delivery Van – Class 3	124,350	136,785	231,000	10	11	11
Delivery – Class 5	124,350	124,350	148,000	10	10	10
Delivery – Class 7	250,000	285,710	360,000	10	10	10
Refuse – Class 8	175,000	250,000	300,000	12	10	7

For the diesel vehicle purchase price, literature sources on public fleet expenditures on buses and shuttles were utilized, as well as retail and data published by CARB and other agencies [34] [35]. Low, moderate, and high costs were selected from the sources found for vehicle costs. Because current EVs are sold at a premium due to their low volumes and high technology costs, the current difference was ignored in this cost study. Manufacturers such as Proterra and BYD expect the base cost of a complete ICE bus to remain constant in 2021 dollars, so this was the assumption for vehicle cost in 2027 for all classes [36]. To determine the incremental costs, the costs of ICE-specific components were determined and subtracted from this price, while the EV component costs were added. The cost difference from the base vehicle price was calculated based on a standard set of options for each scenario. The reference case TCO assumes a mild-hybrid diesel with all improvements needed to reach 2027 emissions standards, an LFP battery EV with heavy-duty specific motors & an on-board charger sized for a 4-hour charge from a depot charger. The low-cost TCO assumes a base diesel ICE vehicle (with all improvements for 2027) and an EV with LFP batteries, light-duty-based motors, and a charging system sized for a 6-hour charge. The high-cost TCO assumes a fully hybridized ICE vehicle compared to an EV with NMC batteries, heavy-duty specific motors, and a DC fast charger shared between three vehicles. To determine the vehicle cost difference between the two, the base vehicle cost was used as a starting point. The costs from the ICE delete package outlined in Sections 2.1 to 2.4 are subtracted from this value, based on the options selected for the given scenario. The electrification add package costs are calculated based on Section 2.5 and added to the vehicle cost after subtracting the powertrain costs.

2.6.2 ICE Vehicle TCO Calculations

Costing elements specific to ICE vehicles include fuel costs, fueling infrastructure, and maintenance. Fuel costs are driven by both the projected fuel efficiency of the vehicle being studied and the projected fuel costs in the 2027 timeframe. The US Energy Information Administration Annual Energy Outlook 2021 was used for fuel costs projections in 2027. A reference, low, and high cost were chosen from the projections seen in Figure 11. It is important to note that diesel fuel costs continue to increase faster than the AEO predicted in 2021, making the TCO analysis more conservative than originally expected.

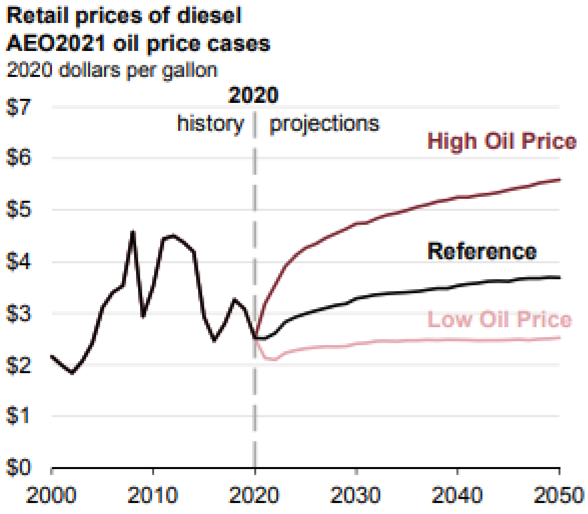


Figure 11: Projected diesel costs per gallon used for the TCO analysis. [37]

Projected fuel economy was sourced from literature sources ([26] [27] [28] [35]) or manufacturer references on the type of vehicle listed, as well as the level of hybridization used in the vehicle. Dividing cost per gallon by miles per gallon provides a $/mi value used in the TCO calculation.

Fueling infrastructure is listed in the literature as a fleet fueling depot and is considered to be $0.02 per gallon of diesel. These would be costs associated with a fleet that operates its own on-site fueling station, though commercial fueling stations are another option that does not incur this cost.

Maintenance cost can be found for each class in various literature sources and considers the cost of vehicle repairs, oil changes, tire changes, brakes, transmission, body, and other general maintenance that may be required throughout the vehicle's life [26] [35]. This is assessed in the TCO on a per-mile basis.

In the case of the class 7 school and class 8 transit bus applications, a midlife refresh may be required on the engine and transmission [38]. This cost is set to the engine for the reference case, and the full cost of an engine and transmission for the high-cost TCO case. No refresh is costed for the low-cost TCO case.

2.6.3 EV TCO Calculations

Electric vehicles utilize unique components compared to ICE vehicles and accrue costs differently than their ICE counterparts. Maintenance costs are still present, but typically lower than ICE vehicles due to the lower complexity and fewer consumables such as engine oil and filters [34] [29]. Additional consumables such as brake pads and rotors last longer due to regenerative braking performed by the drive motors. In other cases, a straight reduction of $0.19 per mile was taken from the diesel maintenance costs [29], [34]. The individual costs for each vehicle class are detailed in the TCO section of the results in Section 4.0.

Energy costs consist of the electricity for charging the bus batteries, typically charged on a per-kWh basis. The Energy Information Administration outlook was used for projected energy prices [37]. By assuming charging at off-peak hours, utility-specific demand charges for high power consumption were not considered in this analysis. These charges are not universal in their application or amount and largely apply to the use of DC fast chargers during daytime hours. In these cases, electricity costs could be higher than presented in this analysis.

Infrastructure is a significant cost when building an EV fleet, as chargers need to be purchased and installed specifically to the use case of the fleet's operation. For the reference case analysis, depot chargers were chosen to allow the vehicle to charge within 4 hours at a depot overnight. This assumption would enable future growth of the fleet with managed charging, allowing two buses to use a single charger in an 8-hour overnight while permitting sufficient flexibility in fleet operation. For this study, however, the reference case assumes a single charger per bus as fleets moving to EVs may not have optimized schedules and charging from the outset, making these assumptions conservative. Charger costs were sourced from various literature sources for the different charger levels. [35] [39]

For the low and high cases, different chargers and methods were selected. The low case increased charging time to 6 hours, reducing the cost of the charger and installation, as well as the onboard charger equipment installed in the vehicle. The high case assumed a direct current fast charger (DCFC) was purchased for the fleet, and that one charger could be split across three buses. Some literature sources note that a single DCFC can support up to 8 buses, but this requires precise optimization and placement of the chargers, which may not be practical for all fleets. For this study, 3 vehicles per DC charger were assumed in the high-cost cases for all vehicle segments. This allows room for future optimization of a fleet, but may more realistically reflect the initial outlay of a fleet looking to adopt DC fast charging. Due to the high costs of DCFC equipment, instances, where more vehicles utilize the same charger, will reduce upfront and total costs, as the high DCFC costs are amortized over more vehicles. An instance where this may be useful is the case of a transit bus fleet with a large central station where many routes converge, allowing buses to charge at a common point.

In the case of the class 7 school and class 8 transit bus applications, a midlife refresh is applicable as in the ICE versions. These costs include a refresh of the motor and inverter and a battery replacement. In these cases, the midlife refresh is considered to be only the cost of the battery in the reference case, while the high case considers the battery, inverter, and motor to be replaced. No midlife refresh is considered in the low-cost cases [38].

2.6.4 Calculations

Costs were input to a spreadsheet that captures all of the items listed in previous sections that contribute to the total cost of ownership. Lifetime mileages and lifespans were broken down into an annual mileage used to calculate the yearly cost of the energy, maintenance, and refueling infrastructure. Vehicle purchase costs and charging infrastructure costs were assumed to be incurred in year 1 at the time of purchase.

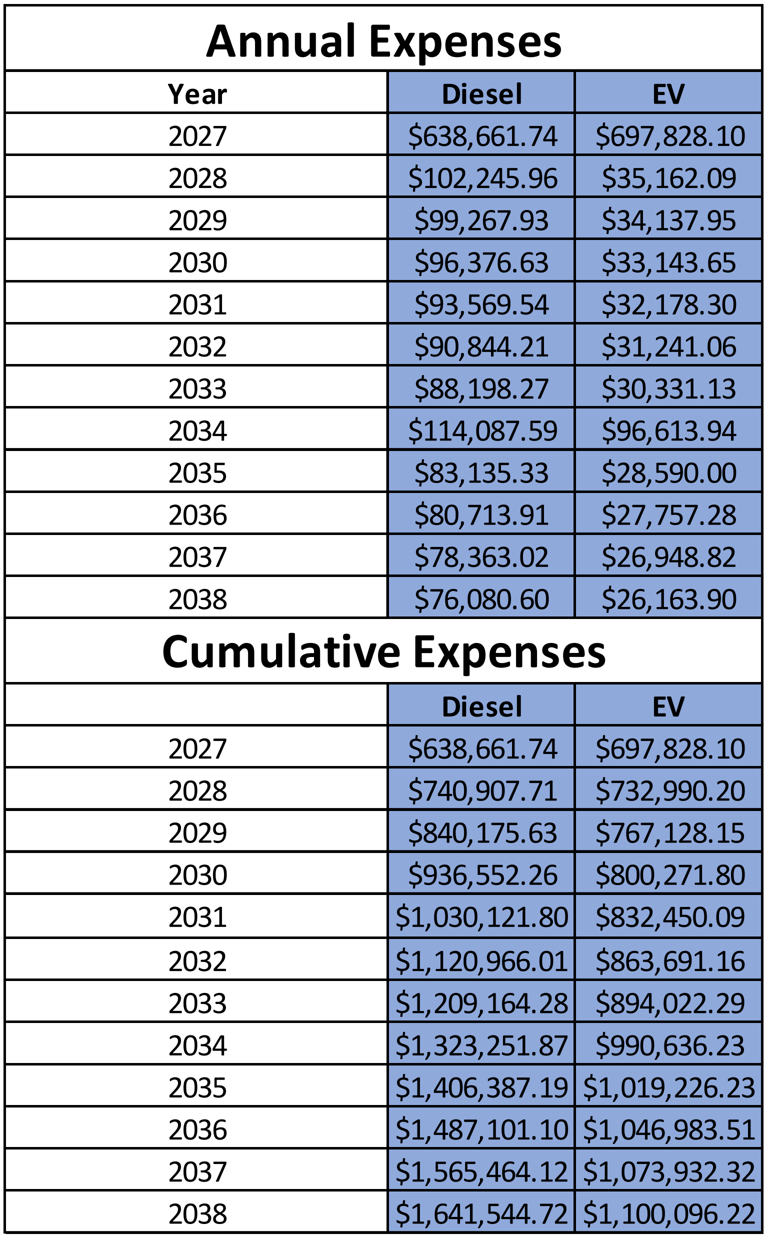
With both upfront and annual costs calculated, the annual costs for each category were subjected to a 3% discount rate following the year of purchase to account for the present values of future cash flows, a value utilized by NREL when examining costs for energy-related projects [40]. Fuel costs were held constant across the calculation period but can vary significantly and unpredictably.

Costs are calculated and presented in a table displaying cumulative (discounted) TCO, as well as cost per mile for each category shown in Figure 12 as an example. Also shown is the year at which cost parity is reached, defined as the year that cumulative costs of an EV are less than or equal to the ICE version.

	Diesel	**Electric**
Cumulative TCO	$1,641,544.72	$1,100,096.22
TCO Per Mile	$3.28	$2.20
Vehicle Cost Per Mile	$1.14	$1.23
Energy Cost Per Mile	$0.91	$0.22
Infrastructure Cost Per Mile	$0.004	$0.26
Maintenance Cost Per Mile	$1.46	$0.61
Year Parity Reached	2028	

Figure 12: Example output of cumulative TCO and costs per mile from the costing exercise (note: not a real scenario presented in this report).

Costs for each year of expected vehicle life are also calculated and output as well to identify the up-front and recurring costs of ownership of both a Diesel and ICE vehicle. These are shown along with the cumulative expenses to date for each year of vehicle ownership, which is also plotted in a line chart showing the crossover of EV costs with ICE costs. Example outputs from the costing spreadsheet are shown in Figure 13. Full vehicle and charger costs are included in the first year (up front), as the infrastructure must be purchased to operate the fleet. Financing strategies and amortization are possible but are not considered here.



Annual Expenses

Year	Diesel	EV
2027	$638,661.74	$697,828.10
2028	$102,245.96	$35,162.09
2029	$99,267.93	$34,137.95
2030	$96,376.63	$33,143.65
2031	$93,569.54	$32,178.30
2032	$90,844.21	$31,241.06
2033	$88,198.27	$30,331.13
2034	$114,087.59	$96,613.94
2035	$83,135.33	$28,590.00
2036	$80,713.91	$27,757.28
2037	$78,363.02	$26,948.82
2038	$76,080.60	$26,163.90

Cumulative Expenses

	Diesel	EV
2027	$638,661.74	$697,828.10
2028	$740,907.71	$732,990.20
2029	$840,175.63	$767,128.15
2030	$936,552.26	$800,271.80
2031	$1,030,121.80	$832,450.09
2032	$1,120,966.01	$863,691.16
2033	$1,209,164.28	$894,022.29
2034	$1,323,251.87	$990,636.23
2035	$1,406,387.19	$1,019,226.23
2036	$1,487,101.10	$1,046,983.51
2037	$1,565,464.12	$1,073,932.32
2038	$1,641,544.72	$1,100,096.22

Figure 13: Example outputs for annual and cumulative costs from the costing exercise.

3.0 Electrification Technology Review

This section provides an overview of the present state of the art and future trajectory of technology in battery, traction motor, and power electronics. The technology review is guided by the following:

1) Technologies that can significantly reduce the direct manufacturing cost and total cost of ownership of MDHD battery electric vehicles from 2021 to 2027 and beyond.
2) Technologies that can mitigate increases in commodity prices or supply constraints due to geopolitical or other factors of raw materials (like rare earth metals, copper, Cobalt, etc.) that might negatively affect the cost of a BEV and increase the cost of electrification.

3.1 Batteries

The three principal criteria that can be used to evaluate battery technologies for MDHD application are

1. Cost ($/kWh) of the battery pack – The cost of the battery pack forms a significant portion (≈80%) of the cost of an electric powertrain (discussed in detail in Section 3.1). It is by far the most important factor determining the pace of adoption of BEVs in the MDHD segment.
2. Energy Density – The two metrics used to measure energy density are the gravimetric energy density measured in Wh/Kg and the volumetric energy density measured in Wh/liter. For light-duty vehicles, the space for packaging a battery pack is at a premium, and hence the volumetric energy density is more important. MD and HD vehicles have a lot more space to package the battery pack making the volumetric energy density less important. MDHD vehicles are classified according to their gross vehicle weight and a heavy battery pack would result in a vehicle that falls into a higher weight class or can carry less cargo for the same vehicle weight class. Also, increased vehicle weight will result in a higher energy consumption per mile. This is a significant problem only for vehicles such as electric semi-trucks that have a heavy payload and require a long driving range per charge. For all applications studied in this report, the energy density of batteries currently in production is sufficient to meet the vehicle's operational needs.
3. Cycle life - MDHD vehicles are on the roads for longer and many cover significantly longer distances when compared to their light-duty counterparts. An extreme use case is a class 8 Semi-truck that can be on the road for 15 years and cover 1.5 million miles [41] with two engine rebuilds. There are battery technologies today that can last more than 5000-7000 cycles enabling an MDHD vehicle to last over a million miles (assuming a range of 200 miles per charge). High-cycle life batteries that can be charged at a higher rate (along with the development of charging infrastructure comprising fast DC chargers) will result in BEVs that have a smaller battery pack resulting in them being cheaper, lighter, and more efficient (Wh of energy consumed per mile).

3.1.1 Battery Costs

Figure 14 shows the present and future battery cost projections made in 2020-2021. The consensus is that battery cell costs are less than $100 a kWh for NMC and NCA cells. LFP chemistry is more than 20% cheaper when compared to the NMC and NCA. Most studies predict a 20-30% reduction in battery cell cost in the next two to three years. Figure 15 gives a compilation of battery pack cost projections made in 2015-2019. Comparing values in Figure 14 and Figure 15, it is evident that the battery costs are falling faster than projections made 4-5 years back. This is due to the rapid pace of innovation and the inability to accurately predict the timeline to volume production and cost implications of

- New/ improved battery chemistries
- Breakthrough manufacturing process improvements (example: dry battery electrode)
- Improvements in cell and pack construction (tabless anode, new in cell factor, and cell to pack – example BYD blade battery pack)
- The rapid adoption of BEVs and grid-scale battery storage leading to considerably higher economies of scale.

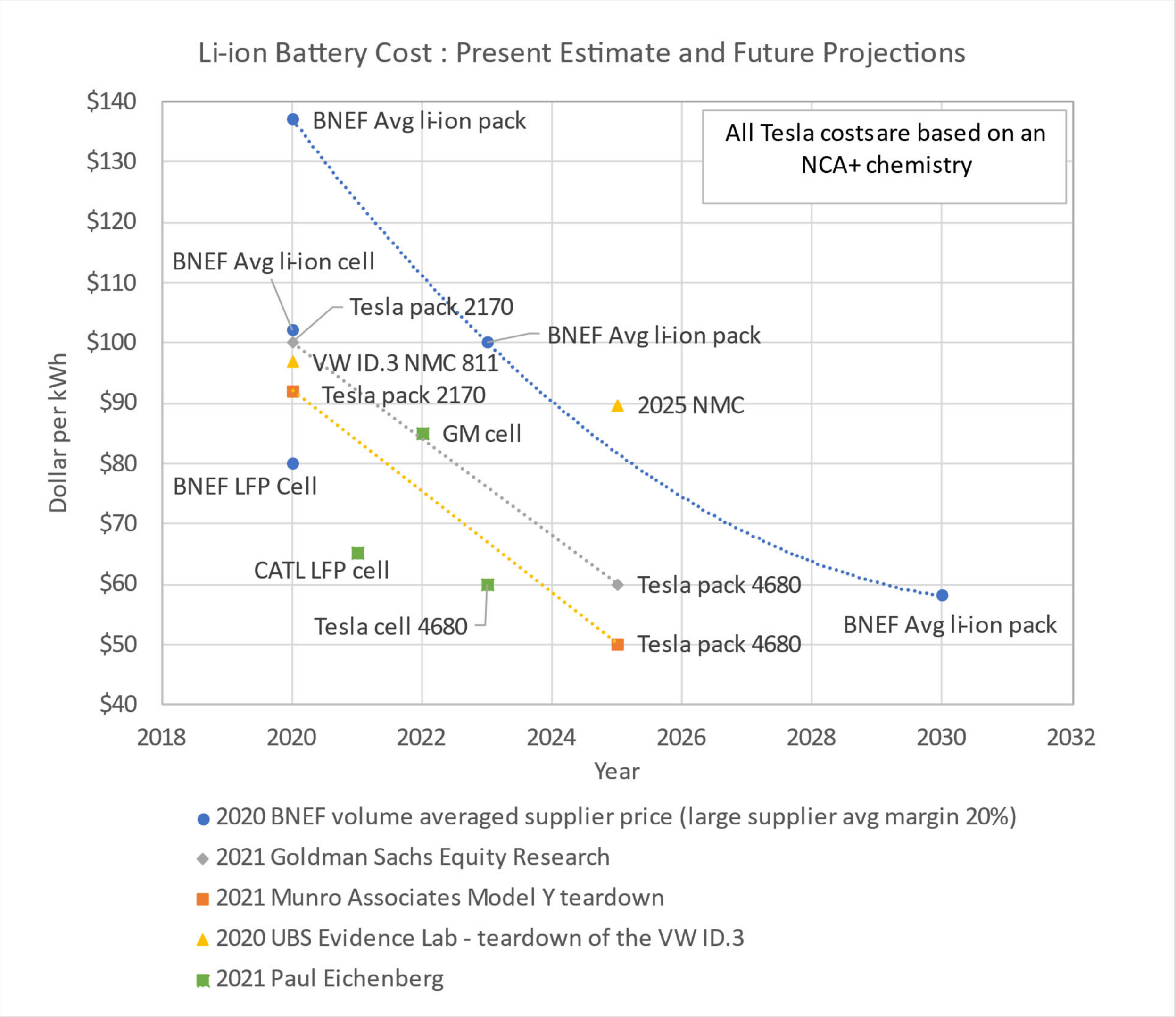
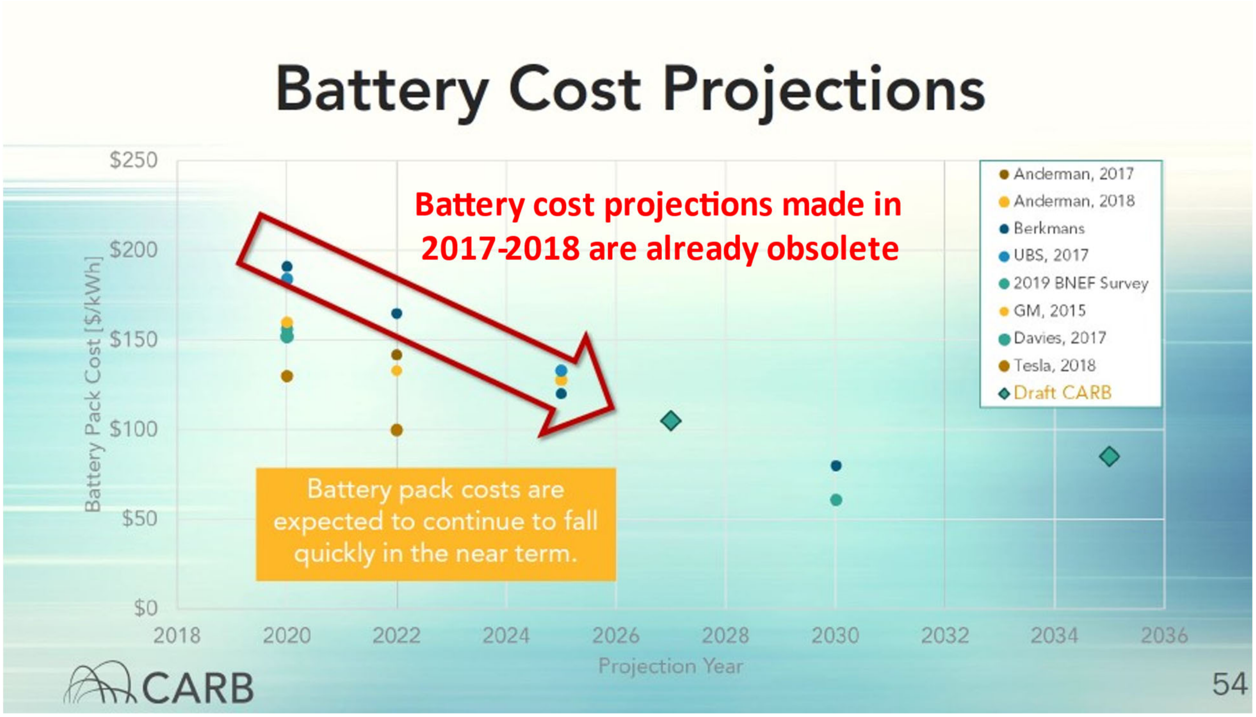


Figure 14: Battery costs. BNEF [42], Goldman Sachs Equity Research [43], Munro & Associates [44], UBS [11]

Several technologies that are currently in pilot production promise a significant reduction in lithium-ion battery costs in the next two to three years without any breakthrough in battery chemistry. Disruptive technologies like high silicon or lithium metal anodes, sulfur-based cathodes, solid-state batteries, etc. will lead to step changes in cost ($/kWh), energy density, and cycle life in 2025-2030. There are several Cobalt-free Lithium-ion cathode chemistries like High Voltage Spinel Lithium Manganese Nickel (LMNO), Nickel Iron Aluminum (NFA), and Nickel Manganese Aluminum (NMA) just to name a few that promise energy densities and costs in between that of LFP and NMC. CATL in 2021 introduced a prototype sodium-ion battery with an energy density of 160 Wh/kg slated for volume production in 2023. It is difficult to accurately predict the costs of these technologies and if and when they will reach commercial adoption. For this study, only NMC and LFP batteries were considered as the basis for calculating the purchase price of a reference case BEV and low-cost BEV (sensitivity 1) respectively. Given the number of technologies that the industry is working on that have the potential to significantly reduce the cost and increase cell and pack energy density, it is likely that the future battery costs will be below than projected in this study.



Battery Cost Projections

Battery cost projections made in 2017-2018 are already obsolete

Battery pack costs are expected to continue to fall quickly in the near term.

Figure 15: Battery pack cost projection, California ARB [45]

Figure 16 shows the worldwide market share of various BEV chemistries in 2020. The major cathode chemistries in production vehicles are

- LFP – Lithium Iron Phosphate
- NMC – Nickel Manganese Cobalt Oxide
- NCA – Nickel Cobalt Aluminum Oxide
- NCA+ - Nickel Cobalt Aluminum Oxide used by Tesla that uses 8-10% less Cobalt

Figure 17 outlines the amount of each metal in the various battery chemistries available.

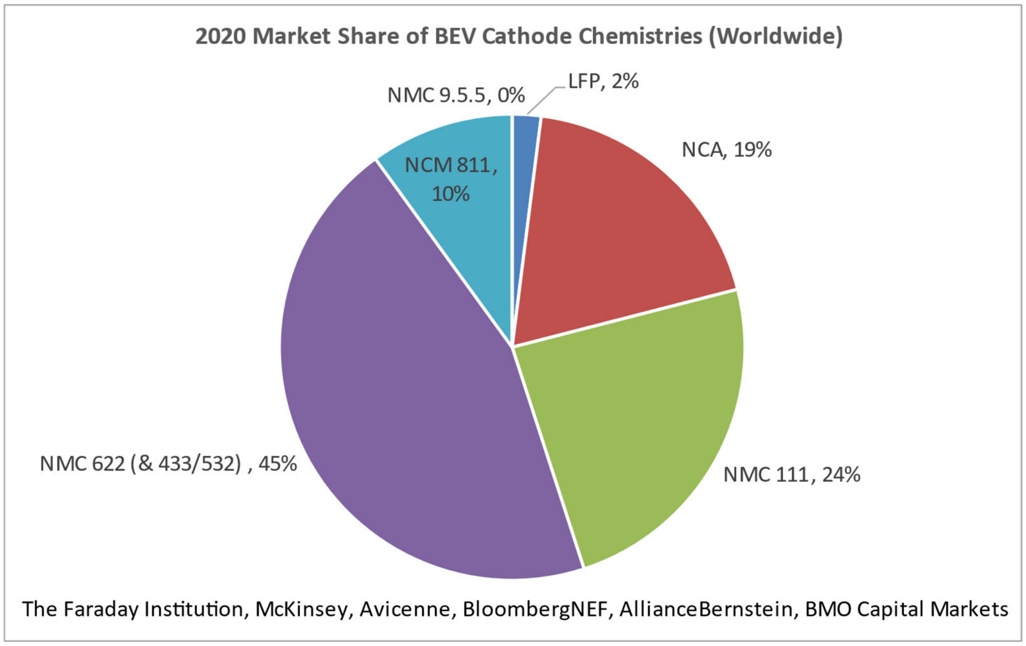


Figure 16: 2020 Market share of BEV cathode chemistries [46]

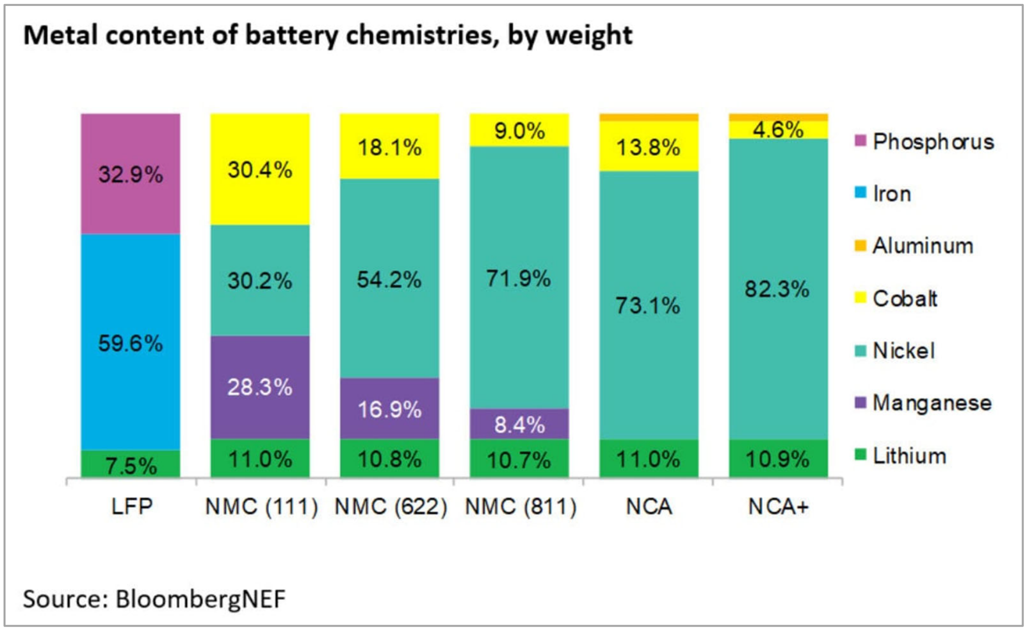


Figure 17: Content of various metals by weighty in different battery chemistries [47]

3.1.2 Production Battery Chemistries and Their Evolution

Nickel Manganese Cobalt Oxide (NMC)

NMC in its various forms (622, 811) comprises a very large portion of the current BEV market (Figure 16). The numbers following “NMC” indicate the relative amounts of Nickel Manganese and Cobalt in the cathode. The industry has been moving in the direction of reducing/ eliminating the use of Cobalt in EV batteries due to its high cost, limited reserves, and human rights violations in countries like the Democratic

Republic of Congo which accounts for 60% of the global production of Cobalt. The industry is moving from high Cobalt NMC variants such as NMC111 and NMC622 to low Cobalt variants such as today's state-of-the-art NMC811 (used in the VW ID.3, BMW iX, Ford Mach-E, etc.) and NCM90 (also known as NMC 9.5.5) in the near future. Figure 17 gives the relative metal content of various battery chemistries by weight. The low Cobalt (and Nickel) NMC variants have higher energy density and lower material costs.

Lithium-Iron Phosphate (LFP)

For most of the last decade, Lithium Iron Phosphate chemistry was considered unsuitable for EV applications due to its low energy density and poor performance at low temperatures (due to high cell internal resistance). The use of Innovative cell form factors and packaging the cells directly into the pack eliminating the use of cell modules has reduced the weight and complexity of the battery pack and increased the Gravimetric Cell to Pack ratio (GCTP: weight of the cells in a battery pack divided by the weight of the battery pack), and Volumetric Cell to Pack ratio (VCTP: volume of the cells in a battery pack divided by the volume of the battery pack). Figure 18 illustrates the large form factor prismatic cell and the cell to pack architecture used by the BYD Blade^{TM} battery pack.

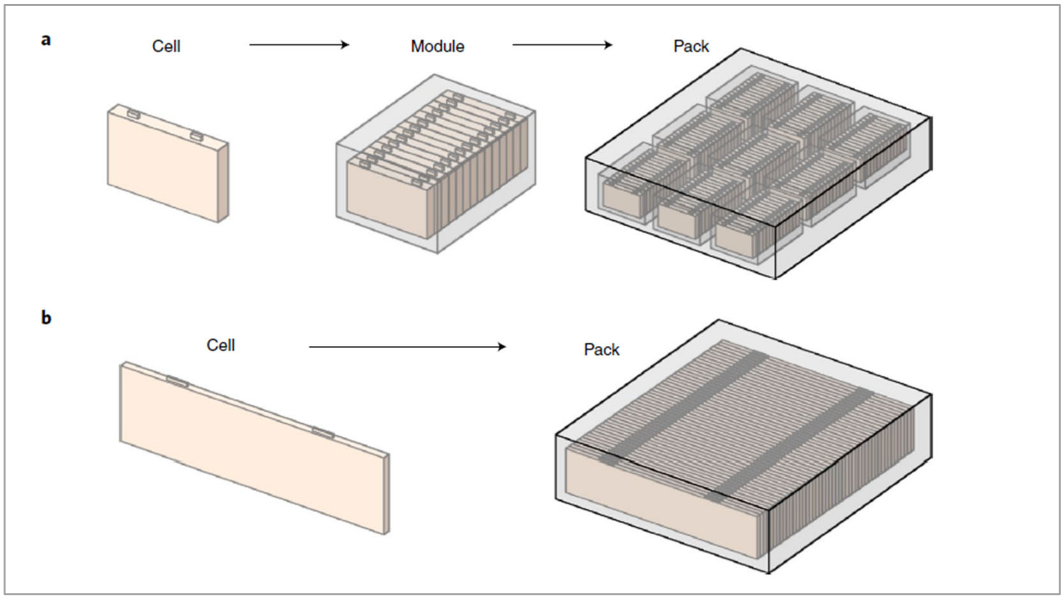


Figure 18: Illustration of a conventional battery pack (a) and the BYD blade battery pack (cell to pack) (b) [48]

This has resulted in an LFP battery pack that has a volumetric energy density higher than the NCA pack used in the Tesla Model 3 and the NMC811 pack used in the VW ID.3 as shown in Table 12. It is also worth noting that LFP cells have a much higher cycler life (7000+ cycles) when compared to NMC and NCA (<3000 cycles) - see Section 3.1.3 for detailed discussion. The cycle life of an LFP battery is less affected (when compared to NCA and NMC) by an increase in the Depth of Discharge enabling manufacturers to reduce/ eliminate the unused buffer capacity needed by NCA and NMC packs to maintain battery cycle life. Being able to use more of the battery capacity (net usable capacity of the battery pack being a larger fraction of the gross battery capacity) increases the real-world energy density of an LFP battery pack and reduces the energy density gap to the more expensive NMC and NCA chemistries.

Table 12: Comparison of battery packs in production vehicles

		2020 VW ID.3[1]	2018 Tesla Model 3[1] *	BYD Blade battery pack[2]
Cell chemistry		**LG NMC**	**Panasonic NCA**	**BYD LFP**
Nominal capacity	kWh	58	75	-
Nominal voltage	V	400	352	294
Gross battery size	kWh	62	78	59.5
Number of modules		9	4	1
Number of cells		216	4416	92
Battery weight	kg	376	474	425
battery volume	L	231	400	213
Gravimetric energy density	Wh/kg	164	164	140
Volumetric energy density	Wh/l	267	195	279

* 2020 Tesla Model 3 has a gross battery capacity of 82 kWh
[1] Source 2020 UBS teardown study **[11]**
[2] Blade battery pack prototype - Source BYD **[49]**

LFP cells can have formulations that are significantly safer than NMC and NCA and immune to thermal runaway when overcharged or punctured. New MIIT (Ministry of Industry and Information Technology - China) regulations approved in May 2020 require EVs to inhibit any fire or explosion within five minutes after a thermal runaway incident occurs [50]. To achieve that level of protection, Chinese EVs using Nickel-based chemistries such as NMC will require mitigation systems such as fire-proof mica plates between pack and vehicle or “aerogel” segments distributed throughout the pack, or battery modules seated by metal beams to isolate the modules, among many other solutions. Such protection systems will decrease the energy density (both volumetric and gravimetric), undoing advances in cell performance of Nickel chemistries. Inherently safer LFP cathode materials would allow for simplified battery packs without modules, and the otherwise necessary but voluminous safety and auxiliary components, decreasing the cost and increasing the real-world energy density of LFP [50].

State-of-the-art battery thermal management systems equipped with a heat pump can keep LFP batteries in the optimum temperature window with minimal energy penalty making their cold-weather performance comparable to that of NMC chemistry. With advances in pack construction and battery pack thermal management, the cheaper LFP chemistry is a viable alternative to more expensive NMC cells (Figure 19). This has resulted in the LFP global EV market share rising from 2% in 2020 to more than 12% in 2022 (Figure 20). (The jagged shape of the graph is due to fluctuating vehicle production numbers of many manufacturers due to chip shortage and supply chain challenges that have plagued the automotive industry in 2020-2021). In 2021 BYD introduced the Gen 3 8TT ER class 8 tandem axis truck with an LFP battery pack size of 563 kWh (GVWR 105,000 lbs, 200-mile range) and Gen 3 6F ER class 6 truck with an LFP battery capacity of 343 kWh (GVWR 26,000 lbs, 200-mile range) (Figure 21) demonstrating the viability of using high capacity LFP battery packs in medium and heavy-duty vehicles.

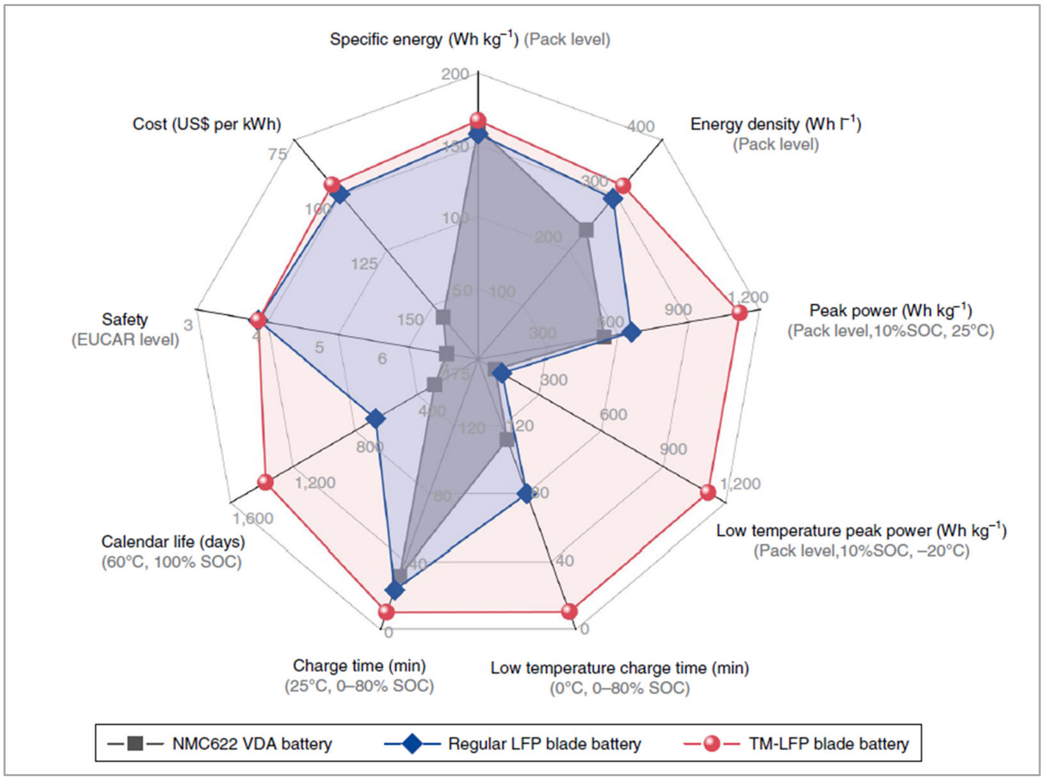


Figure 19: Comparison of TM-LFP blade, LFP blade, and conventional NMC622 battery pack on various requirements for mass-market EVs [48].

Today most of the LFP batteries are produced and used in BEVs and other applications in China. This is due to an agreement between LiFePO4+C AG (The LiFePO consortium comprised of HydroQuebec, University of Montreal, CNRS, and Johnson Matthey), the consortium managing LFP's IP rights, and the Chinese battery industry a decade ago in which, as long as LFP batteries were produced and used within China, the consortium would not charge Chinese manufacturers a licensing fee [50]. As a result, the price of Chinese LFP batteries has always been considerably lower than non-Chinese LFP batteries. However, the patents' restrictions over LFP are expiring in 2021-2022 which will remove the limitations (licensing fees) on LFP exports by Chinese producers, along with the licensing fee for non-Chinese LFP cell producers. The removal of this IP barrier could become a big opportunity for LFP-based Li-ion batteries to rapidly gain market share in the EV market outside China. Thus, LFP was considered as the first cost-reducing sensitivity applied to EV powertrains in this study.

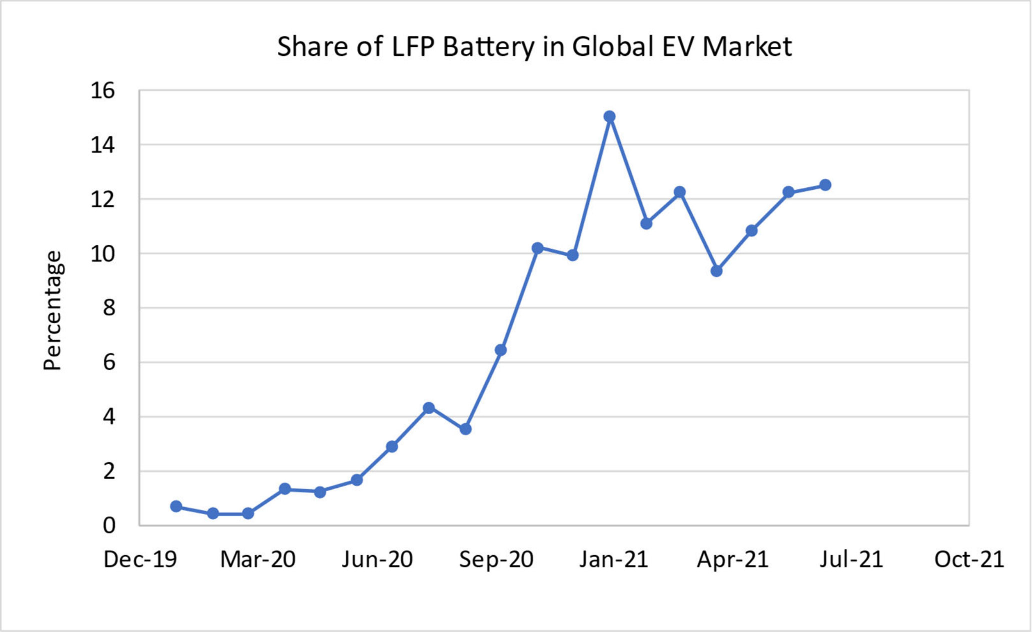


Figure 20: Share of LFP Battery in Global EV Market (Source: Worldwide Monthly BEV & PHEV Tracker from Researcher and Research LLC)

Figure 21: BYD Gen 3 6F (left) and Gen 3 8TT (right) [51]

Several technologies can significantly improve the energy density of the LFP battery making it likely that it will be the predominant lithium-based battery chemistry of the future. Anodes with silicon can improve the energy density from 160-170 Wh/kg to greater than 200 Wh/kg. In 2020 Gotion High Tech, VW's technology partner for developing the "Unified Cell" (prismatic cell for future vehicles) announced a production LFP pouch cell (Anode incorporating Silicon) with an energy density of 210 Wh/kg [52]. A solid-state electrode with a lithium metal anode can further increase the energy density of LFP batteries. Quantumscape [53] working on such an LFP cell architecture estimates an energy density of 600-700 Wh/L and 250 Wh/kg.

Nickel Cobalt Aluminum Oxide (NCA)

Tesla is the world's largest consumer of NCA batteries in the world. Panasonic and Tesla's formulation of the NCA chemistry (NCA+ in Figure 17 [47]) uses 8-10% less Cobalt when compared to standard NCA chemistry and more than 50% less when compared to NMC 811 and 75% less when compared to NMC 622 [47] further reducing costs. NCA cells currently in production have a shorter cycle life when compared to NMC and NCA cells (Figure 22) and are not sufficient for all MDHD applications.

Nickel Cobalt Manganese Aluminum Oxide (NCMA)

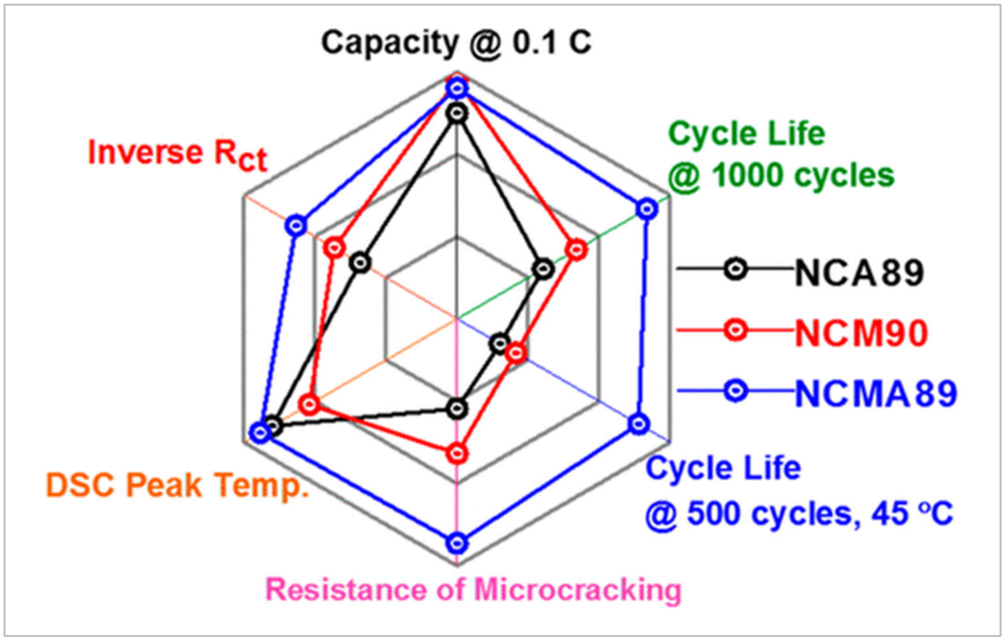


Figure 22: Comparison of NCMA89 chemistry with NCA89 and NCM90 [54]

LG (LG Chem Power, Inc. (LGCPI), a subsidiary of LG Chem, Ltd) is currently ramping up production of the quaternary NCMA battery chemistry that promises similar energy density and significantly higher cycle life compared to NCA and NMC (NCM) chemistries. These cells will initially be used in Tesla and GM (Ultium^{TM} batteries) electric vehicles.

3.1.3 Battery Cycle Life

Cycle life of commercially available cells – NMC, NCA, and LFP

One of the concerns of switching to battery electric vehicles for MDHD applications is that the batteries may not last the life of the vehicle. Figure 23 shows the cycle life for a 100% DOD for commercially available NMC, NCA, and LFP cells used for light-duty applications. Cycle life of a battery pack is defined as the number of cycles at the end of which the battery pack retains 80% of the initial capacity

The cycle life is significantly affected by the depth of discharge (difference between the maximum and minimum charge level between which the cell is charged and discharged) as shown in Figure 23. A small decrease in the depth of discharge can significantly increase the cycle life of the cell. 100% DOD is far from what a production vehicle battery pack is subjected to. Most manufacturers of lithium batteries set software limits for the minimum and maximum pack state of charge (SOC) limits, the usable capacity of the pack being set at 85-90% of the gross capacity significantly increasing the life of the battery pack. When compared to NMC, LFP chemistry can have lower or even no buffer capacity with a negligible effect on battery cycle life. With technology in volume production, the battery cycle life is in the range of 2000-3000 cycles for NMC and more than 7000 cycles for LFP. This range can be further improved by the use of managed charging, especially in fleet applications.

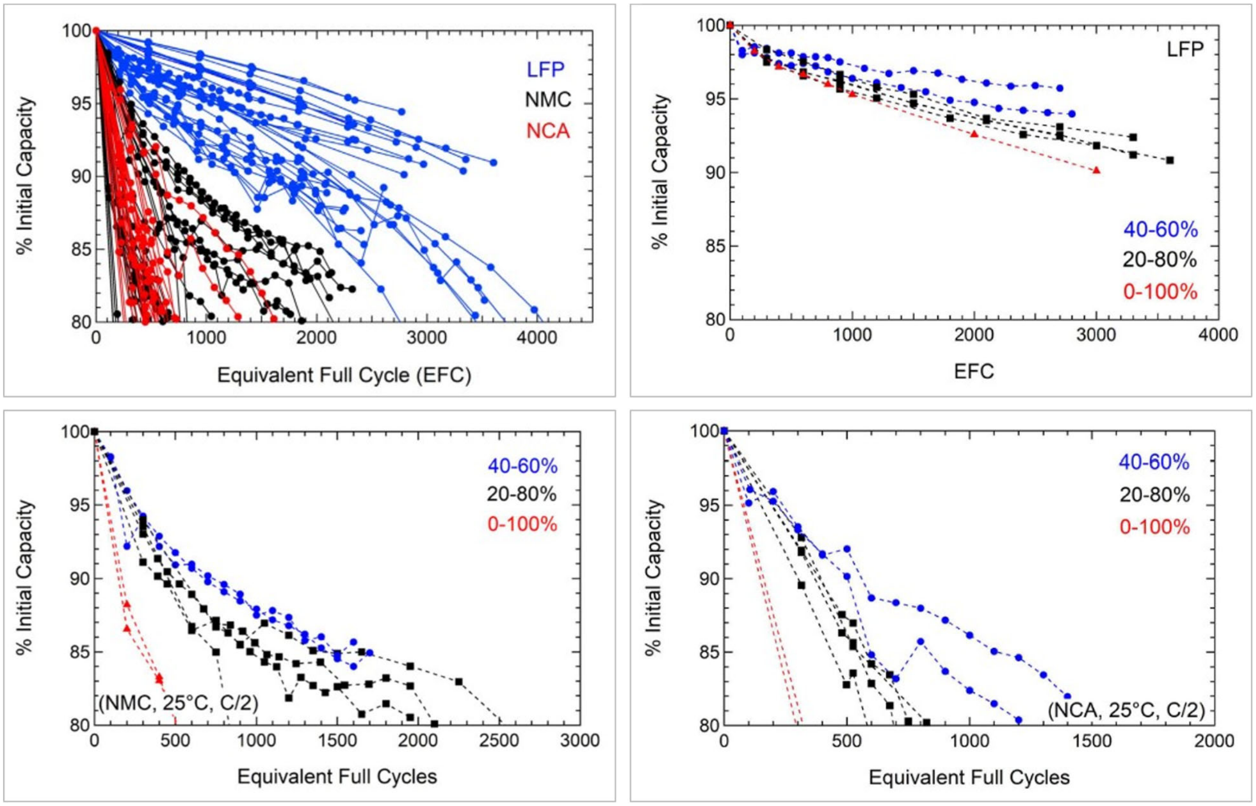


Figure 23: Top left: Capacity retention of various commercially available Lithium cells used in light-duty applications (20°C 100% DOD) others: Effect of depth of discharge on the cycle life of LFP, NMC, and NCA cells. Cycle life = 80% of initial capacity [55]

Present state of the art high cycle life battery technology – Fast Ionic Conductor (FIC) Coatings

NMC batteries with various fast ionic conductor coatings on the cathode particles have demonstrated a significant increase in cycle life [56], [57] [58]. CATL recently unveiled a ready-for-production Lithium NMC battery with a proprietary coating of fast ionic conductor on the cathode particles that can enable it to potentially last 16 years and 1.25 million miles in a vehicle application (CATL did not clarify the assumptions – range of the vehicle, number of cycles, charge-discharge rates used for the mileage calculation). According to CATL, the technology is 10% more expensive than current commercially produced NMC cells used in light-duty applications [59] [60].

Future High cycle life battery technology – Single Crystal cathode materials

Single crystal cathode materials in place of the polycrystalline material used in battery cells today can significantly increase the cycle life of lithium-ion batteries. Under testing, cells with single crystal cathode materials have demonstrated more than 9500 cycles (room temperature, 100% DOD, 1C rate) with capacity retention of over 90% [61]. The industry defines the end of life of a cell/ pack as 80% initial capacity. This paves a way for Semi trucks with over two-million-mile battery life and cell durability to withstand repeated DC fast charging. Companies like NanoOne in collaboration with Johnson Matthey are working on bringing down the production costs of single-crystal cathode materials and are in the pilot production stage before volume production [62], [63]. Single-crystal cathode materials are compatible with commercial battery chemistries with no change required to cell manufacturing process or equipment.

Cathode materials used in commercial applications today are made of aggregates of very small crystals (Figure 24 (A, a)) with the crystal structure oriented in random directions. During cycling (discharging and charging during use), lithium ions are repeatedly inserted between the layers of the cathode material and then extracted, the volume of the cathode material changes. This volume change is much larger in the direction perpendicular to the layers. The random orientation of the crystals results in a volume mismatch in various directions resulting in microcracking of the particles. This leads to a loss of electric contact and access to the cathode’s active mass resulting in capacity loss. A single crystal cathode material (Figure 24 (B, b)) has much larger particles, 2-3 microns, each one comprised of a single crystal with no grain boundaries. The whole particle expands and contracts as a unit resulting in virtually no microcracking even after 5000 cycles [64]. The absence of microcracking makes it possible to maintain an electric connection to these particles as they expand and contract resulting in a near 100% connection to the cathode’s active mass throughout the charge-discharge cycling.

Figure 25 (right) shows the degradation of the battery capacity vs the projected mileage of a vehicle powered by such a battery at different cell temperatures. Assumptions made were one 6-hour 100% DOD cycle per day and 350 km initial driving range per cycle. With good thermal management, a vehicle equipped with such a pack can last over two million miles with a 10% capacity loss. Such high cycle life can enable the Vehicle to Grid (V2G) technology without a noticeable negative impact on vehicle battery life. When possible, fleets can charge their vehicles when electricity is cheap and export electricity back to the grid during peak demand. Lending a vehicle’s V2G capabilities to the utilities will result in subsidizing a vehicle’s electricity (fuel) costs. A large number of vehicles with V2G capabilities will enable the grid to switch to renewables at a much faster pace with lower investment. TCO implication of V2G technologies is not a part of this study.

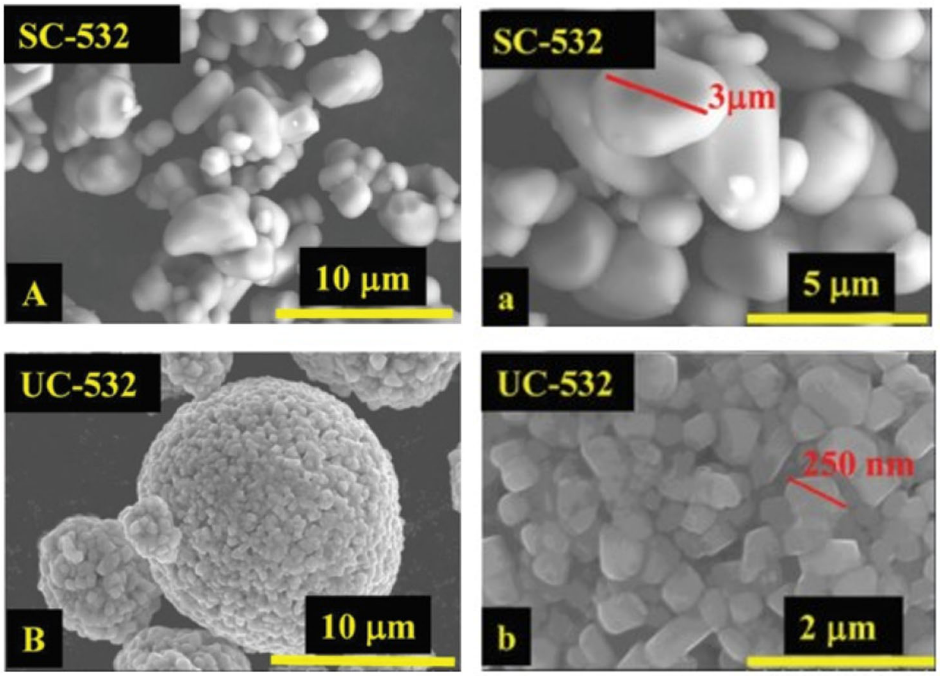


Figure 24: (A, a) – scanning electron microscope (SEM) images of a commercial single crystal NMC532 material with a large grain size of ~3 µm, (B, b) SEM images of commercial polycrystalline (NMC532) [64]

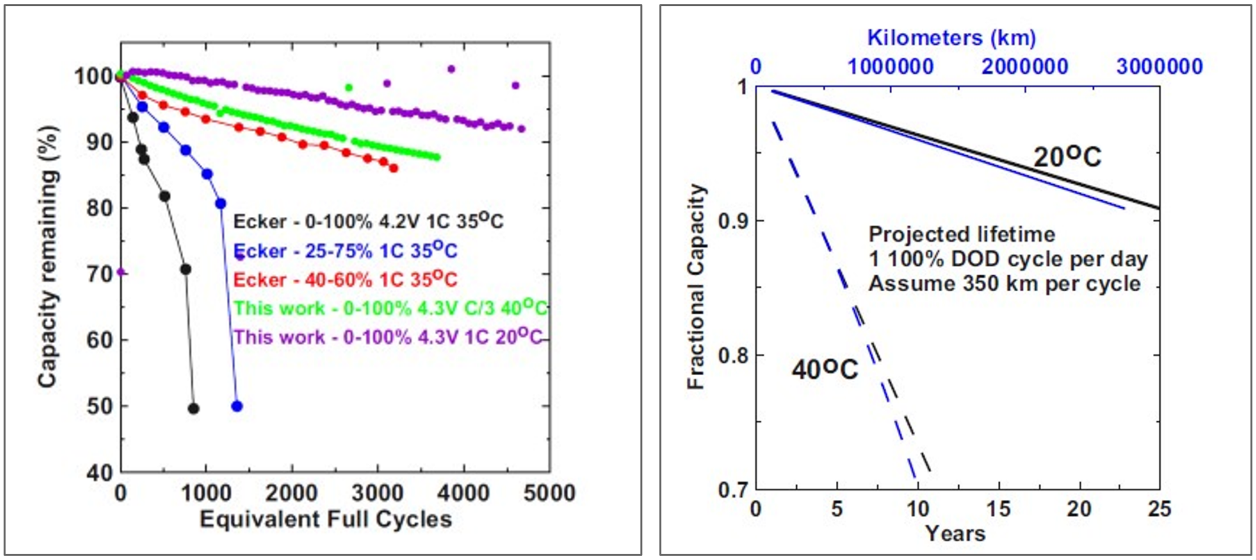


Figure 25: Left: Long-term cycling data plotted as percent initial capacity (left), Right: Worst-case scenario lifetime and total driving range projections for the NMC532/graphite cells 6-hour 100% DOD cycle per day and 350 km initial driving range per cycle [64]

3.1.4 Future Battery Chemistries

Sodium-Ion

CATL unveiled the first generation of Sodium-ion battery with a carbon anode and Prussian White cathode [65] in July 2021, slated for mass production in 2023. The first-generation cell has an energy density of

160 Wh/kg while CATL projected the energy density of the second generation cell to be 200 Wh/kg. The low-temperature performance exceeds that of LFP with capacity retention exceeding 90% at a temperature of -20 °C and the ability to be charged 0% to 80% in 15 minutes. Some analysts estimate the cost of Na-ion cells to be as low 40 $/kWh. The sodium-ion battery uses raw materials that are cheaper, more abundant, free from supply constraints, and is a promising substitute for lithium-based chemistries. Figure 26 shows a comparison to LFP batteries in several performance metrics.

Assuming a similar cell form factor and pack construction of the BYD blade LFP pack (Section 3.1.6 – Gravimetric Cell To Pack (GCTP) ratio of 0.85), a 160-200 Wh/kg cell level gravimetric energy density of sodium-ion will result in a battery pack with a gravimetric energy density of 136-170 Wh/kg, which compares favorably to both 2018 Model 3 NCA and 2020 VW ID.3 NMC811 pack value of 165 Wh/kg and higher than the 2020 BYD blade battery pack value of 140 Wh/kg (Table 12).

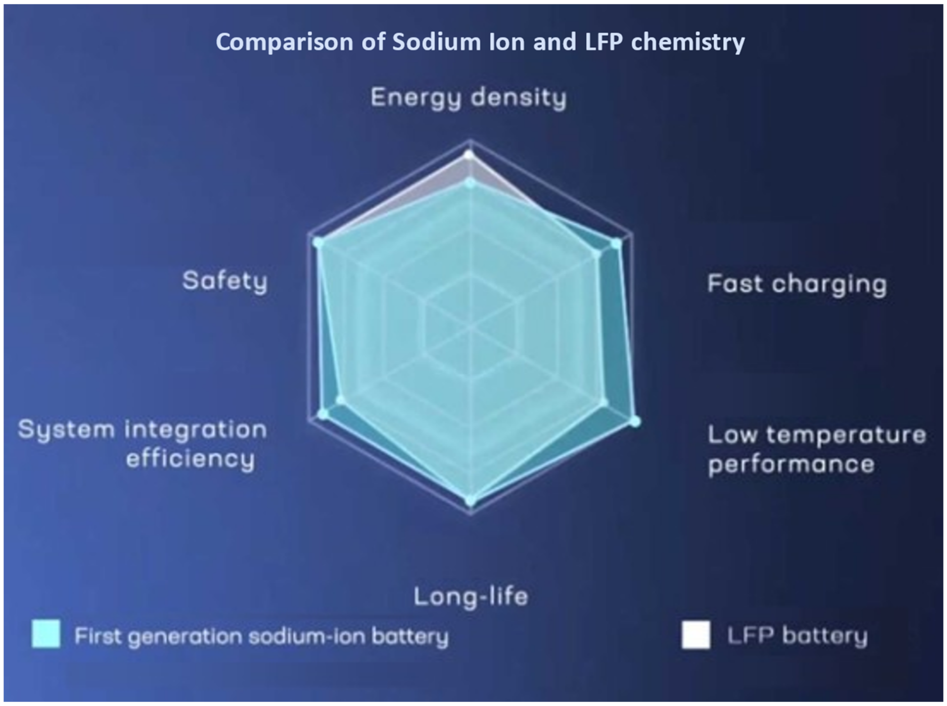


Figure 26: First-generation sodium-ion (2023 volume production) when compared to the state-of-the-art LFP. [66]

Other Battery Chemistries

There are several other promising battery technologies at various levels of technology readiness with various advantages and limitations. Most of them are lithium-based and are focused on using lower cost and more abundant raw materials for their cathodes. Almost all of them eliminate the use of Cobalt. Some of these may include:

- High Voltage Spinel – Lithium Nickel Manganese Oxide (LMNO)
- Lithium Sulphur
- Nickel Iron Aluminum Oxide (NFA)

- Nickel Manganese Aluminum Oxide (NMA)

Some of these technologies may never be adopted for volume production unless their economics and terms of licensing of the intellectual property are attractive to suppliers. Also, they will most certainly need backing from a major OEM for large, assured volume to start production.

3.1.5 Improvements in Cell Manufacture

Dry Battery Electrode (DBE) Process

The DBE process eliminates the wet slurry coating, drying, and solvent recapture steps in a conventional lithium-ion cell manufacturing process. These steps account for 50% of the energy consumption and 23% of the cost of cell manufacture, as shown in Figure 27. The DBE process will significantly reduce the GHG emissions from the battery manufacturing process reducing the gap in GHG emission between the manufacture of an EV and an ICE vehicle. Based on their 10 GWh pilot plant, Tesla estimates the DBE process will result in an 18% cost saving [67]. VW estimates that the dry electrode coating process will result in a 50% reduction in cell manufacturing plant footprint and a 30% reduction in CAPEX [68]. The other advantages of DBE are higher cell energy density due to a higher ratio of active to inactive (binder) material and Higher cycle life. The process also results in a lower cell resistance improving the power density. Alternatively, due to lower cell internal resistance, thicker electrodes can be fabricated for improved energy density.

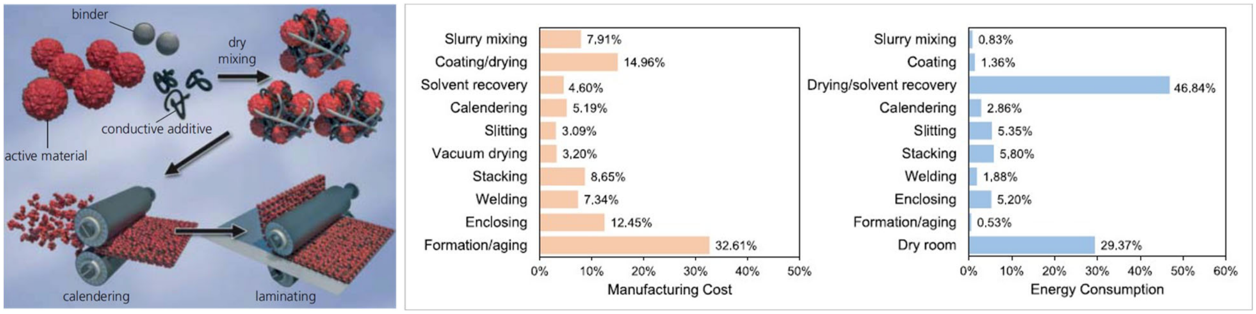


Figure 27: Dry battery electrode (DBE) processing process (left) and the cost and energy consumption breakdown for the conventional wet slurry cell manufacturing process (right) [69]

Tabless Electrode

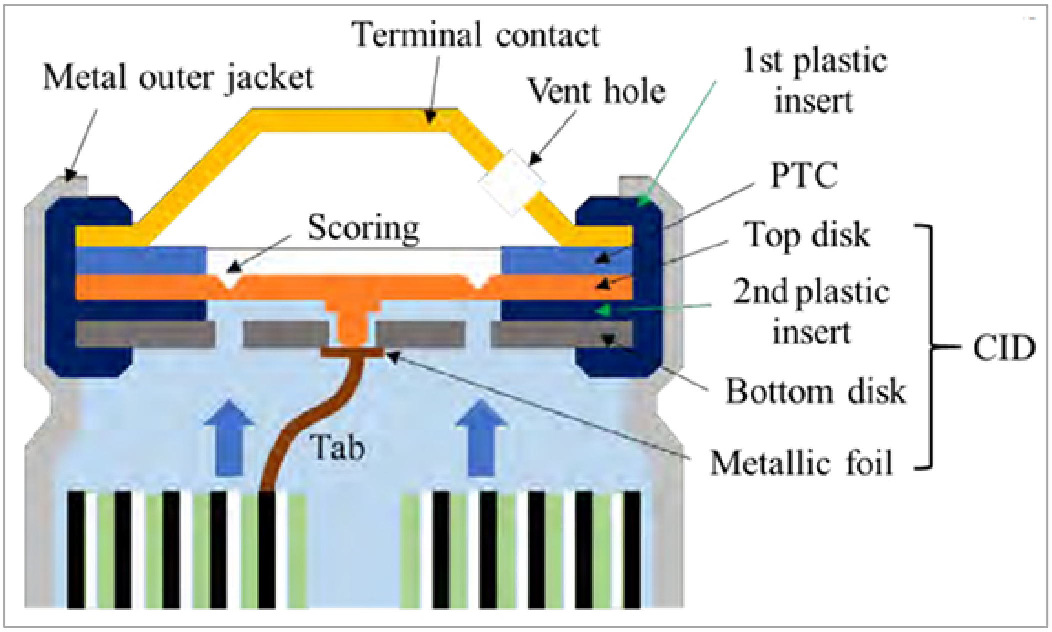


Figure 28: Current Interrupt Device (CID) Source: CALCE (Center for Advanced Life Cycle Engineering)

Figure 28 shows the typical safety mechanism of a cylindrical Li-Ion cell, which consists of a top disk (orange) that breaks under pressure (high pressure or swelling of the cell) and permanently disconnects the current flow. The tab in the figure is part of a fuse-type safety mechanism. Detailed discussion on anode and cathode tab design and failures can be found in [70]. The tab is a good solution in traditional lithium-ion applications which use one or a few cells. In electrical vehicles that use a large number of cells (Tesla Model 3 – 4416 2170 cells), manufacturers use sophisticated battery management systems (BMS) and individual cell fuses external to the cell (Tesla) reducing the reliance on the tab. Some OEMs (Tesla) and battery suppliers are working on tabless electrodes with Tesla establishing a pilot production facility (10 GWh capacity) manufacturing 4680 (cylindrical) cells with tabbed cathode and tabless anode. Tabless electrodes have several advantages.

- Increased cell yield - Welding the tab to the foil is prone to fault, reducing cell yield
- Reduced cell cost - Eliminates the extra step in battery production, reducing cell cost [71]
- Reduced internal resistance – With a tabbed electrode, electrons must travel from all over the electrode to the tab to exit the cell increasing the resistance of the cell. In a tabless electrode Figure 29, the entire edge of the electrode foil is connected to the terminal decreasing the cell internal resistance and the heat generated.

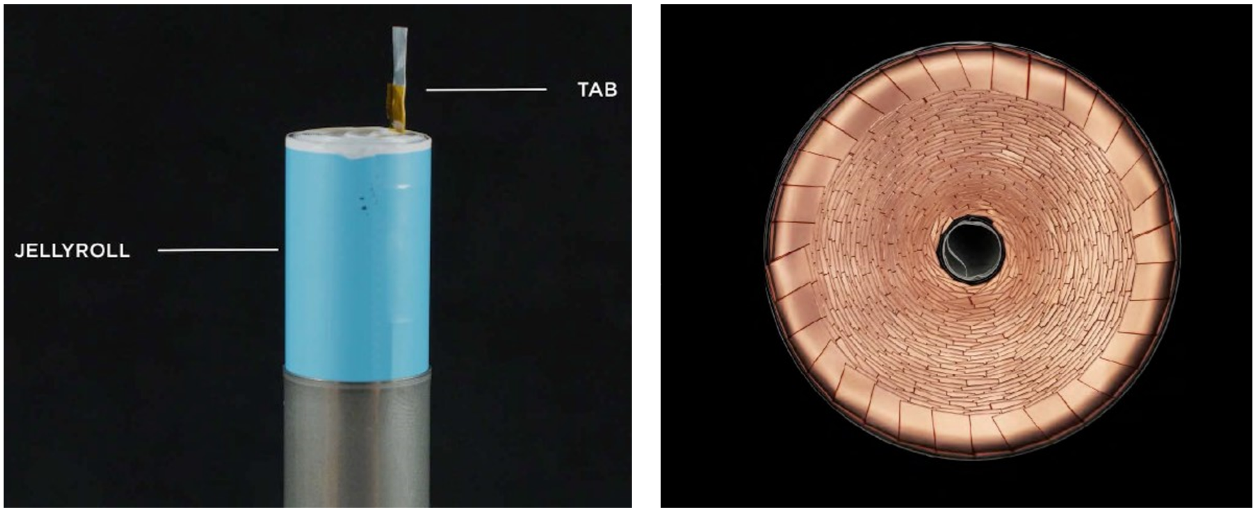


Figure 29: Conventional tabbed electrode (left), Tesla Tabless anode (right)

- Reduced battery wear - Electrons traveling from different parts of the electrode to the tab, create hot sports of electrical activity in the electrode material which also causes hot spots of chemical activity on the electrode and causes undesirable effects like plating of metallic lithium on the surface of the negative electrode. Electrically connecting the entire length of the electrode foil to the cell can evens out the reactions across the battery cell increasing the life of the cell.
- improved thermal management of the cell and reduced battery pack complexity and cost – in a tabless electrode, the entire length of the electrode current collector foil is connected to the cell-can resulting in improved thermal contact and a very short path for the heat generated (height of the cell). The tabless electrode has a significantly larger thermal contact area between the electrode and cell-can enabling the use of a simple cooling plate in contact with the circular face of the cell. This opens the path to manufacturing large diameter (Tesla 4680 vs 2170) cylindrical cells capable of high charging and discharging rates. The smaller number of larger cells simplifies the construction of the battery pack reducing the cost and complexity of the pack.

Since the cost of many of the steps in manufacturing a cell does not increase linearly with the size of the cell, a larger cell is cheaper to manufacture on a $/kWh basis. Moving from 2170 to a larger 4680 cylindrical cell, Tesla achieved an 18% cost reduction per kWh in pilot production. [67]

3.1.6 Improvements in Battery Pack Construction – Cell to Pack and Cell to Chassis

Most vehicles today have cells grouped into modules and multiple modules combined to form the battery pack. The modules are packaged in an enclosure that prevents any stresses from being transmitted to the individual cells or modules (Figure 30 – left VW ID3). This architecture evolved from the reasoning that any faulty module could be replaced without replacing the entire pack. However, this adds weight and complexity and reduces the GCTP and VCTP. With improving quality of and reliability of cell manufacture, pack construction, BMS, and thermal management systems, battery fault rates today are very low. Some manufacturers and suppliers (Tesla, BYD, CATL, etc.) are working on a “cell to pack” architecture (Figure 30 – right BYD “blade” battery pack) that does away with individual modules, reducing the associated cost and complexity, and increasing the GCTP and VCTP. According to CATL, its “cell-to-pack” technology results in a 30% increase in volume utilization of the pack (cell-to-pack volume ratio), a 40% reduction in the number of parts in a battery pack, and a 50% increase in production efficiency [59]. Reduction in battery pack weight will reduce curb weight and increase the payload of MDHD vehicles.

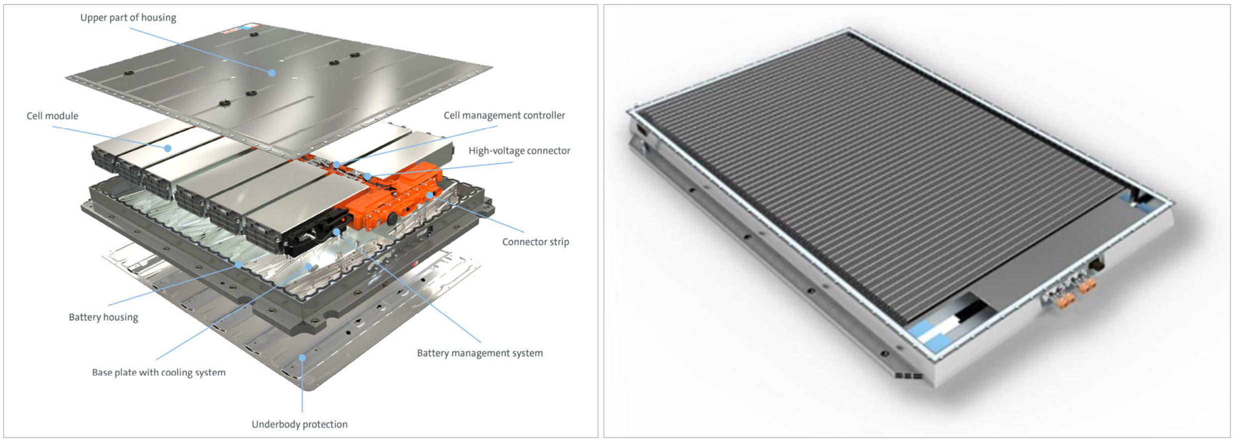


Figure 30: VW ID3 Battery pack with 12 modules (left) [11]. BYD Tang “cell to pack” battery pack (right) [49]

Tesla is going further to mass-produce a structural battery pack, where the pack and the cells are constructed to transmit structural loads resulting in 370 fewer parts, a 10% reduction in mass, and a 14% range improvement of a midsize SUV (production - 2022 Model Y produced in Tesla’s facility in Austin and Berlin) [67]. Structural battery packs may not find wide use in medium and heavy-duty vehicles due to their use of latter frame chassis that takes all the structural loads.

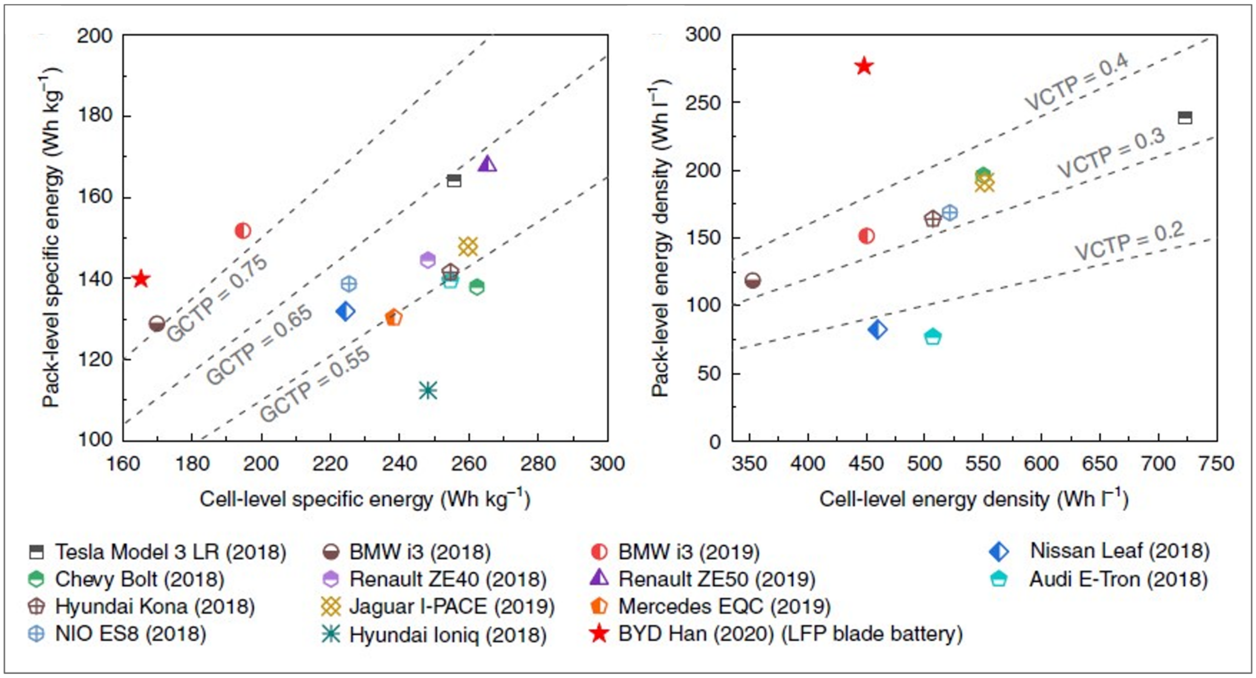


Figure 31: Gravimetric energy density and volumetric energy density of the battery packs in production EVs [48]

Figure 31 shows the gravimetric cell and pack energy density (left) and volumetric cell and pack energy density (right) of various BEVs in production [48]. Most EVs have a GCTP of around 0.55–0.65, i.e., 35 to 45% of pack weight is taken by inactive elements (battery management system, thermal management system, metal casing, cabling, beams, etc.). VCTP of most EVs is below 0.4. The "blade" LFP battery pack in the newly unveiled BYD Han EV achieves a GCTP of 0.85 and VCTP of 0.62, giving gravimetric and volumetric energy densities comparable to NMC and NCA chemistries (Table 13). The LFP battery pack produced by CATL for the Yutong bus in China has an energy density of 161.29 Wh/kg, which is equal to that of the VW ID.3 that uses LG NMC 811 cells [48].

In summary, the EV industry is doing away with battery modules and moving towards cell-to-pack construction that reduces part count, complexity (in construction and manufacturing), weight, and cost of materials and manufacturing.

Table 13: Comparison of battery packs in production vehicles

		2020 VW ID.3[1]	**2018 Tesla Model 3[1] ***	**BYD Blade battery pack[2]**
Cell chemistry		LG NMC	Panasonic NCA	BYD LFP
Nominal capacity	kWh	58	75	-
Nominal voltage	V	400	352	294
Gross battery size	kWh	62	78	59.5
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Number of cells		216	4416	92
Battery weight	kg	376	474	425
battery volume	L	231	400	213
Gravimetric energy density	Wh/kg	164	164	140
Volumetric energy density	Wh/l	267	195	279

*** 2020 Tesla Model 3 has a gross battery capacity of 82 kWh**
[1] Source 2020 UBS teardown study [11]
[2] Blade battery pack prototype - Source BYD [49]

3.2 Traction Motors – Technology Review

Internal combustion engine vehicles need a custom-designed engine and transmission for every narrow range of power output and vehicle application. On the contrary, heavy-duty BEVs can combine multiple smaller motors with the right gear ratio to produce the necessary combination of power and torque at the wheels. This modular approach significantly reduces the number of discrete motor sizes that are required to power vehicles from class 1 to class 8, giving EV components significantly more economies of scale compared to ICE components. As the manufacturing scale of motors increases globally, the design and manufacturing methods will converge into an accepted uniform practice, combining heavy- and light-duty production into a few motor types and sizes. Thus, costs predictions for light-duty motors are relevant when predicting the costs of heavy-duty electrification. Figure 32 shows how the Volvo medium-duty (FE) and the heavy-duty (VNR) trucks share motors and gearbox components and how the Tesla Class 8 Semi uses 4 motors based on the motor used in the Model 3.

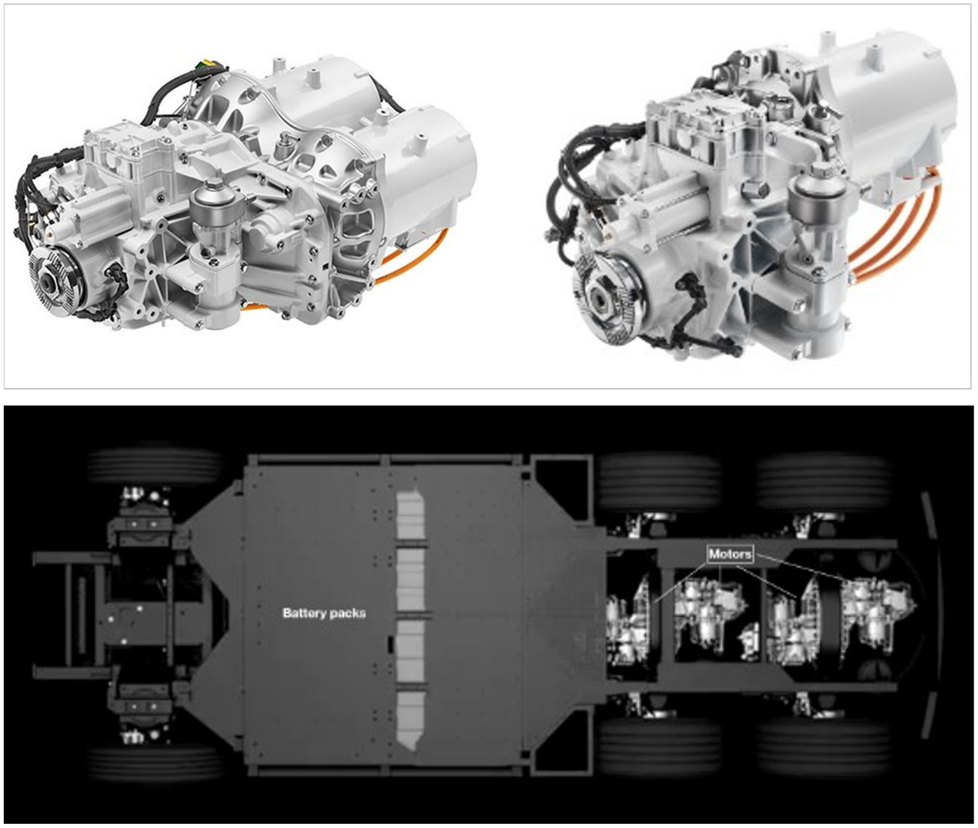


Figure 32: Top: (left) The powertrain of the Volvo VNR and (right) that of the Volvo FE (medium duty). Bottom: The Tesla Class 8 Semi powertrain with 4 PM-SynRMs (motors) and (4) SiC inverters based on the Model 3

Figure 33 shows the different types of electric motors in production EVs in the light-duty segment. Commercial BEVs in many MDHD segments discussed in this report are in a more nascent stage with less optimization of technology and costs, and lower manufacturing scale and automation. It is useful to look at the light-duty space for different types of traction motor technologies, their advantages and limitations since these motor technologies are just as relevant for MDHD vehicles as they are in the light-duty space.

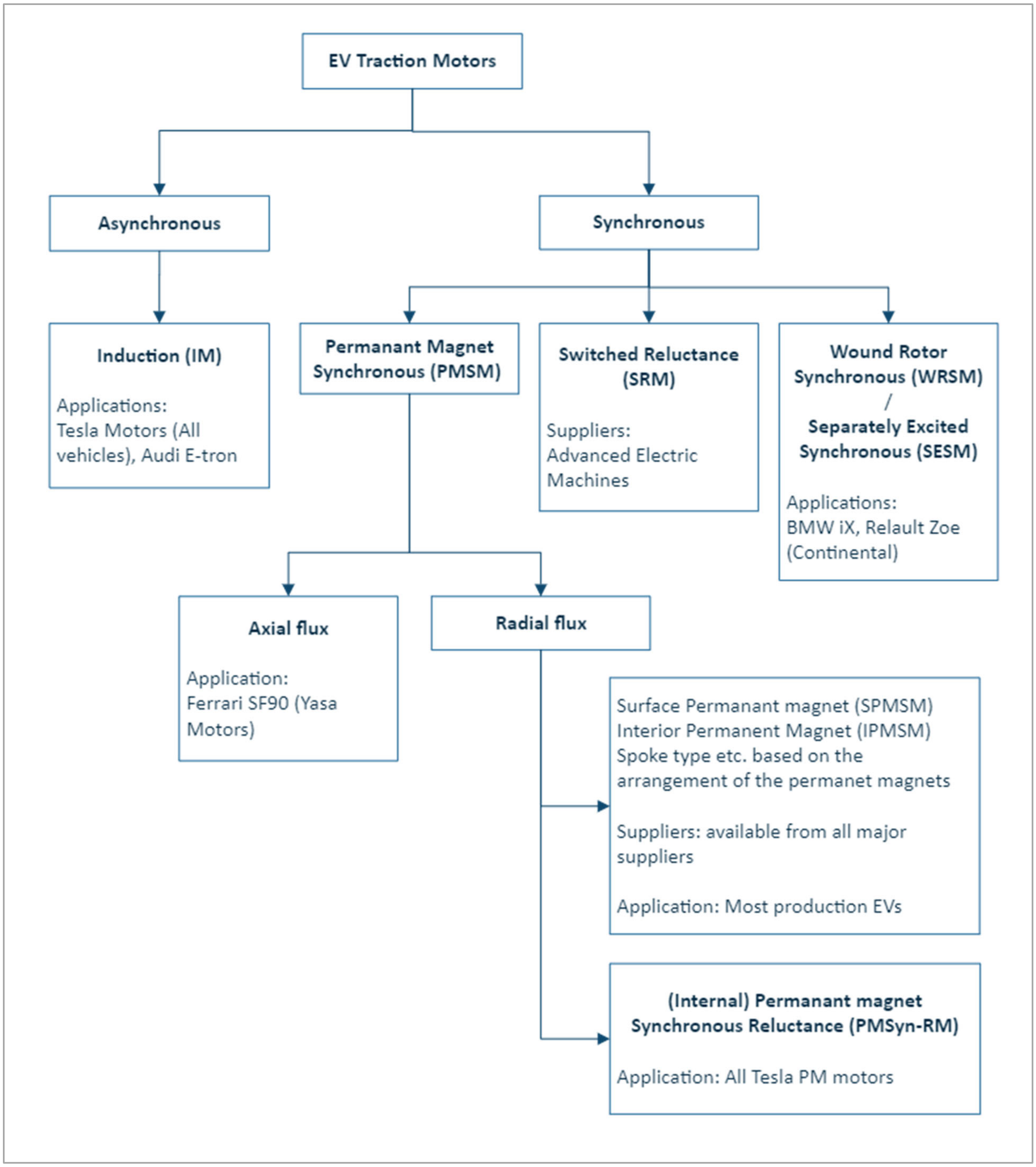
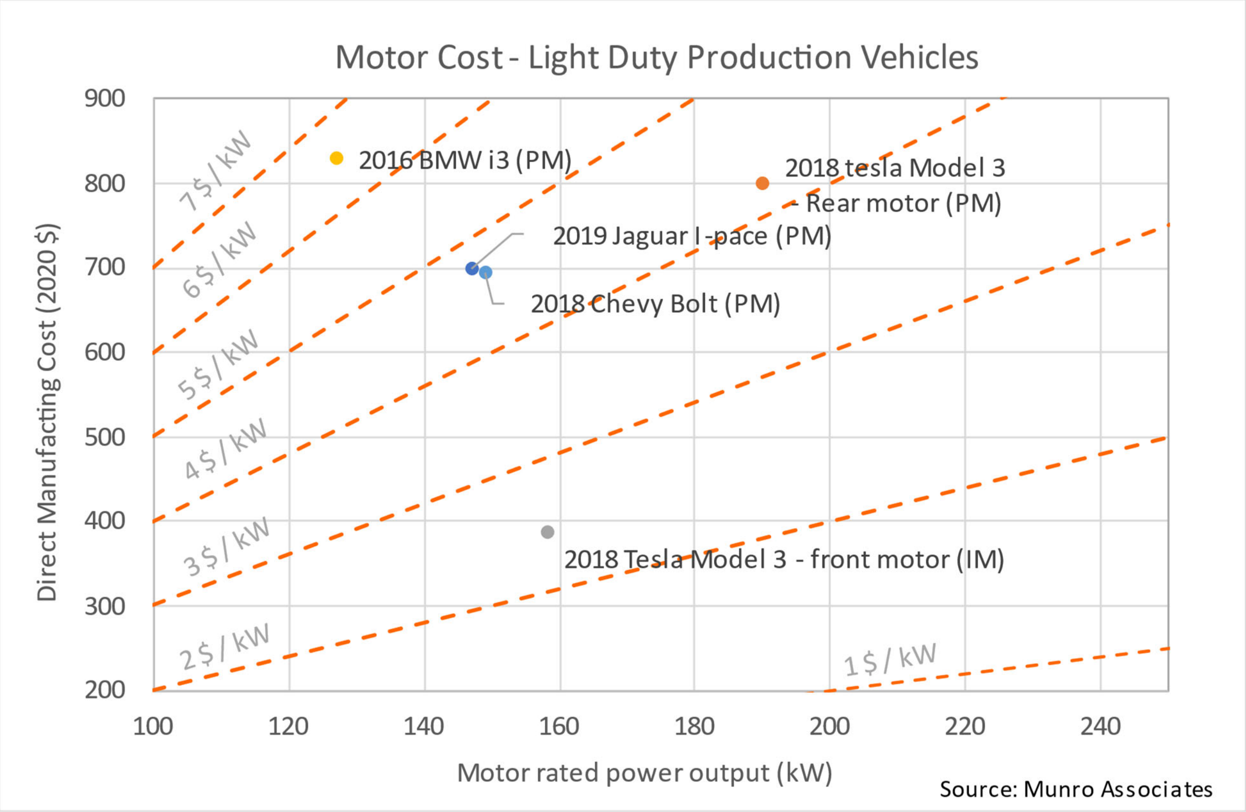


Figure 33: **Different types for traction motors in production battery electric vehicles**

Wound Rotor Synchronous Motors (WRSM), Induction Motors (IM), and Switched Reluctance Motors (SRM) eliminate the use of permanent magnets. In a Permanent Magnet Assisted Synchronous Reluctance Motor (PMSyn-RM) the reluctance torque is significant compared to the PM electrical torque. This results in a motor that matches, and in some cases, exceeds the performance and overall efficiency of a PMSM with a decreased need of expensive permanent magnet (PM) material, which makes it cheaper. The cost of all traction motors can be further reduced by replacing copper stator windings with aluminum windings.

The cost of Induction machines can be further reduced by using aluminum conductor bars in the stator (Tesla Induction motors and Audi E-tron).



Source: Munro Associates

Figure 34: Light Duty Production BEV Motor Cost

Highly automated volume manufacture of motors in the light-duty sector by companies like Tesla has resulted in an impressive reduction in the manufacturing cost of electric motors. Figure 34 plots the results of the motor teardown studies done by Munro & Associates of mass-produced light-duty BEV motors. The cost of permanent magnet synchronous motors is in the range of 4-5 $/kW while that of aluminum rotor induction motors (Tela Model 3 – front motor) is less than 3 $/kW.

3.2.1 Permanent Magnet Synchronous Motor (PMSM)

PMSMs are the most common traction motor technology in production EVs today. PMSMs currently have the highest peak efficiency among the different types of traction motors and are used in most light, medium, and heavy-duty applications. They are classified according to the arrangement of the magnets (Surface mounted, axial, spoke, etc.) and the direction of the magnetic field (axial or radial flux machines). Almost all PMSMs use Neodymium Iron Boron (NdFeB) magnets due to the high magnetic field strength they can generate. Some of these magnets also contain heavy rare earth metals such as dysprosium and terbium. Mining and processing rare-earth metals have a huge environmental impact and are subject to price volatility with increasing demand. Also, China provides 85% of rare earth metals making its supply at risk of geopolitical developments. Hence there is a huge incentive to reduce or eliminate the use of rare-earth magnets in motors.

Magnets with Reduced Rare Earth Metals

In 2016, Honda in collaboration with Daido Steel started manufacturing Neodymium Iron Boron (NdFeB) magnets without heavy rare earth metals such as dysprosium or terbium. In 2018 Toyota started the manufacture of NdFeB magnets which not only eliminated the use of dysprosium and terbium but also reduced the mass fraction of Neodymium by 50% replacing it with Cerium and Lanthanum which are less than a tenth of the cost of Neodymium.

Iron Nitride Magnets

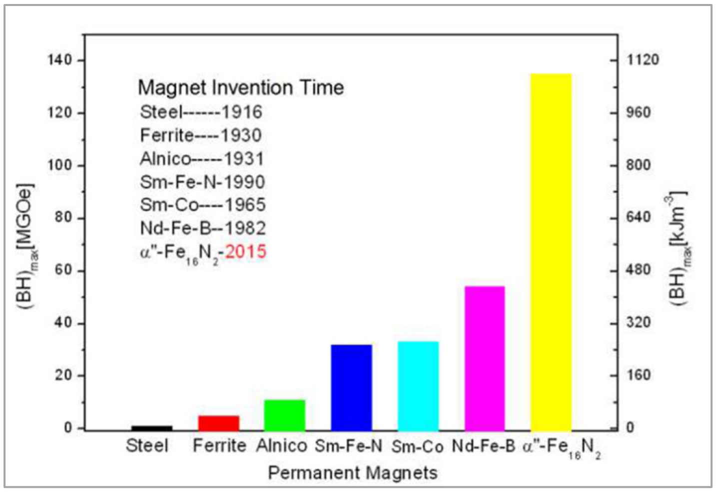


Figure 35: Comparison of energy density (BH)max at room temperature of various permanent magnet materials

Magnet formulations reducing or eliminating the use of rare-earth metals have been a subject of industry research that would significantly reduce the cost of PMSMs widely used in EVs. Iron Nitride Magnets (α''-$Fe_{16}N_2$) are a promising magnet formulation utilizing no rare-earth metals. Research and projections in Figure 35 show that iron nitride magnets can be stronger than current neodymium magnets as well, making them a promising future technology for compact and powerful electric motors. This development has the potential to further reduce motor costs and maintain the sustainability of electric vehicles in the long term.

3.2.2 Permanent Magnet Assisted Synchronous Reluctance Motor (PMSyn-RM)

PMSyn-RMs take advantage of the magnetic and reluctance effect to produce torque. Table 14 shows the comparison between the Internal PMSM used in the 2020 VW ID3 and the PMSyn-RM used in the 2018 Tesla Model 3 Dual Motor Long Range (rear motor). On a Kg/kW basis, Tesla uses 33% less rare earth magnet (by weight) when compared to VW. Mass-produced BEVs are now becoming more prevalent, and this example shows the opportunity available to reduce costs by optimizing the traction motor design to minimize the mass of rare earth magnets used.

Table 14: Comparison of VW ID3 motor and Tesla Model 3 rear motor

		2020 VW ID.3	2018 Tesla Model 3 rear motor
Peak power output	kW	150	190
Overall weight	kg	94	89
Copper weight stator wire + busbar	Kg	6.9	6.8
Magnet (NeFeB) weight - rotor	Kg	2.5	1.8
Magnet (NeFeB) weight / KW output	grams/kW	16.7	9.5
Peak power density	kW/kg	1.6	2.4
Stator copper slot fill factor	%	72	46
Source: Electric Vehicle and Battery Teardowns – UBS Evidence Lab [11]			

3.2.3 Induction Motors

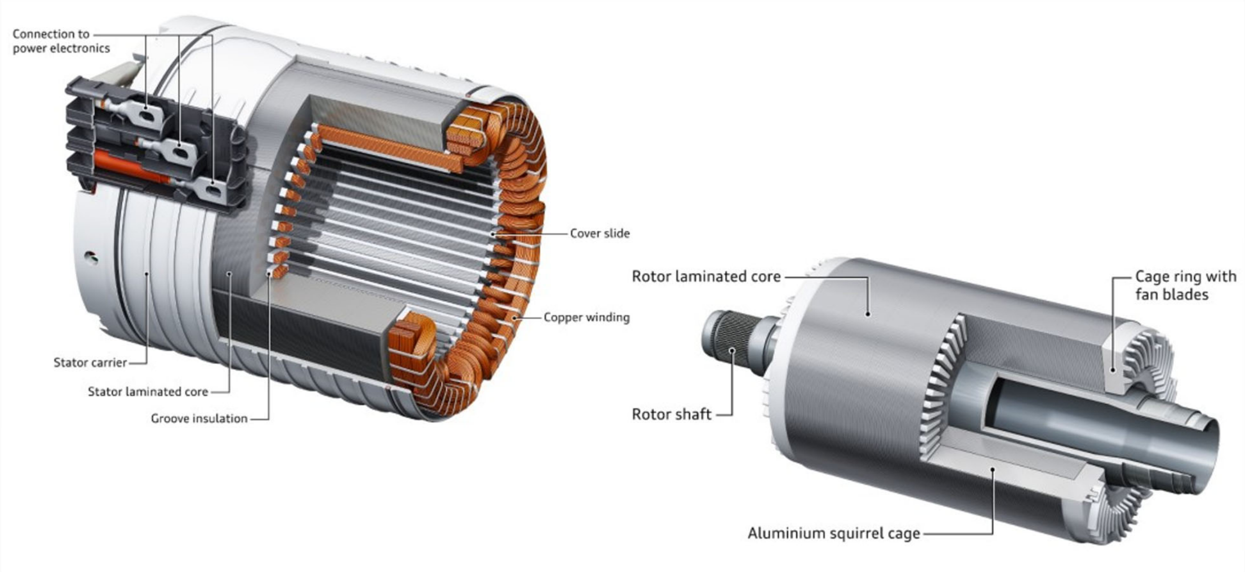


Figure 36: Audi APA250 induction motor with cast aluminum rotor conductors (125kW). Source: Audi

Induction motors (IM) have a lower peak efficiency when compared to PMSM but are attractive due to their significantly lower cost and not needing rare earth permanent magnets. In most current production automotive applications, the copper conductors in the rotor are replaced with aluminum bringing costs down further. An Induction motor with cast aluminum stator conductors is very cost-effective - 2.5$/kW for Tesla Model 3/Y front motor (Figure 34) compared to 4+ $/kWh for PMSMs/ PMSyn-RM. The Tesla Model S, Model X, Model 3, and Model Y use IM on one axle while the Audi E-tron uses induction motors on the front and rear axle. ZF offers a range of MD and HD e-axles and drives based on induction motors- “AxTrax AVE”, “CeTrax [72], [73]. An example of an induction motor used in a current EV is shown in Figure 36.

3.2.4 Wound Rotor Synchronous Motor (WRSM)/ Electrically Excited Synchronous Motor

Wound rotor synchronous motors (alternatively: electrically excited synchronous motors or separately excited synchronous motors) use electromagnets in the place of permanent magnets used in PMSM. The power to magnetize the rotor coils is transmitted wirelessly by inductive (rotating transformer) or capacitive methods. The manufacturing cost of a WRSM is higher than PMSM due to the added complexity of the rotor coils and wireless power transmission to the rotor, but material costs are lower owing to eliminating the NdFeB magnets. The performance characteristics of a WRSM are similar to a PMSM with the peak efficiency being marginally lower. But owing to the ability to adjust the rotor field intensity, a WRSM has a higher efficiency over a larger portion of the operating map (Speed torque map). Figure 37 shows the WRSM powertrain (motor, inverter, and reduction gearbox) used in the BMW-iX, a 5,700 lb. full-size SUV. The two motors on the front and rear axle of an iX M60 produce a combined power output of 447 kW.

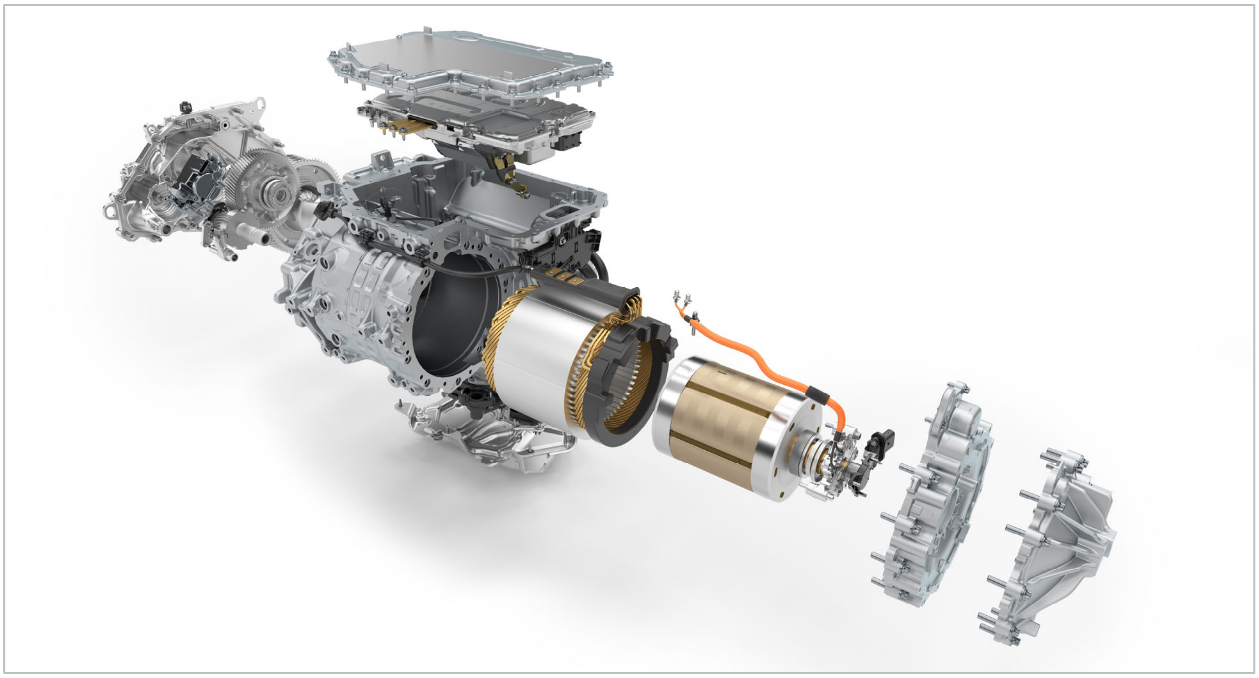
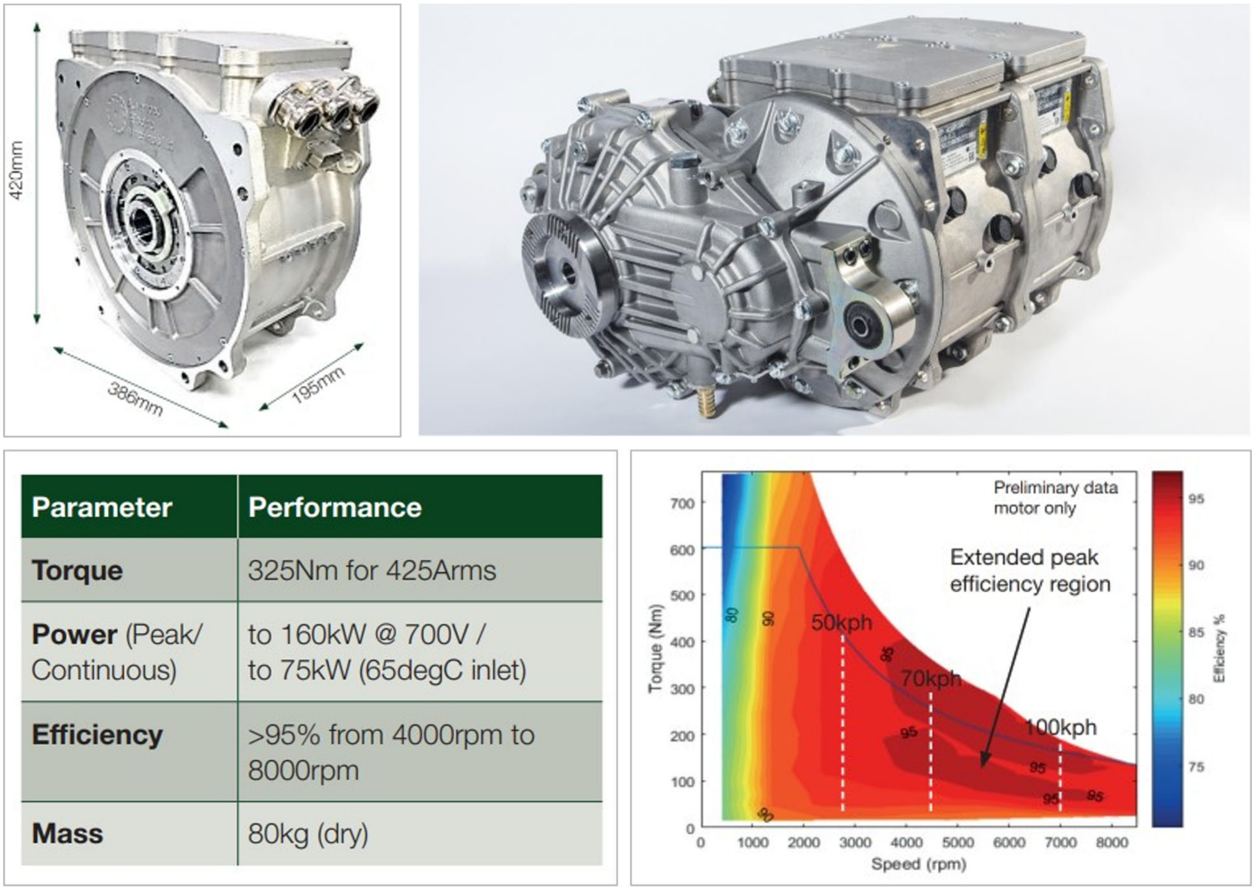


Figure 37: BMW "5th Gen E-drive Technology" employing a wound rotor synchronous rotor used in the BMW iX (Source: BMW)

3.2.5 Switched Reluctance Motor

Switched reluctance motors have the simplest construction (and are the cheapest) among different traction motor technologies with a wound stator and a rotor consisting of toothed laminations. Traditionally these motors have suffered from torque ripple, acoustic noise, and the need for specialized power electronics to drive them (incompatible with standard inverters). Over the past few years, all of these problems have been solved resulting in new motors having started limited production, being available for OEMs to test and integrate into their new product programs. Figure 38 shows the HDSRM300 from Advanced Electric machines (UK), a switched reluctance motor developed for MDHD applications.

The motor is compatible with off-the-shelf 3-phase inverters requiring no special power electronics. To reduce costs the motor also uses compressed aluminum stator windings in place of copper (Figure 40).



Parameter	Performance
Torque	325Nm for 425Arms
Power (Peak/ Continuous)	to 160kW @ 700V / to 75kW (65degC inlet)
Efficiency	>95% from 4000rpm to 8000rpm
Mass	80kg (dry)

Figure 38: SRMs from Advanced Electric Machines UK. Single HDSRM300 motor (top left) and two motors integrated into a single gearbox (top right) (up to 3 motors can be combined into a single drive unit). Bottom: performance numbers and motor efficiency. [74]

3.2.6 Replacing Copper Stator Windings with Aluminum – Reducing The Cost of Electric Motors

Table 14 shows that there is about 6.8 kg of copper in the Tesla and VW ID3 motors. The average annual commodity price of copper (COMEX, average daily closing price) has risen from 1.85 $/kg in 2000 to $9.3 $/kg in 2021 [75] and is projected to be north of 15$/kg in 2025 [76]. Between 2021 and 2030 the global demand for copper is projected to increase by 900% [16] and could result in a significantly higher price of copper.

Aluminum windings as shown in Figure 39 and Figure 40 can be used in place of copper with minimal impact on the performance or efficiency of the electric motor. Cast windings can achieve a 90% slot fill factor compared to 60% achieved by mass-produced machine wound copper wire and 70-75% for hairpin windings. The coils can be manufactured by high-pressure die-casting, investment casting, lost foam casting, low-pressure casting, or metal injection molding.

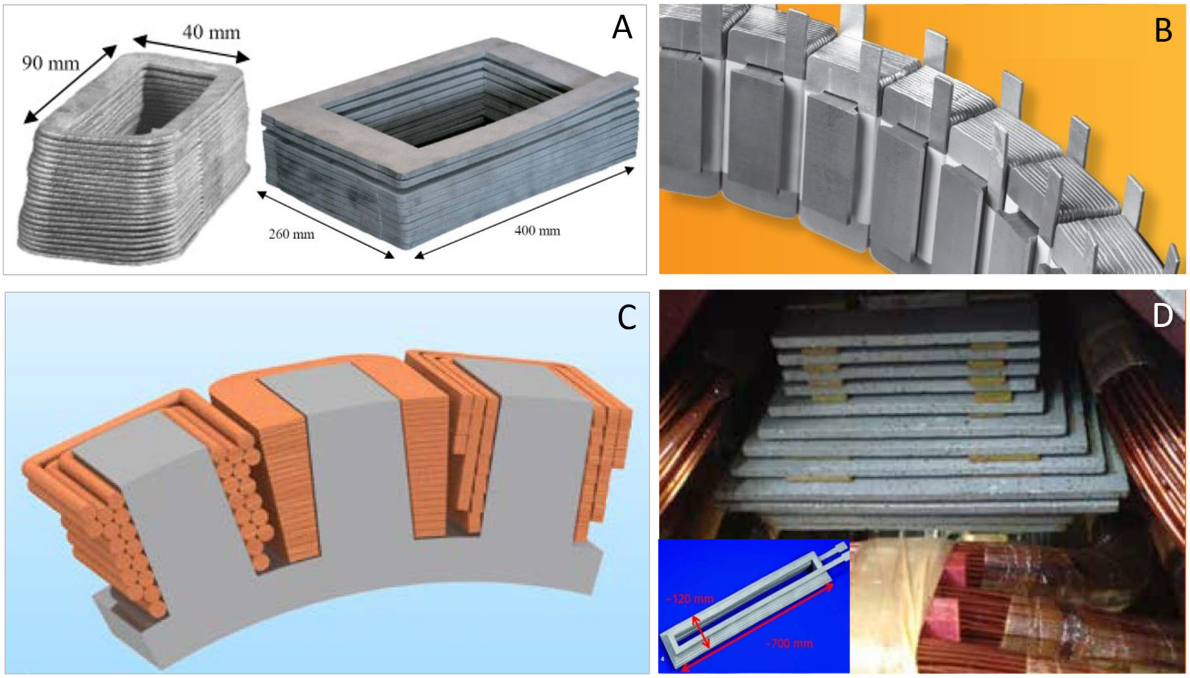
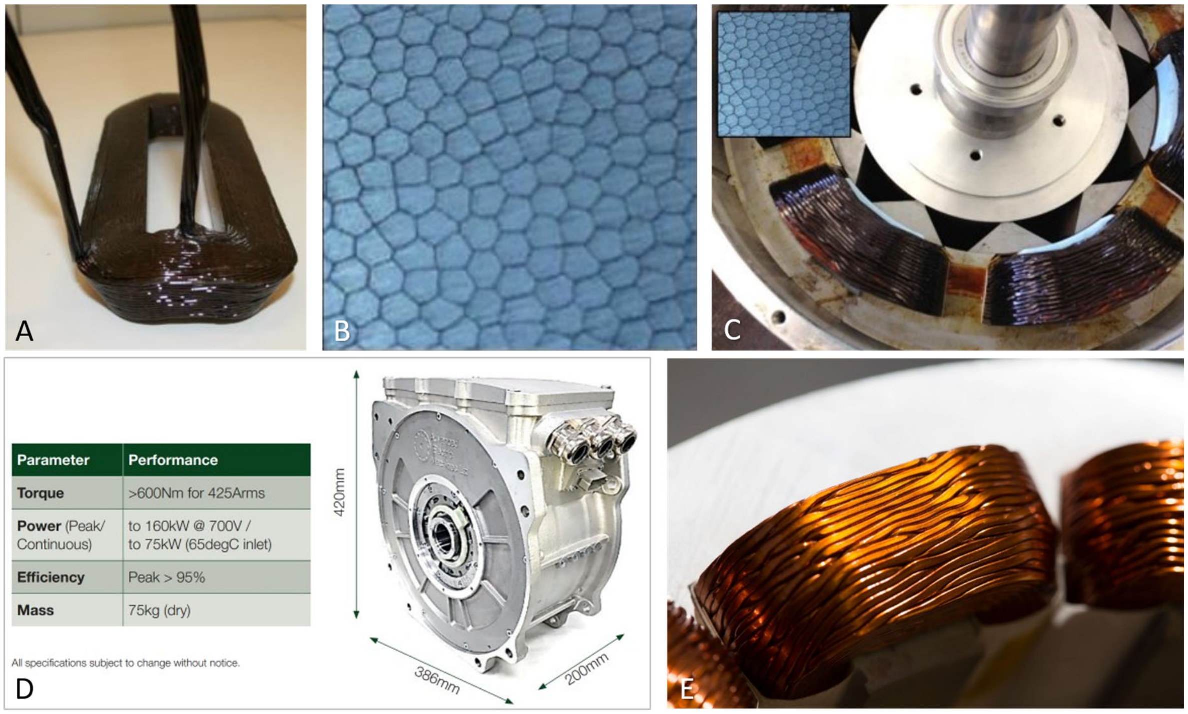


Figure 39: Cast Aluminum Stator Coils (Source: Fraunhofer IFAM). A: Cast coils suitable for all different sizes. B: detail of a stator assembled with cast aluminum coils. C: Illustration of slot fill factor - Comparison of cast coil 90% vs. wound cylindrical wire 60%, and hairpin windings 70-75%. D: Cast coil installed in a 300 kW DC motor



Parameter	Performance
Torque	>600Nm for 425Arms
Power (Peak/ Continuous)	to 160kW @ 700V / to 75kW (65degC inlet)
Efficiency	Peak > 95%
Mass	75kg (dry)

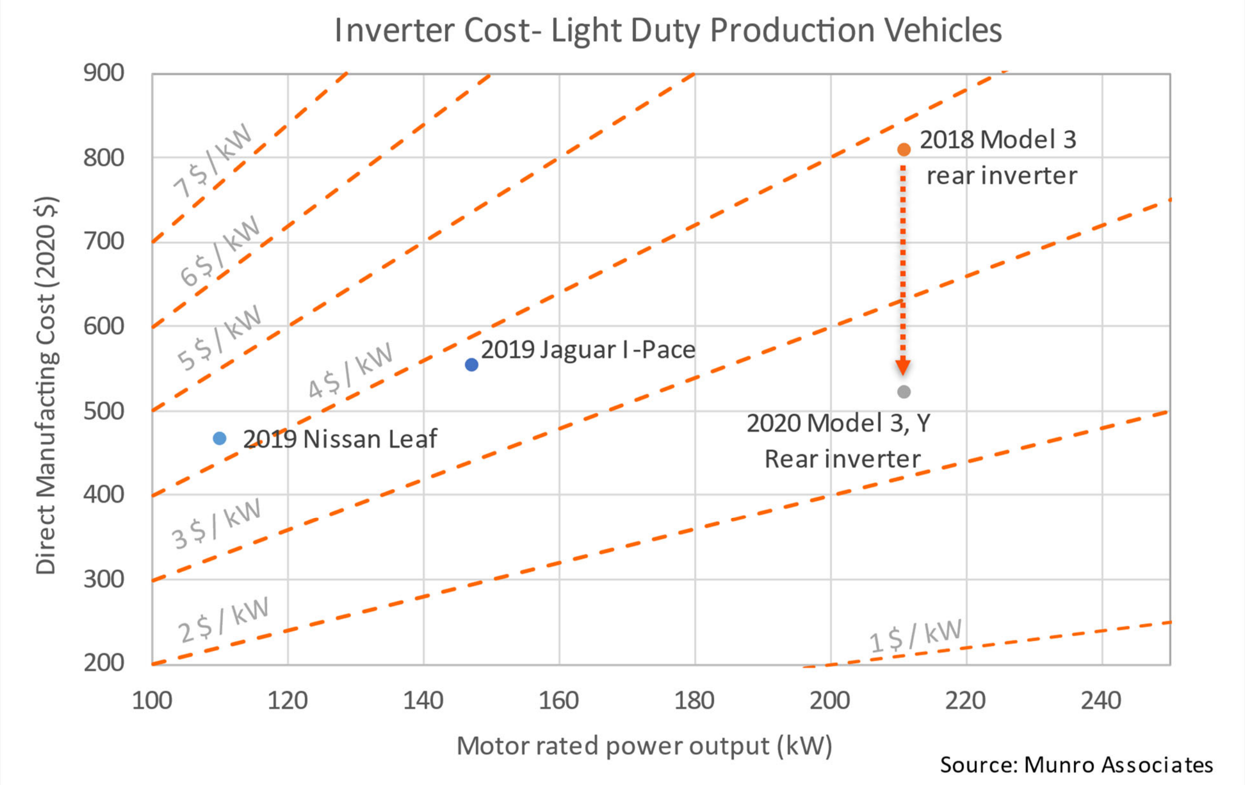
All specifications subject to change without notice.

Figure 40: A: Pre-compressed wound aluminum coil, B: cross-section of the coil showing high slot fill factor, C: coil installed in an 80 kW motor designed for automotive application. E: Specifications of a production switched reluctance traction motor using compressed aluminum winding (Advanced Electric Machines UK) and the detail of its compressed wound aluminum stator coil (E) [74], [77]

Alternatively, wound pre-compressed wound aluminum coils (Figure 40) can be used in place of copper windings. these have demonstrated a slot fill factor of 77% [77]. Advanced Electric machines ltd (UK) offers an MDHD application-specific switched reluctance motor that uses pre-compressed aluminum windings ([74], Figure 38, Figure 40).

3.3 Power Electronics

Inverters convert DC power from the battery to a variable frequency AC power to control the speed of the traction motor. BEVs such as the Nissan Leaf, Chevrolet Bolt, and Jaguar I-Pace use inverters that use Silicon insulated-gate bipolar transistors (Si IGBTs). With the release of the Model 3 in 2018, Tesla became the first company to use silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs) (sourced from ST Microelectronics, in an in-house inverter design) for a mass-produced vehicle. SiC MOSFET-based inverters have higher efficiency when compared to ones using Si IGBTs. Over low speed and load points (typical light-duty city cycle), an Si IGBT inverter has an efficiency of 96% while the SiC MOSFET-based inverter has an efficiency of 99% [78].



Source: Munro Associates

Figure 41: Cost of BEV inverters based on teardown studies. Source: Munro & Associates

Figure 41 shows the cost of various light-duty inverters based on teardown studies by Munro & Associates. The teardown shows that in 2018, the Tesla Model 3 inverter that used SiC MOSFETs (with in-house mass production) was at price parity (≈$4/kW) with the Nissan Leaf and Chevrolet Bolt inverters that used Si IGBTs. The 2020 Tesla Model 3 and Model Y have an inverter with the same performance but at a significantly lower cost (≈$2.5/kW), significantly cheaper than the competition. New BEVs from Hyundai-Kia, Lucid, Riviian, and others all use silicon carbide in their inverters.

New wide bandgap materials like gallium nitride (GaN) and aluminum nitride (AlN) promise inverters with even higher efficiency and performance. These have not been factored into this study.

3.4 Chargers

Chargers for electric vehicles range from low-powered AC chargers in the Level 1 and Level 2 range, which cover chargers up to 2 kW and 20 kW respectively, to higher-powered Level 3 AC chargers up to 70-100 kW, and DC fast chargers of 300 kW or more. The type, power level, and the number of chargers for a given fleet depend on the usage profiles, vehicle battery capacity, depot charging space available, and downtime for charging available for the fleet.

Delivery fleets that depart from a central location in the morning and return at night, while driving varying routes day to day may be more suited to depot charging. Depending on the number of delivery vehicles and overlap in schedules, charging strategies may include one charger per vehicle or one charger shared across multiple vehicles. Other fleets such as transit buses, which travel a set route repeatedly, may opt for overhead or on-route fast DC charging. Fast DC chargers can add a significant amount of range with a 15-minute charge that may overlap with a driver’s break. These fleets can use DC chargers as a standalone solution, or in combination with overnight depot chargers.

Other factors may be accounted for in a certain fleet’s decision to go with depot, on-route, or a combination charging strategy. Utility costs for power, as well as demand charges, levied on top of the per-kW-h cost for high spikes in use can cause electricity costs to be more favorable to one strategy or another. The length of downtime available for a depot charge, as well as staffing availability to manage charging when depot chargers are shared between vehicles, may determine if depot charging is feasible for a given application. New charger designs are now available in the market that can be connected to multiple vehicles and the individual charge rates can be managed remotely. Finally, the equipment costs of the chargers are a driving factor in the charging decision [79]. The optimum mix of chargers and bus battery/on-board charger specifications depends on the number of buses in a fleet, the route distances, and the ability to amortize the higher cost of DC fast chargers over time.

In addition to the charging equipment, installation is a cost associated with the chargers that must be considered. Installation considers the connection to the utility, wiring, trenching, and facility improvements such as concrete pouring that must be made to install the charger. In general, charger installation costs scale with charging power.

3.4.1 AC Chargers – Depot

Depot chargers are considered to be the standard pedestal type chargers that provide AC power to the vehicle’s power port. An on-board charger aboard the vehicle receives this AC power and converts it to DC for charging the batteries. When costing a vehicle and charger, the onboard charger and the depot charger must be properly matched for maximum charging capabilities, or the charge rate will be limited by the lower-rated of the two. AC charging is slower and slightly less efficient due to the conversions that must occur to charge the batteries. AC charging is primarily up to the 19.6 kW level but can exceed that in some applications. Costs for AC charging were sourced for 25, 50, and 70 kW applications, and were extrapolated to a theoretical 100 kW AC charger for the reference case option of the 400 kW-h bus battery capacity to achieve the 4-hour charge time. Table 15 shows the costs for these chargers.

3.4.2 DC Fast Chargers – On-Route Charging

DC fast chargers bypass the onboard charger and deliver Direct Current directly to the battery. DC fast chargers are typically seen in power levels of 50, 150, or 350+ kW, and can deliver significant charge to vehicles in minutes instead of hours.

Due to the fast charging time, DC fast chargers can support an entire fleet with fewer chargers than AC charging would require. In applications where the vehicles operate over a set route repeatedly, such as transit, on-route DC chargers could supplant depot charging. Due to the increased power level and integrated inverting of power from AC to DC, DC chargers are significantly more expensive to procure and install than AC chargers.

3.4.3 Charger Costs

Costs for chargers and their installation are shown per power level in Table 15.

Table 15: Charger costs used in the study

Charger and Installation Costs	
Charger - 25 kW	$3,548
Installation – 25 kW	$3,626
Charger – 50 kW	$25,836
Installation – 50 kW	$14,005
Charger – 70 kW	$54,300
Installation – 70 kW	$21,938
Charger – 100 kW	$85,671
Installation – 100 kW	$34,232
Charger - DCFC 300+	$259,999
Installation - DCFC 300+	$132,707

4.0 Results

This section presents the results of the 2027 BEV vs ICE incremental and TCO cost analysis for the vehicle categories in Table 16. The overall results of the incremental costs and TCO studies are presented, followed by a detailed analysis of each vehicle class.

Table 16: MDHD vehicles studied for 2027 BEV vs ICE TCO

Market Segment	Weight Class	Battery Capacity (kW-h)
Transit Bus	Class 8	400
School Bus	Class 7	60
Shuttle Bus	Class 3-5	200
Delivery and Service Van, Box and Stake Truck	Class 3	100
Short Haul Delivery, Service, Box, and Stake Truck	Class 6-7	150
Short Haul Delivery and Service Van, Box and Stake Truck	Class 4-5	100
Refuse Hauler	Class 8	200

4.1 Incremental Costs – ICE to EV Summary

Incremental costs of each powertrain type were calculated to determine if purchasing an EV over an ICE vehicle in 2027 is an attractive option to a fleet owner. The primary difference in these vehicles is the powertrain, so the combined costs of an engine, aftertreatment system and transmission were compared to the combined costs of an equivalent power battery, inverter, motor, and other power electronics such as an on-board charger.

To cost the ICE powertrain, a representative 2021 regulations-compliant diesel powertrain was selected for each segment and the cost estimated based on published literature sources as shown in Sections 2.1 to 2.3. Sections 4.3 through 4.9 outline the powertrain for each vehicle class costed. To determine the powertrain cost in 2024 and 2027, additional costs for updating the powertrain for compliance with the 2024 and 2027 Phase II GHG rule and the California NOx standards were added to the engine, aftertreatment, and transmission costs as outlined in Sections 2.1, 2.2, and 2.3, respectively. These resulting costs were considered as the base powertrain cost for 2024 and 2027 as “delete costs” to be compared with the electrification “add costs” in the same years. The decreasing cost of electrification and a direct comparison of EV vs emissions-compliant diesel costs in 2027 are shown in Figure 42.

To cost a representative BEV powertrain, the battery, motor, and power electronics (Inverter, DC-DC converter, and onboard charger) costs from published literature are considered as outlined in Section 2.5 for an electric vehicle in 2021, 2024, and 2027.

The incremental costs presented are conservative estimates, in which the lowest-cost diesel option is compared to the highest-cost EV option. For the diesel, the base case does not consider any hybridization, which adds cost and complexity. The EV powertrains consist of a higher-cost NMC battery and heavy-duty specific motors. Even with these conservative estimates, base powertrain incremental costs favored electrification by 2027, except for Class 3 shuttles. Costs required to meet emissions compliance in 2027 caused an increase in the cost of the engine, aftertreatment, and transmission systems, while the projected costs of batteries, motors, and power electronics drop over time due to increasing adoption and advancements in technology. This crossover in incremental cost can be seen in Figure 42, and typically occurs between 2024 and 2027.

To consider the impact of various technologies on the cost of both powertrain types, a cost sensitivity analysis was performed on these incremental powertrain costs. Adoption of technologies such as hybridization of diesels can improve fuel economy, reduce emissions, and help meet more stringent emissions targets, with the effect of increasing the diesel powertrain costs. For electric heavy-duty vehicles, less power-dense battery chemistries such as LFP can provide similar performance (and advantages in some cases, as mentioned in Section 3.1) as NMC while reducing electrification costs. The use of light-duty motors can bring costs down as well. These sensitivities were applied to the 2027 powertrains for both types of vehicles to create a range of possible scenarios.

For the 2027 diesel powertrain cost sensitivity analyses, three ICE powertrain options were considered:

1) Base Case – Lowest cost 2027-compliant powertrain: base powertrain with added costs for emissions compliance in 2027 (shown in Figure 42)
2) Sensitivity 1 – Diesel engine with mild hybridization: 48V system with an integrated starter/generator that enables start/stop operation and some regeneration
3) Sensitivity 2 – Full hybrid powertrain with the diesel engine optimized for hybridization

For the ICE powertrain, hybridization sensitivities were not considered for the 2021 and 2024 timeframes.

For the 2027 EV powertrain cost sensitivity analyses, three BEV powertrain options were considered:

1) Base Case – Highest projected 2027-cost powertrain: NMC Batteries, HD specific motors
2) Sensitivity 1 – EV powertrain with lower-cost battery chemistry: LFP batteries, HD specific motors
3) Sensitivity 2 – Lowest-cost EV powertrain: LFP batteries + Motors based on light duty architecture (based on teardown studies of light-duty vehicles).

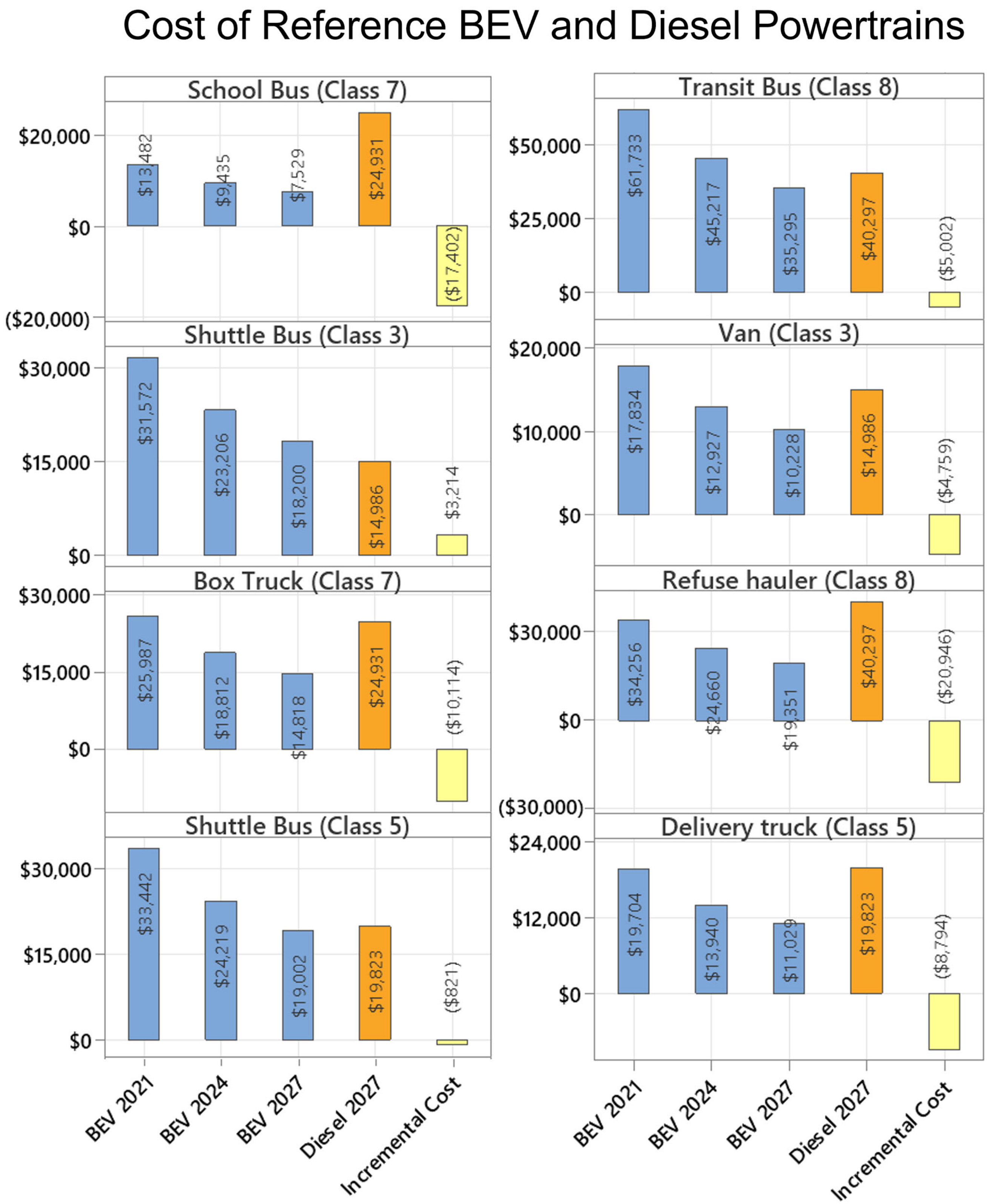


Figure 42: Incremental costs of electrification of MD/HD vehicles. Blue bars are EV powertrain (add) costs in 2021, 2024, and 2027, orange bars are ICE powertrain (delete) costs in 2027, and the yellow bars are incremental costs of the BEV in 2027 (negative value implies that an electric powertrain is cheaper than diesel in 2027

The 2027 differences in costs between the 2027 diesel and EV powertrains were calculated for each combination of costs listed above, resulting in 9 possible incremental costs between a diesel powertrain and an electric powertrain. From these costs for each vehicle class, the low, median, and high incremental cost scenario was selected to highlight the range of possible incremental costs of electrification, which are shown for each vehicle category in Figure 43.

With sensitivities applied, all vehicle classes favor electrification by 2027. Only two scenarios in this analysis do not favor electrification, the median, and the high incremental costs of a class 3 shuttle EV powertrain.

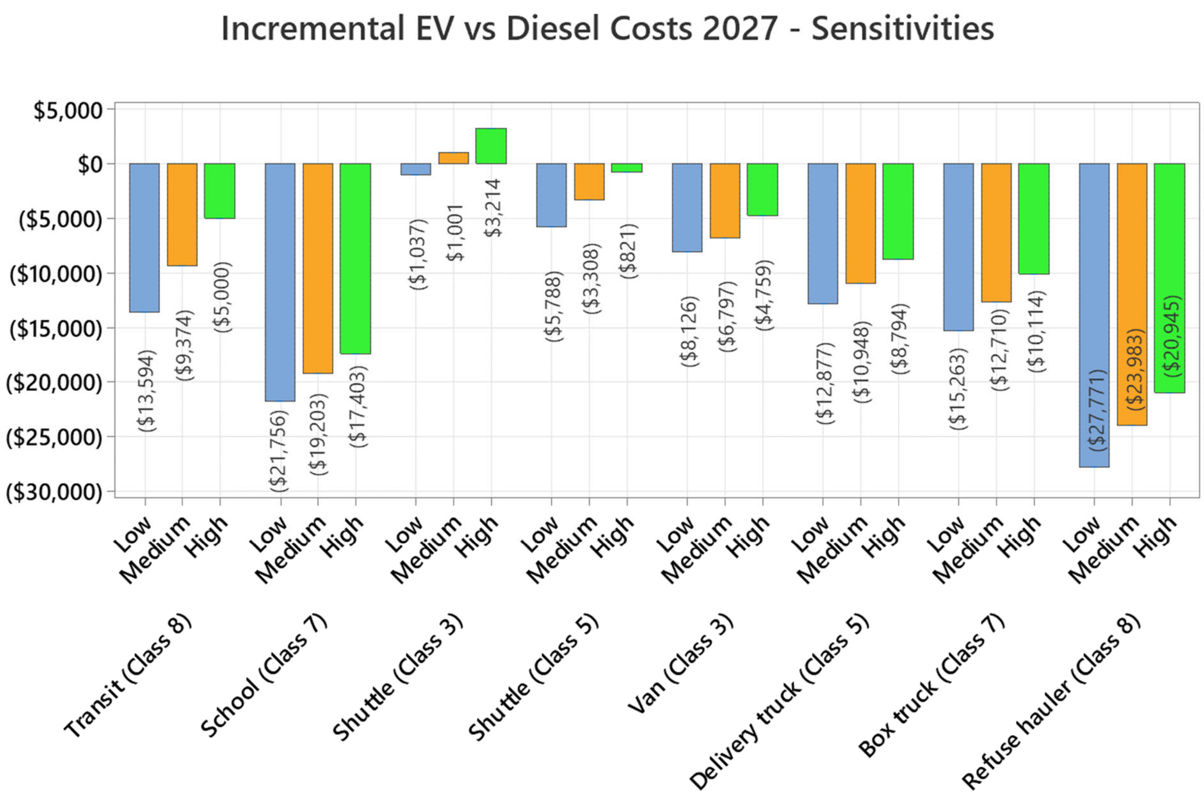


Figure 43: Incremental costs of electrification for three possible scenarios in all classes.

4.2 Total Cost of Ownership Summary

Costs incurred through vehicle operation can far exceed the vehicle purchase price and are a crucial component of evaluating vehicle selection for fleet operators. For calculating the TCO of an ICE vehicle and an EV purchased in 2027, the following categories of expenses were considered:

1. Purchase cost
2. Energy cost (diesel/ electricity)
    a. Fuel or energy economy variances
    b. Diesel or electricity cost variances
3. Maintenance cost (based on published fleet data)

4. Infrastructure type and costs (based on the methodology explained in Section 2.0)
5. Vehicle lifetime in years
6. Yearly vehicle miles

The reference case TCO assumes the approximate average projected cost of all factors and is likely the closest to what a fleet operator would incur over the lifetime of the vehicle. Because the number of factors is too high to account for every possible scenario, a low and high case was created to serve as lower and upper limits, and contain all of the best- and worst-case scenarios, respectively. While unlikely that all these factors overlap simultaneously to create either of these cost scenarios, they work to bound the possible TCO considerations that a fleet operator may consider when making a purchasing decision.

To determine the difference in vehicle cost between an ICE vehicle and an EV, a powertrain assumption is created for each case. The ICE and BEV powertrains for each of the three cases are:

1) Low:
    a. ICE - Base diesel (no hybridization)
    b. BEV - LFP batteries, LD motors, onboard charger sized for 6-hour depot charge
2) Reference:
    a. ICE - Diesel engine with mild hybridization
    b. BEV - LFP batteries, HD motors, onboard charger sized for 4-hour depot charge, mild refresh for transit/school owing to their high mileage, severe driving cycles, and age
3) High:
    a. ICE - Full hybrid
    b. EV - NMC batteries, HD Motors, DC fast charging, full refresh (replacing the battery pack and drive motor)

In addition, a low, reference, and high projected cost for electricity or diesel was used for all TCO cases, based on the EIA Annual Outlook [37]. These costs are shown in Table 17.

Table 17: Energy costs used for the three TCO cases.

	Diesel ($/gal)	Electricity ($/kWh)
Low	$2.10	$0.07
Reference	$3.25	$0.12
High	$4.61	$0.15

Each vehicle class utilized a mileage, lifetime, fuel or energy economy, vehicle price, and maintenance costs specific to the class. These were sourced from available literature, with the lowest values or values resulting in lower costs utilized in the low cases, the highest in the high cases, and the approximate mean value in literature used as the reference case. The values used for each class of vehicle are detailed in the following sections for each class [26] [32] [28] [80] [81] [82] [83] [84] [85] [86] [35] [15] [87] [33] [88].

The report presents the cumulative TCO ($) and a TCO ($/Mile) over the life of the vehicle. A discount rate of 3% is used for calculations. Summary results of the TCO are shown in Figure 44. The specific values and relative effect of the sensitivities studied are detailed in the following sections.

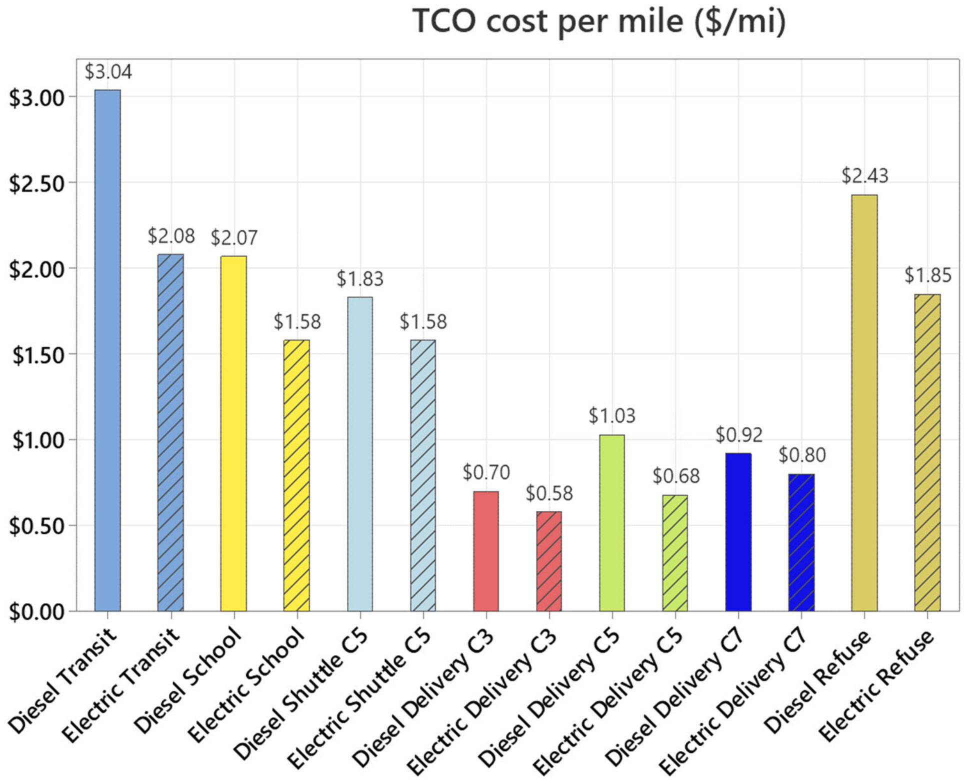


Figure 44: Reference case TCO for all classes considered.

4.3 Class 8 Transit Bus

4.3.1 IC Engine Vehicle Powertrain Cost (Delete Cost)

The representative Class-8 transit bus is assumed to be a 40-foot vehicle equipped with a diesel engine and an automatic transmission. An example powertrain for a 2021 transit bus is shown in Table 18. The representative diesel powertrain was chosen based on offerings in the segment that have a high market share (Example: New Flyer Xcelsior XD40).

Table 18: 2021 Class 8 Transit Bus, 2021 base ICE powertrain example

Engine	Cummins L9 - Transit bus (diesel)
Power	260 kW (350 HP)
Torque	925-1150 lb-ft
Transmission	Allison B400R (Automatic)

The 2021 base powertrain shown in Table 18 consisting of a diesel engine, 2021-compliant aftertreatment system, and an automatic transmission will need to be updated with improved engine, transmission, and aftertreatment technologies to meet GHG regulations in 2024 and 2027, with further improvements for 2027 Low NOx rules. Table 19 breaks down the engine, transmission, and aftertreatment system cost for a conventional diesel ICE engine in 2021, 2024, and 2027 to meet the Phase II greenhouse gas rule and the 2027 Low NOx rule.

Table 19: Class 8 Transit bus - ICE powertrain cost in 2021, 2024, and 2027 to meet regulations.

	2021 w/ GHG	2024 w/ GHG	2027 w/GHG	2027 w/ GHG + Low NOx
Engine	$10,303	$10,775	$10,812	$13,013
Aftertreatment	$6,975	$6,992	$6,993	$9,455
Transmission	$15,628	$15,628	$15,628	$17,829
Total	$23,633	$33,395	$33,433	$40,297

Along with the base conventional diesel powertrain, two alternative ICE powertrains are evaluated for calculating the total cost of ownership in 2027, a mild-hybrid 48-volt system, and a P2 full hybrid system with an optimized engine for increased fuel economy.

Table 20 compares the cost of the regulations-compliant base ICE powertrain (diesel engine + automatic transmission) in 2027 with the mild hybrid and full hybrid options in 2027.

Table 20: Class 8 Transit Bus - ICE, mild-hybrid and full-hybrid cost in 2027

Base Cost	$40,297
Sensitivity 1 - Mild Hybrid	$41,566
Sensitivity 2 - Full Hybrid with improved engine	$44,516

4.3.2 Electric Vehicle Powertrain Cost – (Add Cost)

Table 21 gives the powertrain component costs of a BEV for 2021, 2024, and 2027. The base cost scenario assumes an NMC battery pack with MDHD-specific motors. Sensitivity 1 case assumes an LFP battery pack that is significantly cheaper ($/kWh). Sensitivity 2 case assumes an LFP battery pack along with multiple light-duty-based motors, the costs based on motors mass-produced for light-duty application. All costs assume high-volume manufacturing similar to what OEMs have in the light-duty space.

Table 21: Class 8 Transit Bus - Electric Powertrain Component Cost

Component	Size kW/ kWh	2021	2024	2027
Battery pack (NMC)	400	$49,360	$36,080	$27,360
Inverter	260	$949	$854	$768
Onboard charger	100	$5,594	$5,035	$4,531
DC-DC Converter	10	$559	$503	$453
Motor	260	$4,771	$2,245	$1,683
Gearbox	260	$500	$500	$500
Total Base Case – NMC batteries, HD Motor		**$61,733**	**$45,217**	**$35,295**
LFP battery pack	400	$42,980	$31,416	$23,824
Total Sensitivity 1 Case – LFP batteries, HD motor		**$55,353**	**$40,553**	**$31,760**
Motor, light-duty cost	260	$1,045	$940	$846
Total Sensitivity 2 Case – LFP batteries, LD motor		**$51,627**	**$39,249**	**$30,923**

4.3.3 Incremental Cost - Diesel Vs Battery Electric, Class 8 Transit Bus

Table 22 combines Table 20 and Table 21 to compare the three ICE powertrain costs (base, mild, and full hybrid + improved engine) with the three BEV powertrain costs (base, LFP batteries, and LFP batteries + light-duty motors). The incremental cost of BEVs in 2027 is lower than diesel, mild-hybrid, and full hybrid buses for all scenarios. Factoring the different combinations of the diesel engine, level of hybridization, and BEV components, the powertrain of the electric transit bus is estimated to be between $5000 and $13,594 cheaper than the diesel counterpart.

Table 22: Class 8 Transit Bus ICE Delete Vs BEV add costs – 2027

ICE powertrain description	Diesel	Diesel mild hybrid	Diesel full hybrid
ICE powertrain (delete) cost	$40,297	$41,566	$44,516
BEV powertrain description	**LFP + LD motors**	**LFP + HD motors**	**NMC + HD motors**
BEV powertrain (add) cost	$30,923	$31,760	$35,295

Figure 45 compares the Diesel powertrain cost to BEV powertrain cost in 2021, 2024, and 2027. The cost of the base BEV powertrain is higher in 2021 and 2024 but lower in 2027. (Data from Table 19, Table 20, and Table 21). Powertrain cost parity between diesel and battery electric is reached sometime between 2024 and 2027.

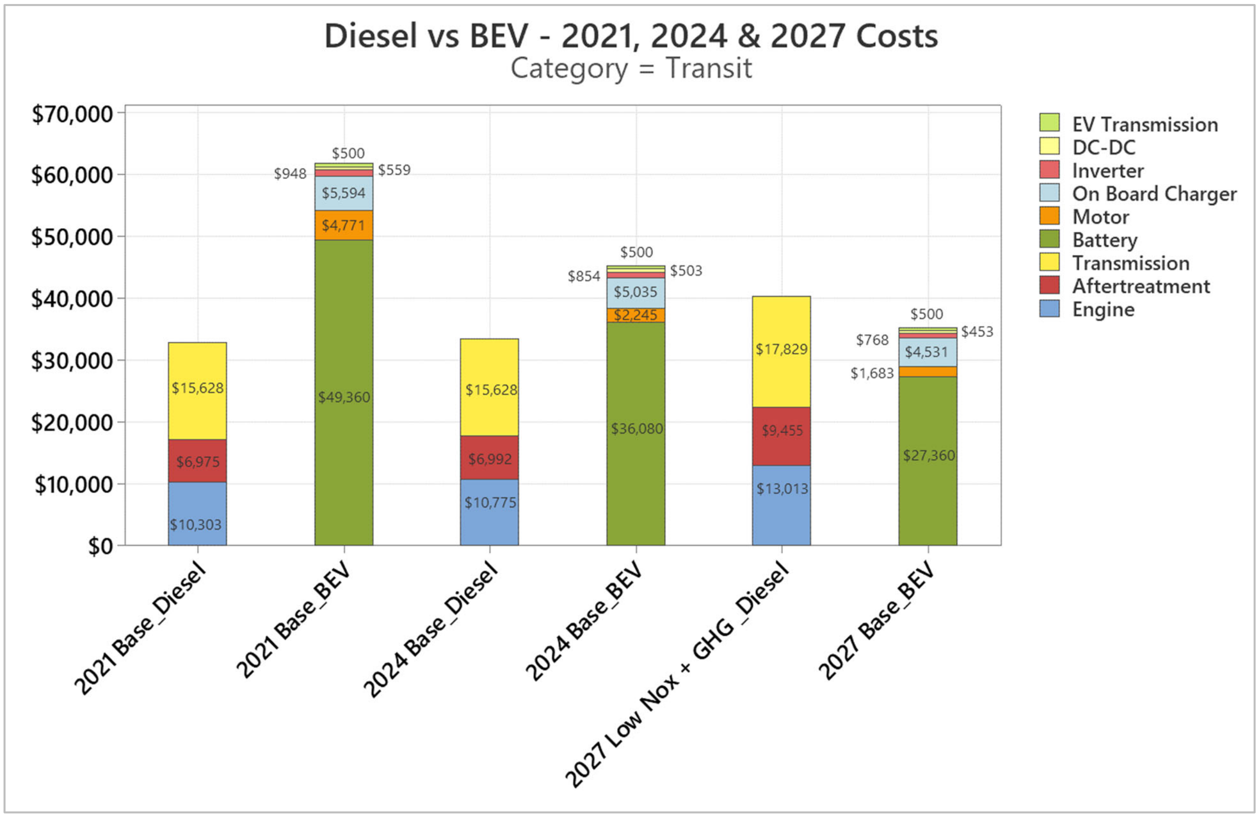


Figure 45: Class 8 Transit bus – Base Diesel and BEV powertrain costs 2021, 2024, and 2027

4.3.4 Total Cost of Ownership

The total cost of ownership is calculated in $/mile to compare an electric vehicle purchased in 2027 with the diesel alternative. Table 23 gives the main assumptions used in the calculation of TCO of transit buses. Table 24 gives the final value of the cost of ownership calculated in $/mile. In the reference case scenario, the TCO of the electric bus is expected to be more than 27% lower in 2027 when compared to the diesel alternative.

Table 23: Class 8 transit bus - Main inputs TCO Calculation

Bus Type	Diesel			Electric		
Case	low	reference	high	low	reference	high
Lifetime age of a vehicle (years)	12			12		
Lifetime mileage (mi)	331,200	500,000	652,836	331,200	500,000	652,836
Fuel consumption (kWh/mile, mpg)	7	4	3	1.6	2.16	2.4
Fuel cost ($/ kWh, $/gal)	$2.10	$3.25	$4.61	$0.07	$0.12	$0.15
Purchase cost ($)	$345,695	$531,337	$603,965	$340,602	$527,173	$600,642
Refresh ($)	$0	$16,971	$34,800	$0	$23,824	$29,957
Infrastructure cost ($/miles)	$0.002	$0.004	$0.01	$0.23	$0.24	$0.20
Maintenance ($/mile)	$0.63	$1.46	$1.65	$0.33	$0.61	$0.81

Table 24: Total cost of ownership for a class 8 transit bus ($/mile).

TCO	Low	Reference	High
Diesel Transit	$1.84	$3.04	$3.70
Electric Transit	$1.64	$2.08	$2.16

Figure 46 gives the effect of the variation of the various factors (purchase cost, fuel/ electricity cost/ maintenance, and infrastructure) on the reference TCO of a diesel and electric bus. Given the long operating life (12 years) and high mileage, the variation in the purchase cost of both diesel and electric buses has a relatively small impact on the TCO, less than ±5%. For a diesel transit bus, the factors with the highest impact on TCO are the cost of diesel and maintenance cost. For an electric bus, the biggest factors are maintenance and infrastructure cost. With batteries and motors with higher durability and mass production of chargers and associated power electronics, the future costs will most likely be lower than projected in the study.

Figure 47 compares the cumulative cost of the reference diesel transit bus to the reference electric bus purchased in 2027. The electric bus is cheaper to buy because of the rapid decline of battery costs. The annual operating cost of an electric transit bus is significantly lower because of the lower fuel cost (electricity vs diesel), lower maintenance cost, and the high annual mileage. The operating cost of an electric bus is low enough to offset the high infrastructure cost of installing captive chargers by the end of the first year of ownership (2028).

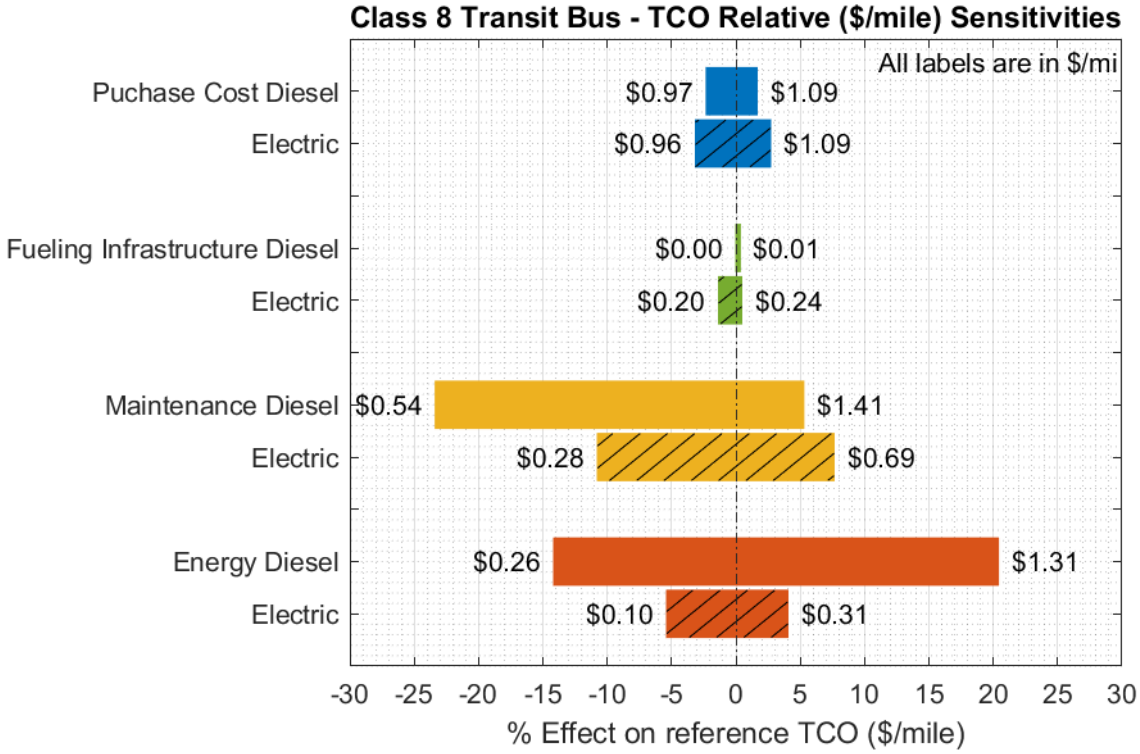


Figure 46: Class 8 Transit Bus TCO sensitivities (listed in Table 23) and their % contribution to reference TCO

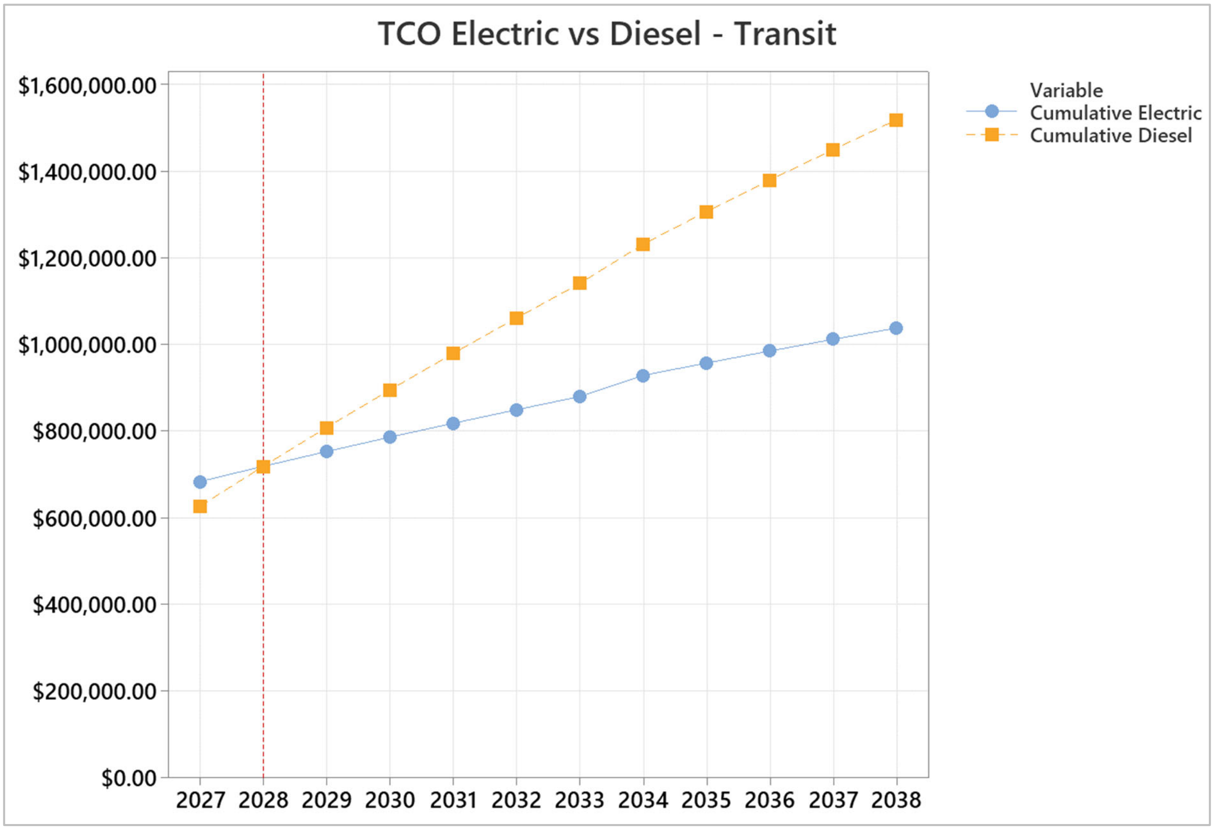


Figure 47: Class 8 Transit bus cumulative cost of ownership for vehicle lifetime (2027-2038)

Figure 48 breaks down the absolute ($/mile) and relative (percentage) contributions of purchase cost, infrastructure cost, powertrain refresh cost, maintenance, and energy costs to the TCO for the low, reference, and high TCO cases of the diesel and electric buses (shown in Table 23).

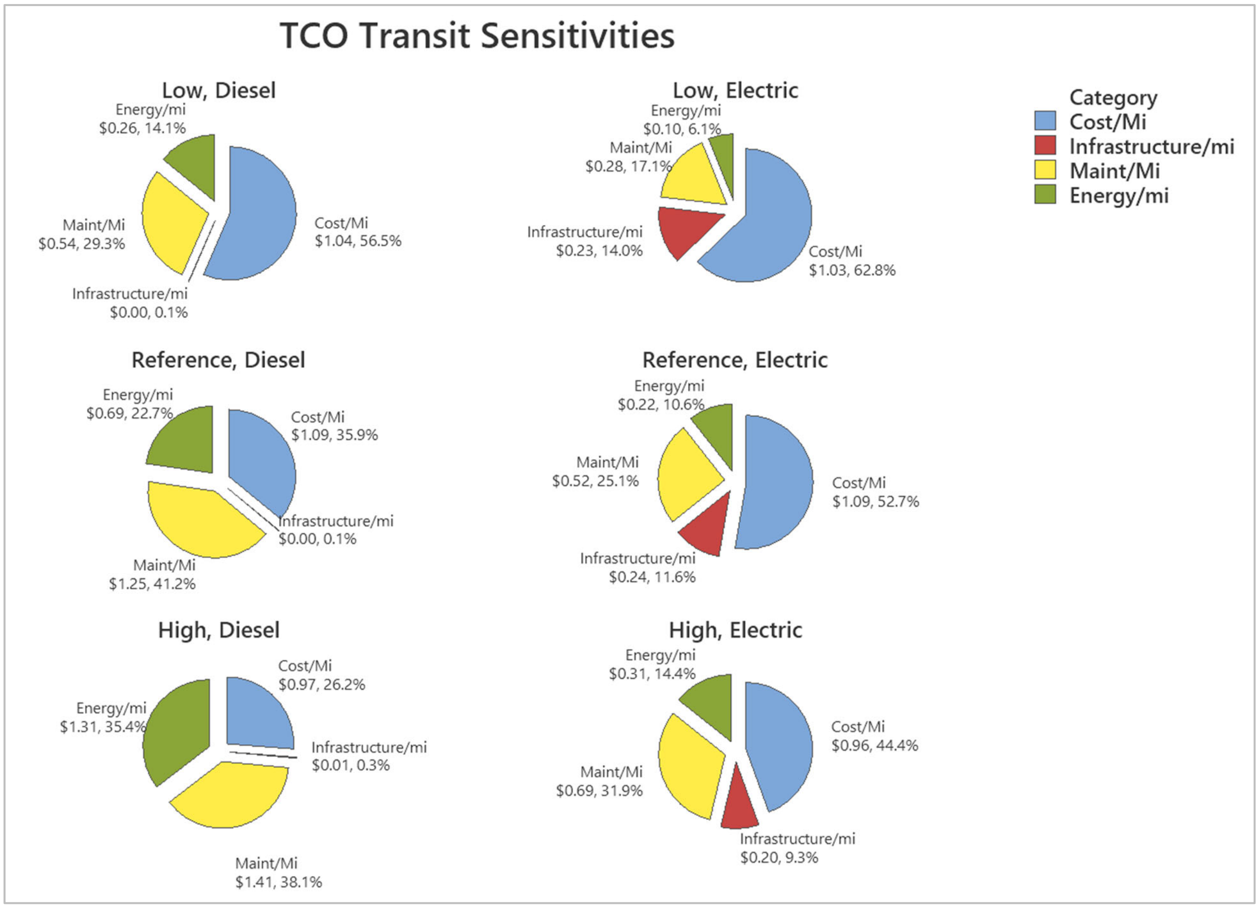


Figure 48: Class 8 Transit bus category contributions to TCO for the low, reference, and high TCO scenarios.

4.4 Class 7 School Bus

4.4.1 IC Engine Vehicle Powertrain Cost (Delete Cost)

An example powertrain for a representative class 7 diesel school bus in 2021 is shown in Table 25

Table 25: 2021 Class 7 School Bus, 2021 base ICE powertrain example

Engine	Cummins B 6.7
Power	191 kW (260 HP)
Torque	660 lb-ft
Transmission	Allison 2500 PTS

The 2021 base powertrain shown in Table 25 consisting of a diesel engine with an automatic transmission will need to be updated with improved engine, transmission, and aftertreatment technologies to meet 2027 (Phase II GHG and the 2027 Low NOx) legislation. Table 26 breaks down the engine, transmission,

and aftertreatment system cost for a conventional diesel ICE engine in 2021, 2024, and 2027 to meet the Phase II greenhouse gas rule and the 2027 Low NOx rule.

Table 26: Class 7 school bus - ICE powertrain cost in 2021, 2024 and 2027

	2021	2024	2027	2027 Low NOx
Engine	$6,508	$6,979	$7,016	$8,435
Aftertreatment	$4,338	$4,355	$4,356	$6,618
Transmission	$7,677	$7,677	$9,878	$9,878
Total	$18,523	$19,011	$21,250	$24,931

Along with the base conventional diesel powertrain, two alternative ICE powertrains are evaluated for calculating the total cost of ownership in 2027, a mild-hybrid 48-volt system, and a P2 full hybrid system with an optimized engine for increased fuel economy.

Table 27 compares the cost of the base ICE powertrain (diesel engine + automatic transmission) in 2027 with the mild hybrid and full hybrid options in 2027.

Table 27: Class 7 school bus - ICE, mild-hybrid and full-hybrid cost in 2027

Base Cost	$24,931
Sensitivity 1 – Mild Hybrid	$26,201
Sensitivity 2 – Full Hybrid with improved engine	$28,142

4.4.2 Electric Vehicle Powertrain Cost – (Add Cost)

Table 28 gives the powertrain component costs of a BEV for 2021, 2024, and 2027. The base cost scenario assumes an NMC battery pack with MDHD-specific motors. Sensitivity 1 case assumes an LFP battery pack that is significantly cheaper ($/kWh). Sensitivity 2 case assumes an LFP battery pack along with motor costs based on high volume mass-produced motors in the light-duty application. All costs assume high-volume manufacture.

Table 28: Class 7 school bus - Electric Powertrain Component Cost

Component	Size kW/ kWh	2021	2024	2027
Battery pack (NMC)	60	$7,404	$5,412	$4,104
Inverter	190	$693	$624	$562
Onboard charger	15	$839	$755	$680
DC-DC Converter	10	$559	$503	$453
Motor	190	$3,486	$1,641	$1,231
Gearbox	190	$500	$500	$500
Total Base Case		**$13,482**	**$9,435**	**$7,529**
LFP battery pack		$6,447	$4,712	$3,573
Total Sensitivity 1 Case		**$12,525**	**$8,736**	**$6,998**
Drive unit, light-duty cost		$763	$687	$618
Total Sensitivity 2 Case		**$9,802**	**$7,782**	**$6,386**

4.4.3 Incremental Cost - Diesel Vs Battery Electric, Class 7 School Bus

Table 29 combines Table 27 and Table 28 to compare the three ICE powertrain costs (base, mild, and full hybrid + improved engine) with the three BEV powertrain costs (base, LFP batteries, and LFP batteries + light-duty motors). Assuming high volume manufacture, the incremental cost of BEVs in 2027 is lower than diesel, mild-hybrid, and full hybrid buses for all scenarios evaluated. Factoring in all the different combinations of the diesel engine, level of hybridization, and BEV components, the powertrain of the electric school bus is estimated to be between $17,400 and $19,200 cheaper than the diesel counterpart in 2027. This large difference is due to the small battery pack size required by a school bus to cover the majority of the routes.

Table 29: Class 7 school bus - ICE Delete Vs BEV add costs – 2027

ICE powertrain description	Diesel	Diesel mild hybrid	Diesel full hybrid
ICE powertrain (delete) cost	$24,931	$26,201	$28,142
BEV powertrain description	**LFP + LD motors**	**LFP + HD motors**	**NMC + HD motors**
BEV powertrain (add) cost	$6,386	$6,998	$7,529

Figure 49 compares the Diesel powertrain cost to the base BEV powertrain cost in 2021, 2024, and 2027 (Data from Table 26, Table 27, and Table 28). Due to the small battery size required by a school bus to cover the majority of routes, the cost of the base BEV powertrain is lower than a comparable diesel powertrain today (2021) when using costs achieved by high volume manufacturing (seen in the light-duty space). Some of these cost savings will be realized in the near future with suppliers scaling up the production of battery cells and modules, motors, and power electronics and the ability to share these standardized components between vehicles of different sizes and use cases providing suppliers with significant manufacturing volumes.

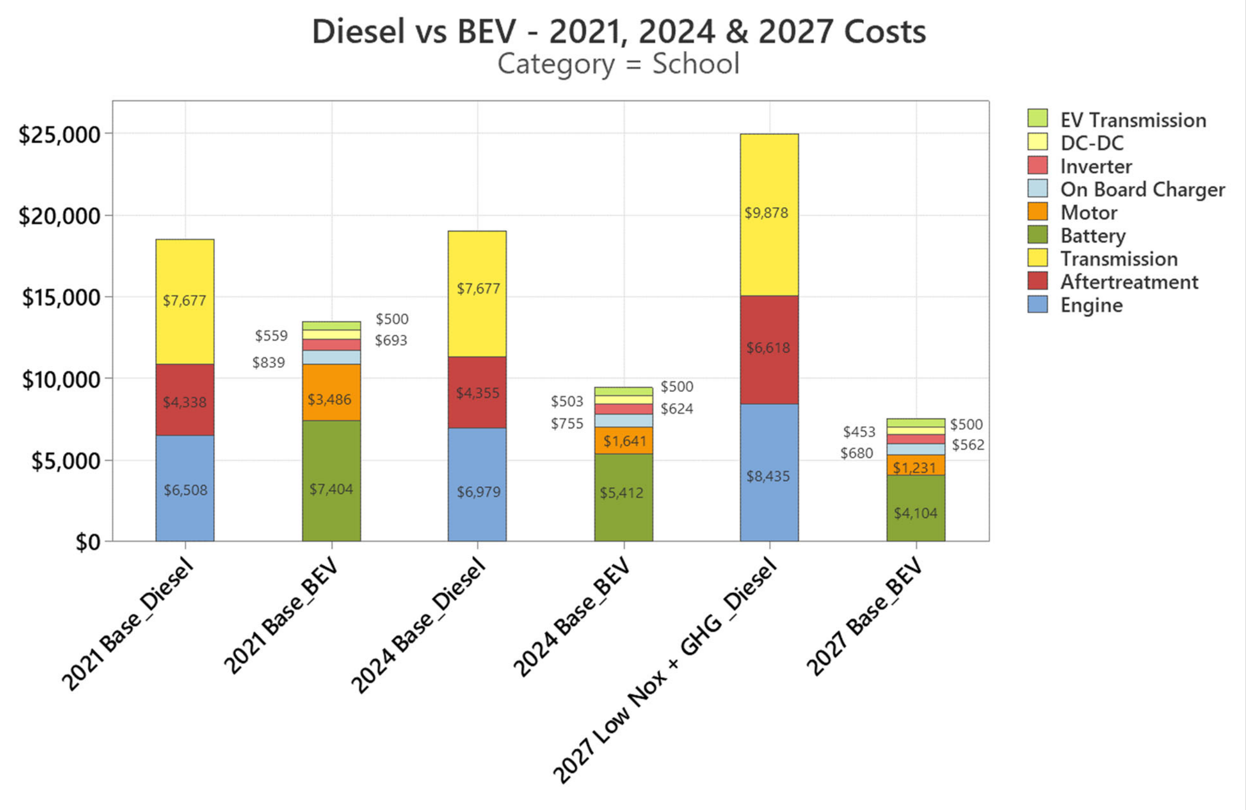


Figure 49: Class 7 school bus – Base Diesel and BEV powertrain costs 2021, 2024, and 2027

4.4.4 Total Cost of Ownership

The total cost of ownership is calculated in $/mile to compare an electric vehicle purchased in 2027 with the diesel alternative. Table 30 gives the main assumptions used in the calculation of TCO of class 7 school buses. Table 30 gives the breakdown of all the costs used in the calculation of the TCO.

Table 30: Class 7 school bus - Main inputs TCO Calculation

Bus Type	Diesel			Electric		
Case	low	reference	high	low	reference	high
Lifetime age of a vehicle (years)	10			10		
Lifetime mileage (mi)	221,120	221,120	425,000	221,120	221,120	425,000
Fuel consumption (kWh/mile, mpg)	7	7	3	1.30	1.40	1.40
Fuel cost ($/ kWh, $/gal)	$2.10	$3.25	$4.61	$0.07	$0.12	$0.15
Purchase price ($)	$108,683	$117,680	$118,992	$94,467	$103,035	$103,565
Refresh ($)	0	$3,574	$20,479	$0	$6,002	$10,602
Infrastructure cost ($/miles)	$0.003	$0.003	$0.006	$0.032	$0.032	$0.031
Maintenance ($/mile)	$0.63	$1.24	$1.65	$0.44	$1.05	$1.46

Table 31 gives the final value of the cost of ownership calculated in $/mile. In the reference case scenario, the TCO of a class 7 electric school bus purchased in 2027 is more than 27% lower when compared to the diesel alternative.

Table 31: Class 7 School Bus – TCO ($/mile)

TCO	Low	Reference	High
Diesel Transit	$1.31	$2.07	$3.13
Electric Transit	$0.93	$1.58	$2.03

Figure 50 gives the effect of the variation of the various factors (purchase cost, fuel/ electricity cost/ maintenance, and infrastructure) on the reference TCO of a diesel and electric bus. Due to the lower annual miles driven, the purchase cost of the class 7 school bus has a higher impact on the TCO compared to a class 8 transit bus. Fuel cost and maintenance have the highest impact on TCO for a diesel bus. These factors have a relatively low impact on the TCO of the electric school bus due to the low cost of electricity and the reduced maintenance costs. The infrastructure cost of electric school busses is relatively low due to the ability to use relatively slower onboard chargers due to the small battery size and long periods during the day when the vehicle is not used.

Figure 51 compares the cumulative cost of the base diesel school bus to the base electric bus purchased in 2027. Due to the lower purchase cost and the limited infrastructure requirements of an electric school bus, the TCO of an electric school bus is lower from the time of purchase. This advantage that the electric bus has on the TCO over diesel increases during the life of the vehicle due to the lower operating costs.

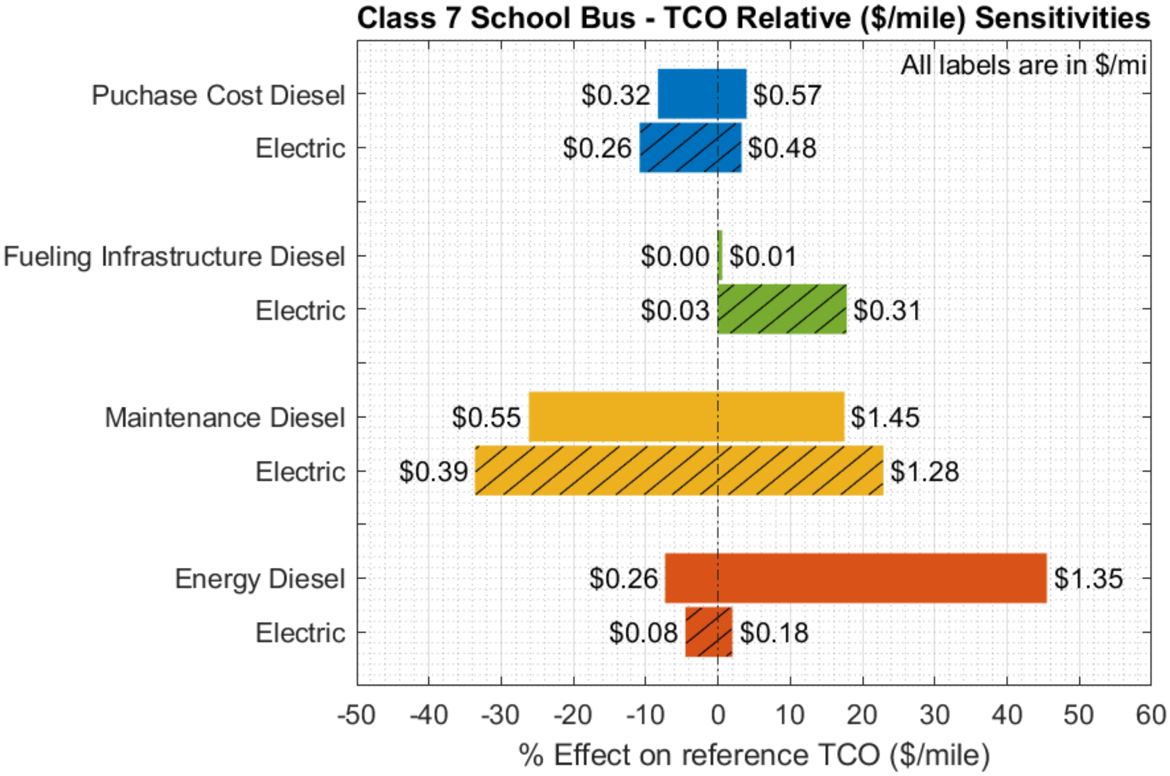


Figure 50: Class 7 School Bus – Sensitivities (listed in Table 30) and their % contribution to reference TCO

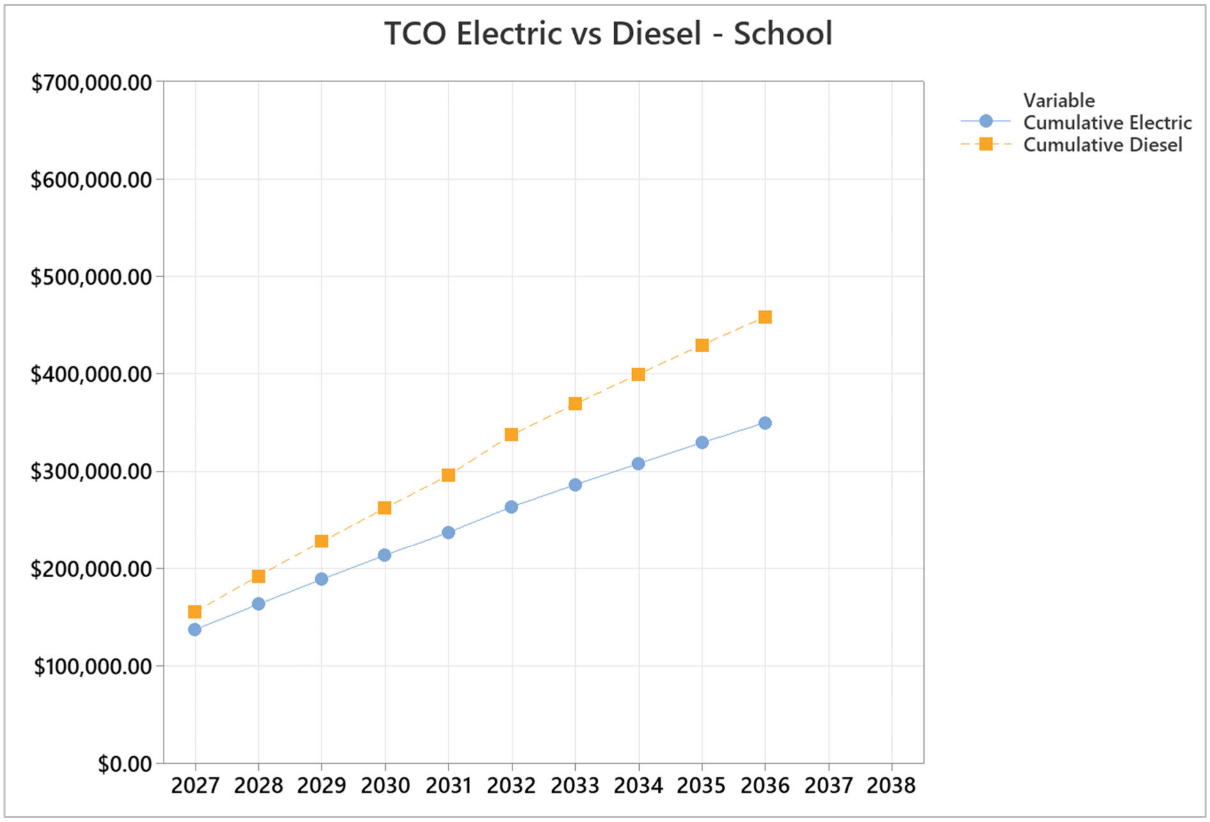


Figure 51: Class 7 school bus - Cumulative cost of ownership for 12 years of ownership (2027-2038)

Figure 52 breaks down the absolute ($/mile) and relative (percentage) contributions of various factors (purchase cost, infrastructure cost, powertrain refresh cost, maintenance, and energy costs) to the TCO for the low reference and high cases of the diesel and electric busses (shown in Table 30).

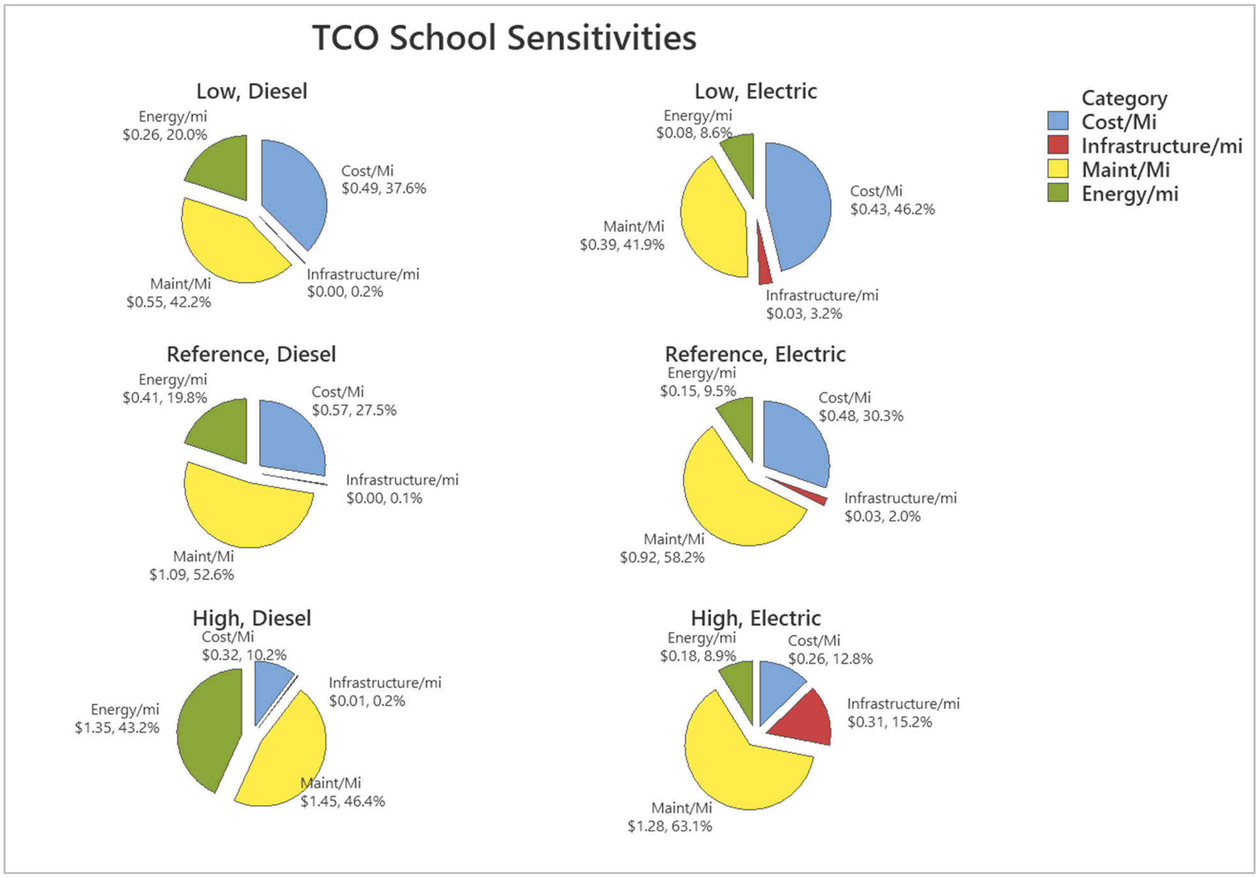


Figure 52: Class 7 school bus: Sensitivities of the total cost of ownership

4.5 Class 5 Shuttle Bus

4.5.1 IC Engine Vehicle Powertrain Cost (Delete Cost)

An example powertrain for a representative class 5 Shuttle bus powertrain in 2021 is shown in Table 32.

Table 32: 2021 class 5 Shuttle Bus, base ICE powertrain example

Engine	6.7-liter V8 Diesel
Power	246 kW (330 HP)
Torque	825 lb-ft
Transmission	6 Speed Automatic SelectShift

The 2021 base powertrain shown in Table 32 consisting of a diesel engine with an automatic transmission will need to be updated with improved engine, transmission, and aftertreatment technologies to meet 2027 (Phase II GHG and the 2027 Low NOx) legislation. Table 33 breaks down the engine, transmission,

and aftertreatment system cost for a conventional diesel ICE engine in 2021, 2024, and 2027 to meet the Phase II greenhouse gas rule and the 2027 Low NOx rule.

Table 33: Class 5 shuttle bus - ICE powertrain cost in 2021, 2024 and 2027

	2021	2024	2027	2027 Low NOx
Engine	$8,134	$8,606	$8,643	$10,062
Aftertreatment	$4,881	$4,897	$4,898	$7,161
Transmission	$2,600	$2,600	$2,600	$2,600
Total	$15,615	$16,103	$16,141	$19,823

Along with the base conventional diesel powertrain, two alternative ICE powertrains are evaluated for calculating the total cost of ownership in 2027, a mild-hybrid 48-volt system, and a P2 full hybrid system with an optimized engine for increased fuel economy.

Table 34 compares the cost of the base ICE powertrain (diesel engine + automatic transmission) in 2027 with the mild hybrid and full hybrid options in 2027.

Table 34: Class 5 shuttle bus - ICE, mild-hybrid, and full-hybrid cost in 2027

Base Cost	$19,823
Sensitivity 1 – Mild Hybrid	$21,093
Sensitivity 2 – Full Hybrid with improved engine	$22,304

4.5.2 Electric Vehicle Powertrain Cost – (Add Cost)

Table 35 gives the powertrain component costs of a BEV for 2021, 2024, and 2027. The base cost scenario assumes an NMC battery pack with MDHD specific motors. Sensitivity 1 case assumes an LFP battery pack that is significantly cheaper ($/kWh). Sensitivity 2 case assumes an LFP battery pack along with motor cost based on high volume mass-produced motors in the light-duty application. All costs assume high-volume manufacture.

Table 35: Class 5 shuttle bus - Electric Powertrain Component Cost

Component	Size kW/ kWh	2021	2024	2027
Battery pack (NMC)	200	$24,680	$18,040	$13,680
Inverter	223	$814	$732	$659
Onboard charger	50	$2,797	$2,517	$2,266
DC-DC Converter	10	$559	$503	$453
Motor	223	$4,092	$1926	$1444
Gearbox	223	$500	$500	$500
Total Base Case		**$33,442**	**$24,219**	**$19,002**
LFP battery pack		$21,490	$15,708	$11,912
Total Sensitivity 1 Case		**$30,252**	**$21,887**	**$17,234**
Drive unit, light-duty cost		$896	$806	$726
Total Sensitivity 2 Case		**$27,056**	**$20,768**	**$16,515**

4.5.3 Incremental Cost - Diesel Vs Battery Electric, Class 5 Shuttle

Table 36 combines Table 34 and Table 35 to compare the three ICE powertrain costs (base, mild, and full hybrid + improved engine) with the three BEV powertrain costs (base, LFP batteries, and LFP batteries + light-duty motors). Assuming high volume manufacture, the cost of a battery-electric powertrain in 2027 is lower than the comparable diesel, mild-hybrid, and full hybrid powertrain in the scenarios evaluated. Factoring in all the different combinations of the diesel engine, level of hybridization, and BEV components, the battery-electric powertrain for a class 5 shuttle bus is estimated to be between $821 and $5,788 cheaper than the diesel counterpart in 2027.

Table 36: Class 5 shuttle bus - ICE Delete Vs BEV add costs – 2027

ICE powertrain description	Diesel	Diesel mild hybrid	Diesel full hybrid
ICE powertrain (delete) cost	$19,823	$21,093	$22,304
BEV powertrain description	**LFP + LD motors**	**LFP + HD motors**	**NMC + HD motors**
BEV powertrain (add) cost	$16,515	$17,234	$19,002

Figure 53 (data from Table 33, Table 34, and Table 35) compares the diesel powertrain cost to BEV powertrain cost in 2021, 2024, and 2027. The cost of the base BEV powertrain is higher in 2021 and 2024 but lower in 2027. Powertrain cost parity between diesel and equivalent battery-electric powertrain is reached sometime between 2024 and 2027.

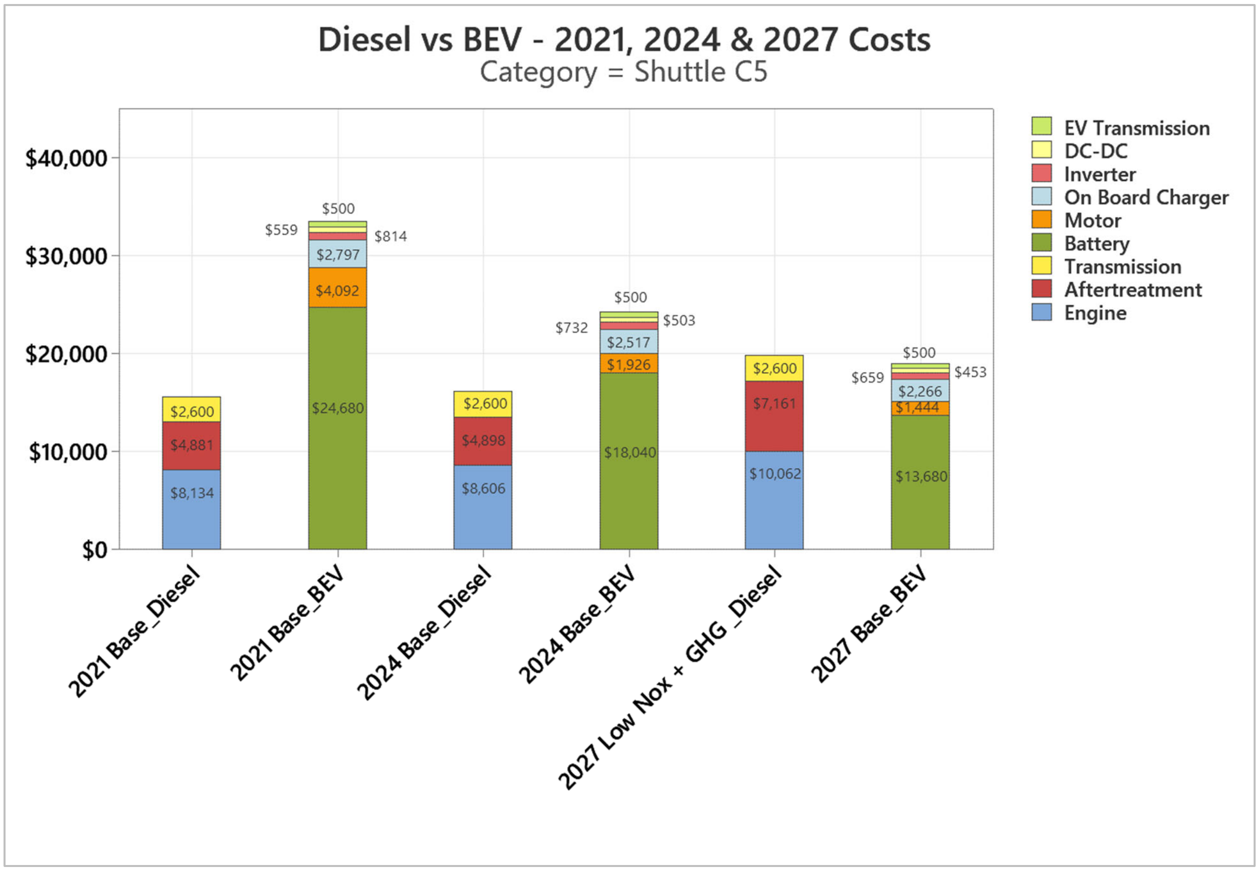


Figure 53: Class 5 shuttle bus – Base Diesel and BEV powertrain costs 2021, 2024, and 2027

4.5.4 Total Cost of Ownership

The total cost of ownership is calculated in $/mile to compare an electric vehicle purchased in 2027 with the diesel alternative. Table 37 gives the main assumptions used in the calculation of TCO for a class 5 shuttle bus. Table 37 gives more detail and the breakdown of all the costs used in the calculation of the TCO.

Table 37: Class 5 shuttle bus - Main inputs TCO Calculation

Bus Type	Diesel			Electric		
Case	low	reference	high	low	reference	high
Lifetime age of a vehicle (years)	7			7		
Lifetime mileage (mi)	100,000	200,000	200,000	100,000	200,000	200,000
Fuel consumption (kWh/mile, mpg)	10	7	3	1.30	1.40	2.00
Fuel cost ($/ kWh, $/gal)	$2.10	$3.25	$4.61	$0.07	$0.12	$0.15
Purchase price ($)	$43,478	$52,245	$96,079	$43,232	$52,130	$96,089
Refresh ($)	$0	$0	$0	$0	$0	$0
Infrastructure cost ($/miles)	$0.002	$0.003	$0.006	$0.40	$0.199	$0.81
Maintenance ($/mile)	$0.63	$1.24	$1.65	$0.44	$1.05	$1.46

Table 38 gives the final value of the total cost of ownership calculated in $/mile. In the reference case scenario, the TCO of the electric bus is more than 27% lower when compared to the diesel bus

Table 38: Class 5 Shuttle Bus – TCO ($/mile)

TCO	Low	Reference	High
Diesel Transit	$1.21	$1.83	$3.41
Electric Transit	$1.32	$1.58	$2.75

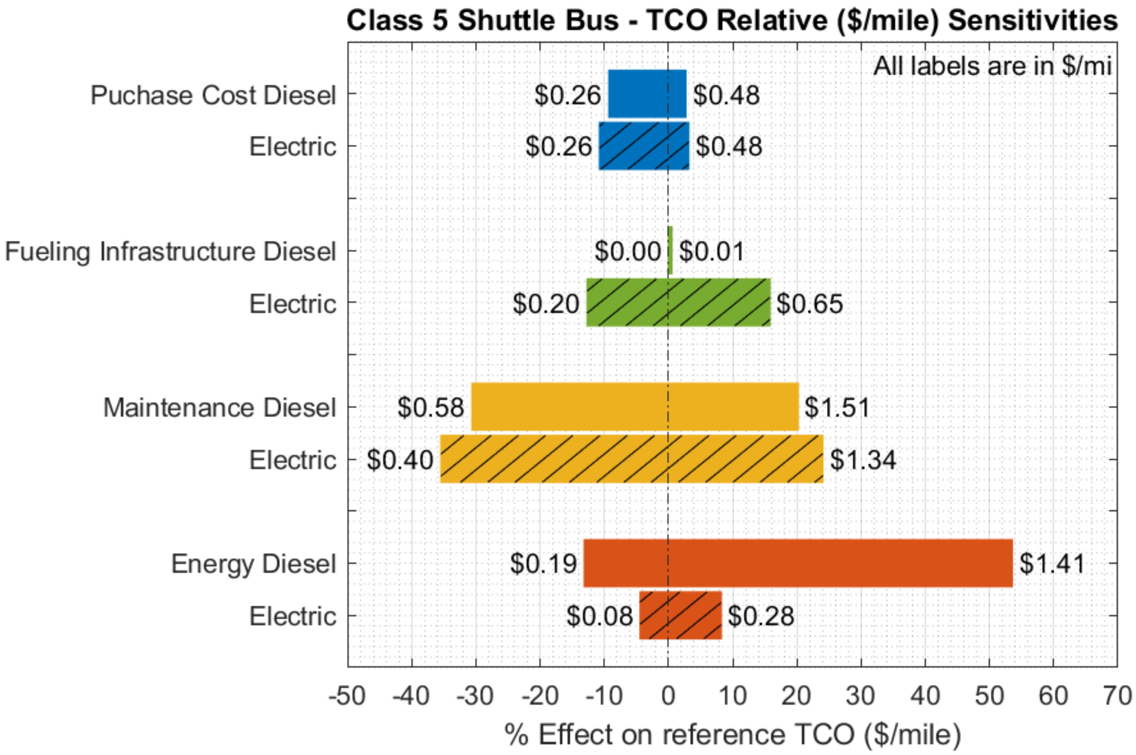


Figure 54: Class 5 shuttle bus – Sensitivities (listed in Table 30) and their % contribution to reference TCO

Figure 54 gives the effect of the variation of the various factors (purchase cost, fuel/ electricity cost/ maintenance, and infrastructure) on the reference TCO of a diesel and electric bus. Maintenance and fuel costs for an electric bus are lower when compared to the equivalent diesel. With the charger costs assumed in the report, it forms a significant part of the total cost of ownership of a BEV. Reducing the charger purchase and installation cost represents an opportunity to significantly reduce the TCO of an electric bus and make switching to a BEV even more attractive.

Figure 55 compares the cumulative cost of ownership of the reference diesel class 5 shuttle to the reference BEV purchased in 2027. The BEV is marginally (about $1000) more expensive to buy. The charging infrastructure that needs to be set up for the BEV adds to this cost. The cumulative TCO parity between the diesel and BEV is reached at the 3-year ownership mark (2029) due to the significantly lower operating cost of the BEV.

Figure 56 breaks down the absolute ($/mile) and relative (percentage) contributions of various factors (purchase cost, infrastructure cost, powertrain refresh cost, maintenance, and energy costs) to the TCO for the low reference and high cases of the diesel and electric class 5 delivery truck. The charging infrastructure accounts for a significant fraction (23.2%-27.2%) of the TCO of a BEV. The development of a robust DC fast-charging network will reduce the amount of spending that fleets have to make to install captive chargers reducing the TCO significantly speeding the adoption of BEVs.

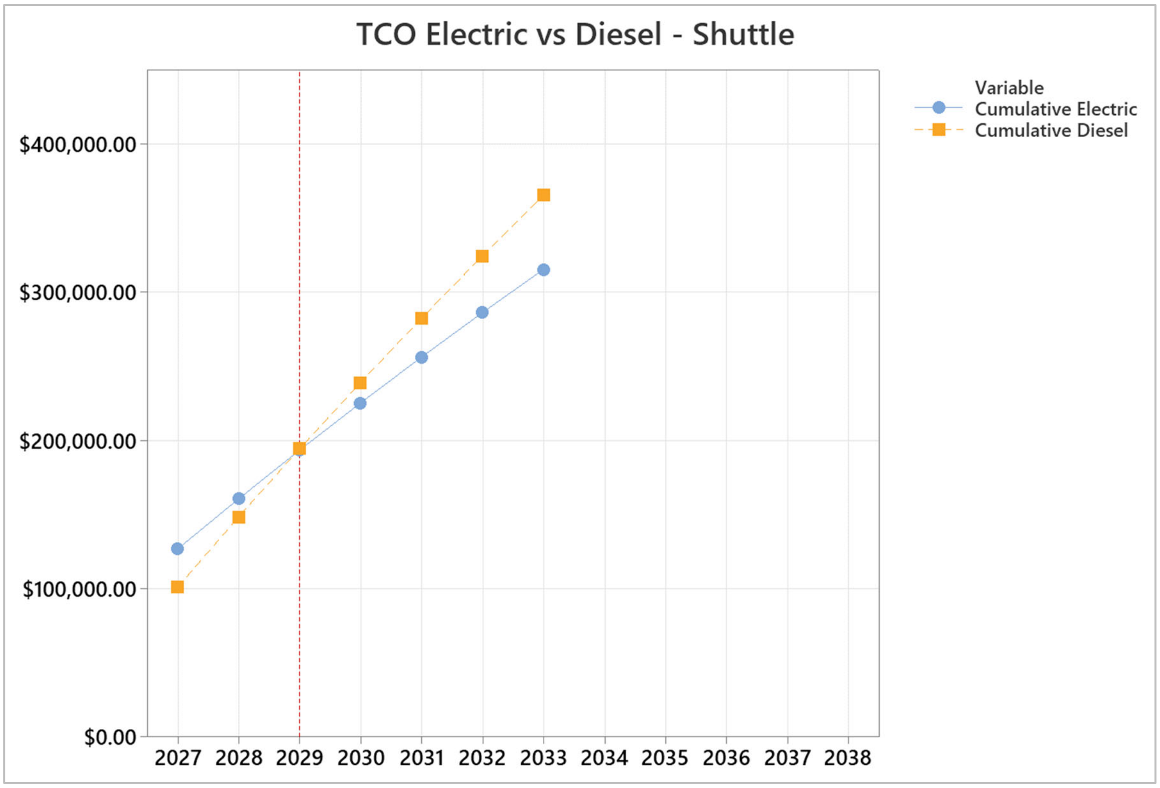


Figure 55: Class 5 shuttle bus - Cumulative cost of ownership for 12 years of ownership (2027-2038)

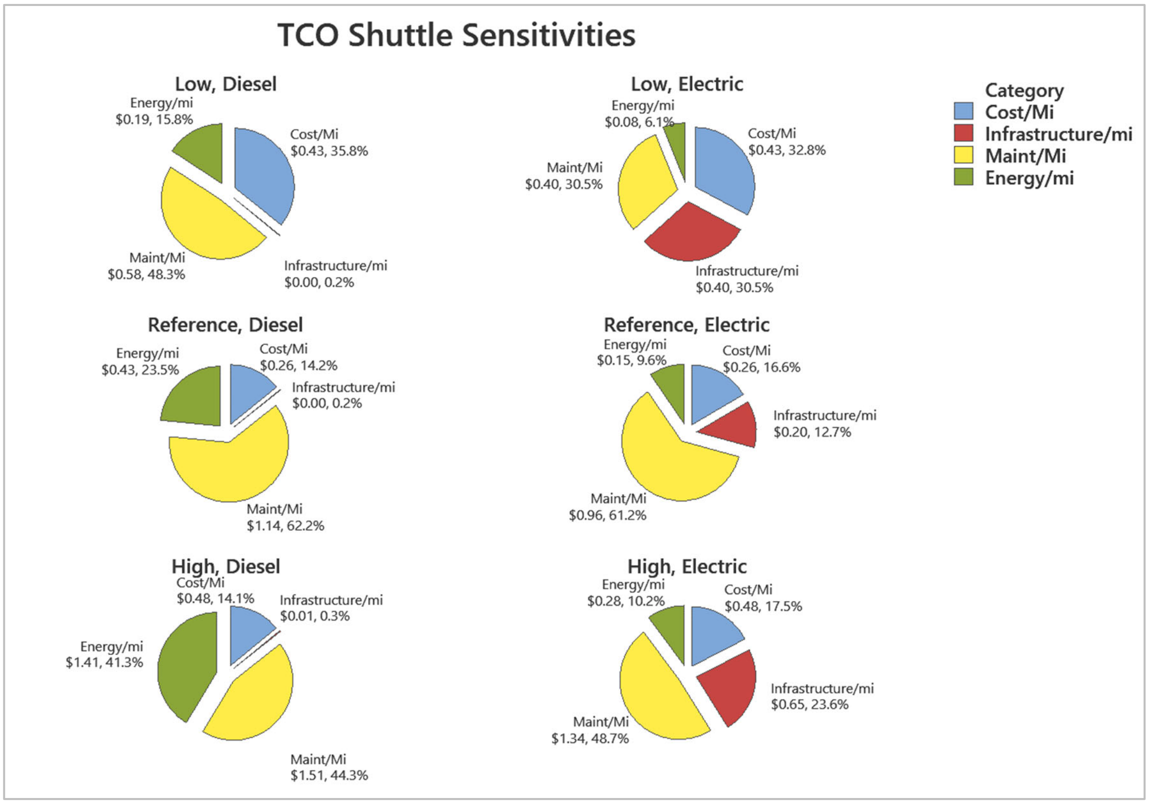


Figure 56: Class 5 shuttle bus: Sensitivities of the total cost of ownership

4.6 Class 3 Delivery Van

4.6.1 IC Engine Vehicle Powertrain Cost (Delete Cost)

An example powertrain for a representative class 3 delivery van powertrain in 2021 is shown in Table 39.

Table 39: 2021 class 3 delivery van, base ICE powertrain example

Engine	3.2 L – I5 Diesel
Power	138 kW (185 HP)
Torque	350 lb-ft
Transmission	6 Speed Automatic SelectShift

The 2021 base powertrain shown in Table 39 consisting of a diesel engine with an automatic transmission will need to be updated with improved engine, transmission, and aftertreatment technologies to meet 2027 (Phase II GHG and the 2027 Low NOx) legislation. Table 40 breaks down the engine, transmission, and aftertreatment system cost for a conventional diesel ICE engine in 2021, 2024, and 2027 to meet the Phase II greenhouse gas rule and the 2027 Low NOx rule.

Table 40: Class 3 Delivery Van - ICE powertrain cost in 2021, 2024 and 2027

	2021	2024	2027	2027 Low NOx
Engine	$3,796	$4,308	$4,348	$5,768
Aftertreatment	$4,338	$4,355	$4,356	$6,618
Transmission	$2,600	$2,600	$2,600	$2,600
Total	$10,734	$11,263	$11,304	$14,986

Along with the base conventional diesel powertrain, two alternative ICE powertrains are evaluated for calculating the total cost of ownership in 2027, a mild-hybrid 48-volt system, and a P2 full hybrid system with an optimized engine for increased fuel economy.

Table 41 compares the cost of the base ICE powertrain (diesel engine + automatic transmission) in 2027 with the mild hybrid and full hybrid options in 2027.

Table 41: Class 3 Delivery Van - ICE, mild-hybrid, and full-hybrid cost in 2027

Base Cost	$14,986
Sensitivity 1 – Mild Hybrid	$16,256
Sensitivity 2 – Full Hybrid with improved engine	$17,025

4.6.2 Electric Vehicle Powertrain Cost – (Add Cost)

Table 42 gives the powertrain component costs of a BEV for 2021, 2024, and 2027. The base cost scenario assumes an NMC battery pack with MDHD-specific motors. Sensitivity 1 case assumes an LFP battery pack that is significantly cheaper ($/kWh). Sensitivity 2 case assumes an LFP battery pack along with multiple smaller motors, the costs based on motors mass-produced for light-duty application. All costs assume high-volume manufacture similar to what OEMs have in the light-duty space.

Table 42: Class 3 Delivery Van - Electric Powertrain Component Cost

Component	Size kW/ kWh	2021	2024	2027
Battery pack (NMC)	100	$12,340	$9,020	$6,840
Inverter	138	$504	$453	$408
Onboard charger	25	$1,399	$1,259	$1,133
DC-DC Converter	10	$559	$503	$453
Motor	138	$2,532	$1,192	$894
Gearbox	138	$500	$500	$500
Total Base Case		**$17,834**	**$12,927**	**$10,228**
LFP battery pack		$10,745	$7,854	$5,956
Total Sensitivity 1 Case		**$16,239**	**$11,761**	**$9,343**
Drive unit, light-duty cost		$555	$499	$449
Total Sensitivity 2 Case		**$14,261**	**$11,069**	**$8,899**

4.6.3 Incremental Cost - Diesel Vs Battery Electric, Class 3 Delivery Van

Table 43 combines Table 41 and Table 42 to compare the three ICE powertrain costs (base, mild, and full hybrid + improved engine) with the three BEV powertrain costs (base, LFP batteries, and LFP batteries + light-duty motors). The incremental cost of BEVs in 2027 is expected to be lower than diesel, mild-hybrid, and full hybrid buses for all scenarios evaluated. . Factoring in all the different combinations of the diesel engine, level of hybridization, and BEV components, the battery-electric powertrain for a class 3 delivery van is estimated to be between $4,759 and $8,126 cheaper than the diesel counterpart in 2027.

Table 43: Class 3 Delivery Van - ICE Delete Vs BEV add costs – 2027

ICE powertrain description	**Diesel**	**Diesel mild hybrid**	**Diesel full hybrid**
ICE powertrain (delete) cost	$14,986	$16,256	$17,025
BEV powertrain description	**LFP + LD motors**	**LFP + HD motors**	**NMC + HD motors**
BEV powertrain (add) cost	$8,899	$9,343	$10,228

Figure 57 compares the base Diesel powertrain cost to Base BEV powertrain cost in 2021, 2024, and 2027. The cost of the base BEV powertrain is lower today in 2021 with the gap widening in 2024 and 2027. (Data from Table 40, Table 41, and Table 42).

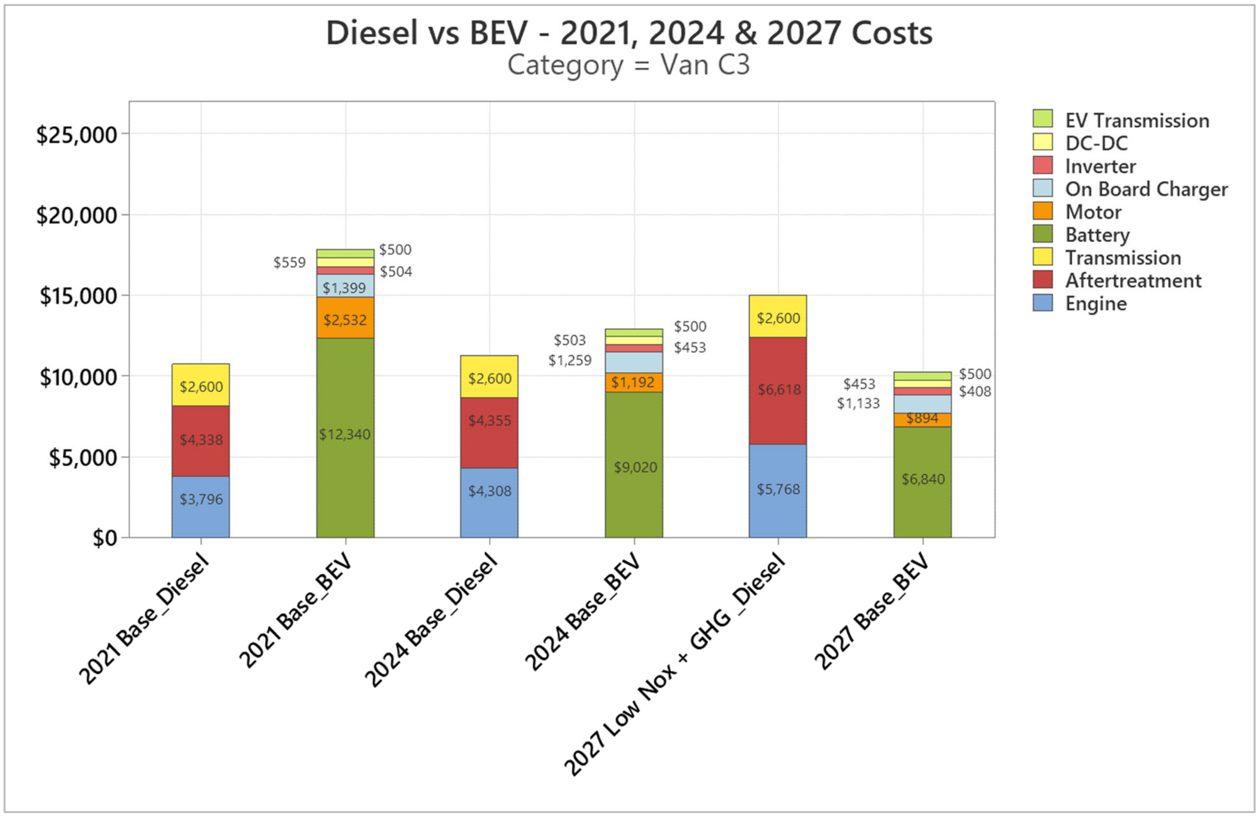


Figure 57: Class 3 delivery van– Base Diesel and BEV powertrain costs 2021, 2024, and 2027

4.6.4 Total Cost of Ownership

The total cost of ownership is calculated in $/mile to compare an electric vehicle purchased in 2027 with the diesel alternative. Table 23 gives the main assumptions used in the calculation of TCO of transit busses. Table 44 gives the breakdown of all the costs used in the calculation of the TCO.

Table 44: Class 3 Delivery Van- Main inputs TCO Calculation

Bus Type	Diesel			Electric		
Case	low	reference	high	low	reference	high
Lifetime age of a vehicle (years)	10	11	11	10	11	11
Lifetime mileage (mi)	124,350	136,785	231,000	124,350	136,785	231,000
Fuel consumption (kWh/mile, mpg)	20	15	12	0.70	0.70	1.37
Fuel cost ($/ kWh, $/gal)	$2.10	$3.25	$4.61	$0.070	$0.12	$0.15
Purchase price ($)	$35,000	$44,748	$50,000	$35,278	$44,428	$51,834
Refresh ($)	$0	$0	$0	$0	$0	$0
Infrastructure cost ($/miles)	$0.001	$0.001	$0.001	$0.058	$0.05	$0.567
Maintenance ($/mile)	$0.13	$0.21	$0.24	$0.07	$0.15	$0.19

Table 45 gives the final value of the total cost of ownership calculated in $/mile. In the reference case scenario, the TCO of the electric class 3 delivery van is 22.7 % lower when compared to the comparable diesel vehicle.

Table 45: Class 3 Delivery Van– TCO ($/mile)

TCO	Low	Reference	High
Diesel Transit	$0.49	$0.70	$0.77
Electric Transit	$0.45	$0.58	$1.13

Figure 58 gives the effect of the variation (low to high) of the various factors (purchase cost, fuel/ electricity cost/ maintenance, and infrastructure) on the reference TCO of a diesel and electric delivery van shown in Figure 59.

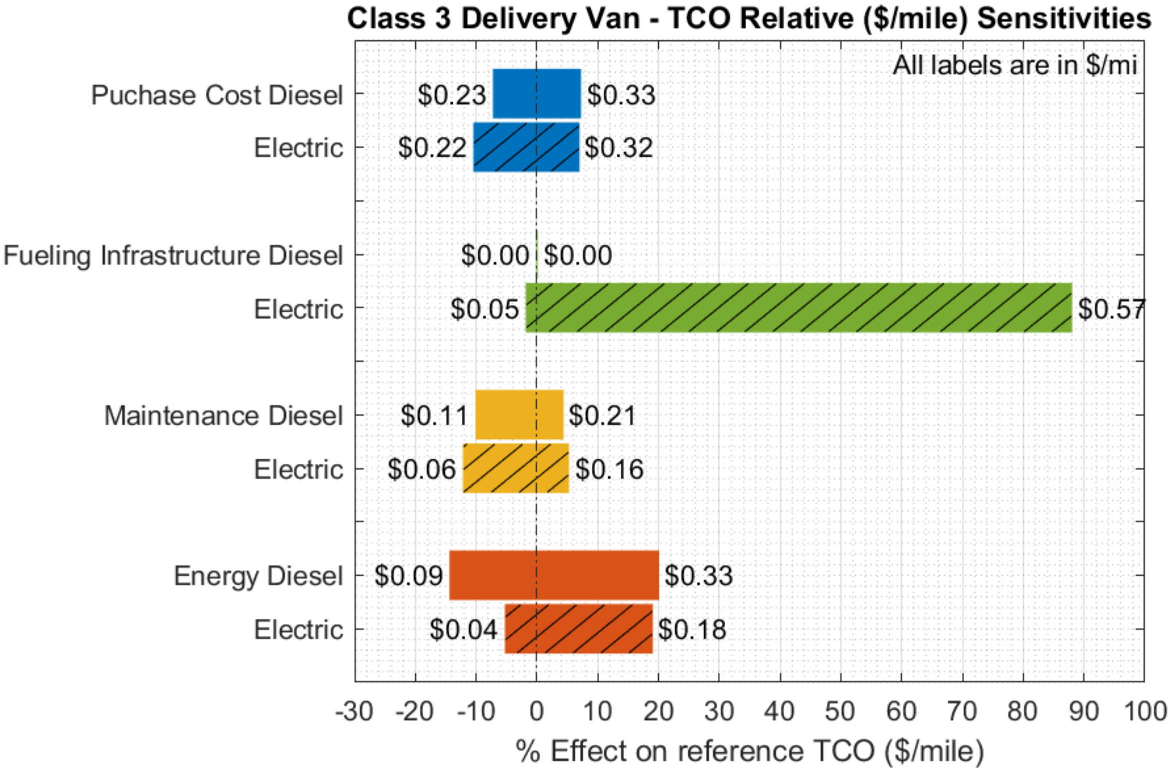


Figure 58: Class 3 Delivery Van – Sensitivities (listed in Table 30) and their % contribution to reference TCO

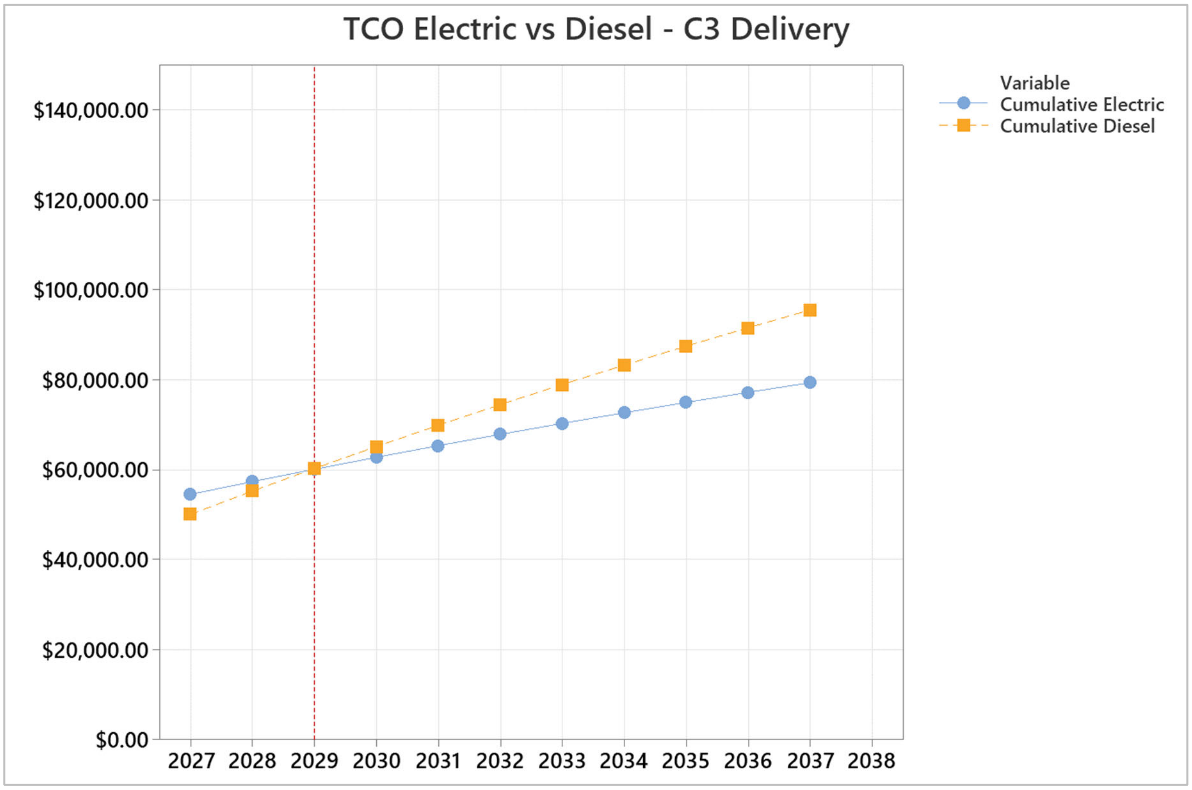


Figure 59: Class 5 shuttle bus - Cumulative cost of ownership for 12 years of ownership (2027-2038)

Figure 59 compares the cumulative cost of the reference class 3 diesel van to the reference electric van purchased in 2027. Even with the extra infrastructure costs incurred (as per our report) by buying electric class 3 delivery vans, due to the lower purchase price, running and maintenance costs, the cumulative TCO of owning a class 3 electric delivery van (bought in 2027) is already lower than the diesel counterpart at the end of the first year of ownership.

Figure 60 breaks down the absolute ($/mile) and relative (percentage) contributions of various factors (purchase cost, infrastructure cost, powertrain refresh cost, maintenance, and energy costs) to the TCO for the low reference and high cases of the diesel and electric class 3 delivery van. From Figure 60, it can be seen the charging infrastructure accounts for a significant fraction (55.4 to 55.9%) of the TCO of a BEV. At the low and high end of the charging infrastructure cost assumption, it can have a huge impact, -40% to +80% of the reference TCO. The development of a robust DC fast-charging network will reduce the amount of spending that fleets have to make to install captive chargers reducing the TCO significantly speeding the adoption of BEVs.

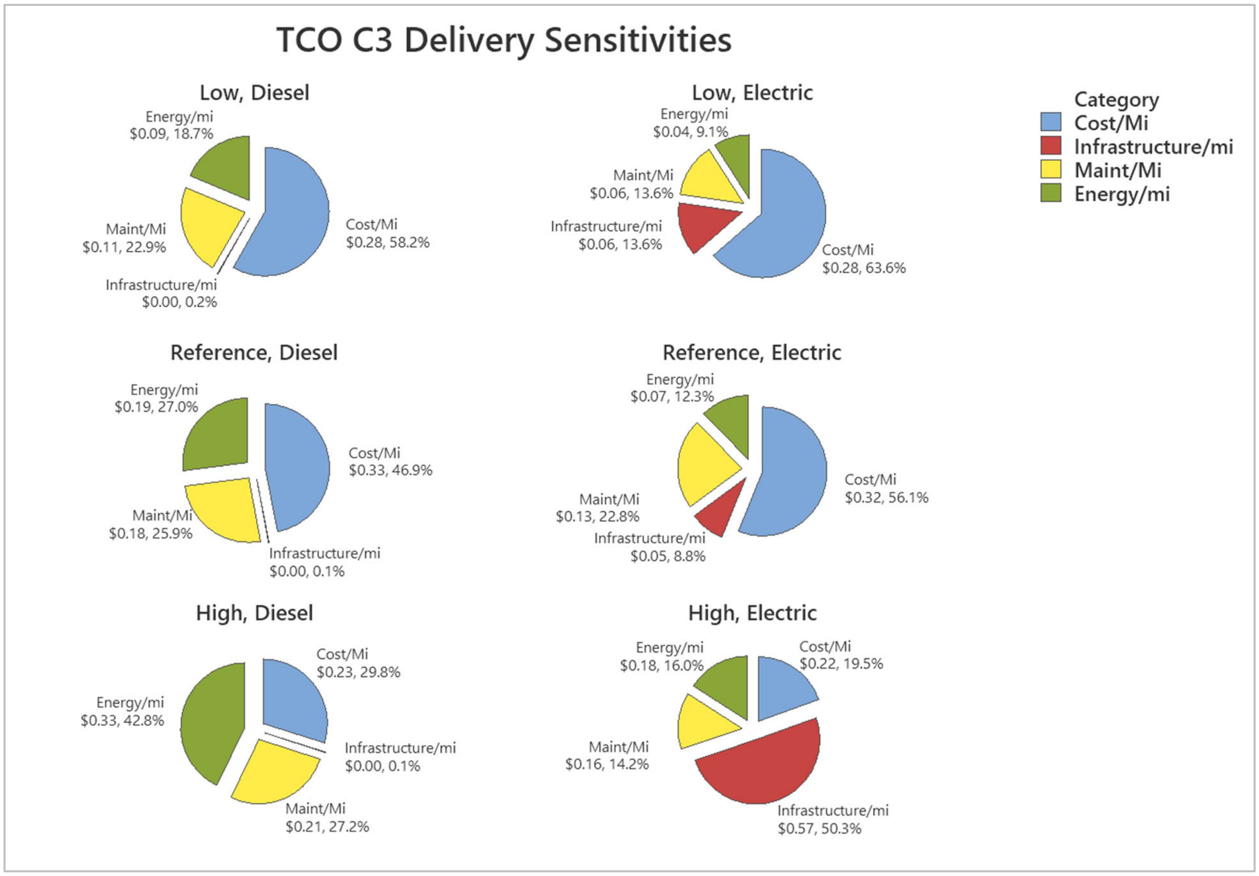


Figure 60: Class 5 shuttle bus: Sensitivities of the total cost of ownership

4.7 Class 5 Delivery Truck

4.7.1 IC Engine Vehicle Powertrain Cost (Delete Cost)

An example powertrain for a representative class 5 delivery truck powertrain in 2021 is shown in Table 46.

Table 46: 2021 class 5 Delivery Truck, base ICE powertrain example

Engine	6.7L Powerstroke
Power	223 kW (300 hp)
Torque	825 lb·ft
Transmission	TorqShift 6 Speed

The 2021 base powertrain shown in Table 46 consisting of a diesel engine with an automatic transmission will need to be updated with improved engine, transmission, and aftertreatment technologies to meet 2027 (Phase II GHG and the 2027 Low NOx) legislation. Table 47 breaks down the engine, transmission, and aftertreatment system cost for a conventional diesel ICE engine in 2021, 2024, and 2027 to meet the Phase II greenhouse gas rule and the 2027 Low NOx rule.

Table 47: Class 5 Delivery Truck - ICE powertrain cost in 2021, 2024 and 2027

	2021	2024	2027	2027 Low NOx
Engine	$8,134	$8,606	$8,643	$10,062
Aftertreatment	$4,881	$4,897	$4,898	$7,161
Transmission	$2,600	$2,600	$2,600	$2,600
Total	$15,615	$16,103	$16,141	$19,823

Along with the base conventional diesel powertrain, two alternative ICE powertrains are evaluated for calculating the total cost of ownership in 2027, a mild-hybrid 48-volt system, and a P2 full hybrid system with an optimized engine for increased fuel economy.

Table 48 compares the cost of the base ICE powertrain (diesel engine + automatic transmission) in 2027 with the mild hybrid and full hybrid options in 2027.

Table 48: Class 5 Delivery Truck - ICE, mild-hybrid, and full-hybrid cost in 2027

Base Cost	$19,823
Sensitivity 1 – Mild Hybrid	$21,093
Sensitivity 2 – Full Hybrid with improved engine	$22,304

4.7.2 Electric Vehicle Powertrain Cost – (Add Cost)

Table 49 gives the powertrain component costs of a BEV for 2021, 2024, and 2027. The base cost scenario assumes an NMC battery pack with MDHD-specific motors. Sensitivity 1 case assumes an LFP battery pack that is significantly cheaper ($/kWh). Sensitivity 2 case assumes an LFP battery pack along with multiple smaller motors, the costs based on motors mass-produced for light-duty application. All costs assume high-volume manufacture similar to what OEMs have in the light-duty space.

Table 49: Class 5 Delivery Truck - Electric Powertrain Component Cost

Component	Size kW/ kWh	2021	2024	2027
Battery pack (NMC)	100	$12,340	$9,020	$6,840
Inverter	223	$814	$732	$659
Onboard charger	25	$1,399	$1,259	$1,133
DC-DC Converter	10	$559	$503	$453
Motor	223	$4,092	$1,926	$1,444
Gearbox	223	$500	$500	$500
Total Base Case		**$19,704**	**$13,940**	**$11,029**
LFP battery pack		$10,745	$7,854	$5,956
Total Sensitivity 1 Case		**$18,109**	**$12,774**	**$10,145**
Drive unit, light-duty cost		$896	$806	$726
Total Sensitivity 2 Case		**$14,913**	**$11,655**	**$9,427**

4.7.3 Incremental Cost - Diesel Vs Battery Electric, Class 5 Delivery Truck

Table 50 combines Table 48 and Table 49 to compare the three ICE powertrain costs (base, mild, and full hybrid + improved engine) with the three BEV powertrain costs (base, LFP batteries, and LFP batteries + light-duty motors). Assuming high volume manufacture, the incremental cost of BEV powertrain in 2027 is lower than diesel, mild-hybrid, and full hybrid buses for all scenarios. Considering the different combinations of the diesel engine, level of hybridization, and BEV components, the powertrain of the Class 5 delivery truck is estimated to be between $8,794 and $10,948 cheaper than the diesel counterpart

Table 50: Class 5 Delivery Truck - ICE Delete Vs BEV add costs – 2027

ICE powertrain description	**Diesel**	**Diesel mild hybrid**	**Diesel full hybrid**
ICE powertrain (delete) cost	$19,823	$21,093	$22,304
BEV powertrain description	**LFP + LD motors**	**LFP + HD motors**	**NMC + HD motors**
BEV powertrain (add) cost	$9,427	$10,145	$11,029

Figure 61 compares the base Diesel powertrain cost to Base BEV powertrain cost in 2021, 2024, and 2027. The cost of the base BEV powertrain is higher in 2021 and 2024 but lower in 2027. (Data from Table 47, Table 48, and Table 49). For the battery size assumed in the study (100 kWh), the cost of the BEV powertrain in 2021 is lower than the comparable diesel powertrain. With the falling cost of electrification components and increasing cost of ICE powertrain to meet future fuel economy and emission standards, this gas increases from 2021 to 2027.

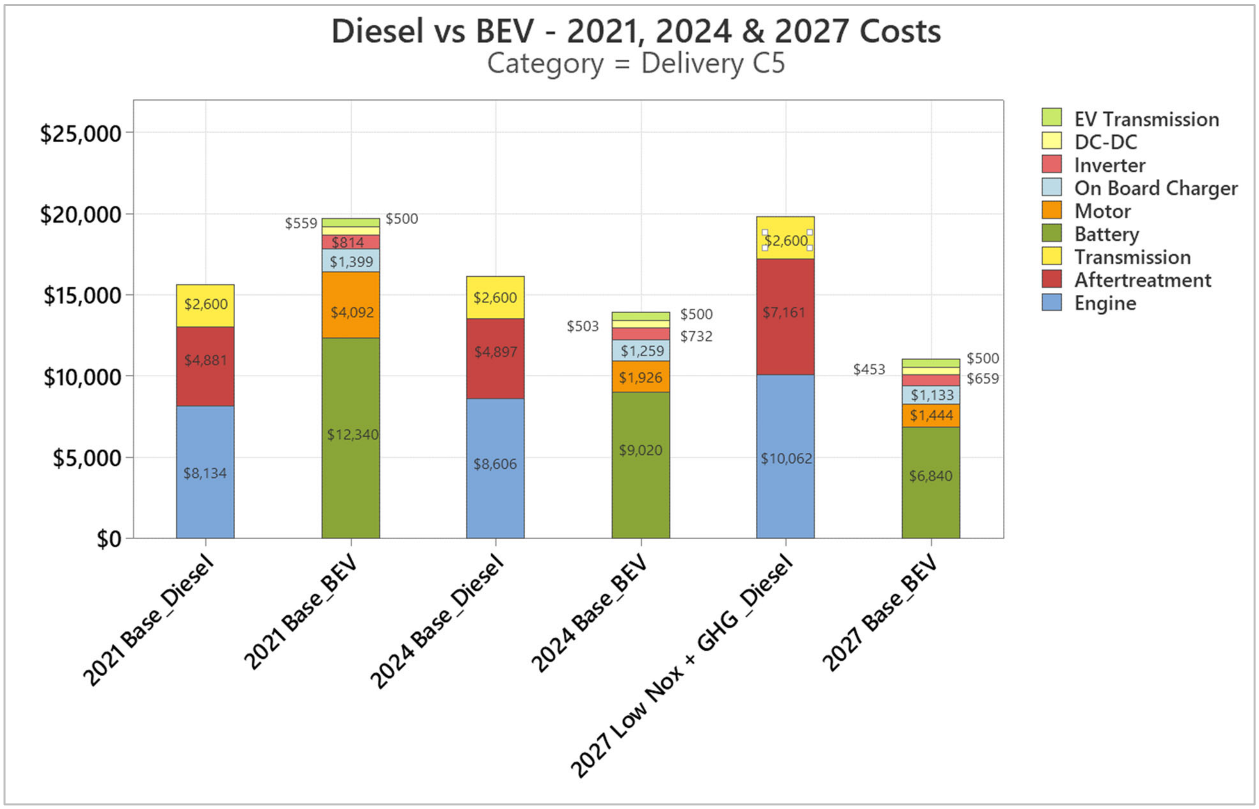


Figure 61: Class 5 Delivery Truck – Base Diesel and BEV powertrain costs 2021, 2024, and 2027

4.7.4 Total Cost of Ownership

The total cost of ownership is calculated in $/mile to compare an electric vehicle purchased in 2027 with the diesel alternative. Table 51 gives the main assumptions used in the calculation of TCO of class 5 delivery trucks and gives the breakdown of all the costs used in the calculation of the TCO.

Table 51: Class 5 Delivery Truck - Main inputs TCO Calculation

Bus Type	Diesel			Electric		
Case	low	reference	high	low	reference	high
Lifetime age of a vehicle (years)	10			10		
Lifetime mileage (mi)	124,350	124,350	148,000	124,350	124,350	148,000
Fuel consumption (kWh/mile, mpg)	12	7	6	0.75	1.00	1.50
Fuel cost ($/ kWh, $/gal)	$2.10	$3.25	$4.61	$0.07	$0.12	$0.15
Purchase price ($)	$45,000	$58,270	$72,912	$38,118	$51,065	$64,949
Refresh ($)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Infrastructure cost ($/miles)	$0.001	$0.002	$0.003	$0.06	$0.06	$0.88
Maintenance ($/mile)	$0.17	$0.17	$0.22	$0.09	$0.12	$0.18

Table 52 gives the final value of the cost of ownership calculated in $/mile. In the reference case scenario, the TCO of the battery-electric class 5 delivery vehicle is estimated to be more than 36% lower when compared to the equivalent diesel-powered vehicle in 2027.

Table 52: Class 5 Delivery Truck – TCO ($/mile)

TCO	Low	Reference	High
Diesel Transit	$0.67	$1.03	$1.36
Electric Transit	$0.49	$0.68	$1.68

Figure 62 gives the effect of the variation (low to high) of the various factors (purchase cost, fuel/ electricity cost/ maintenance, and infrastructure) on the reference TCO of a diesel and electric delivery truck shown in Figure 63. It can be seen that the charging infrastructure assumption introduces the largest swing in the reference TCO value.

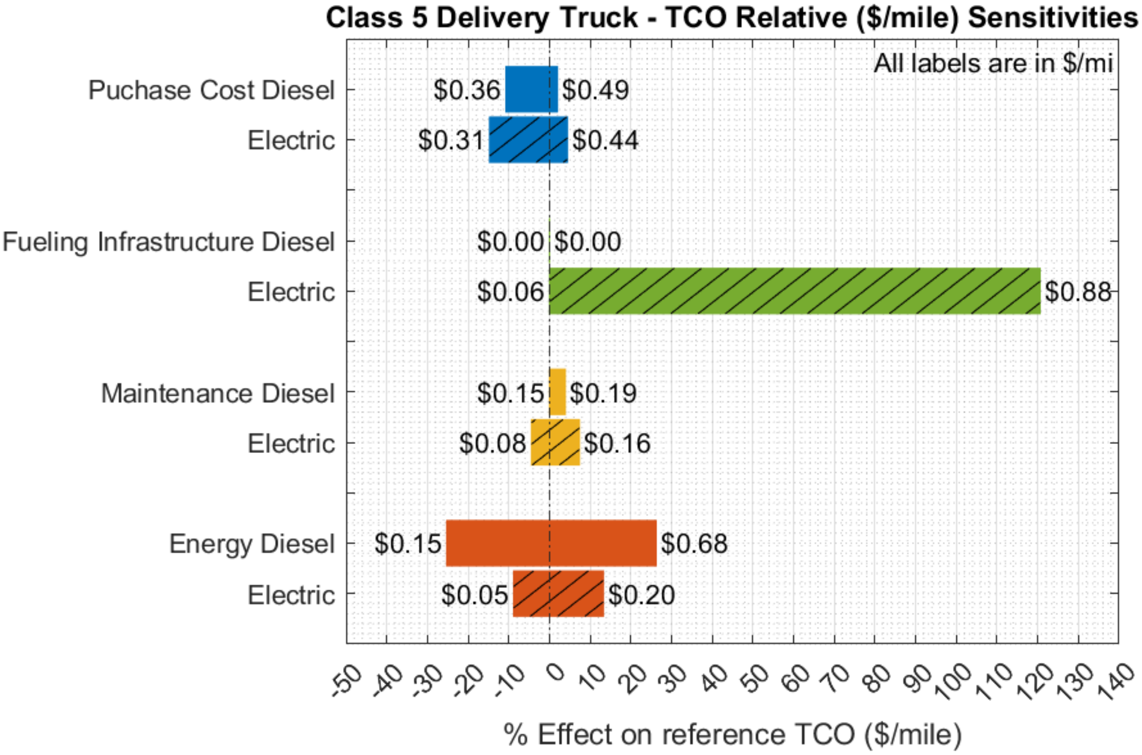


Figure 62: Class 5 Delivery Truck – Sensitivities (listed in Table 30) and their % contribution to reference TCO

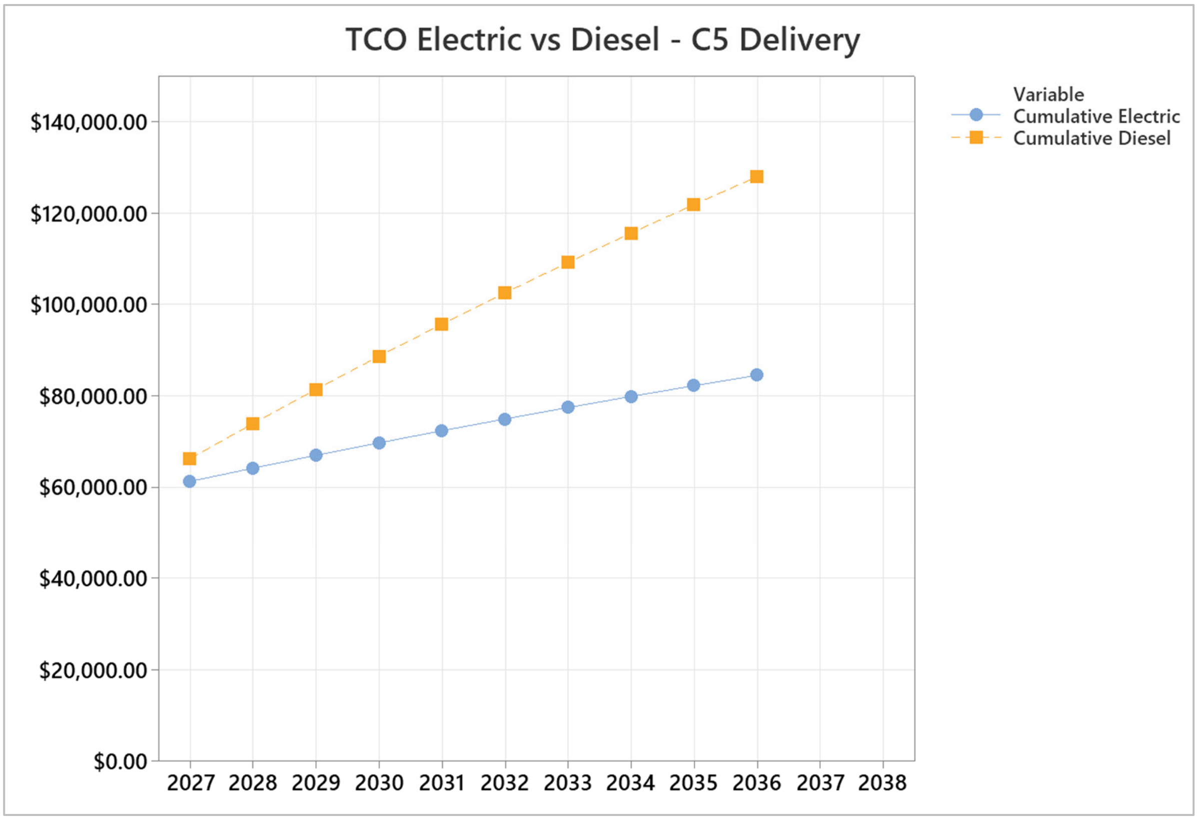


Figure 63: Class 5 Delivery Truck - Cumulative cost of ownership for 12 years of ownership (2027-2038)

Figure 63 compares the cumulative TCO of a Battery electric class 5 delivery truck to the diesel alternative purchased in 2025. Even with the extra infrastructure costs incurred by buying BEVs, due to the lower purchase price, operating costs, the cumulative TCO of owning a BEV (bought in 2027) is already lower than the diesel counterpart at the end of the first year of ownership and this gap widens over the life of the vehicles. Figure 64 breaks down the absolute ($/mile) and relative (percentage) contributions of various factors (purchase cost, infrastructure cost, powertrain refresh cost, maintenance, and energy costs) to the TCO for the low reference and high cases of the diesel and electric delivery truck. Depending on the charging infrastructure assumption, its contribution to the TCO varies from 10.7% (low case) to 42% (high case). The development of a robust public DC fast-charging network or subsidies to set up charging infrastructure will reduce the amount of spending that fleets have to make to install captive chargers reducing the TCO significantly speeding the adoption of BEVs.

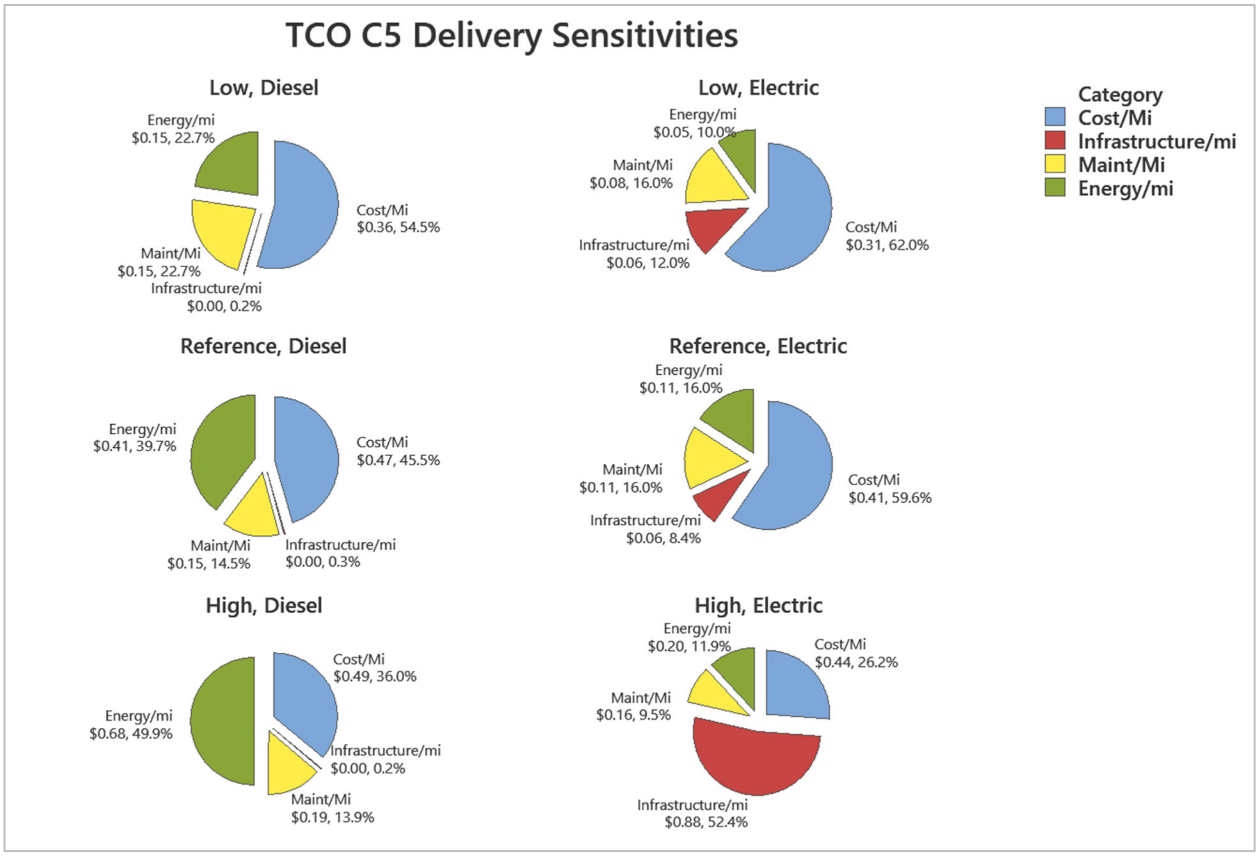


Figure 64: Class 5 Delivery Truck: Sensitivities of the total cost of ownership.

4.8 Class 7 Delivery Truck

4.8.1 IC Engine Vehicle Powertrain Cost (Delete Cost)

A representative diesel powertrain for a class 7 delivery truck in 2021 is shown in Table 53.

Table 53: 2021 Class 7 Delivery Truck, base ICE powertrain example

Engine	Cummins B6.7
Power	190 kW (255 hp)
Torque	750 lb.ft
Transmission	Allison 3000

The 2021 base powertrain shown in Table 53 consisting of a diesel engine with an automatic transmission will need to be updated with improved engine, transmission, and aftertreatment technologies to meet 2027 (Phase II GHG and the 2027 Low NOx) legislation. Table 54 breaks down the engine, transmission, and aftertreatment system cost for a conventional diesel ICE engine in 2021, 2024, and 2027 to meet the Phase II greenhouse gas rule and the 2027 Low NOx rule.

Table 54: Class 7 Delivery Truck - ICE powertrain cost in 2021, 2024 and 2027

	2021	2024	2027	2027 Low NOx
Engine	$6,508	$6,979	$7,016	$8,435
Aftertreatment	$4,338	$4,355	$4,356	$6,618
Transmission	$7,677	$7,677	$9,878	$9,878
Total	$18,523	$19,011	$21,250	$24,931

Along with the base conventional diesel powertrain, two alternative ICE powertrains are evaluated for calculating the total cost of ownership in 2027, a mild-hybrid 48-volt system, and a P2 full hybrid system with an optimized engine for increased fuel economy.

Table 55 compares the cost of the base ICE powertrain (diesel engine + automatic transmission) in 2027 with the mild hybrid and full hybrid options in 2027.

Table 55: Class 7 Delivery Truck - ICE, mild-hybrid and full-hybrid cost in 2027

Base Cost	$24,931
Sensitivity 1 – Mild Hybrid	$26,201
Sensitivity 2 – Full Hybrid with improved engine	$28,142

4.8.2 Electric Vehicle Powertrain Cost – (Add Cost)

Table 56 gives the powertrain component costs of a BEV for 2021, 2024, and 2027. The base cost scenario assumes an NMC battery pack with MDHD-specific motors. Sensitivity 1 case assumes an LFP battery pack that is significantly cheaper ($/kWh). Sensitivity 2 case assumes an LFP battery pack along with multiple smaller motors, the costs based on motors mass-produced for light-duty application. All costs assume high-volume manufacture similar to what OEMs have in the light-duty space.

Table 56: Class 7 Delivery Truck - Electric Powertrain Component Cost

Component	Size kW/ kWh	2021	2024	2027
Battery pack (NMC)	150	$18,510	$13,530	$10,260
Inverter	190	$693	$624	$562
Onboard charger	40	$2,238	$2,014	$1,813
DC-DC Converter	10	$559	$503	$453
Motor	190	$3,486	$1,641	$1,231
Gearbox	190	$500	$500	$500
Total Base Case		**$25,987**	**$18,812**	**$14,818**
LFP battery pack	150	$16,118	$11,781	$8,934
Total Sensitivity 1 Case		**$23,594**	**$17,063**	**$13,492**
Drive unit, light-duty cost	190	$763	$687	$618
Total Sensitivity 2 Case		**$20,871**	**$16,110**	**$12,879**

4.8.3 Incremental Cost - Diesel Vs Battery Electric, Class 7 Delivery Truck

Table 57 combines Table 55 and Table 56 to compare the three ICE powertrain costs (base, mild, and full hybrid + improved engine) with the three BEV powertrain costs (base, LFP batteries, and LFP batteries + light-duty motors). Assuming high volume manufacture, the incremental cost of BEVs in 2027 is lower than diesel, mild-hybrid, and full hybrid buses for all scenarios. Considering the different combinations of the diesel engine, level of hybridization, and BEV components, the powertrain of the class 7 delivery truck is estimated to be between $10,114 and $15,263 cheaper than the diesel counterpart.

Table 57: Class 7 Delivery Truck - ICE Delete Vs BEV add costs – 2027

ICE powertrain description	**Diesel**	**Diesel mild hybrid**	**Diesel full hybrid**
ICE powertrain (delete) cost	$24,931	$26,201	$28,142
BEV powertrain description	**LFP + LD motors**	**LFP + HD motors**	**NMC + HD motors**
BEV powertrain (add) cost	$12,879	$13,492	$14,818

Figure 65 compares the base Diesel powertrain cost to Base BEV powertrain cost in 2021, 2024, and 2027. The cost of the base BEV powertrain is higher in 2021 and 2024 but lower in 2027. (Data from Table 54, Table 55, Table 56, Table 33, Table 34, and Table 35) Powertrain cost parity between diesel and battery electric is reached sometime between 2024 and 2027.

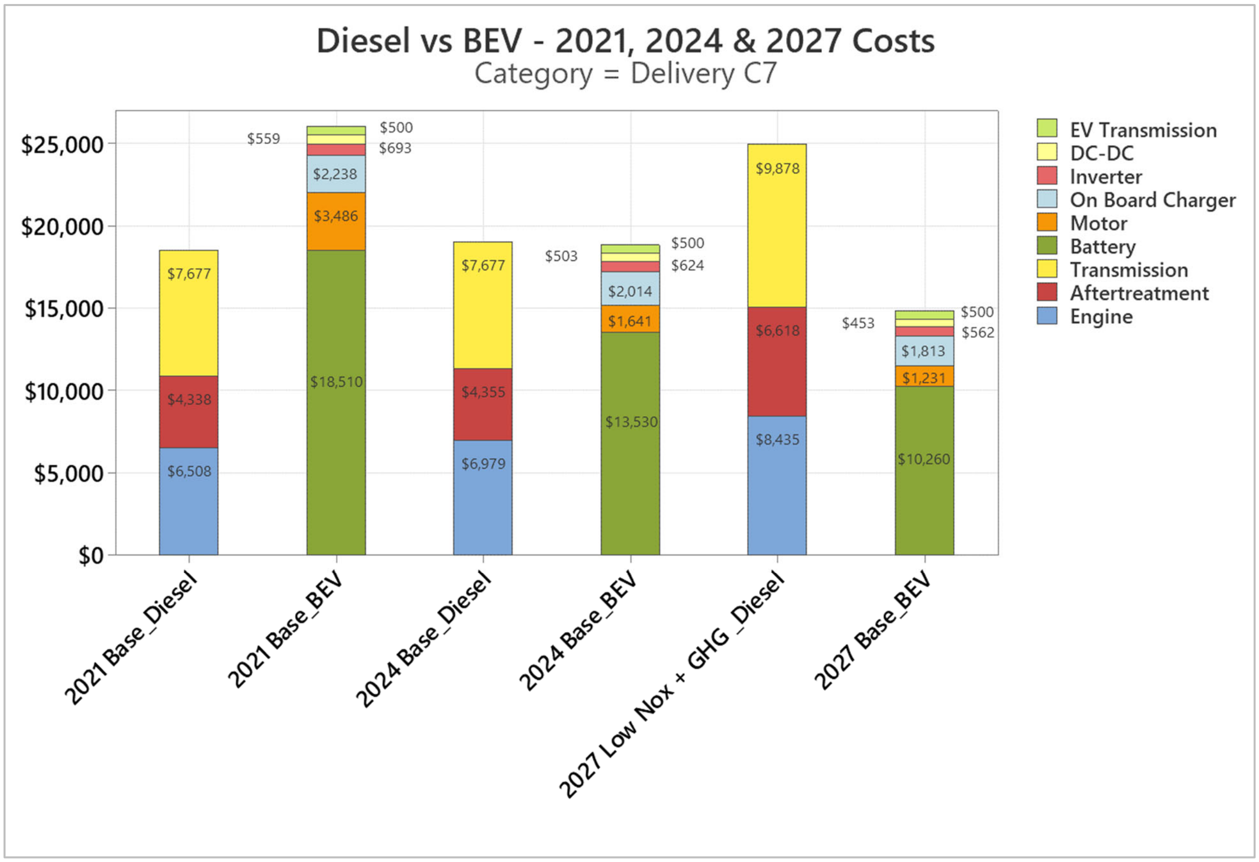


Figure 65: Class 7 Delivery Truck – Base Diesel and BEV powertrain costs 2021, 2024, and 2027

4.8.4 Total Cost of Ownership

The total cost of ownership is calculated in $/mile to compare an electric vehicle purchased in 2027 with the diesel alternative. Table 58 gives the breakdown of all the costs used in the calculation of the TCO.

Table 58: Class 7 Delivery Truck - Main inputs TCO Calculation

Bus Type	Diesel	Electric

Case	low	reference	high	low	reference	high
Lifetime age of a vehicle (years)		10			10	
Lifetime mileage (mi)	250,000	285,710	360,000	250,000	285,710	360,000
Fuel consumption (kWh/mile, mpg)	10	8	6	1.50	2.00	2.50
Fuel cost ($/ kWh, $/gal)	$2.10	$3.25	$4.61	$0.07	$0.12	$0.15
Purchase price ($)	$50,000	$86,270	$95,749	$41,825	$78,118	$87,611
Refresh ($)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Infrastructure cost ($/miles)	$0.002	$0.002	$0.003	$0.03	$0.14	$0.36
Maintenance ($/mile)	$0.29	$0.29	$0.29	$0.15	$0.20	$0.23

Table 59 gives the final value of the cost of ownership calculated in $/mile. In the reference case scenario, the TCO of the electric bus is more than 27% lower when compared to the diesel bus

Table 59: Class 7 Delivery Truck – TCO ($/mile)

TCO	Low	Reference	High
Diesel Transit	$0.64	$0.92	$1.20
Electric Transit	$0.42	$0.80	$1.14

Figure 66 gives the effect of the variation of the various factors (purchase cost, fuel/ electricity cost/ maintenance, and infrastructure) on the reference TCO of a diesel and electric truck shown in Figure 67.

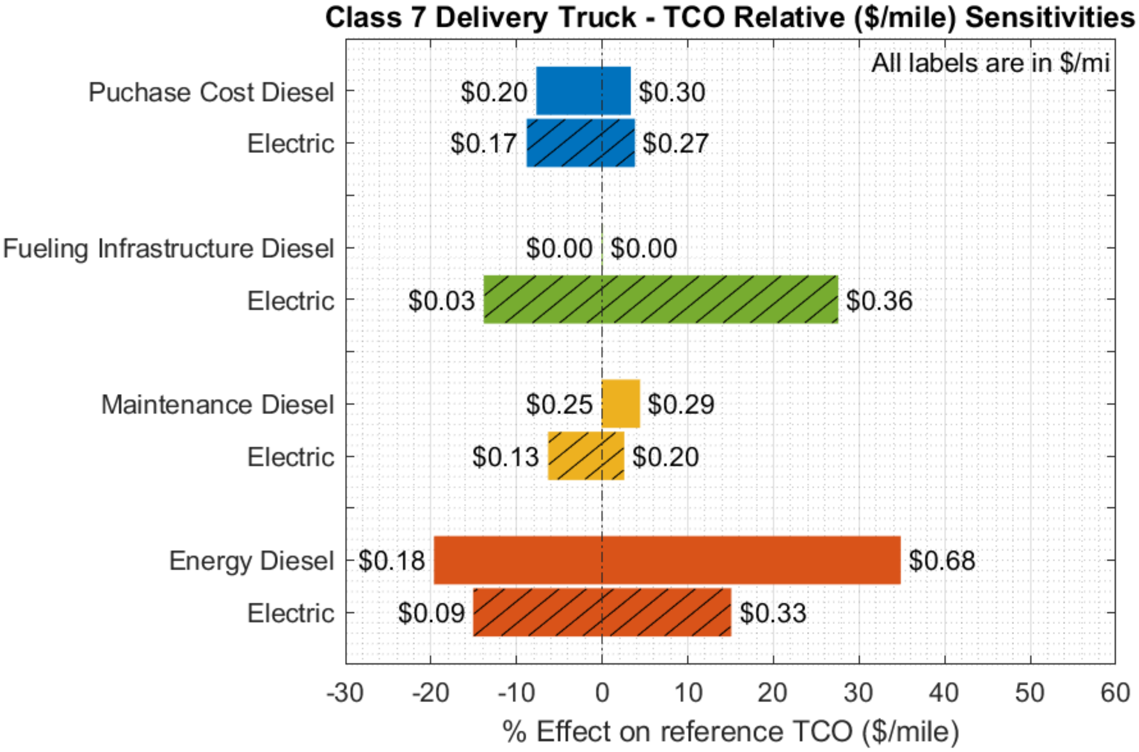


Figure 66: Class 7 Delivery Truck – Sensitivities (listed in Table 30) and their % contribution to reference TCO

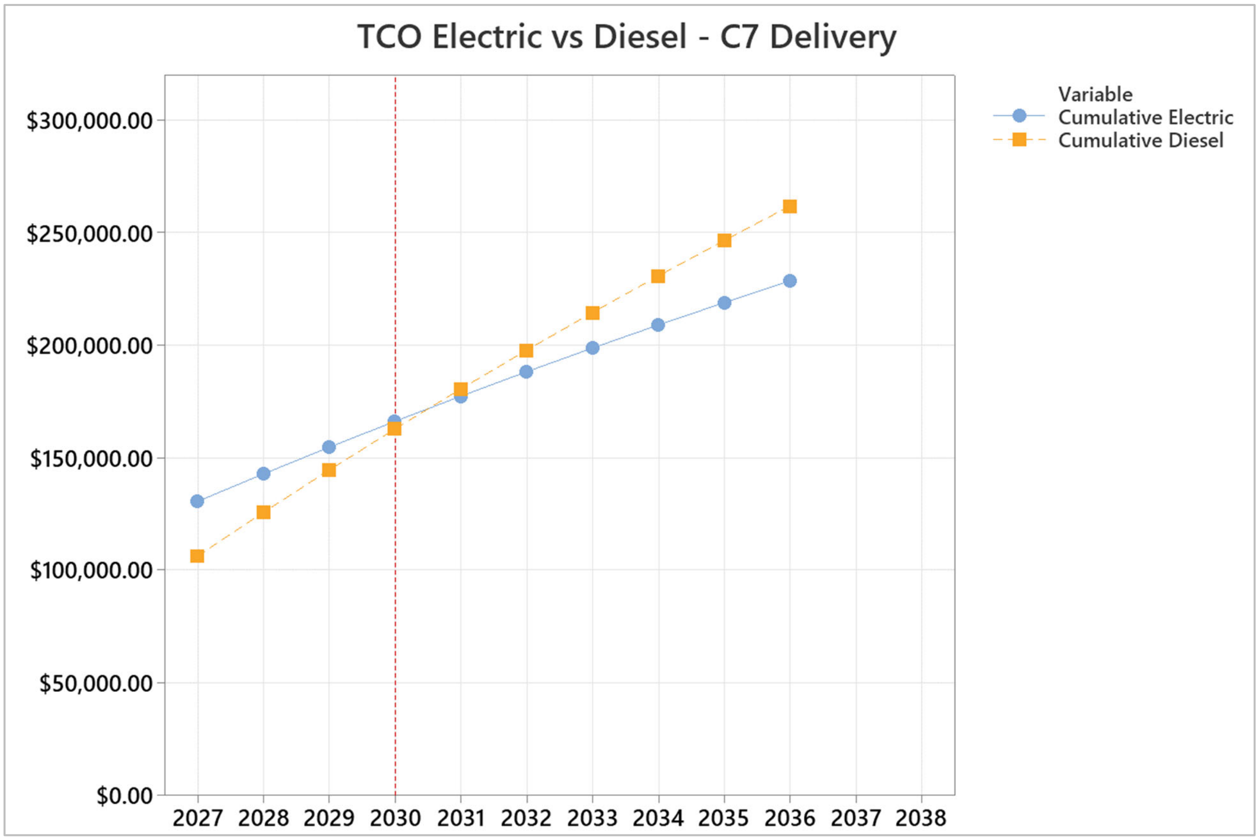


Figure 67: Class 7 Delivery Truck - Cumulative cost of ownership for 12 years of ownership (2027-2038)

Figure 68 compares the total cost of ownership for various sensitivities for diesel and battery electric class 7 delivery trucks.

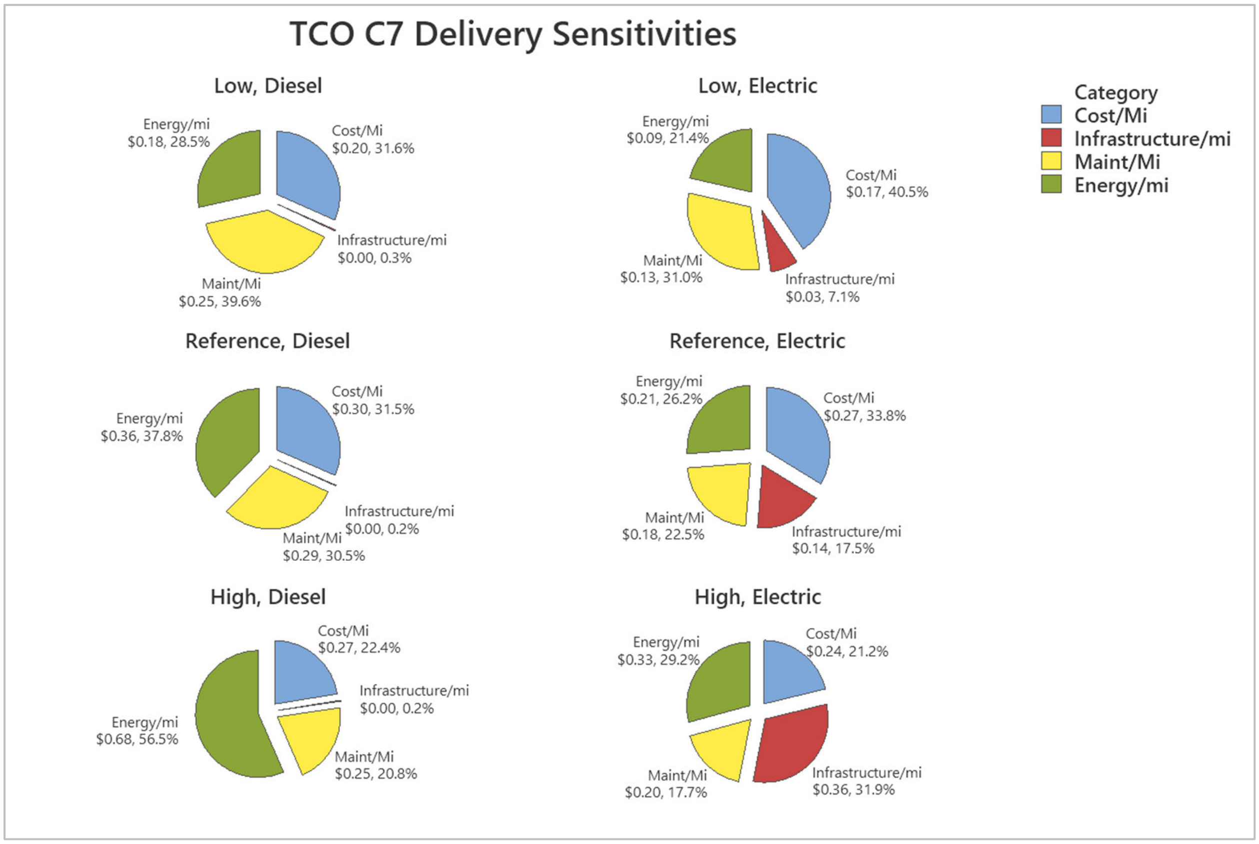


Figure 68: Class 7 Delivery Truck: Sensitivities of the total cost of ownership

4.9 Class 8 Refuse Truck

4.9.1 IC Engine Vehicle Powertrain Cost (Delete Cost)

An example powertrain for a representative class 8 refuse truck bus powertrain in 2021 is shown in Table 60.

Table 60: 2021 Class 8 Refuse Truck, base ICE powertrain example

Engine	Cummins L9 - Transit bus (diesel)
Power	260 kW (350 HP)
Torque	925-1150 lb-ft
Transmission	Allison B400R (Automatic)

The 2021 base powertrain shown in Table 60 consisting of a diesel engine with an automatic transmission will need to be updated with improved engine, transmission, and aftertreatment technologies to meet 2027 (Phase II GHG and the 2027 Low NOx) legislation. Table 61 breaks down the engine, transmission,

and aftertreatment system cost for a conventional diesel ICE engine in 2021, 2024, and 2027 to meet the Phase II greenhouse gas rule and the 2027 Low NOx rule.

Table 61: Class 8 Refuse Truck - ICE powertrain cost in 2021, 2024 and 2027

	2021	2024	2027	2027 Low NOx
Engine	$10,303	$10,775	$10,812	$13,013
Aftertreatment	$6,975	$6,992	$6,993	$9,455
Transmission	$15,628	$15,628	$17,829	$17,829
Total	$32,906	$33,395	$35,634	$40,297

Along with the base conventional diesel powertrain, two alternative ICE powertrains are evaluated for calculating the total cost of ownership in 2027, a mild-hybrid 48-volt system, and a P2 full hybrid system with an optimized engine for increased fuel economy.

Table 62 compares the cost of the base ICE powertrain (diesel engine + automatic transmission) in 2027 with the mild hybrid and full hybrid options in 2027.

Table 62: Class 8 Refuse Truck - ICE, mild-hybrid, and full-hybrid cost in 2027

Base Cost	$40,297
Sensitivity 1 – Mild Hybrid	$41,566
Sensitivity 2 – Full Hybrid with improved engine	$44,516

4.9.2 Electric Vehicle Powertrain Cost – (Add Cost)

Table 63 gives the powertrain component costs of a BEV for 2021, 2024, and 2027. The base cost scenario assumes an NMC battery pack with MDHD-specific motors. Sensitivity 1 case assumes an LFP battery pack that is significantly cheaper ($/kWh). Sensitivity 2 case assumes an LFP battery pack along with multiple smaller motors, the costs based on motors mass-produced for light-duty application. All costs assume high-volume manufacture similar to what OEMs have in the light-duty space.

Table 63: Class 8 Refuse Truck - Electric Powertrain Component Cost

Component	Size kW/ kWh	2021	2024	2027
Battery pack (NMC)	200	$24,680	$18,040	$13,680
Inverter	260	$949	$854	$768
Onboard charger	50	$2,797	$2,517	$2,266
DC-DC Converter	10	$559	$503	$453
Motor	260	$4,771	$2,245	$1,684
Gearbox	260	$500	$500	$500
Total Base Case		**$34,256**	**$24,660**	**$19,351**
LFP battery pack		$21,490	$15,708	$11,912
Total Sensitivity 1 Case		**$31,066**	**$22,328**	**$17,583**
Drive unit, light-duty cost		$1,045	$940	$846
Total Sensitivity 2 Case		**$27,340**	**$21,023**	**$16,745**

4.9.3 Incremental Cost - Diesel Vs Battery Electric, Class 8 Refuse Truck

Table 64 combines Table 62 and Table 63 to compare the three ICE powertrain costs (base, mild, and full hybrid + improved engine) with the three BEV powertrain costs (base, LFP batteries, and LFP batteries + light-duty motors). Assuming high volume manufacture, the incremental cost of BEVs in 2027 is lower than diesel, mild-hybrid, and full hybrid buses for all scenarios. Considering the different combinations of the diesel engine, level of hybridization, and BEV components, the powertrain of a class 8 Refuse Truck is estimated to be between $20,945 and $27,971 cheaper than the diesel counterpart.

Table 64: Class 8 Refuse Truck- ICE Delete Vs BEV add costs – 2027

ICE powertrain description	Diesel	Diesel mild hybrid	Diesel full hybrid
ICE powertrain (delete) cost	$40,297	$41,566	$44,516
BEV powertrain description	**LFP + LD motors**	**LFP + HD motors**	**NMC + HD motors**
BEV powertrain (add) cost	$16,745	$17,583	$19,351

Figure 69 compares the base Diesel powertrain cost to Base BEV powertrain cost in 2021, 2024, and 2027. The cost of the base BEV powertrain is higher in 2021 and 2024 but lower in 2027. (Data from Table 61, Table 62, and Table 63) Powertrain cost parity between diesel and battery electric is reached sometime between 2024 and 2027.

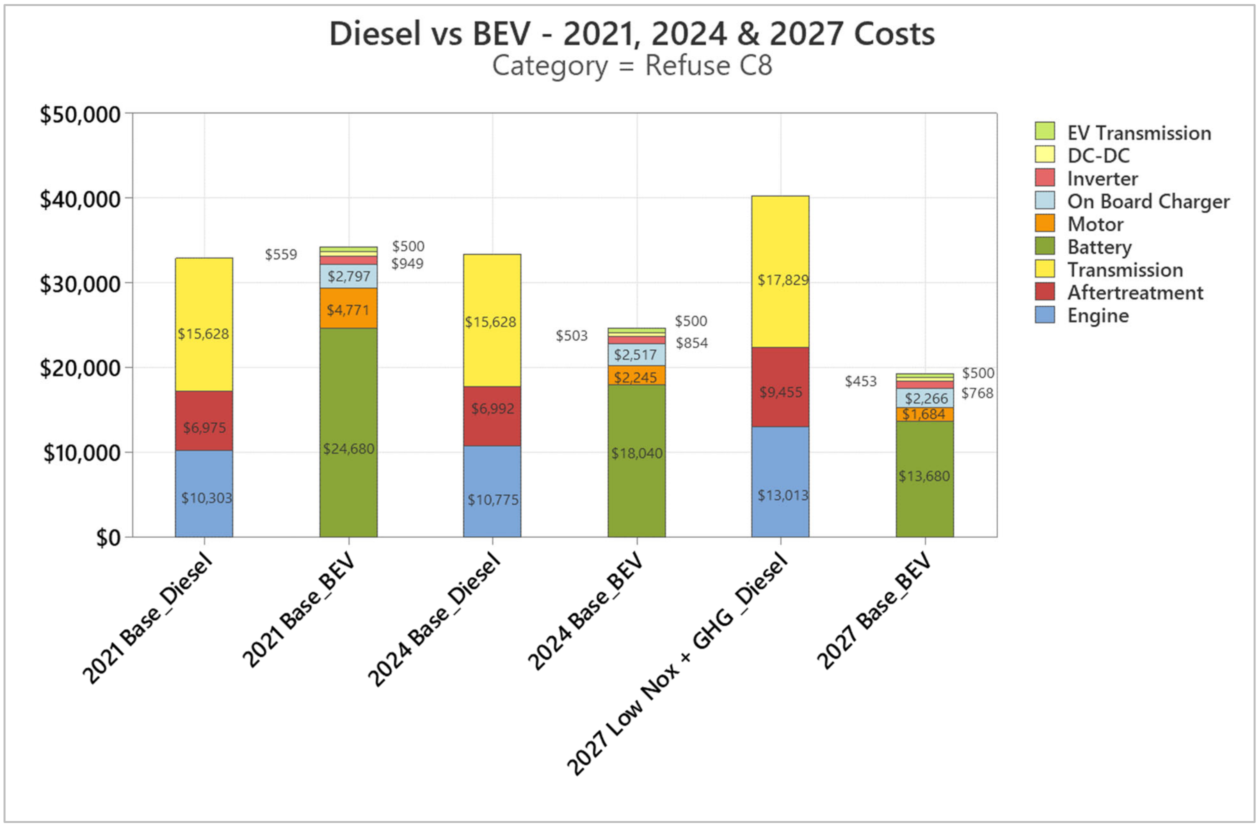


Figure 69: Class 8 Refuse Truck– Base Diesel and BEV powertrain costs 2021, 2024, and 2027

4.9.4 Total Cost of Ownership

The total cost of ownership is calculated in \$/mile to compare an electric vehicle purchased in 2027 with the diesel alternative. Table 65 gives the breakdown of all the costs used in the calculation of the TCO.

Table 65: Class 8 Refuse Truck - Main inputs TCO Calculation

Bus Type	Diesel			Electric		
Case	low	reference	high	low	reference	high
Lifetime age of a vehicle (years)	12	10	7	12	10	7
Total mileage (miles)	175,000	250,000	300000	175,000	250,000	300,000
Fuel consumption (kWh/mile, mpg)	6	4	3	2.00	2.50	4.00
Fuel cost ($/ kWh, $/gal)	$2.10	$3.25	$4.61	$0.07	$0.12	$0.15
Purchase price ($)	$150,000	$251,270	$353,281	$131,409	$232,928	$334,696
Refresh ($)	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Infrastructure cost ($/miles)	$0.003	$0.004	$0.006	$0.13	$0.16	$0.75
Maintenance ($/mile)	$0.80	$0.80	$0.80	$0.40	$0.56	$0.64

Table 66 gives the final value of the cost of ownership calculated in $/mile. In the reference case scenario, the TCO of the electric bus is more than 27% lower when compared to the diesel bus

Table 66: Class 5 Shuttle Bus – TCO ($/mile)

TCO	Low	Reference	High
Diesel Transit	$1.49	$2.43	$4.17
Electric Transit	$1.03	$1.85	$3.80

Figure 70 gives the effect of the variation of the various factors (purchase cost, fuel/ electricity cost/ maintenance, and infrastructure) on the reference TCO of a diesel and electric bus shown in Figure 71.

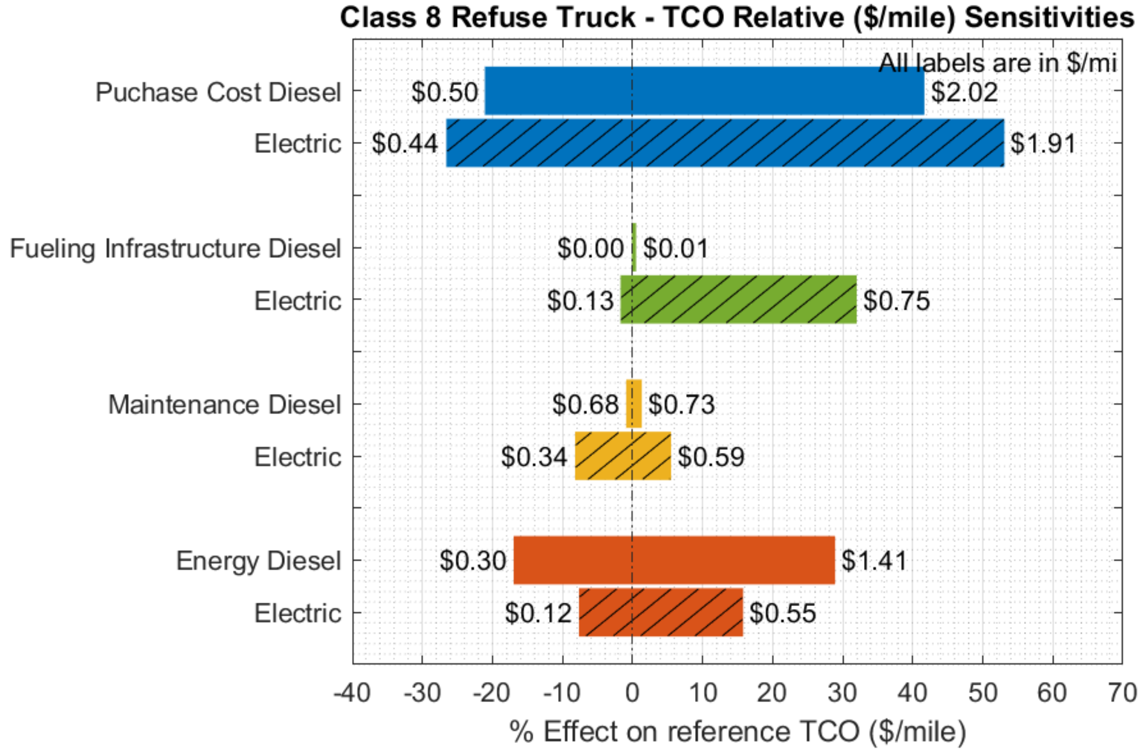


Figure 70: Class 8 Refuse Truck– Sensitivities (listed in Table 30) and their % contribution to reference TCO

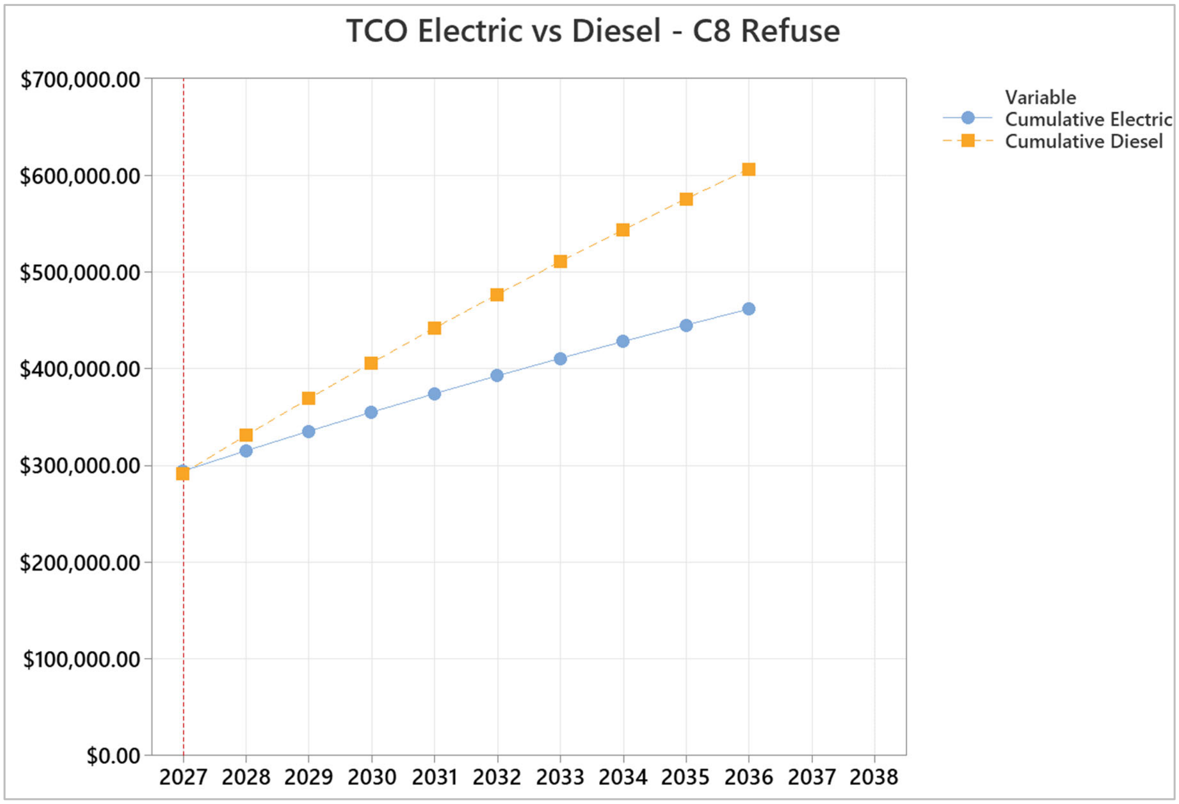


Figure 71: Class 8 Refuse Truck - Cumulative cost of ownership for 12 years of ownership (2027-2038)

Figure 72 compares the total cost of ownership for various sensitivities for diesel and battery electric school busses.

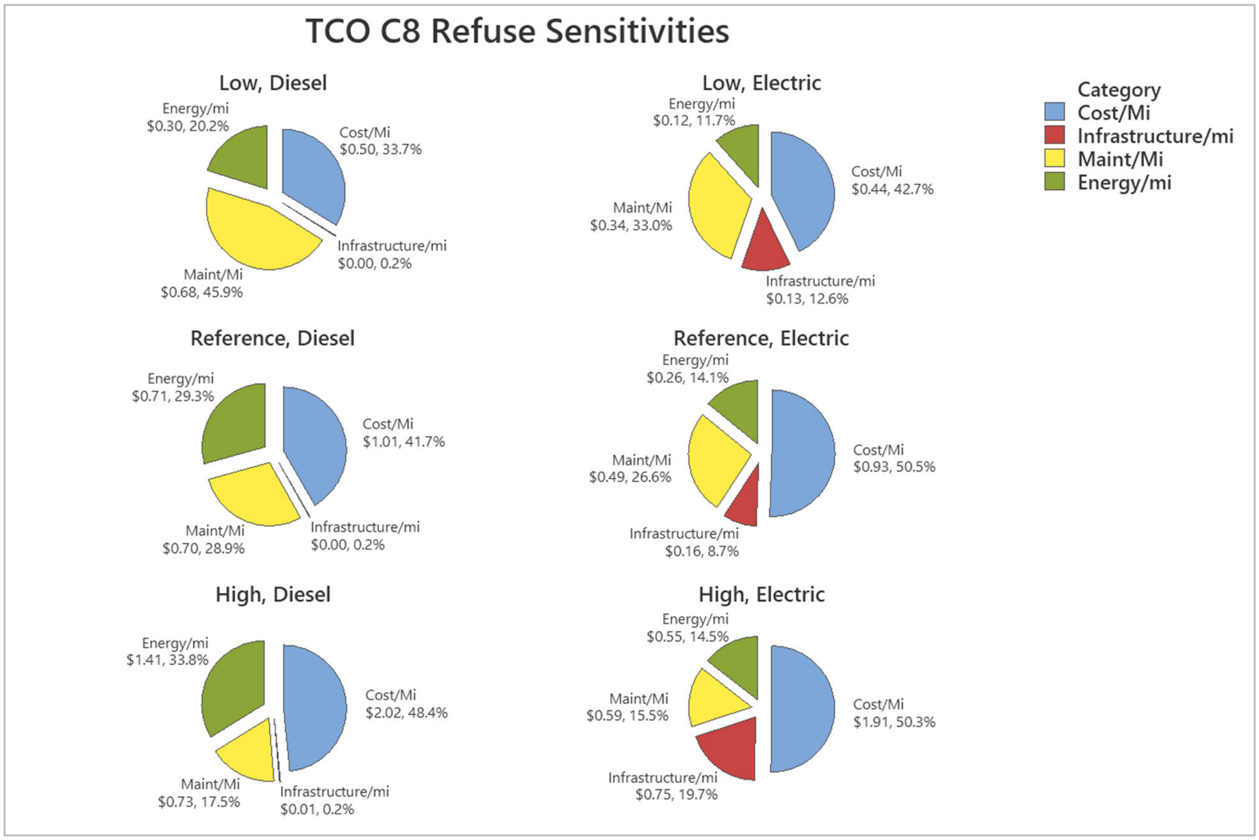


Figure 72: Class 8 Refuse Truck: Sensitivities of the total cost of ownership

5.0 Conclusions

As demonstrated in the analysis of the incremental cost for all transportation segments studied, the cost of electrification significantly decreases, nearing or achieving cost parity with ICE vehicles in 2027. The cost for an ICE vehicle that meets the increasingly stringent GHG regulations and low NOx regulations from EPA and ARB will be higher than a current ICE meeting 2021 regulations. On the opposite side, further technology development of ICE components such as batteries, motors, and power electronics will decrease the costs of these items in the 20207-2035 timeframe, leading to their cost parity or advantage over ICE powertrains. These technology developments decrease EV cost by both improving the scale and efficiency of manufacturing, but by also utilizing new materials, formulations, and architectures to create more power-dense, lighter components with materials that are widely available and not subject to volatile pricing and supply chain issues. In all cases, there is an incremental cost scenario that favors electrification, as shown in Figure 73.

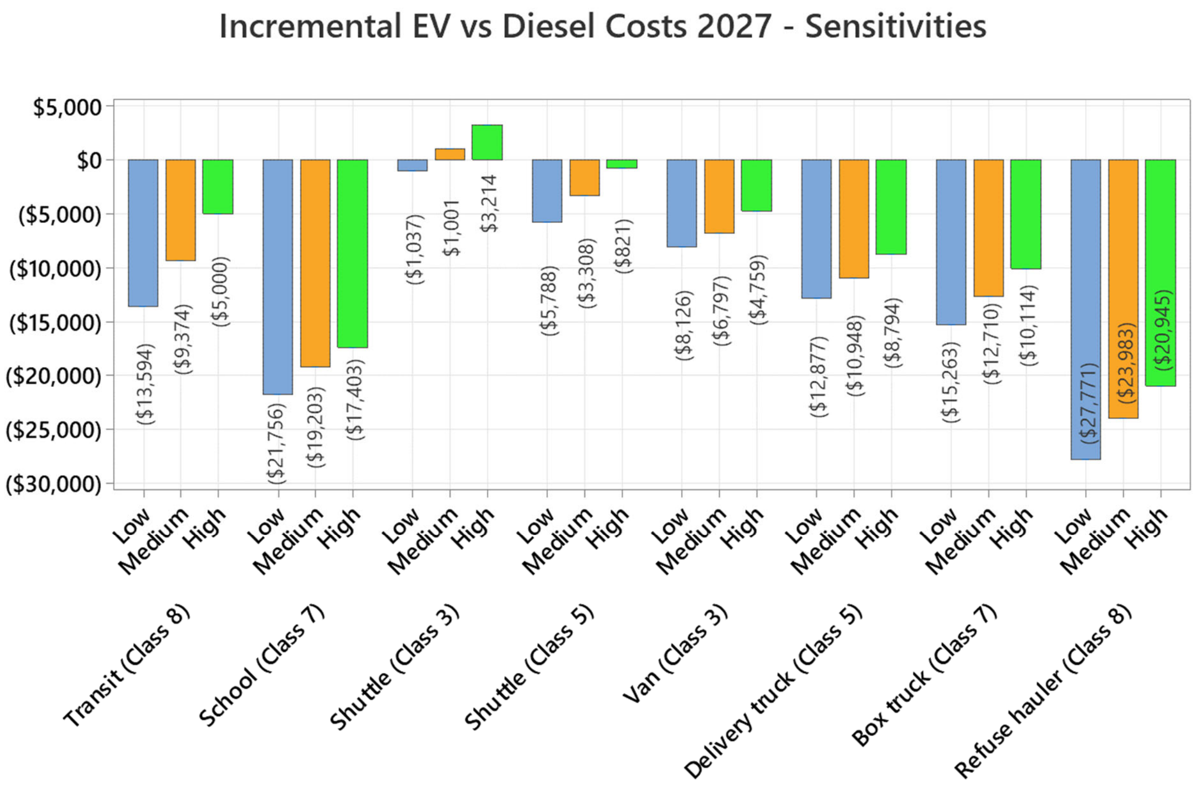


Figure 73: Incremental cost from ICE to EV powertrains in 2027.

Of equal or greater importance to fleet customers than purchase cost parity is the total cost of ownership, representing all capital expenditures related to a vehicle that an owner will encounter over the vehicle's life. EVs are a clear winner in this segment as well due to lower energy and maintenance costs in fleet operation, despite possible high infrastructure costs associated with building out an EV charging solution. To further improve the TCO equation, the cost of chargers and charging infrastructure has significant potential for further cost reduction and optimization through operation optimization and managed charging strategies.

Table 67 summarizes the results of the TCO study reference case. The TCO of BEVs purchased in 2027 for all the different types of vehicles analyzed in the study is lower than the comparable diesel vehicle by a significant margin (between 13.2% and 27.1%).

Table 67: TCO results summary – reference electric vs diesel

Class	Segment	Battery Size	Purchase cost	Operating cost	TCO	Year of TCO parity
		kWh	% Cost Reduction of EV vs ICE			
Class 8	Transit Bus	400	0.8	49.5	31.6	2
Class 7	School Bus	60	12.4	26.5	23.7	1
Class 5	Shuttle Bus	200	0.2	15.9	13.7	3
Class 3	Delivery Van	100	0.7	31.2	16.9	3
Class 5	Delivery Truck	150	12.4	52.0	34.0	1
Class 7	Delivery Truck	100	9.4	14.3	12.7	4
Class 8	Refuse Hauler	200	7.3	35.6	23.9	1

The purchase cost of all vehicles except the class 5 shuttle (only 2% higher – almost at parity) is lower than the equivalent diesel engine vehicle. The purchase price of the vehicles is very sensitive to the size of the battery pack. With the increasing energy density of LFP chemistry (Guoxuan High-Tech – 210 Wh/kg) and the advances in cell form factor and pack construction resulting in higher pack lever energy density (BYD – 140 Wh/kg, 279 Wh/liter), it has a high probability of being the default chemistry of choice for all the applications analyzed in this report. This will reduce the battery pack cost by greater than 13% reducing the purchase price of the vehicle.

As shown in Table 67, the operating cost (fuel + maintenance cost) of BEVs is significantly lower (between 28.7% and 61.8%) when compared to the equivalent diesel vehicle. Even with the cheaper purchase price and significantly lower operating expenses, BEVs in some segments take up to 3 years to reach parity on the cumulative cost of ownership with the comparable diesel vehicle. This is due to the charging infrastructure cost, all of which is assumed to be incurred at the time of purchase. This study assumes that every business that purchases these vehicles installs a captive charging solution which is very expensive. These could be cases where the same charging infrastructure is shared between different MDHD fleets in the city significantly reducing the infrastructure cost per vehicle. Also, there are no studies that look into how the increase in the adoption of BEVs and scaling of production volumes of power electronics, and standardization of processes for installing EV chargers will lead to a lowering of infrastructure costs. Incentives, financing, and government funding for the development of a robust DC fast-charging network will reduce the amount of spending that fleets have to make to install captive chargers reducing the TCO significantly speeding the adoption of BEVs.

In addition to the reduced costs of EV purchase and operation as EVs become more prevalent and charging networks expand, the benefits of switching buses and delivery vehicles to electric are quite significant in indirect costs and societal benefits. Regulations that reduce the emissions of diesel vehicles and encourage EV adoption improves health outcomes, reduces healthcare spending, improves environmental and smog conditions in city centers, and alleviates noise pollution.

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