# Electrification Cost Evaluation of Class 2b and Class 3 Vehicles in 2027–2030

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# Table of Contents

**List of Figures**

**List of Tables**

**Abbreviations & Acronyms**

| | |
|---|---|
| AAA | American Automobile Association |
| ADEAC | Advanced Cylinder Deactivation |
| ADSL | Baseline Diesel Engine Technology |
| AEO | Annual Energy Outlook |
| AER | All-Electric Range |
| ANL | Argonne National Laboratory |
| ASSB | All-Solid-State Battery |
| AT | Automatic Transmissions |
| AT10 | 10-Speed Automatic Transmission |
| AT10L3 | 10-speed Automatic Transmission, Level 3 |
| BEV | Battery Electric Vehicle |
| BEV150 | 150-mile range BEV |
| BEV200 | 200-mile range BEV |
| BEV300 | 300-mile range BEV |
| BEV400 | 400-mile range BEV |
| BISG | Belt Integrated Starter Generator (48-Volt mild hybrid system) |
| BMS | Battery Management System |
| BNEF | Bloomberg New Energy Finance |
| CAFE | Corporate Average Fuel Economy |
| CARB | California Air Resources Board |
| CEGR1 | Advanced turbocharged downsized technology with cooled exhaust gas recirculation |
| CTC | Cell-to-Chassis |
| CVT | Continuously Variable Transmission |
| CVTL2 | Continuous Variable Transmission Level 2 HEG |
| DBE | Dry Battery Electrode |
| DCFC | Direct Current Fast Charging |
| DEAC | Cylinder Deactivation |
| DI | Direct Injection |
| DOE | U.S. Department of Energy |

| | |
|---|---|
| DOHC | Dual Overhead Cam |
| DOT | U.S. Department of Transportation |
| DSLI | Advanced diesel engine with improvements |
| DSLIAD | Advanced diesel engine with improvements and advanced cylinder deactivation |
| eCVT | Electronic Continuously Variable Transmission |
| EFR | Engine Friction Reduction |
| EGR | Exhaust Gas Recirculation |
| EHC | Electrically Heated Catalyst |
| EIA | U.S. Energy Information Administration |
| EOL | End-of-Life |
| EPA | U.S. Environmental Protection Agency |
| ESG | Environmental, Social, and Governance |
| EU | European Union |
| EV | Electric Vehicle |
| FCA | Fiat Chrysler Automobiles |
| FCEV | Fuel Cell Electric Vehicle |
| GCTP | Gravimetric Cell-to-Pack ratio (weight of the cells/weight of the battery pack) |
| GHG | Green House Gas |
| GREET | Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation |
| GVW | Gross Vehicle Weight |
| GVWR | Gross Vehicle Weight Rating |
| GWh | Gigawatt-hour |
| HCR | High Compression Ratio |
| HE-NMC | High Energy-Nickel Manganese Cobalt |
| HEV | Hybrid Electric Vehicle |
| HP | Horsepower |
| HVAC | Heating Ventilation and Air-Conditioning |
| HV-Spinel | High Voltage-Spinel |
| ICCT | International Council on Clean Transportation |

| | |
|---|---|
| ICE | Internal Combustion Engine |
| ICEV | Internal Combustion Engine Vehicle |
| IM | Induction Motor |
| kW | Kilowatt |
| kWh | Kilowatt-hour |
| LAB | Lead Acid Battery |
| LDV | Light Duty Vehicle |
| LFP | Lithium Iron Phosphate |
| LIB | Lithium-Ion Battery |
| LMFP | Lithium Manganese Ferrophosphate |
| LMNO | Lithium Manganese Nickel Oxide |
| LTO | Lithium Titanate Oxide |
| LTVs | Light Trucks and Vans |
| MDHD | Medium-Duty and Heavy-Duty |
| MOVES | Motor Vehicle Emission Simulator |
| MPG | Miles Per Gallon |
| MPGe | Miles-Per-Gallon Equivalent |
| mph | Miles Per Hour |
| MSRP | Manufacturer Suggested Retail Price |
| MT | Manual Transmissions |
| MY | Model Year |
| NA | Naturally Aspirated |
| NCA | Lithium Nickel Cobalt Aluminum Oxide |
| NFA | Lithium-Iron and Aluminum Nickelate |
| NHTSA | National Highway Traffic Safety Administration |
| NiMH | Nickel Metal Hydride |
| NMC | Nickel Manganese Cobalt |
| NOx | Nitrogen Oxide |
| OEM | Original Equipment Manufacturer |
| OHV | Over-Head Valve |
| ORNL | Oak Ridge National Laboratory |

| | |
|---|---|
| PFI | Port Fuel Injection |
| PHEV | Plug-In Hybrid Electric Vehicle |
| PM | Permanent Magnet |
| PMSM | Permanent Magnet Synchronous Motor |
| PMSyn-RM | Permanent Magnet Synchronous Reluctance Motor |
| RPE | Retail Price Equivalent |
| SAE | Society of Automotive Engineers |
| SAFE | Safer Affordable Fuel-Efficient Vehicles Rule |
| SESM | Separately Excited Synchronous Motor |
| SGDI | Stoichiometric Gasoline Direct Injection |
| SHEVP2 | Parallel Strong Hybrid Electric Vehicle |
| SLB | Second-Life Batteries |
| SOC | State of Charge |
| SOHC | Single Overhead Cam |
| SRM | Switched Reluctance Motor |
| SUV | Sport Utility Vehicle |
| TCO | Total Cost of Ownership |
| TM | Thermally Modulated |
| TURBO1 | Turbocharged Engine |
| TWh | Terawatt-Hour |
| U.S.C. | United States Code |
| USABC | United States Advanced Battery Consortium |
| VCR | Variable Compression Ratio |
| VCTP | Volumetric Cell-to-Pack ratio (volume of the cells/volume of the battery pack) |
| VGP | Vehicle Glider Price |
| VMT | Vehicle Miles Traveled |
| VTG | Variable Turbo Geometry Engine |
| VTO | DOE Vehicle Technologies Office |
| VVL | Variable Valve Lift |
| VVT | Variable Valve Timing |
| WRSM | Wound Rotor Synchronous Motor |

## Glossary of Terms and Definitions

**10-speed Automatic Transmission (AT10) with level 3 high-efficiency gearbox (HEG) technology (AT10L3):** A multi-speed transmission that automatically selects and shifts between transmission gears during vehicle operation. Level 3 HEG improvements are projected to improve oil supply by deploying an on-demand electric oil pump and electromechanical shifting [1], [2]. They have been assigned to all class 2b–3 vehicles in the analysis.

**Advanced Diesel System (DSLIAD) with advanced cylinder deactivation technology (ADEAC):** NHTSA/EPA has created this advanced diesel technology system using the baseline diesel engine technology (ADSL), which is based on a standard 2.2-liter turbocharged diesel engine. They developed the most advanced diesel system (DSLIAD) by adding advanced cylinder deactivation technology to the DSLI system [2].

**Belt Integrated Starter Generator (BISG):** Also known as a mild hybrid or start-stop system that provides the idle-stop capability and uses a higher voltage battery (48V). It uses a powerful and efficient electric motor/generator.

**Battery-Electric Vehicles (BEV) 150/250/300/400:** Batteries power the motors that propel the vehicle. The numbers represent the driving range of the BEV in miles.

**Compression Ignition (CI) Engine:** Also known as a diesel engine, the CI engine is a type of internal combustion engine that ignites diesel fuel with the help of hot compressed air. It does not use a spark plug to ignite the fuel-air mixture like gasoline or spark ignition engines.

**Conventional (CONV):** A vehicle that does not include any level of hybridization [2].

**Cooled Exhaust Gas Recirculation (cEGR):** An emissions reduction technique that recirculates a portion of exhaust gas through an intercooler and then mixes it with the incoming fresh air.

**Dual Over-Head Camshaft (DOHC):** DOHC designs are efficient and produce the most horsepower for a given displacement. With dual camshaft, one operates the intake valve and the other the exhaust valves. DOHC allows for four valves per cylinder, improving airflow and increasing power and efficiency.

**Deactivation (DEAC):** A method of selective valve deactivation that shuts off the cylinder. Cylinder deactivation disables intake and exhaust valves and turns off fuel injection for the deactivated cylinders during light-load operation. It reduces pumping losses and improves engine efficiency and fuel economy.

**Electric Vehicle (EV):** A type of vehicle that is powered by batteries, fuel cells, or a combination of both along with one or more electric motors; this is in contrast to an internal combustion engine that runs solely on gasoline or diesel fuel. Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs) are types of EVs.

**Plug-in Hybrid Electric Vehicle (PHEV)**: A type of hybrid vehicle that combines an internal combustion engine with a rechargeable battery pack. They are charged using an external power source. PHEVs are more efficient than conventional hybrid vehicles, as they can run purely on electric power for shorter distances and switch to gasoline or diesel power for longer journeys.

**Strong Hybrid Electric Vehicle with P2 Parallel Drivetrain Architecture or P2 Parallel Hybrids (SHEVP2)** – A strong hybrid vehicle is a vehicle that combines two or more propulsion systems, where one uses gasoline (or diesel) and the other captures energy from the vehicle during deceleration or braking, or from the engine, and stores that energy for later use by the vehicle. It provides idle-stop functionality, regenerative braking, and vehicle launch assist. P2 hybrids rely on the ICE to power the vehicle, with the electric mode kicking in only when the power demands are less than moderate [3].

**Stoichiometric Gasoline Direct Injection (SGDI)** – Sprays fuel directly into the combustion chamber at high pressure. This method cools the in-cylinder air/fuel charge, improving spark knock tolerance, achieving a higher compression ratio, and increasing thermodynamic efficiency.

**Turbocharging and Downsizing Level 1 (TURBO1)** – This represents a basic level of forced air induction technology applied to a DOHC-based engine [1].

**Variable Valve Timing (VVT)** – A family of valve-train designs that alters the timing of the engine valves individually or together relative to the piston position. VVT can reduce pumping losses and increase engine torque over a broad range.

## Executive summary

***Key Highlights***

Emissions from class 2b and class 3 vehicles contribute to air pollution that is damaging to public health and the environment. Recent public policy developments and the announcement of manufacturer product plans and commitments, coupled with the growing demand for battery electric vehicles (BEVs), have accelerated the deployment of clean vehicle technology. At the same time, the anticipated stringency of regulatory requirements beyond 2026 is expected to increase the cost of technologies used in internal combustion engine vehicles (ICEVs). This study evaluates the economic viability of class 2b–3 BEVs in the 2027–2030 timeframe by analyzing three scenarios of the incremental cost of vehicle electrification and assessing the total cost of ownership (TCO) during an assumed vehicle lifetime of 12 years. TCO, expressed in dollars per mile, signifies the cost of owning and operating a vehicle over its lifetime and accounts for both the upfront purchase price and the cost of operation (such as fuel or electricity costs and maintenance costs).

The high-level conclusions of our analysis are:

a) From an incremental cost of electrification standpoint, the vast majority of class 2b–3 vehicles are well-positioned to transition from internal combustion engines to electrified powertrains by model years (MY) 2027 and 2030.
b) While the economics vary based on several factors, the TCO of most MY 2027 and MY 2030 class 2b–3 BEV types is lower than the TCO of comparable ICEVs, largely due to BEVs' lower maintenance and energy costs. Across the vehicle types and three scenarios of electrification considered in this report, the TCO of BEVs averages $0.334 per mile (ranging from $0.291 per mile to $0.39 per mile), while the TCO of ICEVs averages $0.428 per mile (ranging from $0.336 per mile to $0.574 per mile).
c) On average, consumers who purchase class 2b and 3 BEVs instead of ICEVs in MYs 2027 and 2030 could save about $20,000 and $25,000, respectively, during their vehicles' lifetimes.
d) Our sensitivity analysis applying the peak fuel prices observed in the summer of 2022 finds that most MYs 2027 and 2030 class 2b and 3 BEVs would achieve TCO parity within the first year of ownership under a high fuel cost scenario. Under this scenario, consumers who purchase BEVs instead of ICEVs in MYs 2027 and 2030 would enjoy average cumulative net savings of about $56,000 and $60,000, respectively.
e) When accounting for credits available under the Inflation Reduction Act of 2022 (IRA), a significant acceleration in purchase and TCO parity is seen in MY 2027 BEVs across all classes and scenarios. After applying these credits, the TCO of BEVs averages about $0.40 per mile and $0.31 per mile in MYs 2023 and 2027, respectively, which is less than the TCO of comparable ICEVs, which averages $0.42 per mile in MY 2023 and $0.43 per mile in MY 2027.

In short, this study concludes that the economics strongly favor vehicle electrification in the coming years. A typical class 2b–3 BEV owner would save several thousand dollars, compared to a typical ICEV owner, as a result of BEVs' greater fuel efficiency and lower maintenance costs. Additionally, with new tax credits available under the IRA, consumers could enjoy even greater affordability.

## Background

The transportation sector is the largest source of greenhouse gas emissions (GHG) in the United States [4]. In 2021, medium- and heavy-duty (MD/HD) vehicles contributed 24% of U.S. transportation GHG emissions [4]. Class 2b (with a gross vehicle weight rating, also known as GVWR, of 8,501–10,000 lbs.) and class 3 (with a GVWR of 10,001–14,000 lbs.) vehicles form a significant proportion of the MD/HD sector. Prioritizing emission reductions within the transportation sector, including from class 2b–3 vehicles, is a critical strategy for achieving public health, climate, and environmental benefits.

Congress's recent passage of the Inflation Reduction Act (IRA) of 2022 will accelerate the electrification of vehicles and produce benefits across the entire automotive ecosystem. With several states phasing out the sale of new light-duty gasoline- and diesel-powered vehicles by 2035, the automotive industry is currently experiencing a paradigm change, with electric vehicles (EVs) poised to gain greater market share in the coming years. Following early successful entrants like Tesla, legacy automakers such as Ford, General Motors (GM), and Volkswagen (VW) have begun producing battery electric vehicles (BEVs) and expanding their portfolio of EV offerings.

This study evaluates the economic viability of electrification of class 2b–3 vehicles relative to their ICEV counterparts by projecting the incremental costs of vehicle electrification and the total cost of ownership (TCO) of MY 2027 and MY 2030 battery electric vehicles (BEVs) over their lifecycle. The incremental cost of electrification is defined as the excess cost of a BEV powertrain over a comparable internal combustion engine (ICE) powertrain. The primary cost drivers are the ICEV engine, ICEV transmission, ICEV aftertreatment, and BEV electrification systems. Other non-powertrain-related costs are assumed to be similar between the two powertrain options. TCO, expressed in dollars per mile, signifies the cost of owning and operating a vehicle over its lifetime and accounts for both the upfront purchase price, charger-related costs (in the case of BEVs), and the cost of operation (such as fuel/electricity and maintenance costs).

Additionally, this study analyzes the effect of IRA provisions on BEVs purchased in the 2023 and 2027 timeframes and attempts to quantify the impact of IRA credits on the purchase price of a BEV, charger equipment, and the TCO of the vehicle. Through these costing exercises, the approximate timeframe of BEVs' cost parity with their ICEV counterparts can be identified, and the economic viability of electrification in the class 2b–3 segments can be determined for the 2027–2030 timeframe.

## Key Assumptions and Methodology

Only tangible financial aspects related to vehicle ownership are considered, namely vehicle price, charging equipment, fuel, and maintenance costs. Nontangible benefits, such as societal, health, environmental, and enhanced vehicle performance benefits, are not accounted for in this study. Geopolitical conditions, supply chain disruptions, other macroeconomic factors, and environmental, social, and corporate governance (ESG) considerations are also not factored into the analysis. This study assumes that the long-term raw material supply will be sufficient to meet the demand without any supply disruptions or shortages or that alternative technologies, which are assessed later in this report, are available as a potential substitute to offset any technology or supply chain-related challenges. Purchase price parity timeframes and TCO costs were developed for direct comparison of BEVs against comparable ICEVs. In this study, we assume that a BEV powertrain will be retrofitted on an ICEV platform, which *de facto* establishes the equivalence of these vehicles.

Figure 1 summarizes the vehicle classes and types, ICEV powertrains (i.e., engine and transmission types), BEV segments (based on the range in miles, meaning that "BEV150" means a BEV with a 150-mile range), and BEV battery chemistries considered in this study for the 2027–2030 timeframe. These different technology pathways reflect the wide range of technologies likely to be in the marketplace during that timeframe based on anticipated market and regulatory developments.

| Vehicle Class/Type | Engine | Transmission | BEV Segments | Battery |
|---|---|---|---|---|
| Class 2b Van | OHV, DOHC, VVT, SGDI | AT10L3 | BEV150 | LFP |
| Class 3 Package & Delivery Truck | ADEAC | **Electrification** | BEV250 | NMC811 |
| Class 3 Pickup Truck | TURBO1 (Class 2b only) | Conventional | BEV300 | |
| Class 3 Van | DSLIAD (Class 3 only) | BISG | BEV400 | |
| | | SHEVP2 (Class 2b only) | | |

**Figure 1: Technology pathways considered for class 2b–3 vehicle types.**

To assess the cost of electrification compared to fossil fuel-powered ICE vehicles, this analysis uses an incremental cost of electrification approach. This approach tries to capture a wide range of powertrain technologies and their associated costs. On the BEV side, the powertrain choices are driven by battery size and range. The incremental cost of electrification is presented with three different scenarios that reflect increasing levels of cost—Scenario 1, Scenario 2, and Scenario 3. These scenarios compare the powertrain cost and TCO of an ICEV to a comparable BEV. As illustrated in Figure 2, the three scenarios for the incremental cost of electrification are described as follows:

a) Scenario 1 is the cost of electrification when migrating from a high-cost ICEV to a low-cost BEV, or, in other words, the most favorable scenario for switching to a BEV. Scenario 1 has the lowest incremental cost of electrification, and a BEV takes the shortest time to achieve TCO parity against an ICEV.
b) Scenario 2 is the cost of electrification when migrating from a medium-cost ICEV to a medium-cost BEV.
c) Scenario 3 is the cost of electrification when migrating from a low-cost ICEV to a high-cost BEV, or, in other words, the least favorable scenario for switching to a BEV. Scenario 3 has the highest incremental cost of electrification, and a BEV takes the longest time to achieve TCO parity against an ICEV.

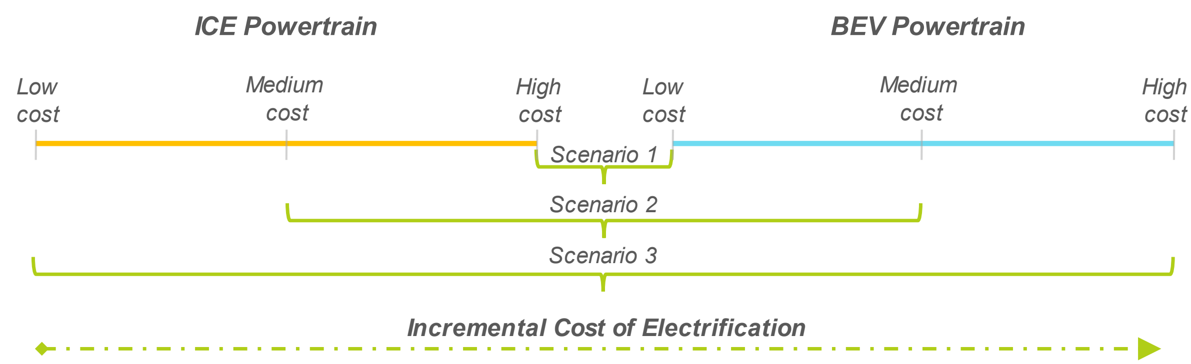


**Figure 2: Conceptual figure illustrating the incremental cost of electrification scenarios.**

The ICEV technology packages considered in the study represent those that we anticipate may be used in the 2027–2030 timeframe under current or future EPA regulations. For class 2b vehicles, this study assumes three gasoline powertrains with varying levels of hybridization: NA SI (non-electrified), NA SI with BISG (mild hybrid), and NA SI SHEVP2 (strong hybrid). For class 3, this study assumes that vehicles have similar low- and medium-cost options, except that a CI powertrain is assumed to be a high-cost option. All vehicle types are assumed to have a 10–speed automatic transmission level 3 (AT10L3).

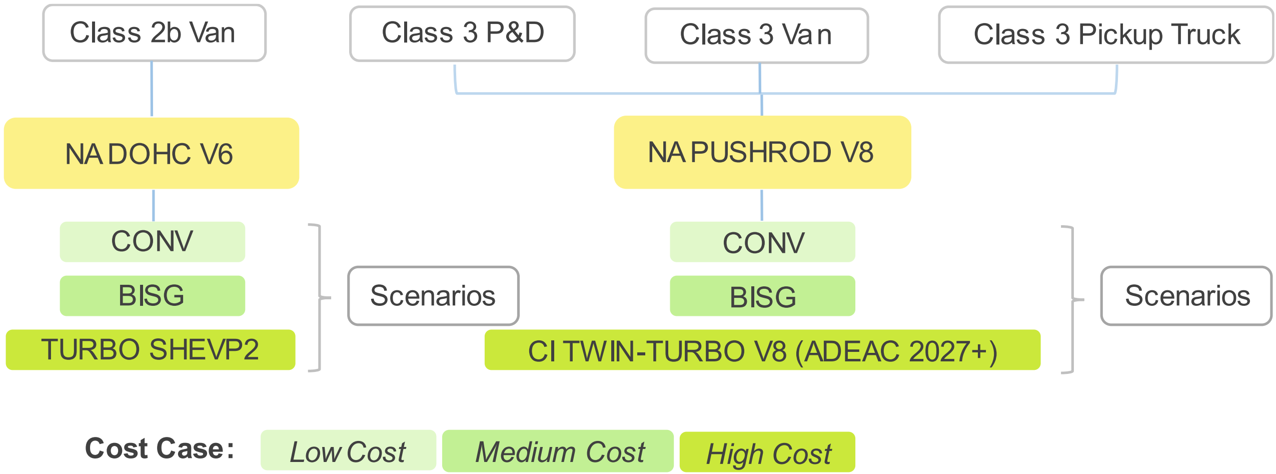


**Figure 3: Technology pathways considered for ICEVs under the three scenarios of electrification.**

BEV technology packages include 150- and 250-mile range options in all the considered vehicle classes and types. 300- and 400-mile range options have also been considered for the class 3 pickup truck. NMC811 and LFP battery chemistries are both considered for the cost analysis of BEVs as they are expected to have a significant presence in the EV market by the 2030 timeframe. It is believed that Original Equipment Manufacturers (OEMs) would follow a tiered approach where entry-level vehicles would be equipped with cobalt-free LFP batteries and high-end models and trims would be equipped with NMC batteries to meet consumer preferences. Additionally, since LFP chemistry is seen as an alternative to cobalt- and nickel-based chemistries, its selection in the low-cost case is more than a simple cost-saving option; it is a path around potential supply issues involving these two metals. LFP, NMC811, and a 10% costlier NMC811 are used to develop the low-, medium-, and high-cost BEV powertrains. An additional $1,800 is assumed to be incurred by the consumer towards the procurement and installation of a 19.2 kW level 2 residential charger.

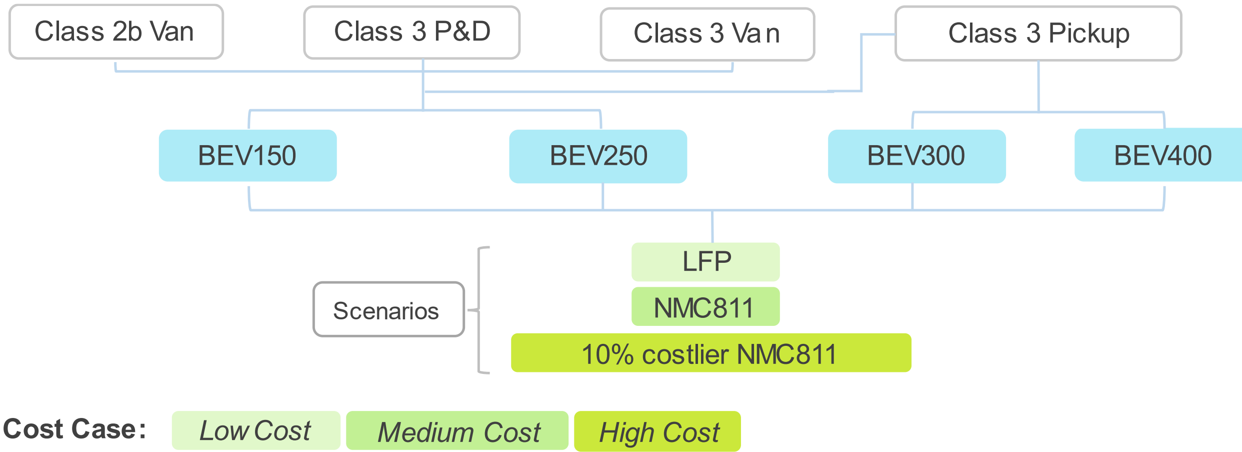


**Figure 4: Technology pathways considered for BEVs under the three scenarios of electrification.**

The breakdown of the retail price equivalents of ICEVs and BEVs is shown in Figure 5. For each vehicle type, the ICEV and BEV are assumed to have the same glider price. The price of the vehicle without the powertrain is the glider price. The powertrain costs are then added to the glider price. The vehicle purchase price was calculated using a retail price equivalent (RPE) factor of 1.5 for ICEVs [5] and 1.2 for BEVs. The RPE factor is lower for BEVs in comparison with ICEVs due to several factors, as explained in Section 2.5 below. The primary reason is that BEVs have a much simpler architecture and lower indirect costs compared to ICEVs. The main driver of indirect costs for BEVs is the production overhead of batteries, which will be substantially absorbed by the battery manufacturers themselves.

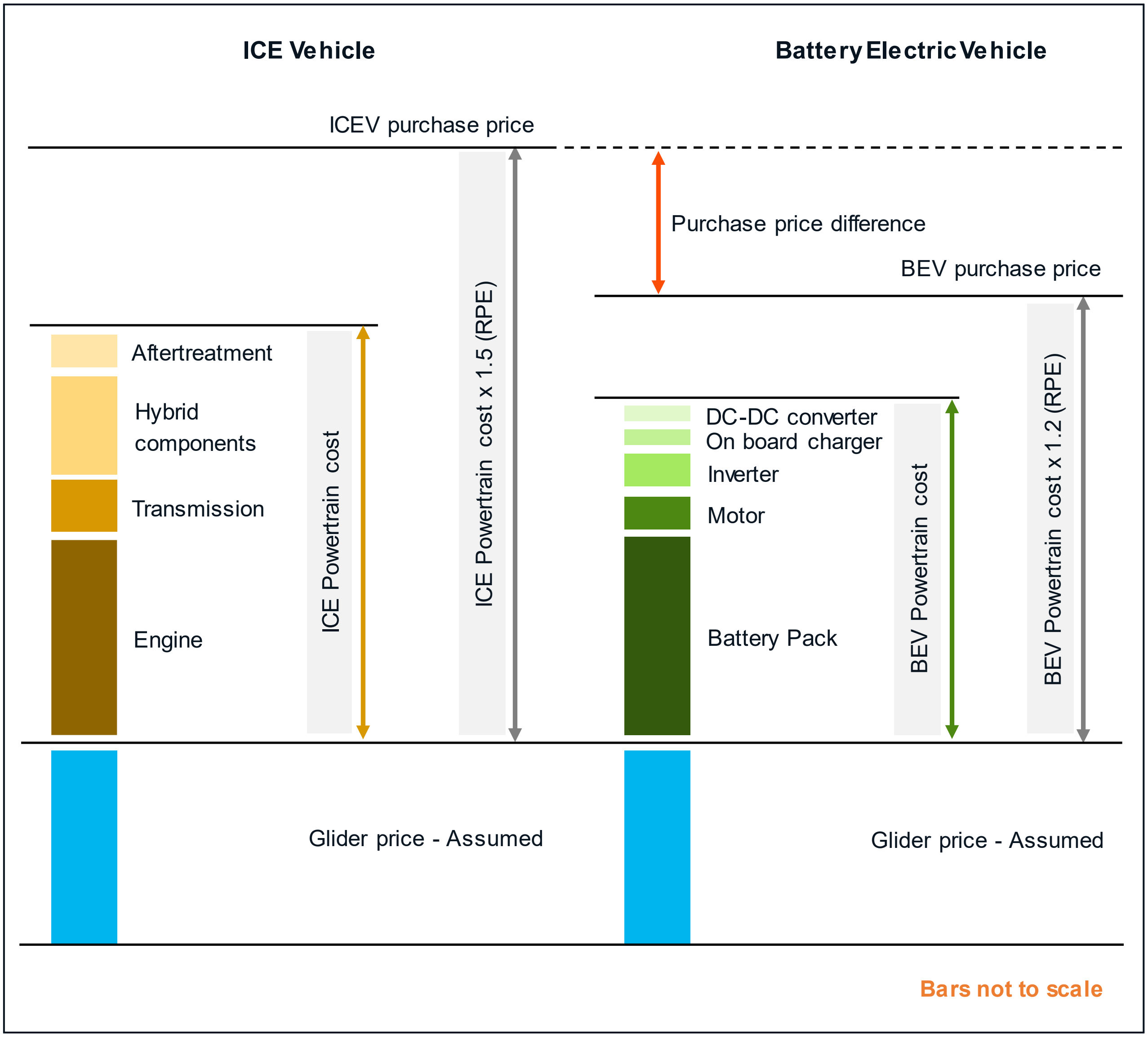


**Figure 5: Methodology of calculation of ICE and BEV purchase price.**

This study also considers the effect of gasoline and diesel prices. For the TCO calculations, high gasoline prices have been applied to the high-cost ICE powertrain and low gasoline prices have been applied to the low-cost ICE powertrain, as shown in Figure 6. As described earlier and illustrated below in the figure, the high-cost ICE powertrain is under Scenario 1, the medium-cost ICE powertrain is under Scenario 2, and the low-cost ICE powertrain is under Scenario 3. We used three distinct gasoline price projections from the EIA in Scenarios 1, 2, and 3, as described. Gasoline price projections from the EIA's high oil price sensitivity case are used in Scenario 1, reference case gasoline prices are used in Scenario 2, and gasoline prices from the low oil price case are used in Scenario 3. Scenario 1 assumes gasoline prices in the range of $4.17/gallon-$4.37/gallon for class 2b and diesel prices in the range of $4.77/gallon-$5.15/gallon for class 3; Scenario 2 assumes gasoline prices in the range of $2.68/gallon-$3.09/gallon; and Scenario 3 assumes gasoline prices in the range of $2.02/gallon-$2.24/gallon. To reiterate, Scenario 1 represents the lowest cost of electrification (highest gasoline prices here), and Scenario 3 represents the highest cost of electrification (lowest gasoline prices here).

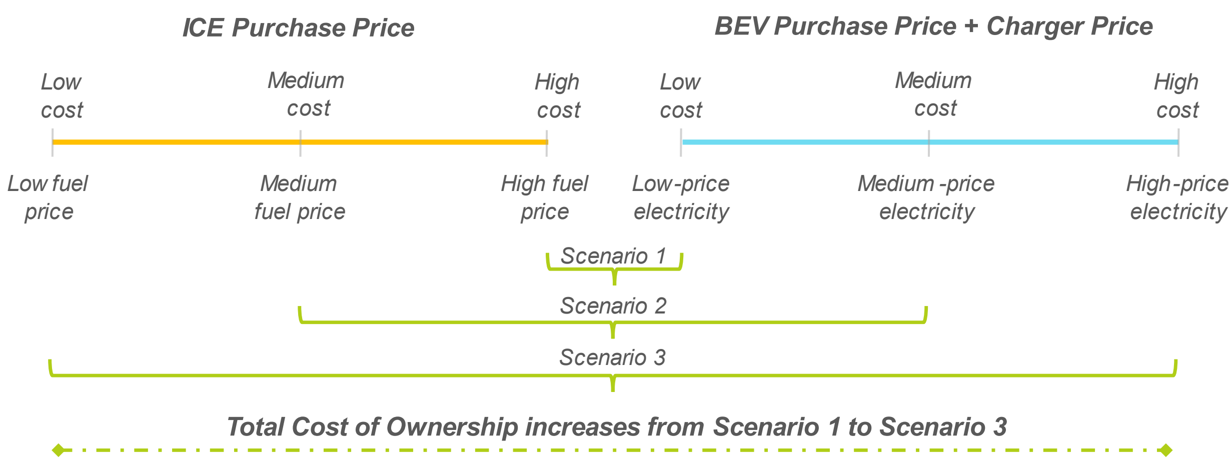


**Figure 6: Conceptual figure illustrating the total cost of ownership (TCO) scenarios. Respective maintenance costs of ICE and BEV do not differ across scenarios.**

Switching from a high-cost ICE powertrain with high fuel prices, such as a SHEVP2 or CI with advanced DEAC (DSLIAD), to a low-cost BEV powertrain with low electricity prices (averaging 12.6¢/kWh) and an LFP battery pack results in the lowest incremental cost of electrification, namely, Scenario 1. Switching from a low-cost ICE powertrain with low fuel prices (conventional NA SI) to a BEV with a high-cost battery pack (10% premium on projected NMC811 cost) and high electricity prices (averaging 13.1¢/kWh) results in the highest incremental cost of electrification, namely, Scenario 3.

While the vehicle purchase price is borne by the consumer upfront, operating costs are incurred by the consumer over the entire lifetime of vehicle ownership. Operating costs include energy and maintenance costs over an assumed lifespan of 12 years. Energy costs are computed using the annual vehicle miles traveled (VMT), fuel economy, and retail fuel prices. Fuel prices are based on the gasoline and diesel retail prices ($/gallon) and end-use residential electricity prices ($/kWh) using the United States Energy Information Administration's (EIA) Annual Energy Outlook 2022 (AEO2022) projections in the 2027–2041 timeframe for ICEVs and BEVs, respectively [6]. Projected gasoline/diesel prices (note: *without* federal and state taxes) and electricity rates are used to compute the energy price across the three scenarios of electrification. Had the analysis accounted for gasoline/diesel taxes, we would expect the results to show increased favorability of BEVs as compared to ICEVs.

## Primary Analysis and Results

### Projected Incremental Cost (with RPE) of BEV over ICEV

As noted earlier, this study examines both the incremental cost of electrification and the TCO. In terms of the former, Figure 7 below illustrates the incremental cost of electrifying class 2b–3 vehicles under Scenarios 1, 2, and 3. In the case of Scenario 1 (the lowest incremental cost of electrification), the powertrain cost of all BEVs analyzed is cheaper than the equivalent ICEV in the 2027–2030 timeframe, except in the case of the class 3 pickup BEV300 (only MY 2027) and BEV400. And in all scenarios (except for class 3 P&D trucks and class 3 vans in Scenario 3 in 2027), the powertrain cost of a BEV150 is cheaper than the equivalent ICEV. However, in Scenarios 2 and 3, BEVs with a 250-mile or greater range in all class 2b–3 vehicle types have more expensive powertrains than a comparable ICEV in MY 2027 and MY 2030. In the case of the class 3 pickup truck, introducing a longer-range BEV (300 and 400 miles) necessitates a heavier, costlier battery pack and a costlier motor and power electronics, resulting in a more expensive electric vehicle. However, these costs are based on NMC811 battery technology, and several technologies that are currently being developed to support higher efficiency and cheaper production costs are expected to be available in the future.

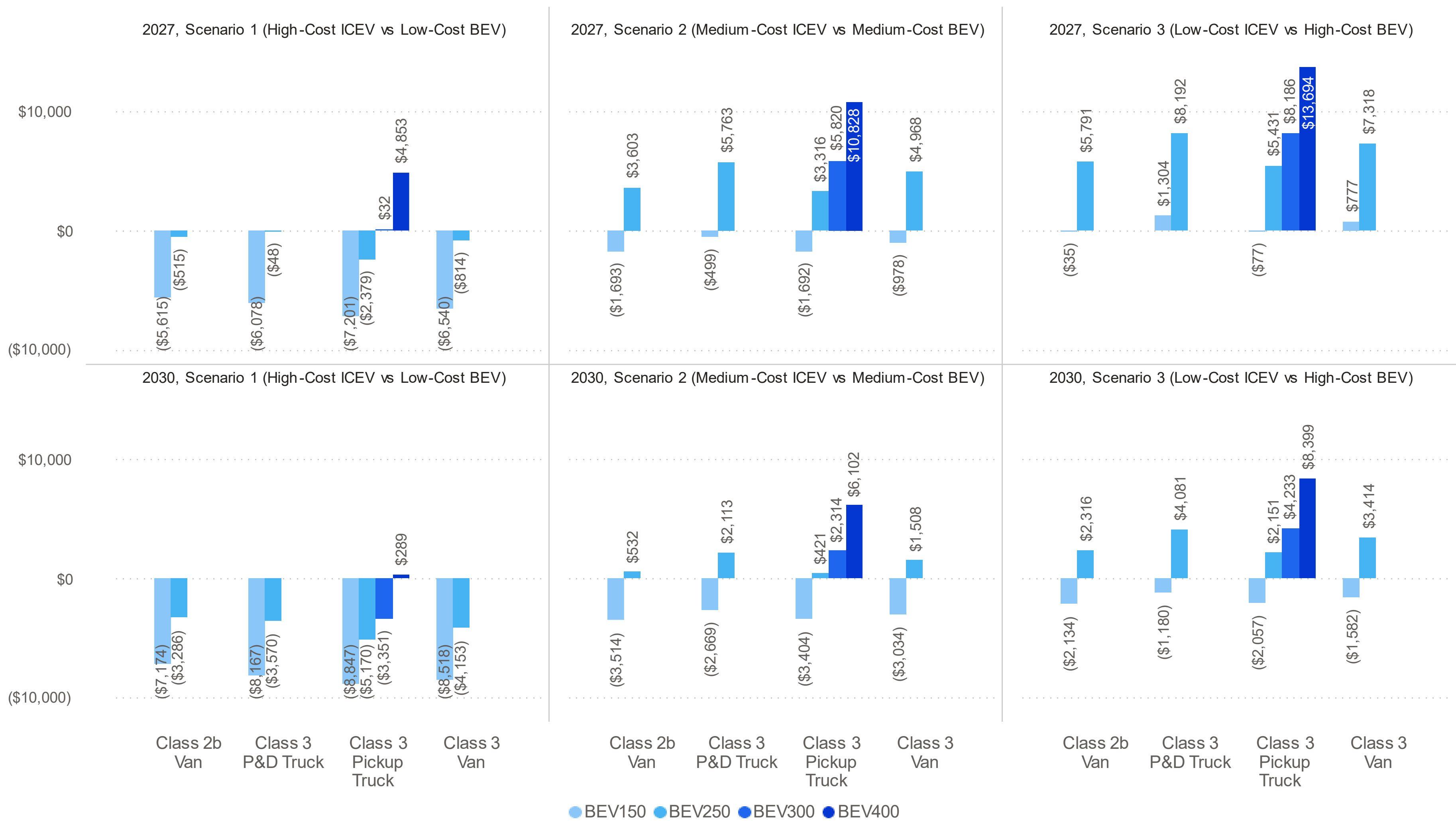


**Figure 7: Projected incremental cost (with RPE) of BEV over ICE powertrain in 2027 and 2030.**

Total Cost of Ownership (TCO)

In terms of TCO, this study concludes that over the life of ownership of class 2b–3 vehicles, BEVs are almost universally cheaper to own and operate than comparable ICEVs, as shown in Figure 8. BEVs have significantly lower operating and maintenance costs due to lower energy costs and fewer moving parts, which makes them economically attractive over their lifetimes. While the economics vary based on several factors, across the vehicle types and three scenarios of electrification considered in this report, the TCO of BEVs averages \$0.334 per mile (ranging from \$0.291 per mile to \$0.39 per mile) while the TCO of ICEVs averages \$0.428 per mile (ranging from \$0.336 per mile to \$0.574 per mile).

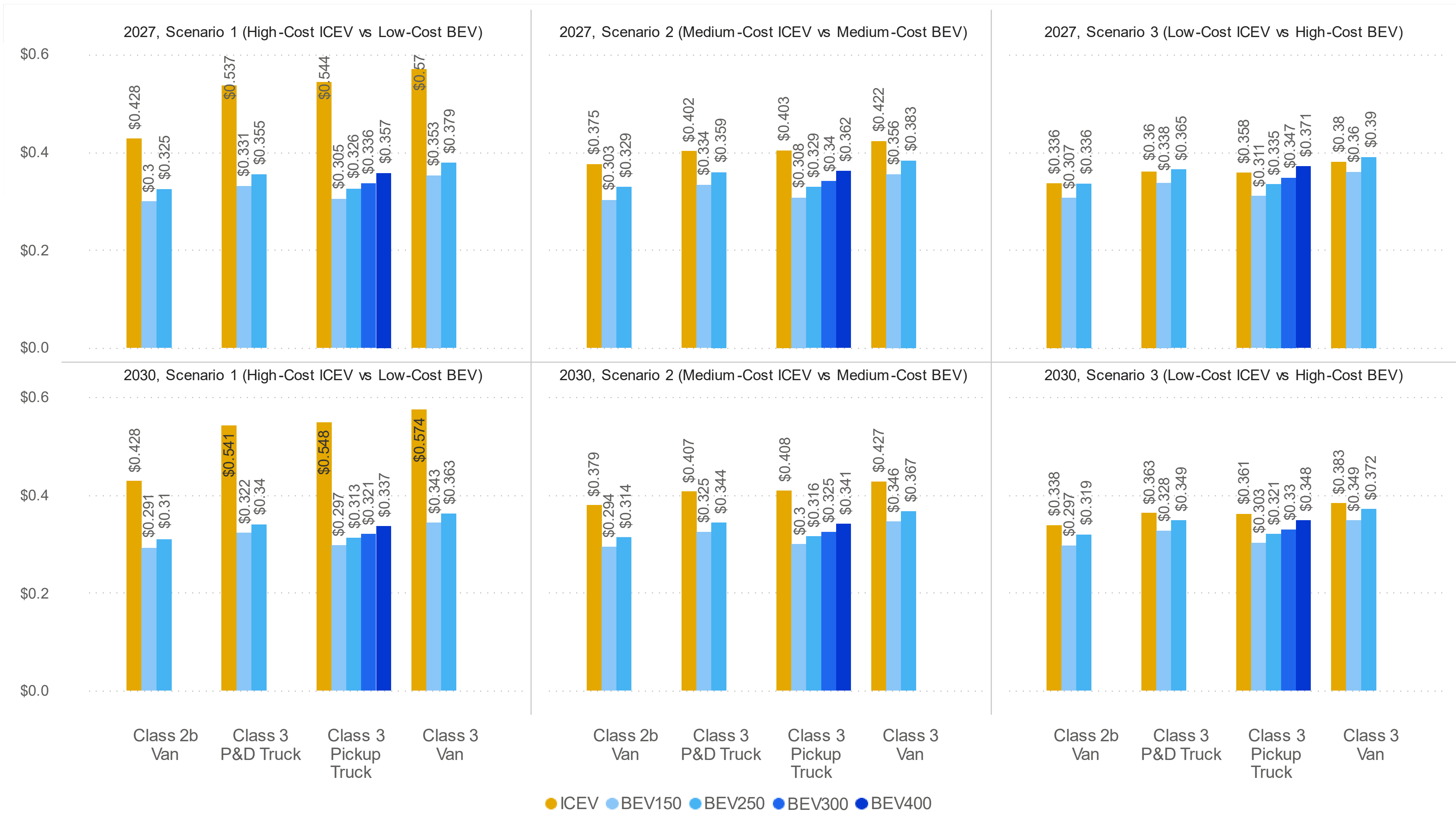


**Figure 8: Projected range of total cost of ownership (TCO) per mile for BEVs and ICEVs in 2027 and 2030.**

As illustrated in Figure 9 below, BEVs produce significant cumulative net savings compared to ICEVs during their assumed lifetime of 12 years. Scenario 1 (which features a high-cost ICEV and a low-cost BEV) has the highest savings; the savings are the lowest in Scenario 3 (which features a low-cost ICEV and a high-cost BEV). Except for certain vehicle types in Scenario 3 in 2027, all BEVs across the three scenarios produce considerable savings compared to ICEV ownership. On average, this study shows that consumers who switch to BEVs can save about $20,000 (for a MY 2027 purchase) and $25,000 (for a MY 2030 purchase) over an assumed vehicle lifetime of 12 years.

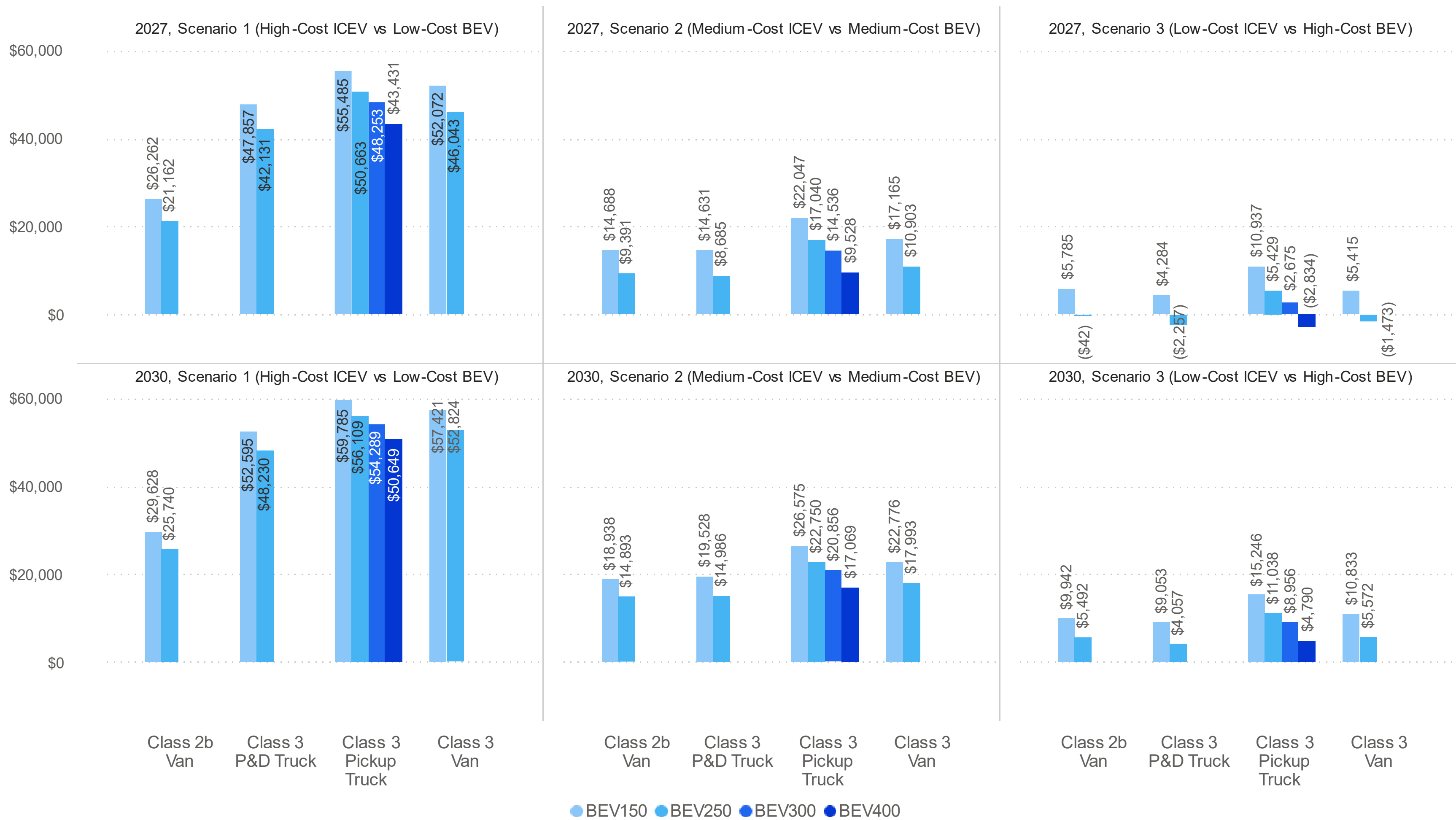


**Figure 9: Projected cumulative net savings of BEVs over ICEVs during their lifetimes.**

### Time to achieve TCO parity

This study also evaluated the time it would take for BEVs purchased in MY 2027 and MY 2030 to achieve TCO parity with equivalent ICEVs. As listed in Table 1 below,

a) In Scenario 1,
   i) All MY 2027 vehicles achieve parity within the first year of ownership, except the BEV400, which achieves parity after 1 year.
   ii) All MY 2030 vehicles achieve parity within the first year of ownership.
b) In Scenario 2,
   i) All MY 2027 BEV150s achieve parity within the first year of ownership; BEV250s and above achieve parity within 6 years.
   ii) All MY 2030 BEV150s achieve parity within the first year of ownership, while BEV250s and above achieve parity within 3 years.
c) In Scenario 3,
   i) MY 2027 BEV150s take up to 4 years to achieve parity, while BEV250 and above may not achieve parity in the assumed lifetime of 12 years. Exceptions are seen in the class 3 pickup trucks BEV250 and BEV300, which achieve parity in 6 and 9 years, respectively.
   ii) All MY 2030 BEV150s achieve parity within the first year of ownership, while BEV250s and above achieve parity in 2-7 years.

**Table 1: Time (in years) for BEVs to achieve TCO parity compared to equivalent ICEVs in 2027 and 2030.**

| Vehicle Type | BEV Segment | 2027 | | | 2030 | | |
|---|---|---|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | <1 | <1 | 2 | <1 | <1 | <1 |
| | BEV250 | <1 | 4 | End of Life | <1 | 1 | 4 |
| Class 3 Pickup | BEV150 | <1 | <1 | 1 | <1 | <1 | <1 |
| | BEV250 | <1 | 2 | 6 | <1 | <1 | 2 |
| | BEV300 | <1 | 4 | 9 | <1 | 1 | 4 |
| | BEV400 | 1 | 6 | End of Life | <1 | 3 | 7 |
| Class 3 P&D | BEV150 | <1 | <1 | 4 | <1 | <1 | <1 |
| | BEV250 | <1 | 4 | End of Life | <1 | 2 | 5 |
| Class 3 Van | BEV150 | <1 | <1 | 4 | <1 | <1 | <1 |
| | BEV250 | <1 | 5 | End of Life | <1 | 2 | 6 |

## Results of Additional Sensitivities

### Commercial Charging

While the primary analysis uses a residential-type charging scenario, we also explore a "what-if" commercial charging scenario wherein business entities bear the high, upfront capital cost of charger hardware and installation and pay 100% commercial electricity rates for charging purposes. Scenario 2 of the incremental cost of electrification is used as the basis for developing the three cases of commercial charging-based tiered charger hardware and installation costs for a 19.2 kW non-networked level 2 charger. The differentiation in infrastructure costs reflects various aspects of developing or upgrading a given charger installation site, such as parking space, underground boring, mounting piers, cable tunneling, bollards, etc. [7], [8]. The results of the "what-if" analysis support the conclusion that the TCO of BEVs will be lower than that of a comparable ICEV in MYs 2027 and 2030. Thus, it is indifferent to the charging scenario and projected electricity rates when compared to the residential-type charging scenario. Charger-related costs are expected to decline further in the future with higher penetration and economies of scale.

### High Fuel Price

To estimate the sensitivity of the TCO of ICEVs to recent high fuel prices, a sensitivity analysis was performed using summer 2022 fuel prices. With ongoing geopolitical crises and volatility in the oil and gas sector, per the EIA, the price of retail gasoline reached an all-time high of $6.294/gallon in California in 2022, about 46% more than the national average gasoline price of $4.30/gallon under Scenario 1. The national retail price of diesel peaked at $5.754/gallon, which is 16% higher than the projected average price of $4.96/gallon under Scenario 1. Such high fuel prices have a direct impact on ICEV's operating expenses and TCO. Using recent peak fuel prices, even the class 3 BEV400 pickup achieved TCO parity within 1-2 years of ownership. These results make a compelling case, from a consumer savings standpoint, to electrify the class 2b–3 segment given the steep rise in oil and fuel prices.

### Electricity Price

We also considered real-world state-specific energy prices which vary more over time than average national prices to evaluate their influence on the three incremental costs of electrification scenarios. Average residential electricity prices in California, New York, and Michigan from January 2022 to July 2022 were selected as inputs to Scenarios 3, 2, and 1, with the rates being 26.26¢, 21.38¢, and 17.63¢, respectively. These represent three distinct takes on "high" residential electricity rates: very high, high, and somewhat high. These three states represent the spread of residential power costs from the west coast to the east coast and are much higher than the average electricity rates for other states and price forecasts in the AEO 2022. The fossil fuel price is unchanged from that of the primary analysis. The results reveal that BEVs have a lower TCO per mile than comparable ICEVs, except in Scenario 3, where California-specific electricity prices are more than double the national average prices.

**Effects of the Inflation Reduction Act of 2022**

This study also examined the potential impacts of the IRA on class 2b–3 BEVs in the near term (MY 2023) and the long term (MY 2027). We assumed economies of scale and sufficient raw material supply to meet demands in the production of MY 2023 BEVs. The various incentives made available by the IRA will have a profound positive impact on the economic viability of MYs 2023 and 2027 class 2b–3 BEVs. We found that these credits will help offset higher purchase prices of BEVs, ultimately resulting in lower purchase prices for consumers. Section 6 explores the impact of using purchase price credits for clean vehicles (§30D credits) and qualified commercial clean vehicles (§45W credits), in conjunction with the IRA’s 30% alternative fueling infrastructure credit, to determine their impact on BEV purchase price and TCO parity. Generally, the results of this IRA impact analysis demonstrate that:

a) Acceleration of purchase parity and TCO parity is seen in BEV150s across all scenarios in MY 2023.
b) For MY 2023 BEVs, acceleration in purchase parity and TCO parity is seen across all vehicle types in Scenario 1. In Scenario 2, TCO parity accelerates in the case of all BEV150 and class 3 pickup trucks BEV250 only. Due to the relatively high cost of BEVs in Scenario 3, our analysis indicates that, except for the class 3 pickup truck BEV150, other MY 2023 BEVs would not achieve TCO parity in their assumed lifetime.
c) Purchase parity and TCO parity are advancing for MY 2027 BEVs across all vehicle types and all scenarios. All BEVs achieve parity within the first year of ownership upon purchase, except for the class 3 pickup truck BEV400 which achieves parity within 2 years of purchase.
d) With clean vehicle credits (§30D) and charger credits, BEVs’ cumulative net TCO savings in MYs 2023 and 2027 average about $5,000 and $27,000, respectively. Furthermore, the average TCO of BEVs will be about $0.40 per mile for MY 2023 and $0.31 per mile for MY 2027; this is less than the TCO of comparable ICEVs, which will average $0.42 per mile and $0.43 per mile in MYs 2023 and 2027, respectively.
e) With qualified commercial clean vehicles (§45W) and charger credits, BEVs’ cumulative net TCO savings in MYs 2023 and 2027 average about $6,000 and $23,000, respectively. Furthermore, the average TCO of BEVs will be about $0.40 per mile for MY 2023 and $0.33 per mile for MY 2027; this is less than the TCO of comparable ICEVs, which will average $0.42 per mile and $0.43 per mile in MYs 2023 and 2027, respectively.
f) Our application of the purchase credit (§30D) and advanced manufacturing production credit (§45X) reveal that these credits can provide OEMs with a financial buffer against

potential market disruptions while also enabling them to produce BEVs at a competitive cost. On average, battery pack costs could reach as high as $218/kWh, almost 187% more than the estimated pack cost of $76/kWh, and still allow for purchase price parity within the first year of BEV ownership in MY 2027.

**Technological Advancements and the Way Ahead**

This study also reviews anticipated developments in vehicle technologies and components. The analysis in this report turns heavily on battery cost, which is the single most important factor in the economic competitiveness of EVs. Due to the high fluctuation of raw material costs and engineering challenges, the battery constitutes anywhere between 25%–40% of the vehicle's cost, depending on its chemistry and configuration [8]–[10]. The battery cost projections in this study are based on economies of scale. With the movement of OEMs towards midstream and potentially upstream of the battery supply chain and vertical integration of cell manufacturing, the costs of battery packs are expected to further decline. After accounting for all the engineering and technological advancements being pursued, clear pathways exist for cost-competitive, sustainable, and reliable BEVs to gain market share. As discussed in Section 3 (Electrification Technology Review), advancements in battery technology could further reduce battery costs and drive down the TCO of BEVs even below the estimates developed in this analysis.

Battery recycling is expected to play a crucial role in the next decade and will make a significant contribution towards achieving sustainability in the BEV sector. Through the recycling of readily available, dense concentrations of battery raw materials, recyclers can create lasting positive social, environmental, and economic impacts. Compared to virgin metal mining, recycling is a relatively low-carbon pathway. In the future, with increased penetration of BEVs, the recycling and reprocessing industry is expected to grow larger than the mining industry. In line with recent attention and initiatives from international and governmental agencies, the recycling and reprocessing industries are poised to play a decisive role in sustaining the BEV industry.

There is also a significant effort at all levels to improve or replace current technologies, giving confidence in a more sustainable and viable supply chain and technology pool to support future rapid growth in BEVs. OEMs have several alternative traction motor technologies to choose from, many of which do not use permanent magnets and would eliminate the cost and potential environmental impacts of mining rare earth materials. Also, copper stator coils can be replaced with aluminum without degrading performance or efficiency. These options provide automakers with alternative technology pathways to reduce motor costs in the event of supply chain constraints or an increase in the price of rare earth (NdFeB) magnets or copper. New, wide-bandgap materials like gallium nitride (GaN) and aluminum nitride (AlN) promise inverters with even higher efficiency and performance. These rapid advancements in the fields of motors, power electronics, and battery management systems will make BEVs a preferred choice from a cost perspective in the future.

Finally, to support the transition to BEVs, charging infrastructure must be scaled adequately to meet rising demand and address consumer concerns about vehicle range. A robust network of charging stations with corridor fast charging, public charging, and workplace charging will be needed to support widespread BEV adoption. There are numerous existing programs to foster the development of widespread charging infrastructure [11], and much progress is being made in this area. Federal agencies are in the process of developing and deploying a national EV charging network to meet the growing demand for robust charging infrastructure.

Several programs under the Infrastructure Investment and Jobs Act and the Inflation Reduction Act of 2022 will drive large investments into the EV ecosystem, benefiting all stakeholders. These policies can only further increase the overall BEV market penetration and economies of scale for BEV components. EV technology is improving at a rapid pace and the cost savings are attractive to a typical consumer. With the acceleration in EV deployment and infrastructure build-up, by 2027, a BEV will be a financially attractive ownership prospect for a typical consumer compared to an ICEV.

# 1. Introduction

## 1.1 Background

The transportation sector is the biggest source of greenhouse gas emissions in the U.S., as shown in Figure 10 [4]. Light-duty vehicles (including passenger cars and light-duty trucks) and medium- and heavy-duty vehicles (GVWR > 8,500 pounds) accounted for 82% of GHG emissions in the transportation sector in 2021 [4]. GHG emissions primarily comprise the carbon dioxide, methane, and nitrous oxide emitted through the combustion of fuel [4]. Vehicles also emit other air pollutants such as ozone precursors (nitrogen oxides and volatile organics compounds), sulfur oxides, and particulate matter [12]. These emission constituents and other pollutants contribute to climate change and air pollution.

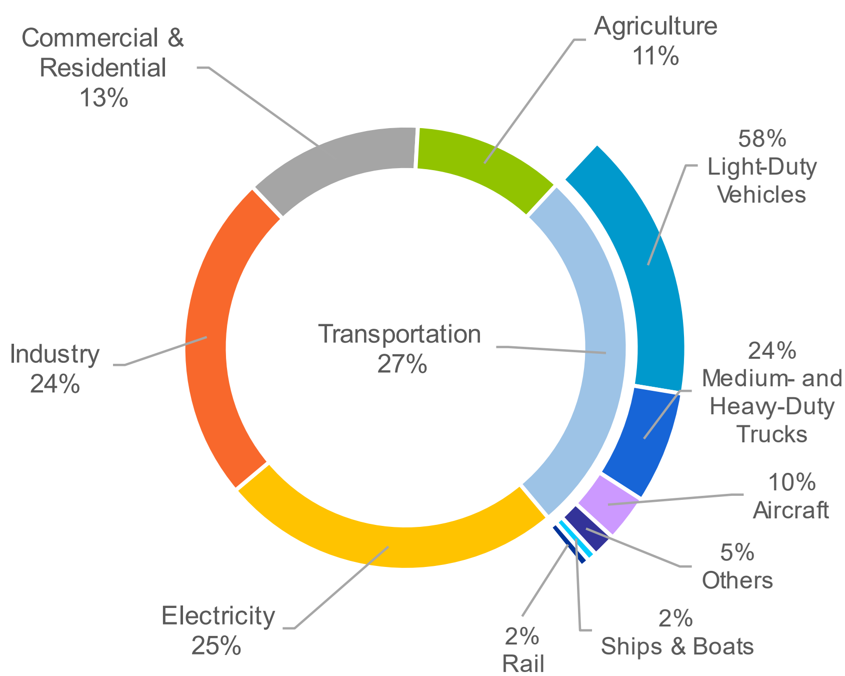


**Figure 10: Distribution of U.S. greenhouse gas (GHG) emissions by sector** [4]

Deploying zero-emission technologies within the transportation sector is a key strategy for reducing emissions of GHGs and other air pollutants. Electrification of class 2b–3 vehicles will be instrumental in curtailing the use of fossil fuel-reliant powertrains while allowing the U.S. to maintain technology leadership and competitiveness. Class 2b (8,501 lbs.–10,000 lbs.) and class 3 (10,001 lbs.–14,000 lbs.) vehicles form a significant proportion of the medium- and heavy-duty fleet. Of the roughly 22.8 million medium- and heavy-duty vehicles (Class 2b–8) registered in the United States, almost 40% are heavy-duty pickups and vans belonging to class 2b–3, per the EPA's MOVES3 model [13], [14].

Class 2b–3 vehicles include heavy-duty pickup trucks, chassis cabs and cutaways, service trucks, cargo vans, delivery vans, box trucks, and conventional van types that meet different functional purposes. These vehicles are used mostly in a commercial setting, except for pickups, which are split between personal and commercial use. Examples of vehicles belonging to the class 2b–3 segment are Ford's F-250 and F350, Ram 2500 and 3500, GM's Silverado 2500, Ford Transit, and Mercedes Sprinter (refer to Table 2). Class 2b–3 vehicles' duty cycle varies considerably depending on their application, route, range needs, and towing requirements. According to CARB's large entity reporting survey data [15], more than 85% of these vehicles were driven 100 miles or less per day. Parcel vans, such as those used by FedEx and UPS, make almost 100 stops per day before returning to their depots at the end of the day [15].

There is little public information regarding the segmentation of classes 2b and 3 and their deployment for personal and commercial uses. The Bureau of Transportation Statistics carried out the 2021 Vehicle Inventory and Use Survey (VIUS) from February 2022 to October 2022. This survey covered 150,000 vehicle owners of class 1 through 8 trucks, which includes vehicle body types such as pickups, SUVs, minivans, light vans, straight trucks, and truck tractors. The data release is planned for Fall 2023 and may shed some light on the segmentation of class 2b–3 vehicles based on their use cases and duty cycles.

The environmental and economic case for the transition to EVs is compelling. With rapidly decreasing battery costs and technological advancements, there are appealing reasons for a typical consumer to switch to an EV. EVs can help consumers save thousands of dollars over the lifetime of ownership, primarily due to their greater fuel economy and fewer maintenance needs. The class 2b–3 segment is poised to benefit from these advancements, which should incentivize consumers to make a transition to BEVs.

### 1.2 Current State

To enable a clean transportation future, the Biden Administration has set a goal to accelerate the development and deployment of zero-emission vehicles and related infrastructure to achieve a target of 50% zero-emission vehicle sales share in 2030 [16]. While this goal applies to all new passenger cars and light trucks sold in 2030, including battery electric, plug-in hybrid electric, and fuel cell electric vehicles, it is expected to provide a boost to the electrification of other class 2b–3 vehicle types as well. Automakers are already offering electrified versions of class 2b–3 vehicles in their portfolios. Additionally, extensive government investments and other efforts to combat climate change are expected to catalyze the transition to clean vehicles. For example, legislation such as the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA) of 2022 incentivize investments in clean transportation that will strengthen American manufacturing and supply chains, create jobs, and lower costs for consumers.

The IIJA, which was signed into law on November 15, 2021, includes the following initiatives to accelerate the deployment of electric vehicles:

a) The National Electric Vehicle Infrastructure (NEVI) Formula Program provides up to \$7.5 billion to invest in U.S. EV charging infrastructure [11]. It will establish a national network to accelerate the adoption of EVs, reduce transportation-related greenhouse gas emissions, and position U.S. industries for global leadership in electrification efforts. In collaboration with the FHWA, the goal is to install 500,000 new public EV chargers across the U.S. by 2030 [17].
b) Apportionment of Highway Infrastructure Program Funds for the National Electric Vehicle Infrastructure Program, which will provide nearly \$5 billion over five years to help states create a network of EV charging stations along designated Alternative Fuel Corridors.
c) Establishment of the Joint Office of Energy and Transportation, an interagency approach to supporting the deployment of zero-emission, convenient, accessible, and equitable transportation infrastructure.
d) Provision of resources to jumpstart the EV transformation, such as a toolkit for Planning and Funding Rural Electric Mobility.

On August 16, 2022, the IRA was signed into law. This legislation contains multiple provisions to support the adoption and deployment of zero-emission vehicles and related infrastructure, including incentives, tax credits, and funding for various programs to electrify the transportation sector. Section 6 of this report analyzes the effect of the IRA on the class 2b–3 segment and attempts to quantify the impact of the IRA's credits on the purchase price of a BEV, charger unit cost, and the TCO of the vehicle. Additionally, this report also looks at the qualitative impact of the IRA on the entire ecosystem of class 2b–3 vehicles, from upstream to downstream.

BEVs rely on electrical energy stored in batteries, as opposed to chemical energy in the form of combustible fuels. This results in the elimination of tailpipe emissions and a reduced carbon footprint compared to an ICEV. The total annual well-to-wheel emissions of a BEV are less than one-third of those of a comparable ICEV on average across the US [18], [19]. The emissions attributed to a BEV result from providing electric energy for charging the batteries [18], [19]. These emissions are related to electrical generation, which also includes the emissions associated with the extraction, processing, and distribution of energy sources [18]. However, decarbonization can be mineral intensive [20], [21], and the pace of the energy transition depends partly on the supply chain and value chain of the raw materials required for producing a lithium-ion battery, as shown in

Figure 11. President Biden signed a determination on March 31, 2022, permitting the use of Defense Production Act (DPA) Title III authorities to encourage the domestic production of minerals for large-capacity batteries [22]. This action allows agencies and industries to increase domestic mining and processing of the critical materials required for creating a large-capacity battery supply chain [22]. Section 3 (Electrification Technology Review) describes numerous potential technologies under development that reduce or eliminate the need for various critical raw materials.

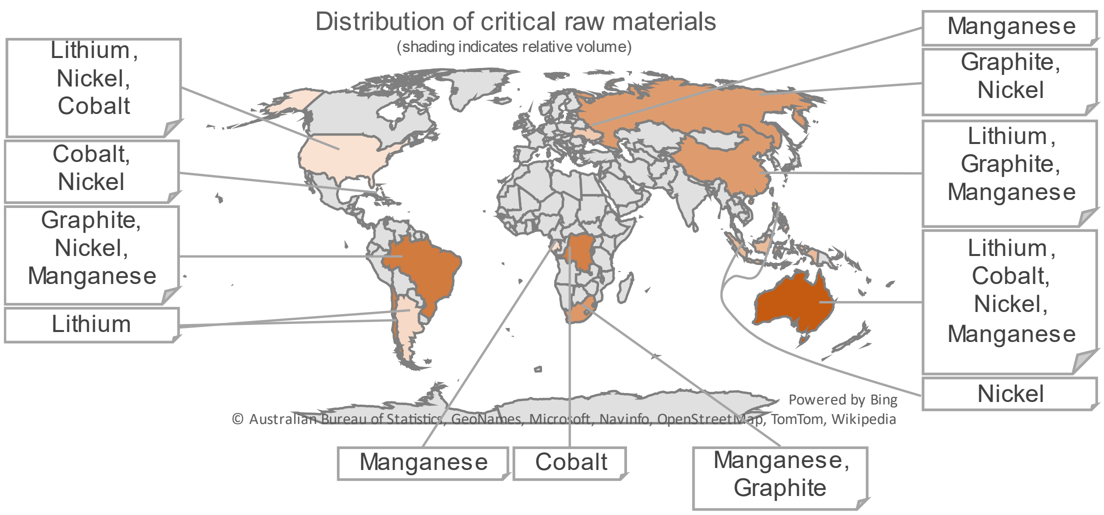


**Figure 11: Distribution of battery-critical raw materials based on the data from the USGS Commodity Summary 2022** [23]

## 1.3 Challenges

The production of a BEV is different from that of an ICEV due to differences in their value chains, manufacturing and assembly lines, and powertrain designs. To maintain their competitive edge, traditional automakers are adopting new flexible manufacturing and cross-platforming practices, training personnel, and investing in the development of BEV technology after nearly 100 years of investment in engine production and vehicle manufacturing suited to the internal combustion engine. Additionally, they will have to focus on providing connectivity and a seamless charging experience for the customer. With increasingly stringent emission regulations, traditional automakers have a mix of hybrid electric vehicles (HEVs) or alternative fuel vehicles in their offerings to comply with the standards. Increased hybridization has resulted in part standardization, lowering costs, and strengthening supply chains. But the challenges for traditional OEMs are unique compared to companies like Tesla and other recent EV startups. Traditional OEMs are retooling and/or reconfiguring their existing production lines to meet the growing demand for EVs while maintaining a mix of ICEVs in their portfolio. Established OEMs like Ford and GM have used different approaches. Ford has restructured to accelerate its transformation by splitting up its ICE and EV production into distinct but strategically interdependent auto units called Ford Blue and Ford Model e, respectively [24]. Alternatively, GM is heavily investing in the creation of EV production plants. In contrast to EV startups, legacy OEMs have the advantage of established brand names and reputations as economic linchpins.

Currently, the battery production chain is concentrated in China and South Korea, but the U.S. and Europe are stressing the importance of greater regionalization [25]. Recently, automakers have begun addressing various choke points to avoid a repeat of the microprocessor supply chain disruption. Cell cost has a direct impact on the economic viability of mass-producing EVs, and automakers are hoping to improve their margins by reaching economies of scale. Investments in gigafactories and offtake agreements for sourcing battery raw materials are also on the rise and can help automakers make a smooth transition. Furthermore, recycling battery materials show promise in terms of providing enough feedstock to reduce reliance on virgin materials.

Broadly, variability in duty cycles, range, payload capacity, vehicle upfitting, and power demands, as well as a lack of coherent operational data, contribute to the challenges of achieving large-scale electrification of class 2b–3 vehicles. Since the majority of class 2b–3 vehicles are used for commercial purposes [26], it would be challenging for OEMs to attract single owners and small business entities unless the purchase price is competitive with a comparable ICEV. By sales volume, pickup trucks, vans, and chassis trucks, which are upfitted and customized to specific business use cases, dominate this class of vehicles [26]. If the vehicle duty cycle is short and/or the vehicle idles for a significant period, then there is a motivation for both large and small businesses to electrify their vehicles and fleets. For big corporations with fleets and small business entities such as landscaping companies, switching to BEVs is economically attractive. The potential to electrify the class 2b–3 vehicle segment based on common vocations and driving patterns is promising. While some of the potential challenges can constrain the migration to EVs, application-specific electrification of classes 2b–3 would be a pragmatic path forward to overcome the potential barriers to adoption.

### 1.4 Study Considerations

The scope of this study is to:

a) project and compare the incremental cost of electrification and TCO of class 2b–3 ICEVs with comparable BEVs in the 2027 and 2030 purchase timeframes; and
b) analyze the effect of IRA provisions on BEVs purchased in the 2023 and 2027 timeframes and attempt to quantify the impact of IRA credits on the purchase price of a BEV, the charger equipment, and the TCO of the vehicle.

The study uses costs that assume nearly 50% BEV penetration in the class 2b–3 segment. This study is based on data drawn from a review of literature, including but not limited to publications, conferences, seminars, press releases by organizations, news articles, and other similar sources. No modeling is performed as a part of this study. We used experience and industry knowledge to vet the information and made reasonable efforts to represent current and accurate information.

Only tangible, direct-cost inputs are considered in this study. Residential-type charging using a non-networked level 2 charger of up to 20 kW is considered the primary choice of a typical class 2b–3 BEV owner. Home infrastructure upgrade costs to install the charger are not considered. Other benefits of BEV adoption, such as societal, health, and environmental benefits, are not accounted for in this study. Geopolitical conditions, supply chain disruptions, other macroeconomic factors, and ESG considerations are also not factored in for analysis purposes, though the potential for technological developments to address potential supply limitations related to current technologies is reviewed. This study assumes that the long-term raw material supply (including as a result of recycling) grows simultaneously to meet demand without any shortages. The U.S. and Europe are in the process of developing local and regional supply chains. Battery and related raw material costs will play a key role in determining the retail price of BEVs. However, for the study, it is assumed that these factors do not significantly influence the costs, perception, and viability of BEVs. At the same time, this study takes a fairly conservative approach to projecting technological advancement, including a case where battery costs are based on current chemistries and their cost increases modestly beyond current projections.

This study describes the initial purchase price and TCO of class 2b–3 vehicle types, comprising pickup trucks and vans. To encompass various use cases/vocations and duty cycles, a class 2b van, a class 3 pickup truck, a class 3 P&D truck, and a class 3 van are selected for analysis. The various technology pathways are used to create cost scenarios for each vehicle type to compare their ICE and electric powertrains, respectively.

We have not considered platform-level changes, as they are outside the scope of the study; however, platform-level changes would further favor BEVs. Additionally, although this study does not account for the expected increase in the stringency of fuel economy and emission standards beyond 2026, more stringent standards would further increase the cost of ICE powertrains and make the production of BEVs even more attractive from a compliance standpoint.

## 2. Methodology

In this study, a subset of class 2b–3 vehicles are selected for analysis based on some of the most common use cases and vocations, as illustrated in Figure 12, and assumed engine size. For each vehicle, three cost cases of powertrains are developed to capture the entire spectrum of low- to high-cost ICE technologies, recognizing their adoption in the 2027 and 2030 timeframes. Conventional and mild hybrid (BISG) electrification pathways are selected with the chosen engine pathways to build three cases per vehicle type for developing the incremental cost of electrification. A strong hybrid (SHEVP2) electrification pathway has been selected as a cost case for class 2b vans only. Similarly, for BEVs, three cost cases using the LFP and NMC811 chemistries are developed, as detailed in Section 2.2.

| Class 2b Van | Class 3 Step Van | Class 3 Pickup Truck | Class 3 Truck Package & Delivery |
|---|---|---|---|

**Figure 12: Snapshot of vehicle classes considered in the analysis. Image Source:** [27]–[29]**.**

The incremental cost of electrification is defined as the difference between the direct manufacturing costs (DMC) with a retail price equivalent (RPE) of ICE components and BEV components on an ICE platform. DMCs are the component and labor costs of producing and assembling the physical parts and systems, assuming a high volume of production [30]. The incremental costs are determined by identifying the major components in an ICEV that would be removed from a BEV, as well as by identifying components that must be added to a vehicle for electrification. In other words, the incremental cost is the difference between the DMCs of an ICE powertrain and a BEV powertrain. In this study, three scenarios, which are developed for the ICEVs and BEVs using their respective cost cases, are used to determine the initial purchase price and TCO, thereby providing a direct comparison between them. The powertrain costs of each vehicle class and type under consideration are used to determine the vehicle purchase price. To estimate the powertrain costs, the draft CAFE (Volpe) model of August 2021 [3] is used to derive the powertrain costs based on assumed technology pathways, as detailed in sections 2.1, 2.3, and 2.4. The rationale for using the CAFE (Volpe) model as a source of costs has been included in Section 2.1. Section 2.5 details the rationale behind the selection of retail price equivalents (RPE) for ICEV and BEV. Section 2.6 details the inputs and approach to calculating the TCO for the various vehicle types under consideration. Each vehicle type is costed independently based on its class and the technology progression required for it to meet anticipated emission regulations in 2027 and beyond. A ground-up modeling effort for powertrain sizing and estimating the energy consumption per mile is outside the scope of this study.

### 2.1 ICE Powertrain

The CAFE model provided costs for class 2b–3 vehicles most recently in a 2016 final rulemaking (FRM), namely, FR 73478, *Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2*, Federal Register / Vol. 81, No. 206 / Tuesday, October 25, 2016 [31]. In 2016, the cost of class 2b–3 vehicles (referred to in these rules as ‘‘HD pickups and vans’’) was based on the cost of light-duty vehicles since these are largely produced by LDV manufacturers in the U.S., primarily Ford, General Motors, and Stellantis. Furthermore, the technologies adopted to reduce fuel consumption and GHG emissions are similar to the technologies used on light-duty pickup trucks, including both engine efficiency improvements (for gasoline and diesel engines) and vehicle efficiency improvements [32]. Also, about 90% of HD pickups and vans are estimated to be 3/4-ton pickup trucks (such as Ford F-250, Chevy Silverado 2500, and Dodge Ram 2500) and 1-ton pickup trucks (such as Ford F-350, Chevy Silverado 3500, and Dodge Ram 3500), 12- and 15-passenger vans, and large work vans that are sold by these LDV manufacturers as complete vehicles, with no secondary manufacturer making substantial modifications before registration and use [31]. Class 2b–3 vehicles comprise a mixture of gasoline and diesel engines. Gasoline engines used in complete class 2b–3 pickups and vans include engines offered in a manufacturer’s light-duty truck counterparts, in addition to the engines specific to the class 2b–3 segment. These engines typically have a displacement range between 5-7 liters, though smaller and larger engines have also been used in this market, usually in a V8 configuration [32].

Table 2 lists the powertrains used in class 2b–3 vehicles, which are like their light-duty counterparts. These are considered in this study to analyze the powertrain technologies in use and to project the market offerings in the 2027–2030 timeframe.

**Table 2: Comparison of class 2b–3 powertrains with their light-duty counterparts.**

| Class 2b–3 vehicles | Engine | Equivalent CAFE model technology | Light-duty application of the same engine | Transmission with manufacturer codes | Light-duty application of same transmission |
|---|---|---|---|---|---|
| ***Class 2b Van gasoline powertrains*** | | | | | |
| Ford Transit | 3.5L PFDI V6 | 6C2B - NA, DOHC, VVT, PFI + DI | F150 | 10R80 - 10-speed Automatic | F-150 |
| | 3.5L Ecoboost V6 | 6C2B - Turbo 1 | F150, Ford Expedition, Lincoln Navigator | 10R80 - 10-speed Automatic | F-150, Ford Expedition, Lincoln Navigator |
| Ram Promaster | 3.6L Pentastar | 6C2B - NA, DOHC, VVT+VVL, PFI | The engine is used in most Stellantis light-duty products. | 62TE - 6-speed transmission | 62TE transmission was used in many Stellantis light-duty applications but has not been phased out |
| GMC Savana/ Chevrolet Express | 4.3L V6 | 6C2B - NA, OHV, VVT, DI | GMC Sierra, Chevy Silverado | GM 8L90 - 8 speed | Chevy Colorado, GMC Canyon, 2015-2017 Cadillac Escalade, GMC Sierra 2015 -present Chevrolet Silverado/GMC Sierra |
| | 6.6L V8 | 8C2B - NA, OHV, VVT, DI | 6.3L V8 - GMC Sierra, Chevy Silverado, Chevy, Cadillac, and GMC large SUVs | | |
| ***Class 3 powertrains*** | | | | | |
| ***Gasoline*** | | | | | |
| Ford F-250/ F-350 | 6.2L V8 | 6C2B - NA, OHV, VVT, PFI | A similar engine is used in GM and Stellantis light-duty vehicles. See below | 6R140 - 6-speed transmission | |
| | 7.3L V8 | | | 10R140 - 10-speed transmission | Similar transmission 10R80 used in the F150, |

| Class 2b–3 vehicles | Engine | Equivalent CAFE model technology | Light-duty application of the same engine | Transmission with manufacturer codes | Light-duty application of same transmission |
|---|---|---|---|---|---|
| | | | | | Ford Expedition, Lincoln Navigator |
| Chevrolet Silverado 2500/35000 GMC Sierra HD | 6.6L V8 | 8C2B - NA, OHV, VVT, DI | 6.3L V8 - GMC Sierra, Chevy Silverado, Chevy, Cadillac, and GMC large SUVs | 6L90 6-speed automatic | 2010-2021 Chevrolet Silverado/GMC Sierra 1500 |
| Ram 2500/ 3500 | 6.4L V8 Hemi | 8C2B - NA, OHV, VVT, PFI | Jeep Grand Wagoneer, Chrysler 300 SRT, Dodge Challenger SRT | ZF 8HP75 | Used by BMW, Alfa Romeo, Aston Martin, Jeep, etc. in their light-duty vehicles |
| ***Diesel*** | | | | | |
| Ford F-250/ F-350 | 6.7L Power stroke V8 | 8C2B - DSLI | Costs taken from the 10C2B sheet in the CAFE (Volpe) model since the power level of these engines is higher than an 8C2B gasoline engine | 10R140 - 10-speed transmission | Similar transmission 10R80 used in the F150, Ford Expedition, Lincoln Navigator |
| Chevrolet Silverado 2500/35000 GMC Sierra HD | 6.6L Duramax V8 | 8C2B - DSLI | | Allison 10-speed automatic | - |
| Ram 2500/ 3500 | 6.7L Cummins inline-6 | 6C1B - DSLI | | 68RFE 6-speed transmission | - |

Due to the relatively small sales volumes of class 2b–3 vehicles as compared to LDVs, OEMs may choose not to invest in developing a separate, more efficient engine technology [31]. Hence, based on the above-mentioned reasons and shared or similar technology options between class 2b–3 and light-duty vehicles, the engine cost is sourced from the CAFE model [3].

To ascertain the costs of electrification technology pathways, we evaluated the *Technologies* file used in the Central Analysis for the 2016 FRM [31], which contained the costs associated with class 2b–3 technology options. The BISG and SHEVP2 costs were found to be the same between the light-duty pickups and HD pickups and vans. Hence, the projected hybridization costs [3] for class 2b–3 vehicles are assumed to be the same as those for light-duty trucks for this analysis, as the market offerings and options haven't changed much between them since 2016.

The technical specifications for class 2b–3 are taken from the 2021 ANL published study, titled "*A Detailed Vehicle Modeling & Simulation Study Quantifying Energy Consumption and Cost Reduction of Advanced Vehicle Technologies Through 2050"* [33]. ANL [33] simulated various powertrain configurations to evaluate the energy consumption and cost of advanced powertrain technologies for 2021, 2027, 2035, and 2050 using Autonomie, an in-house tool developed in collaboration with General Motors. Based on the EPA and NHTSA compliance procedures for medium- and heavy-duty vehicles, ANL estimated fuel consumption from simulations over three drive cycles, i.e., the California Air Resource Board (ARB) transient cycle, the EPA 55 mph cruise cycle, and the EPA 65 mph cruise cycle. The combined fuel economy value was computed by applying different weighting factors to each of the EPA-prescribed cycles. ANL determined the performance parameters such as launch capability (by measuring acceleration time), gradeability (by quantifying sustainable maximum speed at 6% grade), driving range, cargo mass, and maximum cruising speed by simulating various vehicle models over various test cycles [33]. Table 3 lists the performance requirements considered by ANL for class 2-3 vehicles.

**Table 3: Performance requirements considered for class 2 and class 3 vehicles in the ANL study [33].**

| Class | Purpose | 0-30mph (s) | 0-60mph (s) | Grade Speed (mph) | Percent Grade | Cruise Speed (mph) | Cruise Grade (%) | Max. Speed (mph) | Startability (%) | Test Weight (lb.) | Test Weight (kg) | 90 percentile Daily Driving Range (miles) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | Van | 7 | 18 | 50 | 6 | 70 | 1.5 | 75 | 15 | 10,000 | 4,545 | 150 |
| 3 | Pickup | 7 | 15 | 65 | 6 | 70 | 1.5 | 75 | 15 | 14,000 | 6,364 | 150 |
| 3 | P&D (Package and Delivery) | 7 | 30 | 50 | 6 | 65 | 1.5 | 70 | 15 | 14,000 | 6,364 | 150 |
| 3 | Van | 7 | 24 | 50 | 6 | 65 | 1.5 | 70 | 15 | 14,000 | 6,364 | 150 |

Two technology progress uncertainty levels were simulated: a low case, which is based on regulations or business as usual, and a high case, which aligns with aggressive technology advancement based on the U.S. Department of Energy (DOE) Vehicle Technologies Office (VTO) and Hydrogen and Fuel Cell Technologies Office (HFTO) programs. Still, we selected the fuel economy numbers from ANL's high case for our analysis. We expect that on-road fuel economy for MY 2027 vehicles would be lower; however, we chose the higher estimates to be consistent with our conservative approach taken in this study. Table 4 lists the weighted fuel economy in miles per gallon diesel equivalent (MPGDe) with the corresponding simulated test weights for each class and purpose of the vehicle. Only 2027 values have been used in this analysis for MYs 2027 and 2030. It is pertinent to note that the listed test weight for class 2 vehicles is much higher than their GVWR. We could not establish if this was an erroneous assumption or a typographical error while tabulating the weight units (kg rather than lbs.).

**Table 4: Autonomie results of class 2 and class 3 vehicles as published in the ANL study** [33]**. Conv, ISG, and ParHEV stand for conventional, integrated starter generator, and parallel hybrid electric vehicles, respectively. Highlighted test weights in yellow are above the GVWR of that vehicle class.**

| Class/ Purpose | Powertrain | 2021 | | | | 2027 | | | | 2035 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Diesel | | Gasoline | | Diesel | | Gasoline | | Diesel | | Gasoline | |
| | | Test Weight (kg) | Weighted MPGDe | Test Weight (kg) | Weighted MPGDe | Test Weight (kg) | Weighted MPGDe | Test Weight (kg) | Weighted MPGDe | Test Weight (kg) | Weighted MPGDe | Test Weight (kg) | Weighted MPGDe |
| ***Class 2*** | | | | | | | | | | | | | |
| Van | Conv | 6192 | 13.3 | 5769 | 14.6 | 5960 | 16.3 | 5547 | 18.7 | 5773 | 18 | 5361 | 21.2 |
| | ISG | 6163 | 14.3 | 6033 | 14.7 | 5917 | 18 | 5814 | 19 | 5729 | 19.4 | 5628 | 21.8 |
| | ParHEV | 6135 | 18.7 | 6146 | 16.9 | 5873 | 24.1 | 5907 | 23.3 | 5676 | 27.4 | 5744 | 27.9 |
| ***Class 3*** | | | | | | | | | | | | | |
| Pickup | Conv | 6429 | 12.4 | *Not considered by ANL* | | 6194 | 14.6 | *Not considered by ANL* | | 6008 | 16.1 | *Not considered by ANL* | |
| Pickup | ISG | 6433 | 12.4 | | | 6200 | 14.7 | | | 6009 | 16.4 | | |
| Pickup | ParHEV | 6344 | 19 | | | 6056 | 23.7 | | | 5855 | 26.2 | | |
| P&D | Conv | 6188 | 12.5 | 5772 | 13.2 | 5967 | 15.3 | 5555 | 17.1 | 5780 | 17 | 5370 | 19.4 |
| P&D | ISG | 6156 | 13.4 | 6026 | 13.4 | 5924 | 16.8 | 5825 | 17.3 | 5742 | 18 | 5626 | 20.4 |
| P&D | ParHEV | 6262 | 15.7 | 6171 | 14.5 | 5969 | 20 | 5956 | 20.3 | 5767 | 22.6 | 5779 | 24 |
| Van | Conv | 6235 | 12.4 | 5779 | 14.1 | 6012 | 15.1 | 5554 | 18.5 | 5826 | 16.7 | 5369 | 21 |
| Van | ISG | 6224 | 12.3 | 6046 | 13.8 | 5991 | 15.7 | 5824 | 18.3 | 5802 | 17.6 | 5639 | 21 |
| Van | ParHEV | 6217 | 16.8 | 6170 | 15 | 5944 | 22.1 | 5952 | 21.1 | 5732 | 24.3 | 5771 | 24.5 |

Figure 13 plots the fuel economy results of classes 2 and 3 listed in Table 4 based on the ANL study [33]. It can be observed that there are some inconsistent trends in fuel economy based on the hybridization options and the choice of fuel. For instance, in the case of an MY 2021 gasoline-powered class 3 van, the fuel economy slightly drops when migrating from a conventional to a mild hybrid BISG vehicle. Furthermore, diesel-powered vehicles are known to be more fuel efficient at high loads when compared to gasoline-powered vehicles. Since nothing is towed during the test, towing is not factored in here. However, the observed differences could be due to the relative differences in their test weights, as the correlation between test weight and fuel consumption is strong. We recognize that this could be due to certain modeling assumptions or limitations made about the technical requirements of these vehicles. Only 2027 values have been used in this analysis.

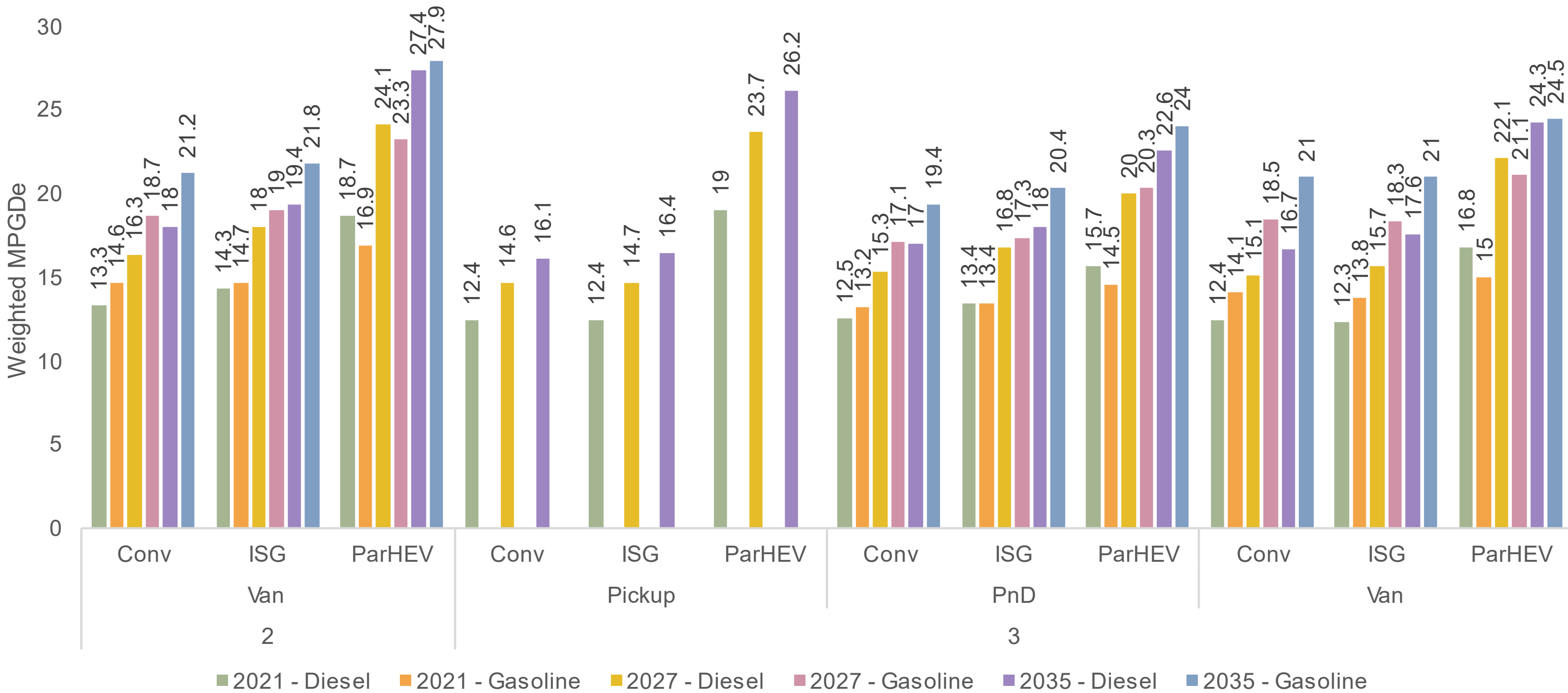


**Figure 13: Weighted miles per gallon diesel equivalent (MPGDe) of class 2 and class 3 vehicles based on Autonomie results published in the ANL study** [33]**. Gasoline-powered pickups are not considered by ANL.**

The gasoline fuel economy numbers for class 3 pickup trucks, which were not analyzed by ANL, have been developed for this analysis using assumed relationships to other vehicles modeled by ANL. Specifically, they have been computed using the P&D (package and delivery vehicle) fuel economies using the following formulae:

a) Conventional Gasoline $_{Pickup}$ = (Conventional Gasoline $_{P\&D}$ ÷ Conventional Diesel $_{P\&D}$) × Conventional Diesel $_{Pickup}$
b) BISG Gasoline $_{Pickup}$ = (BISG Gasoline $_{P\&D}$ ÷ Conventional Gasoline $_{P\&D}$) × Conventional Gasoline $_{Pickup}$

The test (simulation) weight of the vehicles, which is over the GVWR of the class in some cases, as highlighted in yellow in Table 4, is used to size components and estimate energy consumption per mile (Wh/mile) in the study [33]. Since most vehicles are rarely loaded to their maximum GVWR, this ensures a conservative range estimate for a given battery size. The longer-range vehicles are assumed to have the same test (simulation) weight with a bigger and heavier battery pack. Hence, by definition, they will have a lower-rated payload. The ANL study [33] doesn't have a class 2b pickup in their analysis, so we have considered only a class 3 pickup for this study. However, there is a significant overlap between the GVWR of class 2b and class 3 pickup trucks from Ford. The same is true for offerings from GM and Stellantis. Hence, class 2b and 3 pickup trucks are not studied separately in this report. They are grouped within the class 3 pickup trucks. Table 5 lists the different class 2b and class 3 vehicle types and range options considered in this study.

**Table 5: Class 2b–3 vehicle specifications used in this study.**

<table>
<tr><th>Class</th><th>2b</th><th colspan="3">3</th></tr>
<tr><td>GVWR (lbs.)</td><td>8,501–10,000</td><td colspan="3">10,001–14,000</td></tr>
<tr><td>Vehicle type</td><td>Van</td><td>Pickup Truck</td><td>P&D Truck</td><td>Van</td></tr>
<tr><td>Range (miles)</td><td>150/250</td><td>150/250/300/400</td><td>150/250</td><td>150/250</td></tr>
</table>

Figure 14 depicts the curb weight, GVWR, and the maximum towing rating of different trim and powertrain options for the heavy-duty pickup trucks (class 2b–3) from Ford [34].

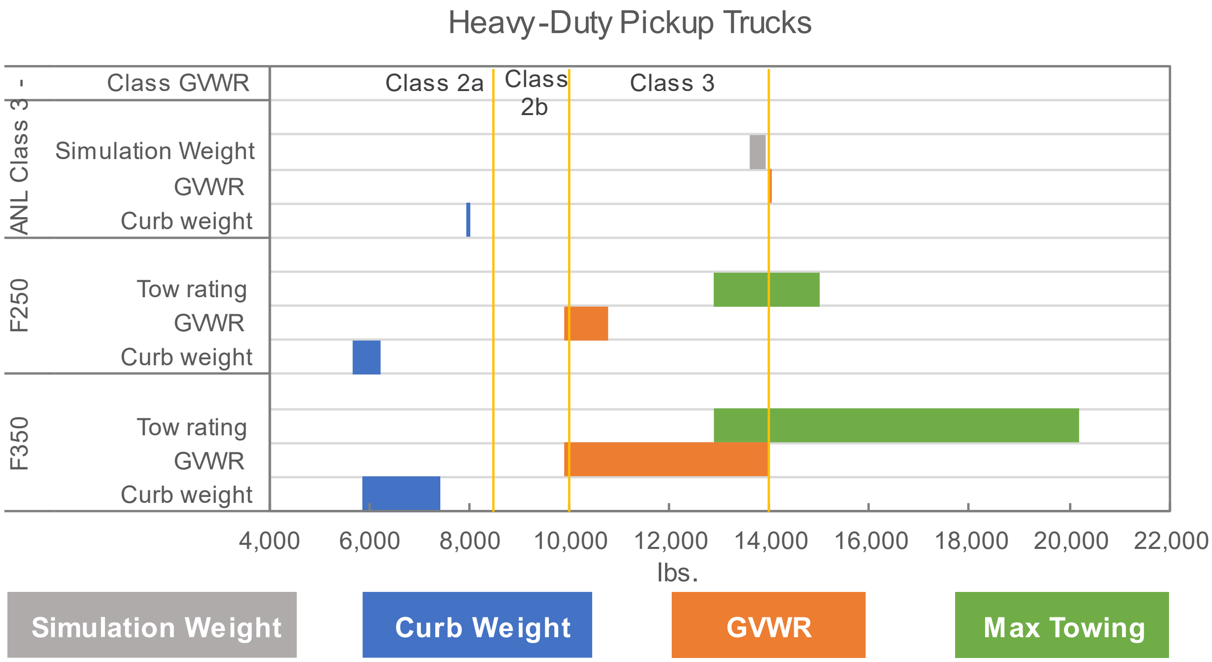


**Figure 14: Variation of the curb weight, GVWR, and maximum tow ratings of a sample of class 2b–3 heavy-duty pickup trucks in the market.**

The selection of powertrain technologies is based on the current mix of vehicles on sale today, as listed in Table 2, the various future vehicles under development, and the assumed technological trends [3]. Table 6 lists the ICEV powertrain options (engine and technology content) considered in this study. The green highlight, the red text, and the pink highlight represent the low-, medium-, and high-cost ICE powertrain options, respectively. The technology options and descriptors are taken from the CAFE model [3].

**Table 6: Representative class 2b–3 vehicles considered for this study.**

| Class | Vehicle Type | Representative ICEV | Powertrain type | Engine | Transmission |
|---|---|---|---|---|---|
| 2b | Van | Ford Transit, Ram Promaster | NA SI | NA DOHC V6 | 10 Speed (AT10L3) |
| | | | NA SI BISG | NA DOHC V6 + 48V BISG | |
| | | | SI TURBO SHEVP2 | TURBO1 cEGR | |
| 3 | Pickup truck | F-250, F-350, F-450 | NA SI | NA Pushrod V8 | |
| | | | NA SI BISG | NA Pushrod V8 + 48V BISG | |
| | | | CI | Twin-Turbo V8 (ADEAC 2027+) | |
| | Package and Delivery truck (P&D) | F-350 chassis cab, Ford Transit 350HD | NA SI | NA Pushrod V8 | |
| | | | NA SI BISG | NA Pushrod V8 + 48V BISG | |
| | | | CI | Twin-Turbo V8 (ADEAC 2027+) | |
| | Van | FORD E-450 Utilimaster P700 STEPVAN (UPS, FedEx) | NA SI | NA Pushrod V8 | |
| | | | NA SI BISG | NA Pushrod V8 + 48V BISG | |
| | | | CI | Twin-Turbo V8 (ADEAC 2027+) | |

| |
|---|
| Low cost |
| Medium cost |
| High cost |

For the class 2b van, an NA engine is selected in the low-cost case, with a progression to an NA SI engine with a 48V mild-hybrid system deploying BISG in the medium-cost case. In the high-cost case, a turbocharged gasoline engine with a P2 parallel drivetrain architecture is chosen. The three powertrain cases for a class 2b van progress from a conventional to a mild hybrid, and finally to a strong hybrid. BISG provides the idle-stop capability and uses a 48V battery, which allows the use of a smaller, more powerful, and more efficient electric motor/generator. It assists during the vehicle launch phase by providing acceleration, thereby improving energy efficiency, or limited electric assist, delaying the start of the engine, and during regenerative braking [35]. A strong hybrid can have a P2 parallel drivetrain architecture (SHEVP2) or a power-split architecture (SHEVPS). SHEVP2 can combine with most of the engine technologies, while SHEVPS is a more advanced electrified system. Both provide idle-stop functionality, regenerative braking, and vehicle launch assist. P2 hybrids rely on the ICE to power the vehicle, with the electric mode only kicking in when the power demands are less than moderate [5].

In the case of class 3 vehicles, in the low-cost case, a conventional NA SI engine is considered with progression to an NA SI BISG engine, representing a mild hybrid engine, in the medium-cost case. While turbocharging technology is potentially more advanced under some operating conditions, we do not include it here for the following reasons: Turbocharged SI engines have a fuel economy advantage over naturally aspirated SI engines when operating in the low-to-medium load range. As the engine operating load increases, this fuel economy advantage of the turbo SI engine decreases. Operating under medium to high loads, the fuel economy of the turbo SI engine is lower than that of the NA SI engine. This is due to a combination of retarded combustion phasing required to mitigate knock and fuel enrichment employed to control exhaust temperatures (and control knock). There is data to support the conclusion that a full-size SUV or pickup truck from an LDV segment with a turbocharged engine will have superior fuel economy compared to a comparable vehicle with an NA engine on fuel economy certification test cycles and normal daily driving, but the NA engine will return better fuel economy while carrying a heavy payload or when towing. For example, in a towing test over the same loop, the F-150 (class 2a) with the 2.7-liter V6 liter turbocharged engine returned 8.7 mpg, while the F-150 with the 5.0-liter NA V8 returned 9.8 mpg [36]. Hence, a turbocharged engine will deliver lower fuel economy compared to an NA gasoline engine if the pickup is operated with a medium-to-high payload or is used for towing. Since such operating conditions are common in a class 3 pickup truck and since no manufacturer offers a turbocharged engine in a class 3 pickup truck, we have not considered it for our analysis. NA SI engines in class 3 vehicles have lower specific output and relatively lower technology content when compared to the LDV powertrains. This keeps engine DMC and maintenance and repair (M&R) costs low while providing high reliability over the vehicle's useful life. Maintaining high efficiency in a turbocharged SI engine at medium to high loads will require technologies (or a combination of technologies) such as variable compression ratio, extremely high levels of EGR dilution (greater than 50%), and high energy ignition systems capable of maintaining high combustion rates and high combustion efficiencies at high dilution rates. Quantifying the cost and benefit of such technologies is beyond the scope of this study. Between the rapidly falling cost of electrification, the projected reduction of ICE market share, the reduction in R&D budgets, and the cancellation of new clean sheet engine designs by many manufacturers, there is a possibility that many of these advanced ICE technologies will not reach production. These technologies are in a testing phase and are highly unlikely to reach production within the purchase timeframe of this study. Hence, turbocharged engines are not considered for 2027 and 2030. Instead, a conventional diesel (compression ignition, CI) engine is considered in the high-cost case, as the study aims to cover the entire spectrum of powertrains on a cost basis. We do not include a turbocharged SHEVP2 SI engine here for the following reasons: per the CAFE model, a CI engine is costlier than a turbocharged SHEVP2 SI engine. Furthermore, a CI powertrain is more capable of towing heavy trailers than a SHEVP2 powertrain based on the gross combined weight ratings (GCWR). With the deployment of exhaust brakes on diesel trucks, brake wear, and overheating are also reduced. These factors weigh in favor of CI powertrains in class 3 pickups in the 2027 timeframe. All segments are assumed to have an AT10L3 10–speed transmission. Diesel engines are not considered in class 2b vans due to the present and future cost of the engine and after-treatment system (cost of NOx compliance). Many OEMs have stopped offering diesel engines in this space. Likewise, diesel hybrids are not considered for classes 2b and 3 due to their high cost.

Table 7 gives the after-treatment system costs assumed in this report for a stoichiometric gasoline engine. The costs are based on the breakdown costs of a three-way catalyst (TWC), estimated in a Euro 7 Impact Assessment Study [37] to meet proposed Euro 7 standards. The TWC used for the gasoline engine after-treatment system is assumed to be a mature technology with no further cost reductions that can be attributed to technology learning [38]. The impact of global supply chain disruptions and the price volatility of platinum group metals on after-treatment system costs between 2022 and 2035 is also not considered. In the case of diesel powertrains, the powertrain costs include the cost of the after-treatment system to meet the emission standards [2], hence the costs are not shown separately.

**Table 7: Gasoline three-way catalyst (TWC) after-treatment system cost (expressed in €$_{2021}$). (Average in 2021, €1 = $1.183). *Cost source: Euro 7 Impact Assessment Study** [37]**.**

| **Technology*** | **Unit Cost** | |
| --- | --- | --- |
| | **€/liter** | **$/liter** |
| Three-Way Catalyst (TWC) | 80 | 81.6 |
| **Technology*** | **Unit Cost** | |
| | **€/unit** | **$/unit** |
| Optimized coated GPF (no size increase) | 15 | 15.3 |
| Onboard refueling vapor recovery (ORVR) canister | 10 | 10.2 |
| Anti-spitback/vapor valve | 2 | 2.04 |
| High-flow purge valve | 2 | 2.04 |
| Pump for on-board diagnostics (OBD) leak check | 25 | 25.5 |
| Over-the-air (OTA) data transmission | 40 | 40.8 |
| **Engine Configuration** | **Volume (liter)** | **Cost (assumed)** |
| 8-cylinder engine | 6.3 | $610 |

Table 8 lists the component-level costs of the ICE powertrain used in this analysis. It can be observed that the considered class 2b–3 powertrains share the same costs related to aftertreatment, transmission, and BISG systems.

**Table 8: ICE powertrain costs from the CAFE model [3] without RPE.**

| Vehicle Class | Powertrain | Description | Component | 2022 | 2027 | 2030 |
|---|---|---|---|---|---|---|
| ***Class 2b*** | | | | | | |
| Van | Conventional SI, Mild Hybrid BISG SI | Engine | V6 DOHC + VVT + GDI | $4,582 | $4,560 | $4,548 |
| | SHEVP2 TURBO1 SI | Engine | V6 DOHC + VVT + GDI | $5,555 | $5,514 | $5,497 |
| | | Transmission | AT8L2 to AT10L3 | $196 | $182 | $178 |
| | | Strong hybrid excluding battery | SHEVP2 excluding battery | $2,728 | $2,571 | $2,519 |
| | | Strong hybrid battery | SHEVP2 battery | $1,473 | $1,067 | $930 |
| ***Class 3*** | | | | | | |
| Pickup, P&D, Van | Conventional SI, Mild Hybrid BISG SI | Engine | V8 OHV + VVT + GDI + DEAC | $4,374 | $4,958 | $4,944 |
| | Conventional CI (includes aftertreatment) | Engine | DSLI, 2027 - DSLIAD | $8,944 | $9,630 | $9,554 |
| ***Common Costs*** | | | | | | |
| Class 2b Van<br>Class 3 Pickup<br>Class 3 Van<br>Class 3 P&D | Conventional SI, Mild Hybrid BISG SI, SHEVP2 TURBO1 SI | Aftertreatment | Aftertreatment | $610 | $610 | $610 |
| | Conventional SI, Mild Hybrid BISG SI, Conventional CI | Transmission | AT10L3 | $1,811 | $1,781 | $1,772 |
| | Mild Hybrid BISG SI | Mild hybrid excluding battery | BISG excluding battery | $389 | $328 | $304 |
| | | Mild hybrid battery | BISG battery | $342 | $248 | $216 |

## 2.2 BEV Powertrain

Due to limited literature on BEV component sizing, the 2021 ANL study, "*A Detailed Vehicle Modeling & Simulation Study Quantifying Energy Consumption and Cost Reduction of Advanced Vehicle Technologies Through 2050"* is used for this analysis to size the BEV powertrains [33]. Charger efficiency was also considered by ANL when computing the efficiency and costs of future electric traction drive systems. It is expected that the battery technologies for class 2b–3 vehicles will be like those that are used in the light-duty segment, with component sizing being the only variable. With heavier battery packs delivering more power and energy, ANL simulated the energy consumption of BEVs. Automated sizing algorithms were used by ANL to provide a fair comparison among various technologies. Table 9 lists the Autonomie results published by ANL [33] with the energy consumption and corresponding simulated test weights for each class and purpose, respectively. Only 2027 values have been used in this analysis.

**Table 9: Autonomie results of vehicle classes 2 and 3 as published in the ANL study** [33]**.**

| Class/ Purpose | 2021 | | | 2027 | | | 2035 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Test Weight (kg) | Motor Peak Power (kW) | DC Whpm | Test Weight (kg) | Motor Peak Power (kW) | DC Whpm | Test Weight (kg) | Motor Peak Power (kW) | DC Whpm |
| ***Class 2*** | | | | | | | | | |
| Van | 6156 | 177 | 706 | 5677 | 161 | 520 | 5383 | 159 | 469 |
| ***Class 3*** | | | | | | | | | |
| Pickup | 6203 | 331 | 660 | 5728 | 312 | 492 | 5422 | 309 | 441 |
| P&D | 6348 | 228 | 839 | 5812 | 211 | 615 | 5487 | 209 | 556 |
| Van | 6320 | 226 | 796 | 5791 | 210 | 584 | 5472 | 208 | 529 |

In the ANL study [33], the test weight of the vehicles is close to the upper end of the class GVW. The battery sizing is done based on the available Autonomie modeling data from an ANL study [33]. For the inputs listed in Table 10, we assume that the GVW remains the same. A smaller or larger pack reduces or increases the payload; for longer-range BEVs, the energy consumption is kept the same despite an increase in the battery pack weight, as we assumed that the corresponding payload has been reduced to keep the test weight, and, thereby, the GVW is the same across all ranges. The energy consumption depends on the test weight and the aerodynamics of the vehicle, which have been assumed to be the same as the BEV150 for longer-range BEVs. Additionally, the ANL study assumed a net-to-gross battery capacity of 80%, which leads to unreasonably high-capacity estimates. We have assumed 90%, which is in line with the production of NMC battery electric vehicles. But most applications can be powered by LFP, which can be charged to 100%

without adverse effects on battery cycle life. Hence, the net-to-gross battery capacity can be 100%. For this analysis, battery pack usable capacity is computed using the product of range (miles) and energy consumption (Wh/mile). The battery pack gross capacity is computed by dividing the battery pack usable capacity by 0.9, as we have assumed a battery pack net to a gross capacity of 90%. The motor size is a function of the performance requirements of the vehicle (refer to Table 3). Since the performance requirements and test weight of the vehicle remain the same across all BEV ranges, the motor size is also kept the same. Between 2027 and 2030, the motor size remains unchanged as there is little to no change in peak power requirements. A DC-DC converter of 2 kW has been assumed for all considered vehicle types based on the production BEVs and projected demands of the 12V system. An onboard charger of 11.5 kW has been assumed for all vehicle types for this analysis based on production BEVs. However, for MY 2030, we have assumed a 10% efficiency gain in the energy consumption of the BEVs, and, therefore, the battery pack capacity changes accordingly. Table 10 lists the assumed BEV specifications for this study.

**Table 10: BEV specifications assumed for this study.**

| Class | Category | Specification | Units | 2022 | 2027 | 2030 |
|---|---|---|---|---|---|---|
| Class 2b Van | BEV150 | Range | miles | 150 | 150 | 150 |
| | | Energy consumption | Wh/mile | 706 | 520 | 468 |
| | | Battery pack usable capacity | kWh | 106 | 78 | 70 |
| | | Battery pack gross capacity | kWh | 118 | 87 | 78 |
| | | Motor | kW | 177 | 161 | 161 |
| | | Inverter | kW | 177 | 161 | 161 |
| | BEV250 | Range | miles | 250 | 250 | 250 |
| | | Energy consumption | Wh/mile | 706 | 520 | 468 |
| | | Battery pack usable capacity | kWh | 177 | 130 | 118 |
| | | Battery pack gross capacity | kWh | 196 | 145 | 131 |
| | | Motor | kW | 177 | 161 | 161 |
| | | Inverter | kW | 177 | 161 | 161 |
| Class 3 Pickup | BEV150 | Range | miles | 150 | 150 | 150 |
| | | Energy consumption | Wh/mile | 660 | 492 | 443 |
| | | Battery pack usable capacity | kWh | 99 | 74 | 66 |
| | | Battery pack gross capacity | kWh | 110 | 82 | 74 |
| | | Motor | kW | 331 | 312 | 312 |
| | | Inverter | kW | 331 | 312 | 312 |
| | BEV250 | Range | miles | 250 | 250 | 250 |
| | | Energy consumption | Wh/mile | 660 | 492 | 443 |
| | | Battery pack usable capacity | kWh | 165 | 123 | 111 |
| | | Battery pack gross capacity | kWh | 183 | 137 | 123 |
| | | Motor | kW | 331 | 312 | 312 |
| | | Inverter | kW | 331 | 312 | 312 |

| Class | Category | Specification | Units | 2022 | 2027 | 2030 |
|---|---|---|---|---|---|---|
| | BEV300 | Range | miles | 300 | 300 | 300 |
| | | Energy consumption | Wh/mile | 660 | 492 | 443 |
| | | Battery pack usable capacity | kWh | 198 | 148 | 133 |
| | | Battery pack gross capacity | kWh | 220 | 164 | 148 |
| | | Motor | kW | 331 | 312 | 312 |
| | | Inverter | kW | 331 | 312 | 312 |
| | BEV400 | Range | miles | 400 | 400 | 400 |
| | | Energy consumption | Wh/mile | 660 | 492 | 443 |
| | | Battery pack usable capacity | kWh | 264 | 197 | 178 |
| | | Battery pack gross capacity | kWh | 293 | 219 | 197 |
| | | Motor | kW | 331 | 312 | 312 |
| | | Inverter | kW | 331 | 312 | 312 |
| Class 3 P&D | BEV150 | Range | miles | 150 | 150 | 150 |
| | | Energy consumption | Wh/mile | 839 | 615 | 554 |
| | | Battery pack usable capacity | kWh | 126 | 92 | 83 |
| | | Battery pack gross capacity | kWh | 140 | 103 | 92 |
| | | Motor | kW | 228 | 211 | 211 |
| | | Inverter | kW | 228 | 211 | 211 |
| | BEV250 | Range | miles | 250 | 250 | 250 |
| | | Energy consumption | Wh/mile | 839 | 615 | 554 |
| | | Battery pack usable capacity | kWh | 210 | 154 | 139 |
| | | Battery pack gross capacity | kWh | 233 | 171 | 154 |
| | | Motor | kW | 228 | 211 | 211 |
| | | Inverter | kW | 228 | 211 | 211 |
| Class 3 Van | BEV150 | Range | miles | 150 | 150 | 150 |
| | | Energy consumption | Wh/mile | 796 | 584 | 526 |
| | | Battery pack usable capacity | kWh | 119 | 88 | 79 |
| | | Battery pack gross capacity | kWh | 133 | 97 | 88 |
| | | Motor | kW | 226 | 210 | 210 |
| | | Inverter | kW | 226 | 210 | 210 |
| | BEV250 | Range | miles | 250 | 250 | 250 |
| | | Energy consumption | Wh/mile | 796 | 584 | 526 |
| | | Battery pack usable capacity | kWh | 199 | 146 | 132 |
| | | Battery pack gross capacity | kWh | 221 | 162 | 147 |
| | | Motor | kW | 226 | 210 | 210 |
| | | Inverter | kW | 226 | 210 | 210 |
| ***Same across all vehicles*** | | | | | | |
| Class 2b Van, Class 3 Pickup, Class 3 Van, Class 3 P&D | BEVs 150/250/300/400 | DC-DC converter | kW | 2 | | |
| | | Onboard charger | kW | 11.5 | | |

The BEV ranges are chosen based on a variety of consumer needs and upcoming market offerings, as shown in Table 11. Various studies have indicated that class 2b–3 vehicles take an average daily trip of anywhere between 60 to 100 miles with a maximum of 150 to 260 miles, with level 2 chargers adequately meeting the charging requirements of 72% to 97% of annual mileage, or VMT [39]–[42]. As a low-cost option, a 150-mile range on a single charge satisfies the needs of a user with frequent starts/stops, with the driving limited to a city circuit. For a segment of fleet vehicles, a range of 150 miles is sufficient to meet daily trip requirements. From 30 million miles of Ford-Pro customer telematics data, Ford found that the average daily driven distance for commercial vans in the US is 74 miles [43]. In the performance segment, a 250-mile range would provide the consumer with the option to travel long distances, haul additional payloads, or meet specific requirements of a short duty cycle but significant idling. Heavy-duty pickup trucks see a wide range of personal and fleet applications, and hence an electric range of 150, 250, 300, and 400 miles is considered for this study.

Table 11 lists some of the class 2b and 3 BEVs currently on sale or soon to be sold in the near term in the US market. Some manufacturers provide the gross battery size, which represents the total capacity that the battery pack can hold, while others provide the net battery size, which is the usable capacity of the pack. Both metrics are proxies for an EV's range and thus an important differentiator when comparing vehicles in the same class. However, the range depends on several variables, like the cargo being carried or towed, weather conditions, and driving patterns. Nevertheless, the upcoming market offerings provide a reliable snapshot of the lower and upper bounds of EV ranges and validate the ranges considered in this study.

**Table 11: Class 2b–3 vehicles currently present or anticipated in the US market**

| S.No. | Manufacturer | Vehicle nameplate | Year | Curb Weight (lbs.) | GVW (lbs.) | Payload (lbs.) | Towing (lbs.) | Class | Gross battery size (kWh) | Net battery size (kWh) | Driving range (miles) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | Rivian | R1T | 2021 | - | 8,532 | - | 11,000 | 2b | 135 | - | 300 |
| | | | | - | | - | | | 180 | - | 400 |
| | | EDV 500 | 2022 | - | 9,350 | - | - | | - | - | 150 |
| | | EDV 700 | | - | 9,350 | - | - | | - | - | 150 |
| | | EDV 900 | | - | 14,000 | - | - | 3 | - | - | 120 |
| 2. | GM Brightdrop | EV600 | 2022 | - | 9,990 | 2,200 | - | 2b | 177.6 | - | 250 |
| | | EV410 | | - | <10,000 | - | - | | - | - | |
| 3. | Arrival | H3L3 | 2022 | 5005 | 9,350 | 4,345 | - | 2b | 67 | - | 112 (WLTP) |
| | | | | 5269 | | 4,081 | - | | 89 | - | 149 (WLTP) |
| | | | | 5533 | | 3,817 | - | | 111 | - | 180 (WLTP) |
| | | | | 5797 | | 3,553 | - | | 133 | - | 211 (WLTP) |
| 4. | Lightning systems | Transit passenger van | 2021 | - | 10360 | - | - | 3 | 80 | 73.6 | 140 |
| | | | | - | | - | - | | 120 | 110.4 | 170 |
| 5. | Ford | E-Transit | 2022 | - | 10,130 | - | - | 3 | - | 67 | 108-126 |
| 6. | Workhorse | C1000 | 2021 | - | 13000 | - | - | 3 | - | 70 | 100 |
| | | | | - | | - | - | | - | 105 | 150 |

A large share of the class 2b–3 ICE market is held by OEMs that also manufacture LDVs. The design philosophy of traditional OEMs and EV makers is to create and produce a dedicated platform with a modular electric architecture, enabling optimization and commonization of parts. This allows class 2b–3 BEVs to combine multiple smaller light-duty motors with the right gear ratio to produce the necessary output of power and torque at the wheels. They can also share battery modules with LDVs. This modular approach reduces or eliminates the need for custom EV components, giving class 2b–3 BEVs significantly higher economies of scale compared to their ICEV counterparts. ICEVs need custom-built engines and transmissions for every narrow range of power output and vehicle application, affecting their economies of scale. Cost projections for LDV electrification components are relevant for the class 2b–3 segment. Table 12 summarizes the unit component used for calculating the BEV powertrain costs for 2022, 2027, and 2030. The costs for power electronics decline as it is assumed that, with the maturation of technology, the integration of power electronics with the motor housing would cut down material and associated cooling costs significantly. However, the volume and the level of integration would not be as high as the LDVs; hence, the costs are higher compared to the LDV segment.

**Table 12: BEV powertrain costs.**

| Cost case | Component | Unit | 2022 | 2027 | 2030 |
|---|---|---|---|---|---|
| Low cost | Battery (LFP) | $/kWh | 108.3 | 73.5 | 61.7 |
| | Motor | $/kW | 4 | 3.3 | 3.3 |
| | Inverter | $/kW | 3.5 | 2.4 | 2.4 |
| | DC-DC converter | $/kW | 50 | 30 | 30 |
| | Onboard charger | $/kW | 50 | 35 | 35 |
| Medium cost | Battery (NMC) | $/kWh | 111.7 | 76.4 | 64.2 |
| | Motor | $/kW | 4 | 3.3 | 3.3 |
| | Inverter | $/kW | 3.5 | 2.4 | 2.4 |
| | DC-DC converter | $/kW | 50 | 30 | 30 |
| | Onboard charger | $/kW | 50 | 35 | 35 |
| High cost | Battery (NMC * 1.1) | $/kWh | 122.8 | 84 | 70.6 |
| | Motor | $/kW | 4 | 3.3 | 3.3 |
| | Inverter | $/kW | 3.5 | 2.4 | 2.4 |
| | DC-DC converter | $/kW | 50 | 30 | 30 |
| | Onboard charger | $/kW | 50 | 35 | 35 |

Table 13 lists the component-level costs of the BEV powertrain used in this analysis. As mentioned earlier, the unchanged sizing of the motor and the related power electronics between MY 2027 and MY 2030 is reflected in the costs. Based on our estimates, only the battery costs will decline between MYs 2027 and 2030.

**Table 13: Breakdown of BEV powertrain costs without RPE.**

| Class | Category | Component | Low Cost | | | Medium Cost | | | High Cost | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2022 | 2027 | 2030 | 2022 | 2027 | 2030 | 2022 | 2027 | 2030 |
| Class 2b Van | BEV150 | Battery | $12,744 | $6,375 | $4,812 | $13,143 | $6,621 | $5,007 | $14,457 | $7,283 | $5,508 |
| | | Motor | $713 | $522 | $522 | $713 | $522 | $522 | $713 | $522 | $522 |
| | | Inverter | $621 | $392 | $392 | $621 | $392 | $392 | $621 | $392 | $392 |
| | | DC-DC converter | $100 | $60 | $60 | $100 | $60 | $60 | $100 | $60 | $60 |
| | | Onboard charger | $575 | $403 | $403 | $575 | $403 | $403 | $575 | $403 | $403 |
| | BEV250 | Battery | $21,239 | $10,625 | $8,053 | $21,905 | $11,035 | $8,378 | $24,095 | $12,138 | $9,216 |
| | | Motor | $713 | $522 | $522 | $713 | $522 | $522 | $713 | $522 | $522 |
| | | Inverter | $621 | $392 | $392 | $621 | $392 | $392 | $621 | $392 | $392 |
| | | DC-DC converter | $100 | $60 | $60 | $100 | $60 | $60 | $100 | $60 | $60 |
| | | Onboard charger | $575 | $403 | $403 | $575 | $403 | $403 | $575 | $403 | $403 |
| Class 3 Pickup | BEV150 | Battery | $11,903 | $6,027 | $4,550 | $12,276 | $6,260 | $4,734 | $13,503 | $6,886 | $5,207 |
| | | Motor | $1,332 | $1,013 | $1,013 | $1,332 | $1,013 | $1,013 | $1,332 | $1,013 | $1,013 |
| | | Inverter | $1,160 | $760 | $760 | $1,160 | $760 | $760 | $1,160 | $760 | $760 |
| | | DC-DC converter | $100 | $60 | $60 | $100 | $60 | $60 | $100 | $60 | $60 |
| | | Onboard charger | $575 | $403 | $403 | $575 | $403 | $403 | $575 | $403 | $403 |
| | BEV250 | Battery | $19,838 | $10,046 | $7,613 | $20,460 | $10,433 | $7,921 | $22,506 | $11,476 | $8,713 |
| | | Motor | $1,332 | $1,013 | $1,013 | $1,332 | $1,013 | $1,013 | $1,332 | $1,013 | $1,013 |
| | | Inverter | $1,160 | $760 | $760 | $1,160 | $760 | $760 | $1,160 | $760 | $760 |
| | | DC-DC converter | $100 | $60 | $60 | $100 | $60 | $60 | $100 | $60 | $60 |
| | | Onboard charger | $575 | $403 | $403 | $575 | $403 | $403 | $575 | $403 | $403 |
| | BEV300 | Battery | $23,806 | $12,055 | $9,130 | $24,552 | $12,519 | $9,499 | $27,007 | $13,771 | $10,449 |
| | | Motor | $1,332 | $1,013 | $1,013 | $1,332 | $1,013 | $1,013 | $1,332 | $1,013 | $1,013 |
| | | Inverter | $1,160 | $760 | $760 | $1,160 | $760 | $760 | $1,160 | $760 | $760 |
| | | DC-DC converter | $100 | $60 | $60 | $100 | $60 | $60 | $100 | $60 | $60 |
| | | Onboard charger | $575 | $403 | $403 | $575 | $403 | $403 | $575 | $403 | $403 |
| | BEV400 | Battery | $31,741 | $16,073 | $12,163 | $32,736 | $16,693 | $12,655 | $36,009 | $18,362 | $13,921 |
| | | Motor | $1,332 | $1,013 | $1,013 | $1,332 | $1,013 | $1,013 | $1,332 | $1,013 | $1,013 |
| | | Inverter | $1,160 | $760 | $760 | $1,160 | $760 | $760 | $1,160 | $760 | $760 |

| Class | Category | Component | Low Cost | | | Medium Cost | | | High Cost | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2022 | 2027 | 2030 | 2022 | 2027 | 2030 | 2022 | 2027 | 2030 |
| | | DC-DC converter | $100 | $60 | $60 | $100 | $60 | $60 | $100 | $60 | $60 |
| | | Onboard charger | $575 | $403 | $403 | $575 | $403 | $403 | $575 | $403 | $403 |
| Class 3 P&D | BEV150 | Battery | $15,146 | $7,537 | $5,689 | $15,621 | $7,827 | $5,919 | $17,183 | $8,610 | $6,511 |
| | | Motor | $917 | $685 | $685 | $917 | $685 | $685 | $917 | $685 | $685 |
| | | Inverter | $798 | $515 | $515 | $798 | $515 | $515 | $798 | $515 | $515 |
| | | DC-DC converter | $100 | $60 | $60 | $100 | $60 | $60 | $100 | $60 | $60 |
| | | Onboard charger | $575 | $403 | $403 | $575 | $403 | $403 | $575 | $403 | $403 |
| | BEV250 | Battery | $25,244 | $12,561 | $9,520 | $26,035 | $13,046 | $9,905 | $28,638 | $14,350 | $10,896 |
| | | Motor | $917 | $685 | $685 | $917 | $685 | $685 | $917 | $685 | $685 |
| | | Inverter | $798 | $515 | $515 | $798 | $515 | $515 | $798 | $515 | $515 |
| | | DC-DC converter | $100 | $60 | $60 | $100 | $60 | $60 | $100 | $60 | $60 |
| | | Onboard charger | $575 | $403 | $403 | $575 | $403 | $403 | $575 | $403 | $403 |
| Class 3 Van | BEV150 | Battery | $14,364 | $7,157 | $5,403 | $14,814 | $7,433 | $5,621 | $16,295 | $8,176 | $6,183 |
| | | Motor | $910 | $682 | $682 | $910 | $682 | $682 | $910 | $682 | $682 |
| | | Inverter | $792 | $512 | $512 | $792 | $512 | $512 | $792 | $512 | $512 |
| | | DC-DC converter | $100 | $60 | $60 | $100 | $60 | $60 | $100 | $60 | $60 |
| | | Onboard charger | $575 | $403 | $403 | $575 | $403 | $403 | $575 | $403 | $403 |
| | BEV250 | Battery | $23,939 | $11,928 | $9,040 | $24,689 | $12,388 | $9,406 | $27,158 | $13,627 | $10,347 |
| | | Motor | $910 | $682 | $682 | $910 | $682 | $682 | $910 | $682 | $682 |
| | | Inverter | $792 | $512 | $512 | $792 | $512 | $512 | $792 | $512 | $512 |
| | | DC-DC converter | $100 | $60 | $60 | $100 | $60 | $60 | $100 | $60 | $60 |
| | | Onboard charger | $575 | $403 | $403 | $575 | $403 | $403 | $575 | $403 | $403 |

### 2.2.1 Motor costs

Figure 15 summarizes the results of the motor teardown studies done by Munro & Associates, Inc. [44] of mass-produced light-duty BEV motors. Permanent magnet synchronous motors (PMSM) cost $4-$5 per kW, while induction motors (IM) with aluminum rotor conductors (Tesla Model 3 – front motor) cost about $2.5 per kW. Several vehicles (Tesla, VW Group, etc.) that offer AWD BEVs use a combination of PMSM in the rear and IM in the front. The IM is typically used in situations with high wheel torque demand or limited traction. The front axle IM is freewheeling under normal driving conditions. This enables the rear PMSM to operate at higher average loads and efficiencies. Unlike the PMSM, the IM has no parasitic losses when freewheeling due to the absence of cogging torque. This combination of PMSM on the rear axle and IM on the front axle reduces the average cost ($/kW) of the total traction motor output and increases the efficiency (miles per kWh) of the BEV. Hence, we have taken a conservative value of $4/kW for motor costs in 2022.

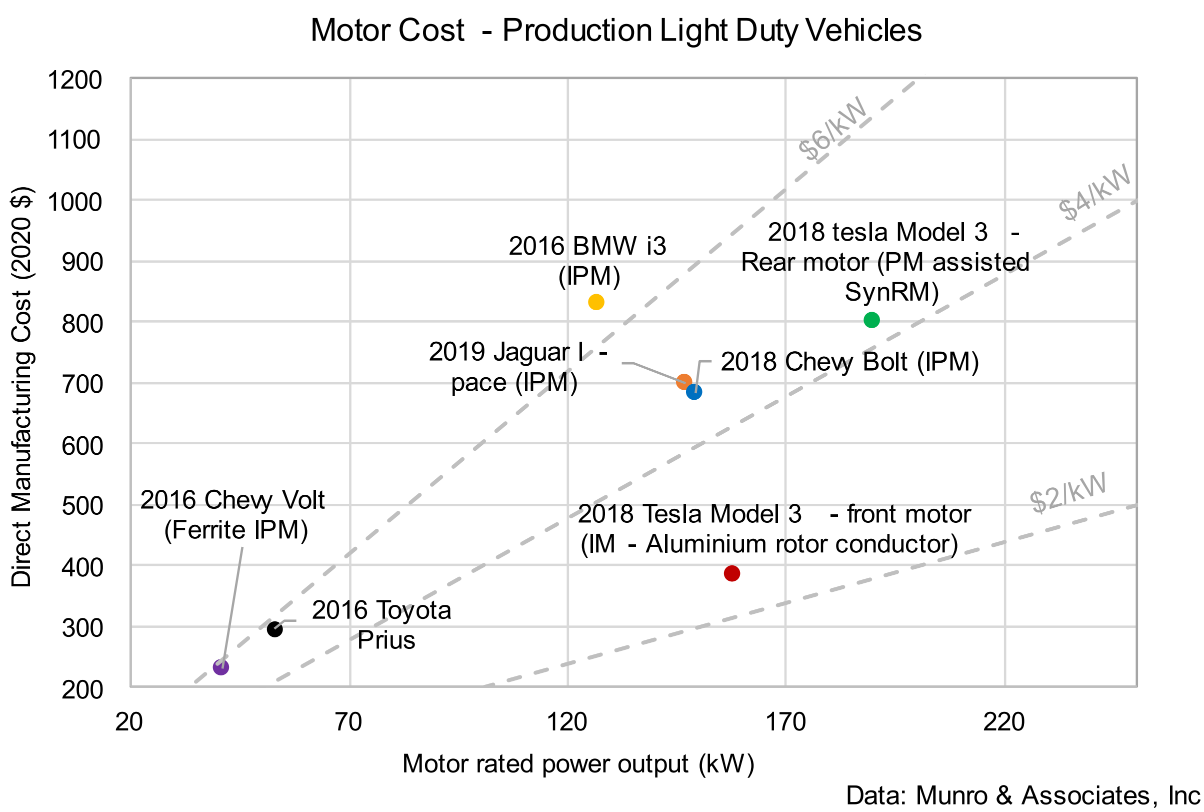


**Figure 15: Production light-duty BEV motor cost [9].**

As of 2022, there are several production LDVs using induction motors (Rivian, Tesla, Audi, etc.) and wound rotor synchronous motors (BMW, Renault, etc.) that use no (rare earth) permanent magnets. Switched reluctance motors in limited production further simplify rotor construction, bringing down material and manufacturing costs. Compressed and diecast aluminum stator windings can replace the more expensive copper stator windings while matching the performance and efficiency. Section 3, "Electrification Technology Review," discusses future traction motor technologies in detail. Based on future technologies in the pipeline and the projected increase in economies of scale, a reduced motor cost of $3.3/kW in 2027 and 2030 is assumed.

### 2.2.2 Power Electronics Cost

For power electronics, the three main components considered in determining the cost of BEV powertrains in this report are the traction inverter, the DC-to-DC converter, and the onboard charger.

Traction inverters convert DC power from the battery to 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). In 2018, the Tesla Model 3 became the first mass-produced vehicle to use silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs) (sourced from ST Microelectronics in a Tesla in-house inverter design). SiC MOSFET-based inverters have higher efficiency when compared to ones using Si IGBTs. Over low speeds and load points (typical light-duty city cycle), a silicon IGBT inverter has an average efficiency of 96%, while the SiC MOSFET-based inverter has an efficiency of 99% [45].

Figure 16 shows the cost of various light-duty inverters based on teardown studies by Munro & Associates, Inc. [46]. The cost includes "housing, printed circuit board assembly (PCBA), IGBT or MOSFET module and cooling structure, DC-link capacitor, motor-phase lead, connectors, self-contained structural components, and connected components." The teardown shows that in 2018, the Tesla Model 3 inverter that used SiC MOSFETs was at price parity (about $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 (about $2.5/kW). As of 2022, most newly introduced BEVs from manufacturers such as Hyundai-Kia, Lucid, Rivian, etc.) use SiC MOSFETs in their inverters.

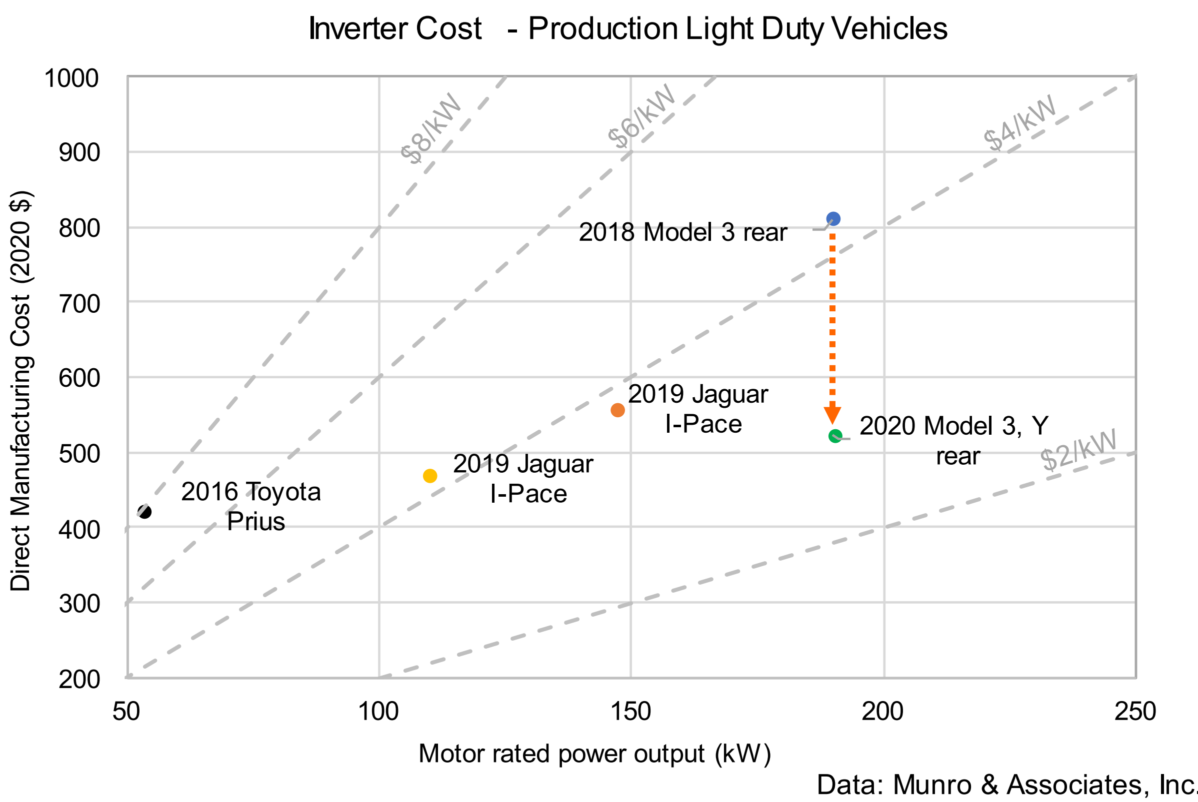


**Figure 16: Production BEV inverter cost based on teardown studies. The cost includes Housing, PCBA, IGBT module and cooling structure, DC-link Capacitor, Motor phase lead, connectors, self-contained structural, and connected components.**

The DC-DC converter reduces the high voltage of the BEV traction motor to power all 12V loads and keeps the 12-volt battery charged. This report assumes a 2 kW DC-DC converter size for all vehicles. The onboard charger converts the AC supply from a level 2 charger into DC at the right voltage to charge the traction battery. Most BEVs have a 10 kW-12 kW onboard charger, while some, like the Lucid Air, have a 19.2 kW onboard charger. We have assumed an onboard charger size of 11.5 kW for all vehicle segments.

Currently, many OEMs source traction inverters, DC-DC converters, and onboard chargers from tier-1 suppliers. Each component is a separate box under the hood, resulting in a higher $ per kW cost. It is projected that OEMs will have the traction inverter, the DC-DC converter, and the onboard charger all integrated into one package, even as part of a single PCB. In line with this observation, based on the U.S. Drive 2017 projected cost, a cost of $50/kW each for the DC-DC converter and the onboard charger is used for 2022 [47].

### 2.2.3 Battery Cost

#### 2.2.3.1 Current Trend

Lithium-ion batteries of various cathode chemistries are nearly universally deployed in EVs. Each chemistry has its own set of performance characteristics and tradeoffs, resulting in a diverse class of chemistries produced globally by top industry players for a variety of EV manufacturers. The EV space is currently dominated by nickel-based chemistries like the NMC (nickel-manganese-cobalt) and the NCA (nickel-cobalt-aluminum), followed by the non-cobalt, iron-based chemistry, LFP (lithium iron phosphate). These chemistries are used in various combinations of minerals, and the appended numbers represent the ratios of minerals used in the cathode.

In 2021, the average battery capacity was 55 kWh, with a volume-weighted average battery pack price of $118/kWh for BEVs [48], [49]. The demand is projected to climb from 340 GWh in 2021 to nearly 4 TWh by 2030 [48]. Tesla is currently the leading EV producer in North America and is believed to use NCA955 with 3% cobalt (an advanced version of NCA80, which uses 9% cobalt) in its cars [50]. However, since 2021, Tesla has pivoted to LFP in their standard-range vehicles since it reduces dependence on critical elements like cobalt and nickel, in addition to being more environmentally sustainable, cheaper, and safer. Price volatility in the commodity market has led to the resurgence of LFP. Other automakers, like Volkswagen and Rivian, are also in favor of LFP over nickel-based cells for their entry-level, high-volume EVs. It is expected that due to the expiration of LFP patents at the end of April 2022, OEMs across North America will be able to mass-produce LFP battery-based vehicles [48].

Lithium-ion chemistries like NMC955, NMC9525, HE-NMC (high-energy NMC), and high-manganese NMC combinations are in various stages of development. They are expected to replace the currently popular NMC 5- and 6- series chemistries because they have the potential to reduce cobalt while maintaining safety and offering higher energy density. Furthermore, cobalt-free chemistries like NFA (lithium-iron and aluminum nickelate), NMA (lithium nickel manganese aluminum oxide), LMFP (lithium manganese iron phosphate), LNMO (lithium nickel manganese oxide, also known as high-voltage spinel), Li-S (lithium-sulfur), Li-air, Na-ion (sodium-ion), other metal-air batteries (metals like sodium, aluminum, and zinc), and all-solid-state batteries (ASSB) are in the pipeline. Besides the advancements made in the field of cathode chemistries, high-density anodes are also under development, which will boost the energy density of the battery chemistries. These technological advancements offer superior performance and safety while reducing the dependence on resource-constrained critical elements. However, only some of them may be commercially available by 2030, and those would have to be cost-competitive to overcome the fundamental barrier to adoption.

#### 2.2.3.2 Forecasting Methods

Battery cost is the single most important factor that determines the economic viability of manufacturing and adoption of EVs. Due to the high fluctuation of raw material costs, engineering, and manufacturing challenges, the battery constitutes anywhere between 25%–40% of the vehicle's cost, depending on its chemistry and configuration [10], [51], [52]. For BEVs to be cost-competitive with ICEVs, BloombergNEF has estimated that battery pack prices need to drop below $100/kWh, while the Vehicle Technologies Office of the U.S. Department of Energy has set a federal target of reducing the cost of EV batteries to $80/kWh by 2025 [10], [49], [53].

Various scientific literature articles and market reports published since 2017 on battery costs were reviewed and evaluated for this study. After thoroughly reviewing various chemistries deployed in EVs, their raw material costs, and manufacturing practices, "*Battery cost forecasting: a review of methods and results with an outlook to 2050"* (hereafter "*Battery cost forecasting")* and *BatPaC V5.0* for calculating battery cost projections in the 2027–2030 timeframe, as described in more detail below, were selected [54], [55]. The field of EV batteries is continuously and rapidly evolving, and forecasting battery costs that represent all chemistries without accounting for various market forces, future volumes of production, technological and manufacturing advancements, and more, is challenging.

In general, the following methods [54] can be used to estimate battery costs:

a) Technological learning, also known as a learning curve or experience curve analysis, uses historical costs and a learning rate to arrive at a prediction. BloombergNEF used an 18% learning rate to estimate that pack prices will drop below $100/kWh in 2024 and will reach $58/kWh in 2030 [10].
b) Literature-based projections use battery price and cost data aggregated from previously published literature forecasts.
c) The expert elicitations approach uses a structured interview method to gain insights and make predictions where data is uncertain and/or not easily available.
d) Bottom-up modeling uses cost estimation via first principles at the part or item level to "build up" the manufacturing cost of the battery.

Due to a fragmented, nascent, and volatile EV battery market, chemistry-dependent battery forecasting to 2027–2030 using any of those mentioned methods is a challenging exercise. Each method has its advantages and drawbacks based on the assumptions made and inherent biases. There is no single method that captures all the elements of uncertainty surrounding battery cost forecasting. Hence, this study adopts a hybrid approach to arriving at battery costs in 2027–2030, using a combination of literature articles and BatPaC.

#### 2.2.3.3 Roush Approach

The selected publications from *Battery cost forecasting* use technological learning, literature-based projection, and expert elicitation for forecasting battery costs. BatPaC uses a bottom-up modeling approach to calculate pack costs that include profit and warranty (referred to as “Cost to Consumer”) or do not (referred to as “Cost to Build”). For forecasting the pack cost in 2027–2030, an approach that combines these sources is used. From among the various chemistries currently deployed in EVs, we selected NMC811-G and LFP-G battery chemistries for TCO analysis of BEVs in the 2027–2030 timeframe. It is expected that in the NCM series, NMC811, and the non-nickel series, LFP will have a significant market presence in the EV space in 2027–2030. While there are other advanced chemistries under various stages of development, estimating their costs for TCO analysis is a speculative exercise without grounding it in available performance data. Section 3, “Electrification Technology Review,” of this report covers other chemistries and developments expected to take shape in the future.

Using BatPaC 5.0 [55], the cost to build a cell ($/kWh) of LFP-G (Energy) and NMC811-G (Energy) for 2022 was estimated by indexing it to a plant size of 20 GWh. This approach allows the costs to be influenced only by the size of the plant and remains agnostic to the battery system parameters such as the system capacity (Ah), rated power (kW), and total energy (kWh). It can be noted that the BatPaC tool offers the user a choice between power and energy applications for a given cell chemistry. The ‘Energy’ option is relevant to this analysis of EVs and was therefore chosen. The ‘Power’ option is used for modeling the cells for HEVs, as they augment and support the power requirement of a downsized gasoline engine during their drive cycle [12], [55]. The cost to build an LFP-G (Energy) and NMC811-G (Energy) cell in a 20 GWh plant is $75/kWh and $78/kWh, respectively. Table 15 details the battery cost inputs used in the analysis.

For the 2027 timeframe, the plant size is assumed to be 80 GWh, considering the scaling of the production volumes of these cells to meet the projected market demand of nearly 4 TWh. In addition to volume scaling, a cost factor of 0.78 and 0.66 is applied to the BatPaC-derived costs in 2027 and 2030, respectively. The cost factor is derived to account for improvements in manufacturing technology and processes and is not an outcome of the BatPaC tool. It is computed from the selected publications, as shown in Table 14, from the 2021 review article, *Battery cost forecasting: a review of methods and results with an outlook to 2050* [54]. *Battery cost forecasting* analyzes 53 relevant peer-reviewed publications with original battery costs or price forecasts from 2361 publications. It presents the findings in a comprehensive, systematic, and transparent manner and provides supplementary information citing relevant article sources and methodologies. We used the detailed time-based forecasted values from the supplementary information provided by the article’s authors. The table enumerates the peer-reviewed articles published from 2010-2020 with the forecasted technology, scenario, years forecasted, and source of the data from the cited literature. The following steps detail the methodology used to evaluate the cost factor:

a) Selection of articles published between 2018-2020, as most of the literature published before 2018 had forecasts with significant errors. The primary reason behind this is the exponential fall in battery prices since 2010 [49].
b) Identification of articles with estimated/forecasted values in the years 2020 and 2027–2030. This resulted in the selection of 7 articles out of the 24 articles with time-based forecasted values tabulated by the authors [54].
c) Calculate the ratio of the forecasted item using the formula, (2027 value ÷ 2020 value) and (2030 value ÷ 2020 value).
d) Calculate the average cost factor from the computed ratios.

**Table 14: Publications selected for determining cost factor.**

| Authors & year | Publication Title |
|---|---|
| Edelenbosch et al. (2018) | Transport electrification: the effect of recent battery cost reduction on future emission scenarios |
| Nykvist et al. (2019) | Assessing the progress toward lower-priced long-range battery electric vehicles |
| Schmidt et al. (2019, b) | Projecting the future levelized cost of electricity storage technologies |
| Hsieh et al. (2019) | Learning only buys you so much: Practical limits on battery price reduction |
| Penisa et al. (2020) | Projecting the price of lithium-ion NMC battery packs using a multifactor learning curve model |
| He et al. (2020) | Greenhouse gas consequences of the China dual credit policy |
| Few et al. (2018) | Prospective improvements in cost and cycle life of off-grid lithium-ion battery packs: an analysis informed by expert elicitations |

The calculation of the cost factor includes a mix of approaches such as expert elicitation, technological learning, and literature-based projection. BatPaC 5.0 provides a cost using the bottom-up modeling method. This approach encompasses all the cost estimation techniques used for battery cost forecasting. However, because the literature forecast may have accounted for volume scaling in their respective projections, there is a possibility of double counting, which could affect the estimated cost. Still, this is deemed to have a minimal influence on the results as the overall approach for this study is more conservative.

**Table 15: Battery costs considered for this study.**

| Year | Plant Size GWh | Cost to Build $/kWh | | Supplier Margin | Cell cost to OEM $/kWh | | Cell-to-Pack multiplier | OEM cost to build pack, $/kWh | |
|---|---|---|---|---|---|---|---|---|---|
| | | NMC811 | LFP | | NMC811 | LFP | | NMC811 | LFP |
| 2022 | 20 | $78 | $75 | 15% | $89 | $87 | 1.25 | $112 | $108 |
| 2027 | 80 | $59 | $57 | 10% | $65 | $62 | 1.18 | $76 | $74 |
| 2030 | 120 | $50 | $48 | 10% | $55 | $52 | 1.18 | $64 | $62 |

For the 2027 projections with a plant size of 80 GWh, the average cost factor of 0.78 is applied, and for the 2030 projections with a plant size of 120 GWh, the average cost factor of 0.66 is applied to the battery costs of $75/kWh and $72/kWh for NMC811-G (Energy) and LFP-G (Energy) cells, respectively, derived from BatPaC 5.0 [55]. The resulting cell costs of NMC811-G (Energy) and LFP-G (Energy) in 2027 are $59/kWh and $57/kWh, respectively, and in 2030, they are $50/kWh and $48/kWh, respectively.

A supplier margin from the battery manufacturer to the automotive OEM, as well as the cell-to-pack multiplier, are also used to calculate the cost incurred by an OEM for building before assembling onto a vehicle. A conservative supplier margin of 15% in 2022 is assumed and will likely decrease as the automotive OEMs vertically integrate battery production within their vehicle manufacturing ecosystem. There is already a rush of joint ventures and offtake agreements that the automotive OEMs are signing with the battery producers to bring down the costs. Thus, a conservative 10% supplier margin in 2027 and 2030 is assumed in this study, though it could be much lower. Based on BloombergNEF price surveys, a cell-to-pack split of 80:20 is considered in 2022 [10], [49], and going forward to 2027 and 2030, a conservative split of 85:15 is used. Per BNEF, the cell-to-pack ratio was 70:30 in 2019 and 82:18 in 2021 [10], [49]. Historical data suggests that the cell-to-pack split will further improve as learning efficiency and resource utilization improves (despite lower cell costs). Furthermore, as cell-to-pack (CTP), cell-to-chassis (CTC), and cell-to-vehicle technology improve, the cell-to-pack split will fall below the projected split. After applying the supplier margin and cell-to-pack split, the resulting cost to build a pack of NMC811-G (Energy) and LFP-G (Energy) in 2027 is $76/kWh and $74/kWh, respectively; in 2030, it is $64/kWh and $62/kWh, respectively.

The projected pack costs are believed to be conservative and may decline further, considering the disruptive technologies in the pipeline. In addition to the promising cathode and anode chemistries, rapid advancements are being made in the manufacturing of these battery packs to trim the costs further. Further cost savings will be realized through advancements in battery management systems (BMS), thermal management systems, and pack architecture.

### 2.3 Powertrain Incremental Cost Scenarios

Based on the powertrains used in ICEVs and BEVs, this study considers three different incremental cost scenarios for electrification. This approach captures the entire spectrum of various combinations of technological pathways within each category. It does not project the use of these specific technologies in 2027 and 2030 but attempts to present the wide range of associated costs within these powertrain choices. The bottom line is that between the different combinations of technologies considered here, the cost would fall within one of these ranges, even if different combinations are considered other than the ones presented. The powertrain incremental cost is the difference between the DMCs (with RPE) of the powertrains of an ICEV and a BEV, respectively. Figure 17 depicts the three scenarios developed to compare the ICEV and BEV powertrain costs, vehicle purchase price, and TCO for class 2b–3 vehicles. A sample plot representing the incremental cost of electrifying a class 2b van is also shown in the figure. The detailed results of all the other segments are shown in Appendix 9.1.

a) **Incremental Cost of Electrification Scenario 1**: Migrating from a high-cost ICE powertrain (SHEVP2 in class 2b and a diesel engine in class 3) to a low-cost BEV powertrain (low-cost LFP batteries). This represents moving from the most expensive ICEV to the lowest-cost BEV, i.e., the most favorable case for switching to a BEV. The incremental cost of the BEV powertrain and the incremental expense of purchasing a new BEV are the lowest. The BEV achieves TCO parity with the ICEV in the shortest amount of time after purchase.
b) **Incremental Cost of Electrification Scenario 2**: Migrating from a medium-cost ICE powertrain (NA SI 48V BISG mild hybrid) to a medium-cost BEV powertrain (medium-cost NMC811 batteries). The incremental cost of the BEV powertrain, the incremental BEV purchase price, and the time required for TCO parity are between Scenarios 1 and 3.
c) **Incremental Cost of Electrification Scenario 3**: Migrating from a low-cost ICE powertrain (NA SI) to a high-cost BEV powertrain (high-cost NMC811 batteries that are 10% more costly than those under Scenario 2). This represents moving from the lowest-cost ICE powertrain to the most expensive BEV powertrain, i.e., the least favorable case for switching to a BEV. The incremental cost of the BEV powertrain and the incremental expense of purchasing a new BEV are the highest. The BEV achieves TCO parity with the ICEV in the longest amount of time after purchase.

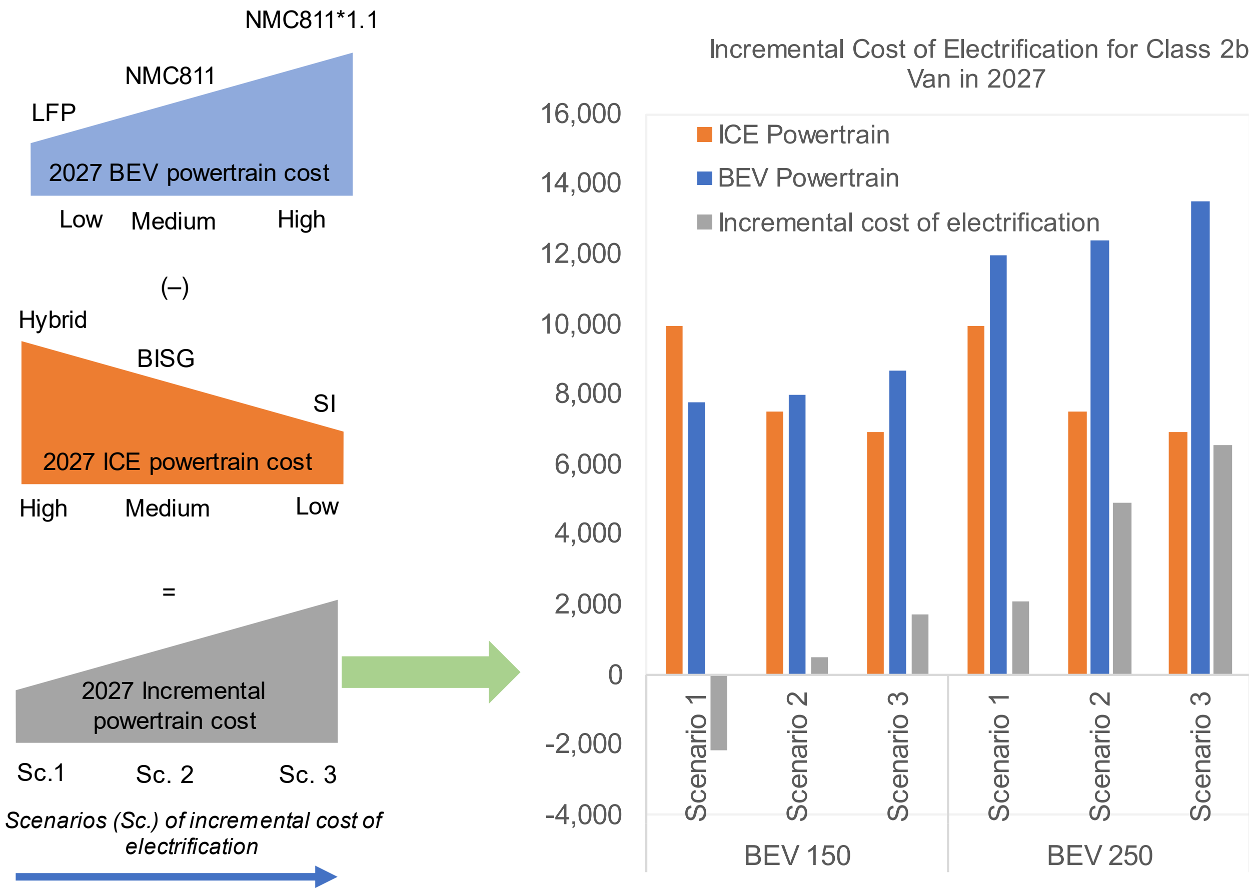


**Figure 17: Scenarios 1, 2, and 3 incremental costs of electrification with a sample plot of class 2b Van in 2027.**

## 2.4 Purchase Price Estimation

Figure 18 depicts the methodology for calculating the purchase price of ICEVs and BEVs. The ICEV and BEV are assumed to have the same glider price. The price of the vehicle without the powertrain is the glider price. A glider's subsystems may consist of the vehicle body, chassis, interior, steering, electrical accessory, brake, and wheel systems [56]. With the advent of dedicated BEV platforms, the potential for light weighting would benefit the glider price when compared to a comparable ICEV. For this report, the reduction in DMCs of the non-powertrain components of a BEV when compared to an ICEV is ignored. The powertrain costs are then added to the glider price. An RPE of 1.5 is used for ICE powertrain components as used in the CAFE model [3]. An RPE of 1.2 is assumed for the battery-electric powertrain components, as discussed in more detail below.

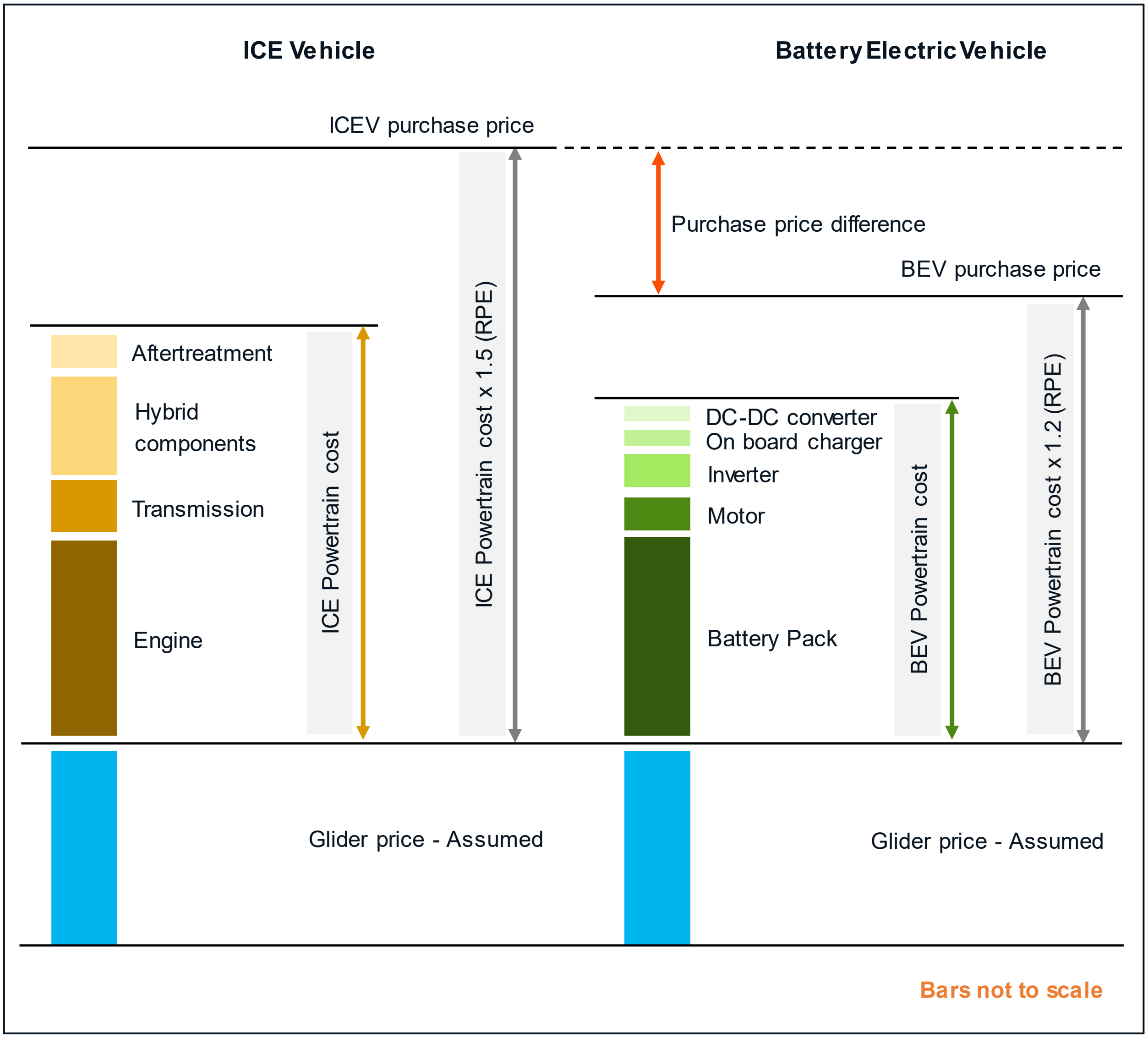


**Figure 18: Methodology of calculation of ICE and battery electric vehicle purchase price**

## 2.5 Determination of Retail Price Equivalent (RPE)

The DMCs do not account for the indirect costs of tools, capital equipment, financing costs, engineering, sales, administrative support, or return on investment. Regulatory agencies account for these indirect costs using a scalar markup of DMCs known as the retail price equivalent, or RPE [2]. RPE is the ratio of vehicle retail price to manufacturing cost [57], a scalar markup factor used by OEMs to earn a competitive rate of return on their production investment [58]. The RPE multiplier is applied to direct manufacturing costs to account for the difference between the cost of producing vehicle components and the price that manufacturers typically charge when selling a vehicle. The difference between these two costs is referred to as indirect costs and includes the retail price associated with the indirect costs such as production overhead, corporate overhead, selling costs, dealer costs, and net income before taxes, as shown in Table 16 [2]. The individual overheads in the indirect costs vary widely between manufacturers; however, the aggregate share of the indirect costs to revenues is similar amongst them. These indirect costs add to the price that the consumer incurs when purchasing a vehicle.

**Table 16: Retail Price Components as considered by DOT** [2]

| | |
|---|---|
| **Direct Costs** | |
| Manufacturing Cost | Cost of materials, labor, and variable energy needed for production |
| **Indirect Costs** | |
| *Production Overhead* | |
| Warranty | Cost of providing product warranty |
| Research and Development | Cost of developing and engineering the product |
| Depreciation and amortization | Depreciation and amortization of manufacturing facilities and equipment |
| Maintenance, repair, operations | Cost of maintaining and operating manufacturing facilities and equipment |
| *Corporate Overhead* | |
| General and Administrative | Salaries of nonmanufacturing labor, operations of corporate offices, etc. |
| Retirement | Cost of pensions for manufacturing labor |
| Health Care | Cost of health care for nonmanufacturing labor |
| *Selling Costs* | |
| Transportation | Cost of transporting manufactured goods |
| Marketing | Manufacturer costs of advertising manufactured goods |
| *Dealer Costs* | |
| Dealer selling expense | Dealer selling and advertising expense |
| Dealer profit | Net Income to dealers from sales of new vehicles |
| *Net income* | Net Income to manufacturers from production and sales of new vehicles |

Regulatory agencies, like the EPA or NHTSA, have traditionally used an RPE multiplier of 1.5 to estimate the indirect costs of producing an ICEV based on historical financial data gathered and analyzed from various sources, including OEMs' 10-K filings [2]. Figure 19 depicts RPE over three decades (1972-1997 and 2007), trending between 1.4 and 1.6. However, it is important to note that the RPE of 1.5 used by the regulatory agencies in the context of estimating the costs of regulation does not equate to an automaker using the same to mark up their vehicles. Vehicle price is always determined by various market forces; however, it is fair to assume that on average, for each dollar of DMC, the retail price paid by consumers has risen by approximately $1.50 for ICEVs [2]. An RPE of 1.5 for ICEVs is used in this study.

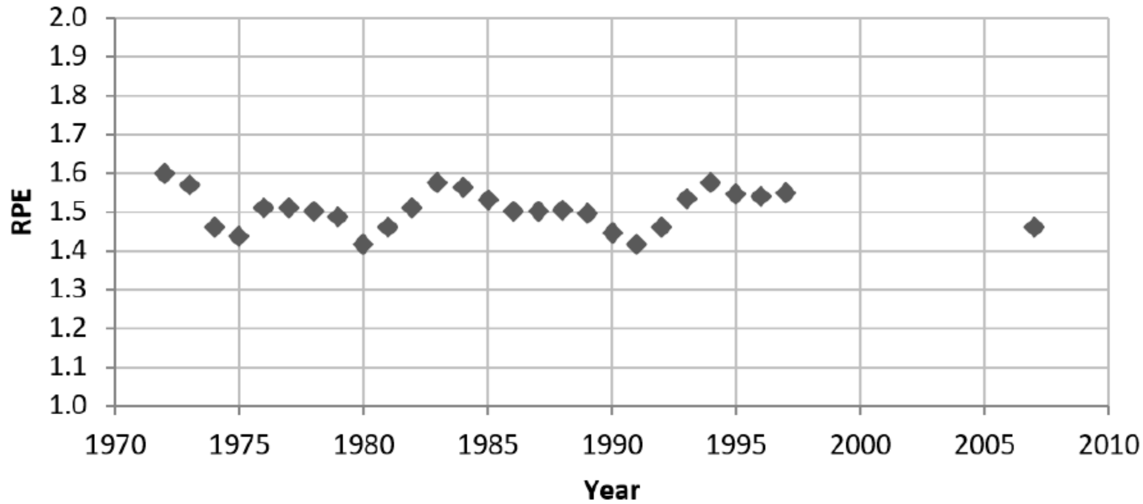


**Figure 19: Historical data for Retail Price Equivalent (RPE). Source: NHTSA** [2]**.**

With respect to BEVs, it is pertinent to note that a battery pack accounts for 70% to 90% of the DMC of a BEV powertrain. Therefore, battery pack costs are the main drivers of direct and indirect costs and the key target of cost reductions. Hence, it can be implied that research and development (R&D) into batteries and their architecture would be a significant contributor to production overhead and indirect costs. Most of the automakers have joint ventures or long-term contracts with battery makers such as LG Chem, CATL, Panasonic, and others for cell production. Therefore, the battery pack cost estimated in this study, as shown in Table 12, would, in a real-world scenario, have the indirect cost components baked into its cost. With the battery makers bearing the bulk of the indirect costs related to batteries, including extensive R&D, the OEMs are focused on R&D in areas such as, but not limited to, packaging and thermal management of the battery in their vehicles.

A singular markup factor may fail to capture the actual OEM markups and the complexity of emerging technologies [57], [58]. Furthermore, the factor would differ for short-term low-complexity technology versus long-term high-complexity technology, tailored and stratified for fleets or vehicle subclasses or segments, and finally, whether the parts are outsourced or manufactured in-house [58]. The RPE markup is widely acknowledged to be agnostic to any part, vehicle type, or manufacturer. Also, it is thought that BEVs may use a lower RPE and, hence, end up being sold with lower profit margins [57].

To cite an example of the R&D expenses incurred by BEV automakers, we looked at the 10-K filings of Tesla, an established BEV manufacturer. Table 17 illustrates the cost of revenues and R&D expenses in the years 2019, 2020, and 2021. Per their filing, revenues are a result of automotive sales and leasing, the energy generation and storage segment, and other services [59]. Total revenue is the sum of the total cost of revenues and total gross profit results. R&D expenses consist primarily of personnel costs for their teams in engineering and research, manufacturing engineering and manufacturing test organizations, prototyping expenses, contract and professional services, and amortized equipment expenses. Though R&D expenses increased proportionately with total revenues, they remained consistent at 5% of revenue from 2019 to 2021 and reduced to 4% in 2022. It should be noted that the R&D expenses are not just limited to the automotive arm.

**Table 17: Research and development expenses as a percentage of revenues from Tesla's 10-K filing of 2022** [59]

| ***Cost of Revenues and Gross Margin*** | | | | |
|---|---|---|---|---|
| **(Dollars in millions)** | **2022** | **2021** | **2020** | **2019** |
| Cost of revenues | | | | |
| Automotive sales | $49,599 | $32,415 | $19,696 | $15,939 |
| Automotive leasing | $1,509 | $978 | $563 | $459 |
| Total automotive cost of revenues | $51,108 | $33,393 | $20,259 | $16,398 |
| Services and other | $5,880 | $3,906 | $2,671 | $2,770 |
| Total automotive & services and other segment cost of revenues | $56,988 | $37,299 | $22,930 | $19,168 |
| Energy generation and storage segment | $3,621 | $2,918 | $1,976 | $1,341 |
| Total cost of revenues | $60,609 | $40,217 | $24,906 | $20,509 |
| | | | | |
| Gross profit total automotive | $20,354 | $13,839 | $6,977 | $4,423 |
| Gross margin total automotive | 28.5% | 29.3% | 25.6% | 21.2% |
| | | | | |
| Gross profit total automotive & services and other segment | $20,565 | $13,735 | $6,612 | $3,879 |
| Gross margin total automotive & services and other segment | 26.5% | 26.9% | 22.4% | 16.8% |
| | | | | |
| Gross profit energy generation and storage segment | $288 | -$129 | $18 | $190 |
| Gross margin energy generation and storage segment | 7.4% | -4.6% | 0.9% | 12.4% |
| | | | | |
| Total gross profit | $20,853 | $13,606 | $6,630 | $4,069 |
| Total gross margin | 25.6% | 25.3% | 21% | 16.6% |
| | | | | |
| Total revenues | $81,462 | $53,823 | $31,536 | $24,578 |
| ***Research and Development Expenses*** | | | | |
| **(Dollars in millions)** | **2022** | **2021** | **2020** | **2019** |
| Research and development | $3,075 | $2,593 | $1,491 | $1,343 |
| As a percentage of revenues | 4% | 5% | 5% | 5% |

Based on our assessment, an RPE of 1.2 for BEVs is used in this study for the 2030 purchase timeframe. To summarize, the selection of the RPE markup factor for BEV powertrains is influenced by:

a) The literature sources, as listed in Table 14, used to determine inputs to battery costing had both price and cost data points. Of the seven selected articles, four have projected price points and three have projected cost points. In general, prices do not equal costs, and factors like strategic pricing, long-term contracts, and subsidies influence battery pricing significantly [54]. Hence, we believe that the estimated battery pack cost has indirect costs baked into it. To be more specific, these articles' price and cost projections are used to calculate the cost factor (or cost ratio) and apply it to the BatPaC-derived costs.
b) In the ICEV space, there is an established ecosystem of tiered suppliers, which allows the automakers to markup their offerings on average by a factor of 1.5. However, it would take time and learning to vertically integrate the battery supply chain into their production lines. Until then, battery manufacturers markup cell costs when selling to automakers. This indicates that the battery cost is partially factoring into the retail element of pricing. We elected not to apply a higher RPE to BEVs to avoid unduly biasing the results of this study.
c) With expected increases in the stringency of fuel economy and emission standards, automakers' costs of achieving regulatory compliance for ICEVs could further increase. In the case of BEVs, though the technology is still immature, the number of components or the overall architecture remains the same without regard to changes in fuel economy and emission standards. We believe that the RPE of BEVs will be lower than that of ICEVs in the 2027–2030 timeframe.
d) Additionally, since the BEV powertrains are simpler in architecture and due to the commonality and interoperability of parts, they would have a lower production overhead compared to their ICE counterparts. However, the relative costs would be dependent on the battery size.
e) Furthermore, the R&D costs of a BEV, a crucial contributor to indirect costs, are not borne solely by the automaker. The battery manufacturer and others in the battery value chain bear the majority of the R&D costs associated with battery and power electronics development.
f) Finally, we believe that net income from selling BEVs will not be as high compared to selling ICEVs in the 2027–2030 timeframe. This is, however, outside the scope of the study and has not been considered.

## 2.6 Total Cost of Ownership (TCO)

The methodology to analyze TCO is similar to Roush's previous work on the Medium- and Heavy-Duty Electrification Costs for MY 2027–2030 [60]. Consistent with the three cases of the incremental cost of electrification, three cases of TCO are developed, denoted as Scenario 1, Scenario 2, and Scenario 3. Only tangible financial aspects of ownership related to the vehicle are considered for the TCO analysis, as shown in Table 18. They include:

a) Vehicle Glider Price (VGP) is an estimate based on the vehicle type under consideration. It does not change depending on the choice of powertrain for the low-cost, medium-cost, and high-cost cases, and is the same for ICEVs and BEVs in a class. For clarification, these powertrain cost cases are used as inputs to develop scenarios. This study assumes the swapping of an ICE powertrain with a BEV one on the same platform, thereby making the costing exercise independent of the vehicle platform.
b) Powertrain cost (as described in the above sections)
c) Fossil fuel prices for ICEVs
d) Electricity price for BEVs
e) Maintenance and repair (M&R) costs
f) Charger costs (for BEVs only)

Costs associated with staffing and labor, scrap or resale, insurance, taxes, grants, or subsidies, and intangible benefits such as reduced healthcare and environmental costs related to emission reductions or fuel economy improvements, are not considered. Staffing and labor costs, scrappage, and resale are not expected to change significantly between the two types of vehicles.

VGP, vehicle age or lifespan, annual VMT, annual discount rate, and 2027–2030 purchase years are the common inputs to both ICEV and BEV categories, as mentioned in Table 18. An annual VMT of 17,114 miles for a class 2b van, 19,345 miles for a class 3 pickup truck, 21,085 miles for a class 3 P&D, and 18,364 miles for a class 3 van have been considered for analysis [61]. In general, fuel efficiency and annual VMT are crucial inputs as they determine the M&R and fuel costs of a vehicle while also influencing the vehicle purchase price. The TCO in $/mile is an implicit function of age and vehicle VMT [57]. Based on the California Air Resources Board (CARB) discussion document, a lifespan of 12 years is considered for all vehicle classes to simplify the comparison [8]. As class 2b–3 vehicles are often used by individuals and corporations to transport larger packages and goods, the ownership period widely varies and is dependent on the duty cycle and driving patterns. For instance, they could be used for short-range driving with high idling or occasional long-range driving while hauling cargo. Amazon, FedEx, and UPS delivery vans with short, regular routes with frequent stops are good examples of short-range driving combined with high idling. Cargo vans and pickups are used by a variety of fleets for transporting passengers, towing, and hauling cargo, with occasional long-range driving. Based on CARB's analysis, 12 years represents a middle ground between businesses that operate their fleet trucks for anywhere between 5 and 20 years. An annual discount rate of 3% is considered for both categories across all classes.

**Table 18: Inputs used for Total Cost of Ownership (TCO) analysis.**

| Inputs | ICEV | BEV |
|---|---|---|
| Vehicle Glider Price (VGP) | VGP (same for both) | |
| Powertrain (p/t) cost | ICE p/t | BEV p/t |
| Retail Price Equivalent (RPE) | 1.5 | 1.2 |
| Vehicle Purchase Price | VGP + (1.5 × ICE p/t) | VGP + (1.2 × BEV p/t) |
| Maintenance and Repair (M&R) ($/mile) | Depending on class | 30% less than the comparable ICEVs |
| Fuel Efficiency (mpg or kWh/mile) | Depending on class | Depending on class |
| Annual VMT (miles/annum) | Same for both depending on vehicle class | |
| Charger cost including installation for BEVs | – | a) $1,800 – residential-type charging scenario<br>b) Tiered costs – commercial charging scenario |
| Lifetime | 12 years | |
| Annual Discount Rate | 3% | |
| Purchase years | 2027 and 2030 | |

### 2.6.1 ICEVs

Annual VMT is sourced from the 2015 ANL study [62], and an RPE of 1.5 is considered for TCO analysis [57]. Fuel economy is sourced from the 2021 ANL study [33]. The vehicle's initial purchase price, estimated from the glider price and powertrain price, represents the upfront price. For the computation of energy and maintenance costs, fuel economy, VMT, and fuel prices are used as inputs. Table 19 lists the fuel economy inputs used for the considered vehicle types for MYs 2027 and 2030. We assumed the same fuel economy numbers for MYs 2027 and 2030 as we do not foresee significant developments in ICEV technology that would boost the fuel economy further between 2027 and 2030. These modeled fuel economy projections with high payloads from ANL are already much higher than the current offerings and anticipated efficiency gains. The resultant values are discounted by 3% annually to arrive at the cumulative cost of operating the vehicle. The discount rate accounts for the opportunity cost associated with the financial return that is forgone by investing the capital into the ownership of a vehicle.

**Table 19: Glider Price and fuel economy inputs considered for TCO analysis. MPGDe is an acronym for miles per gallon diesel equivalent.**

| Class | Vehicle | Representative vehicle | Vehicle Glider Price | Powertrain | Fuel | 2027 & 2030 MPGDe |
|---|---|---|---|---|---|---|
| 2b | Van | Ford Transit, Ram Promaster | $25,000 | Conventional | Gas | 18.7 |
| | | | | BISG | Gas | 19.0 |
| | | | | SHEVP2 | Gas | 23.3 |
| 3 | Pickup Truck | F-250, F-350, F-450 | $30,000 | Conventional | Gas | 16.4 |
| | | | | BISG | Gas | 16.6 |
| | | | | Conventional | Diesel | 14.6 |
| | P&D Truck | F-350 chassis cab, Ford Transit 350HD | $35,000 | Conventional | Gas | 17.1 |
| | | | | BISG | Gas | 17.3 |
| | | | | Conventional | Diesel | 15.3 |
| | Van | F-350 chassis cab, Ford Transit 350HD | | Conventional | Gas | 18.5 |
| | | | | BISG | Gas | 18.3 |
| | | | | Conventional | Diesel | 15.1 |

Figure 20 and Figure 21 show retail gasoline and retail diesel prices from the EIA AEO 2022 [6]. The application of retail fuel prices is linked to the respective ICE powertrain. High gasoline prices have been applied to the high-cost ICE powertrain, and low gasoline prices have been applied to the low-cost ICE powertrain. As described earlier, the high-cost ICE powertrain is under Scenario 1, the medium-cost ICE powertrain is under Scenario 2, and the low-cost ICE powertrain is under Scenario 3. We used three distinct gasoline price projections in Scenarios 1, 2, and 3, as described. Gasoline price projections from the EIA's high oil price sensitivity case are used in Scenario 1, reference case gasoline prices are used in Scenario 2, and gasoline prices from the low oil price case are used in Scenario 3. Scenario 1 assumes gasoline prices in the range of $4.17/gallon-$4.37/gallon and diesel prices in the range of $4.77/gallon-$5.15/gallon for class 2b and class 3, respectively; scenario 2 in the range of $2.68/gallon-$3.09/gallon range; and scenario 3 in the range of $2.02/gallon-$2.24/gallon. To reiterate, Scenario 1 represents the lowest cost of electrification (highest gasoline prices here), and Scenario 3 represents the highest cost of electrification (lowest gasoline prices here). The electricity prices described below do not include any taxes to support road construction or maintenance, whereas retail gasoline prices do. To provide a fair comparison of energy costs, the federal and state tax components amounting to 49.4¢ and 57.1¢ have been removed from the retail prices of gasoline and diesel, respectively, as we assumed that a comparable road tax will be eventually added to the automotive electricity charging costs.

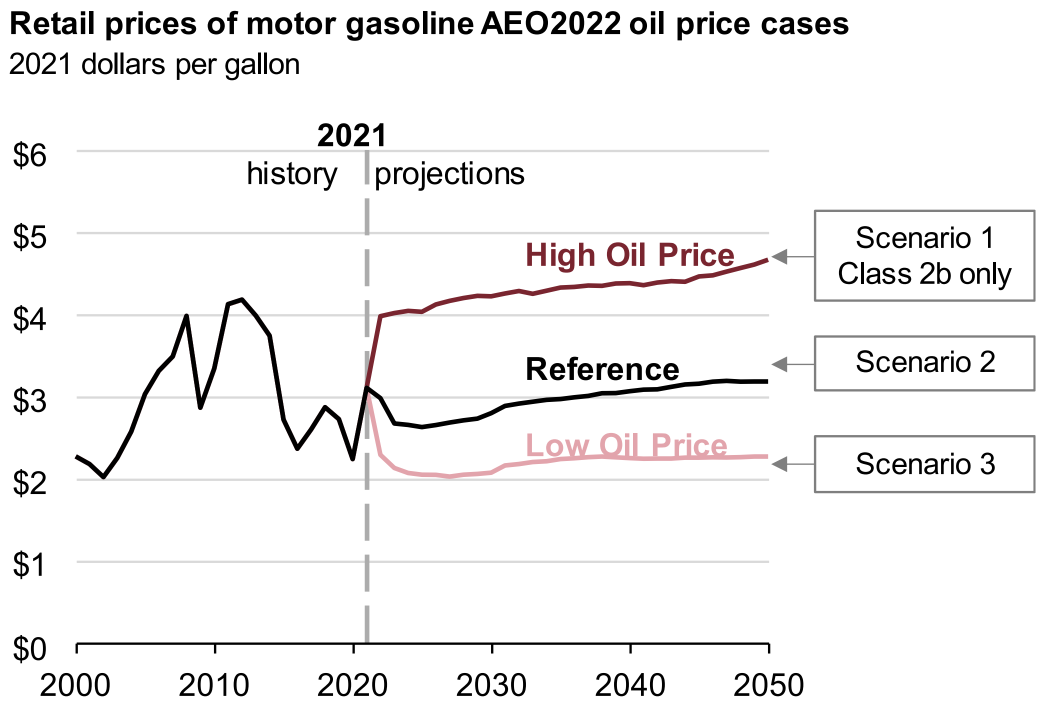


**Figure 20: AEO2022 projected retail prices of motor gasoline in 2021 dollars per gallon** [6].

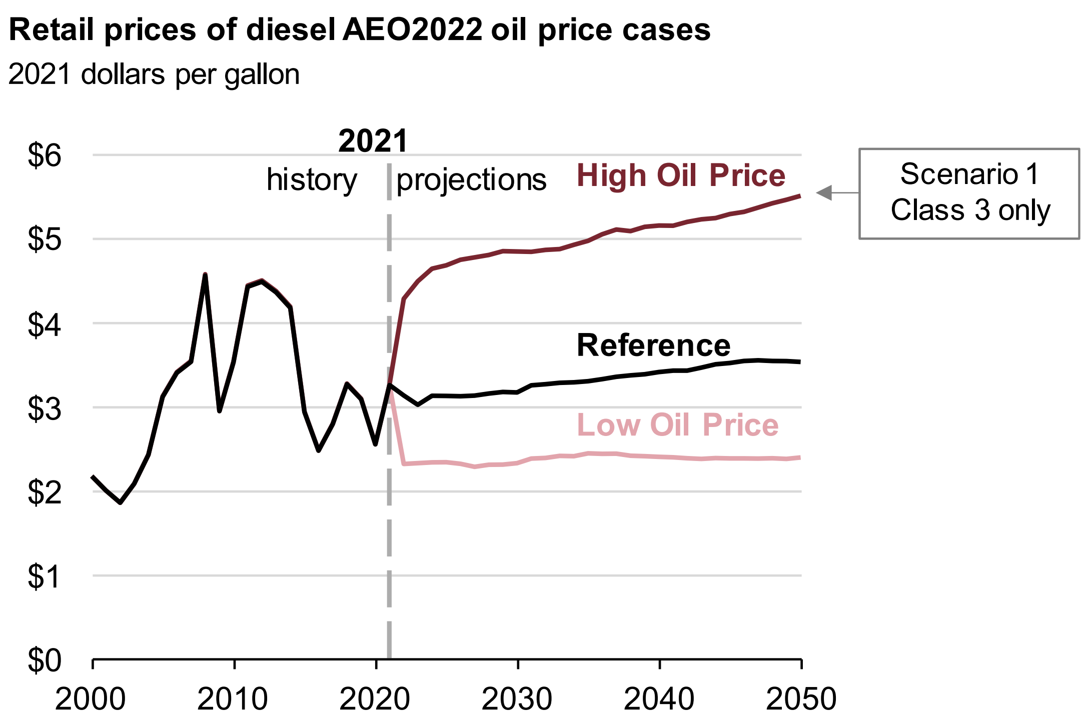


**Figure 21: AEO2022 projected retail prices of diesel in 2021 dollars per gallon** [6]**.**

The projected gasoline rates vary by 2X, from $2.02/gallon to $4.39/gallon. It is critical to note that recent oil prices have spiked above EIA projections, especially in certain parts of the country, and, as a result, future oil prices could be considerably higher than those of the projected high oil price used in this study. It is also important to note that the range in fuel prices across the three scenarios masks the impact of the varying fuel economy of the chosen powertrains. This is important because fuel economy is somewhat within the control of the vehicle purchaser, while fuel prices are not. The M&R cost of ICEVs ranges from 9.2¢ to 9.9¢ per mile [63]. A fuel price sensitivity analysis is performed to provide a perspective on TCO and its parity timeline with real-world fuel prices which can be found in Section 5.2.

### 2.6.2 BEVs

There is a dearth of data regarding the M&R costs of class 2b–3 ICEVs and BEVs. However, due to fewer moving parts, reduced use of consumables (lubrication oil, gaskets, etc.), and utilization of unique components, BEVs have a lower maintenance cost compared to ICEVs. For example, Tesla claims that its drivetrain has 17 moving parts, including two in the motor, compared to the hundreds of moving parts in a conventional ICEV. It is pertinent to note that most of the TCO studies [8], [57], [60], [64]–[66] indicate that the maintenance cost of BEVs is cheaper than ICEVs by 30%–40% due to fewer moving parts, no engine oil, automatic transmission fluid, spark plugs, or timing belts [34], [38], [40], [43]–[45]. As a result, in the analysis, a conservative M&R cost 30% lower than ICEVs is assumed for comparable BEVs [57], [64]. The assumed M&R cost for BEVs ranges from 6.4¢ to 7.7¢.

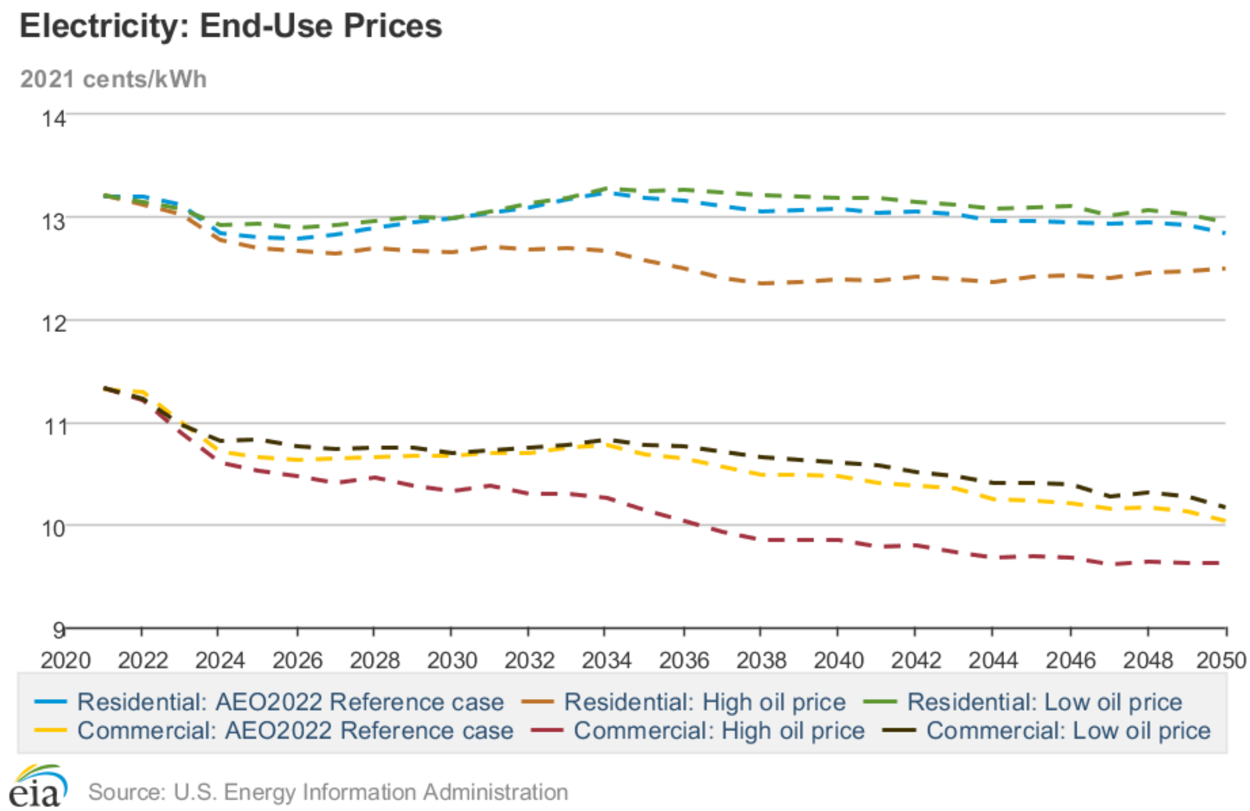


**Figure 22: AEO2022 projected electricity prices in 2021 cents/kWh** [6]**.**

To factor in the costs related to charging BEVs, a residential-type scenario has been developed. Residential-type charging is defined as a scenario where a residence or residence-type setting, i.e., a home, a reserved parking location (carport), or a designated parking spot, is the primary choice for charging a BEV. Residential end-use electricity retail price projections from the EIA AEO 2022, as shown in Figure 22, and charger costs are accounted for as EV energy inputs [6]. Compared to the wide range seen in projected fuel prices, the variation in the projected residential electricity prices is hardly a cent, ranging from 12.4¢/kWh to 13.3¢/kWh. Also, it is worth noting that, electricity prices are less sensitive than oil prices to political and economic factors. A 90:10 mix of residential and public charging is assumed here for all three cases of electrification. It is assumed that a typical user's vehicle is going to spend 90% of its charging time in a residential-type setting and will have access to charging at residential end-use electricity rates. The remaining time (10%) assumes the use of publicly available DCFC network charging, with electricity costs at the current highest per kWh price. These rates have the potential to be lower in the future. An upfront cost of $1,800 for a level 2 AC (non-networked) 19.2 kW residential charger is considered [7], [56]. Public charging at an Electrify America DCFC station is assumed to be at 43¢/kWh based on the pricing plans available on their website [57]. Additionally, to provide a perspective on TCO and its parity timeline with real-world electricity prices, an energy price sensitivity analysis is conducted and can be found in

Section 5.3. Furthermore, a what-if scenario analysis (termed "commercial charging" in this report) is also developed to consider a scenario involving fleet owners who choose to invest in a dedicated charging infrastructure to charge and operate their BEV fleet. A 100% commercial charging scenario with commercial electricity prices and three different charger infrastructure costs of $4,000, $6,000, and $15,000 is developed using Scenario 2 of the incremental cost of electrification [8], [67], [68]. This exploratory exercise provides the fleet owner a glimpse into the costs incurred for the installation of a level 2 19.2 kW charger with three different infrastructure costs. This scenario is covered in detail in Section 5.1.

### 2.6.3 Calculations

The vehicle purchase price is computed by summing the glider price with the RPE marked-up powertrain cost for ICEV and BEV, respectively. In the case of BEV, this study assumes the consumer also purchases and installs a level 2 charger. In addition to the initial purchase price, operating costs are the additional costs incurred by the consumer after purchasing a vehicle to operate it. Operating costs include the energy and M&R costs assumed to be incurred each year over the lifetime of the vehicle. The equations used to arrive at the energy costs on an annual basis are:

a) ICEV energy cost ($) = Annual VMT(mile) ÷ Fuel economy(mpg) × Gasoline cost($/gallon)

b) BEV energy cost ($) = Annual VMT(mile) × Energy consumption $\left(\frac{\text{kWh}}{\text{mile}}\right)$ × Electricity cost($/kWh)

Cumulative TCO is calculated by adding the upfront purchase price and discounted annual operating costs. TCO per mile is calculated by dividing the cumulative TCO by the lifetime miles traveled (annual VMT × 12 years).

# 3. Electrification Technology Review

This section reviews the state-of-the-art and future trajectory of various technologies in batteries, traction motors, and power electronics. We considered the following types of technologies in this review:

a) Technologies that can significantly lower the DMC and TCO of class 2b-3 vehicles from 2022 to 2027-2030 and beyond; and
b) Technologies that can mitigate potential increases in commodity prices or supply constraints caused by geopolitical or other factors (such as impacts on rare earth metals, critical raw materials, and so on) that may have a negative impact on the cost of a BEV and increase the cost of electrification.

Section 3.1 (Battery Technology) introduces various aspects of the battery supply chain and their significance in achieving a sustainable and circular economy while transitioning to BEVs. Furthermore, a snapshot of promising chemistries in the lithium-ion battery (LIB) and beyond-LIB spaces along with manufacturing advancements, is also presented. Sections 3.2 (Traction Motors) and 3.3 (Power Electronics) present a roundup of key technologies that are focal points in the electrification of powertrains. It is important to note that technological and business developments related to the battery supply chain and BEV ecosystem as a whole are occurring at a breakneck speed, and the information contained in this section reflects just one snapshot in time. Though most of the technologies discussed in this section have not been considered in the costing exercise undertaken in this study, they demonstrate that the analysis in the 2027 and 2030 timeframes is conservative because future developments will likely further reduce BEV costs.

## 3.1 Battery Technology

### 3.1.1 Introduction

Lithium-ion batteries have become the battery of choice for currently sold BEVs, though other types of batteries are being researched and are discussed further below. 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, future battery costs will likely be below those projected in this study.

Batteries convert stored chemical energy into electrical energy, which powers the motors that propel BEVs. Batteries replace fossil fuel as the energy source with an electric motor, thereby eliminating the hazardous tailpipe emissions associated with an ICEV. LIBs were first introduced in the 1980s by Dr. John B. Goodenough and were eventually commercialized in the early 1990s [69]. As found in any standard battery, the key components are a cathode (positive electrode), an anode (negative electrode), an electrolyte, and a micro-permeable separator to allow the flow of lithium ions. During a charging cycle, the lithium ions move from the cathode to the anode, and during a discharge cycle, the ionized lithium ions move from the anode to the cathode. The shuttling of lithium ions between the cathode and anode allows the lithium-ion batteries to provide power or recharge using an external power source.

The family of lithium-ion chemistries, as shown in Figure 23, is usually identified by the compounds used to form their cathodes. Some of the most common lithium-ion chemistries in use are lithium cobalt oxide (LCO), lithium manganese oxide (LMO), nickel cobalt aluminum oxide (NCA), nickel cobalt manganese oxide (NCM or NMC), and lithium iron phosphate/lithium ferrophosphate (LFP). The chemistry of the cathode is typically identified in shorthand by the stoichiometric ratio used, which influences the properties of the LIB (e.g., NMC811 = $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$). Currently, cathodes of NCM, NCA, and LFP dominate the EV market.

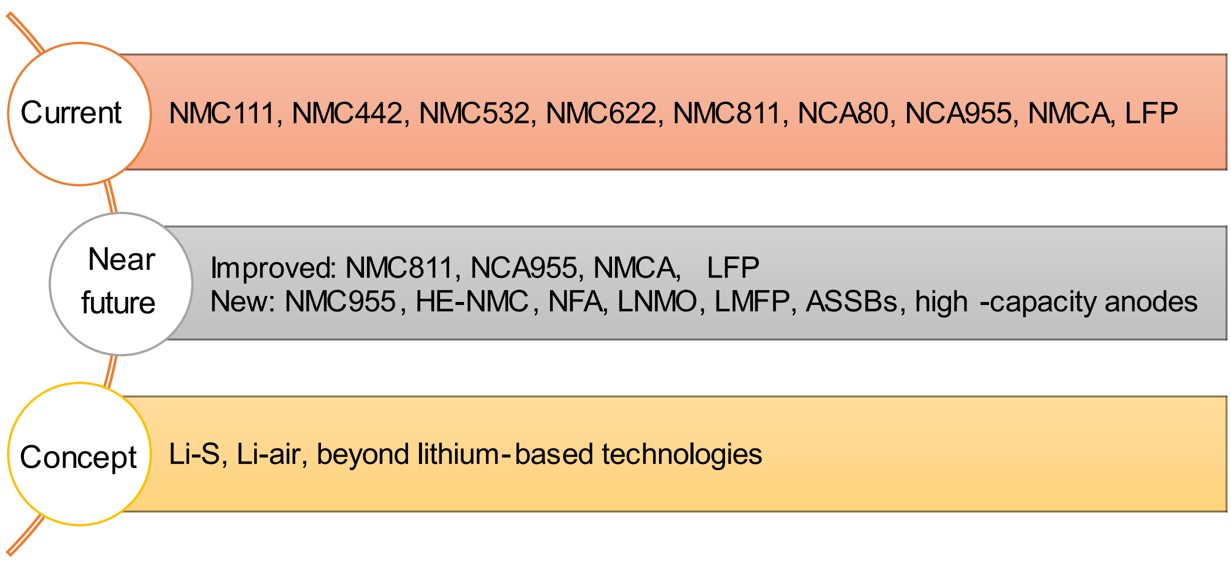


**Figure 23: Snapshot of current and expected EV battery chemistries. Numbers represent the ratios of nickel-manganese-cobalt or nickel-cobalt-aluminum in the cathode.**

NMC chemistries include NMC111/NMC333, NMC442, NMC532/NCM523, NMC622, NMC721, NMC811, and NMC9.5.5/NMC90, which have largely dominated the LIBs used in the EV space. NMC 5- and NMC 6-series chemistries were the most widely used in 2021, followed by NCA+ and LFP chemistries [70]. Additionally, LFP was one of the fastest-growing chemistries in 2021 and is expected to continue the trend in the coming years [70]. LFP is expected to increase its market share by gaining a foothold in the US following the expiration of patents in April 2022. Per a recent projection by Wood Mackenzie, LFP will be the dominant chemistry, surpassing NMC's market share in 2028

[71]. LFP is growing in the EV industry because it does not require cobalt and nickel, which are two of the most expensive battery minerals and which present supply constraints.

A battery supply chain consists of five main value-chain steps: (a) raw material production; (b) material refinement and processing; (c) battery material manufacturing and cell fabrication; (d) battery pack and end-use product manufacturing; and (e) battery end-of-life recycling [72]. The U.S. currently has a deficit in the upstream and midstream of the battery supply chain (mining, refining, and processing of battery-critical raw materials). A typical BEV is much more mineral intensive than a comparable ICEV, as shown in Figure 24 and Table 20. The demand for critical minerals, which are key in clean energy technologies, is expected to increase by as much as six times, with lithium's demand projected to rise even faster [21]. Some reports anticipate a future shortage of lithium due to a current lack of investment leading to a scenario where the sheer volume of lithium demand may outstrip supply [73], which could present a barrier to fully achieving electrification targets [74]–[76]. Battery-related extraction and mining projects have a long lead time; a quarry or mine takes around 7–10 years to set up and produce a battery-grade supply of raw materials. Automakers are exploring scenarios for entering the upstream and midstream segments of the battery value chain to ensure a consistent supply of materials. For example, Tesla plans to build a spodumene converter near its Austin Gigafactory, which is a midstream project to refine raw materials and produce high-quality battery-grade precursor materials [77]. Investments associated with the Inflation Reduction Act of 2022, along with other government initiatives, are expected to boost domestic projects throughout the supply chain in both the short and long term.

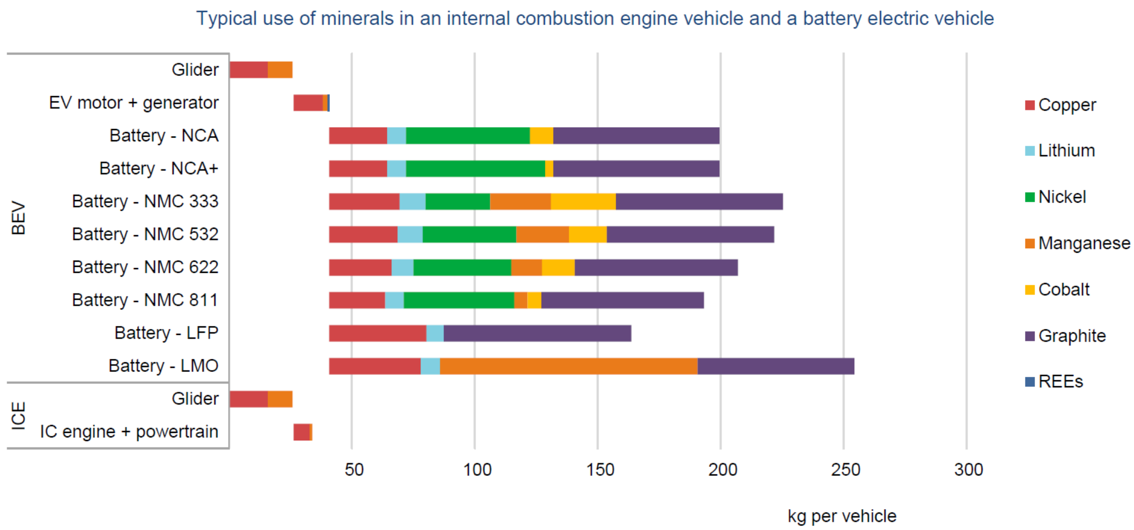


**Figure 24: IEA estimates a typical BEV requires around six times more minerals than a conventional ICEV. 75 kWh battery with graphite anodes and PMSM shown here** [21]**.**

**Table 20: Requirements of critical raw materials** [20]

| Element | Material | Purity requirements | Uses |
|---|---|---|---|
| Lithium | Lithium carbonate ($Li_2CO_3$), lithium hydroxide monohydrate ($LiOH{\cdot}H_2O$) | 99.5%+ $Li_2CO_3$ in a lithium carbonate product and 56.5%+ LiOH in a lithium hydroxide product, both with impurities below specified levels | Battery cathode |
| Nickel | Nickel sulfate ($NiSO_4(H_2O)_6$) | High purity | Battery cathode |
| Cobalt | Cobalt sulfate ($CoSO_4{\cdot}7H_2O$) | High purity | Battery cathode |
| Manganese | Manganese sulfate monohydrate ($MnSO_4{\cdot}H_2O$) | 32% manganese content | Battery cathode |
| Graphite | Natural graphite, synthetic graphite | 99.95% by weight, synthetic often higher purity, lower thermal expansion, and better thermal stability | Battery anode |
| Rare-earth elements | Neodymium (Nd), dysprosium (Dy) | 99.95%+ | Direct drive motor (permanent magnet) |

The bill of materials of a battery is dictated by the cathode chemistry and stringent purity requirements set forth by the cell manufacturer [20]. For example, lithium hydroxide monohydrate is preferred by cell manufacturers to produce high-energy NMC cells compared to lithium carbonate, which is used for LFP production.

### 3.1.2 Critical Raw Material Availability

Critical materials like lithium, nickel, cobalt, graphite, manganese, and rare earth elements will be in high demand in the coming decades to meet the growing demands of the EV market and other clean energy technologies. According to J.B. Straubel, CEO of Redwood Materials and ex-CTO of Tesla, metals account for 50%-70% of battery costs [78]. With the projected growth of EVs, the automotive demand for lithium, nickel, and cobalt will keep growing, as shown in Figure 25 [79]. Xu, C., *et al.* have attempted to quantify the future demand for battery-critical raw materials [79]. Three battery chemistry scenarios were considered: nickel-based NCX chemistry, iron-based LFP, and Li–S/Air, which is considered disruptive chemistry. The NCX scenario considers both the NCM and

NCA chemistries, with X being either aluminum or manganese. To put this into perspective, Benchmark Mineral Intelligence quantified the consumption of raw materials in this scenario: a 30 GWh NMC LIB mega factory would require about 25,000 tonnes of lithium, 19,000 tonnes of nickel, 6,000 tonnes of cobalt, and 80,000 tonnes of flake graphite or 45,000 tonnes of synthetic graphite [80]. By 2030, demand is expected to be nearly 4 TWh [48]. Due to the concentration of these materials in a few countries, as depicted in Figure 26, the challenge of creating and expanding a sustainable, regional supply of critical raw materials will play a role in the long-term financial viability of mass production and penetration of EVs. Both the public and private sectors are undertaking numerous initiatives to secure the necessary supply of these materials. Substitution of materials such as nickel and cobalt (including through the use of LFP batteries, as discussed in this report) will also likely play an important role.

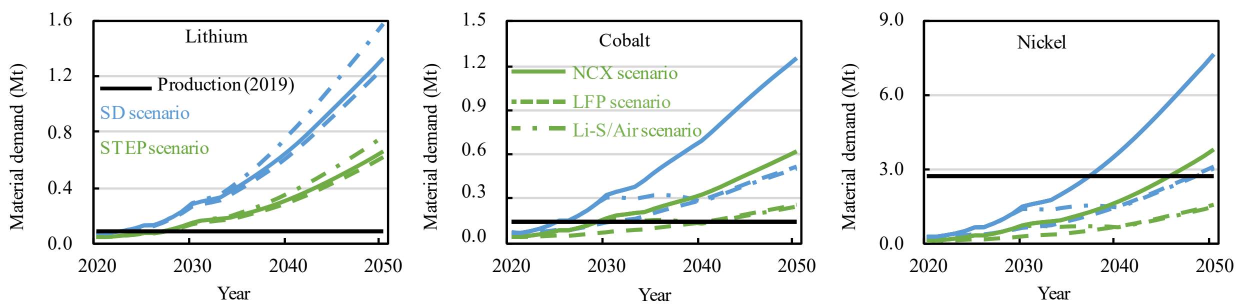


**Figure 25: Projected global demand for lithium, cobalt, and nickel for EV batteries in million tons in the NCX, LFP, and Li-S/Air battery scenarios based on two scenarios of the International Energy Agency (IEA), the Stated Policies (STEP) and Sustainable Development (SD) scenario** [79]**.**

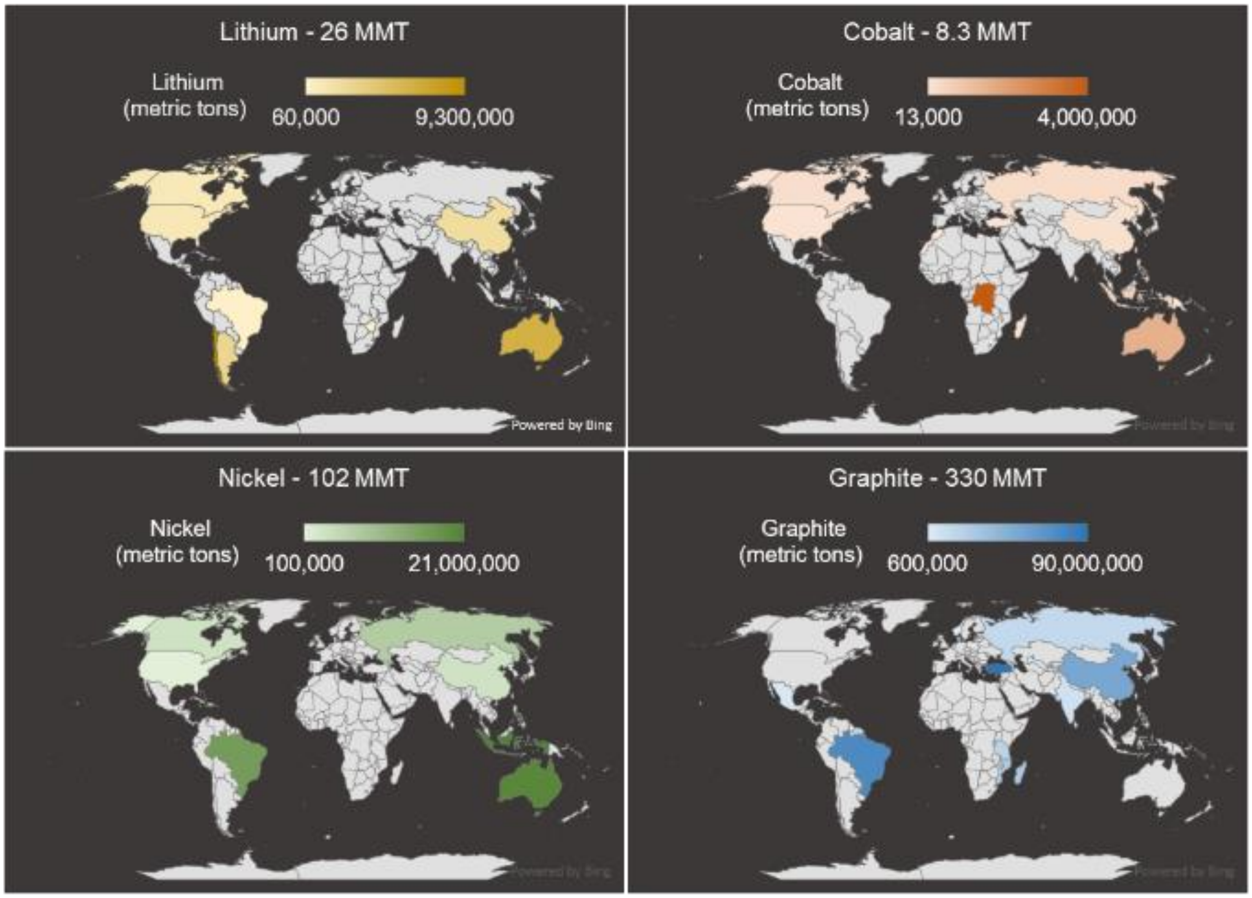


**Figure 26: Estimated reserves of battery critical raw materials in million metric tons (MMT) based on Mineral Commodity Summaries 2023 by U.S. Geological Survey** [23]

#### 3.1.2.1 Lithium

Lithium is found naturally in the form of pegmatites, brines, and sediments [20], [81]–[84]. Australia, Argentina, Chile, and China accounted for the majority of the lithium production in 2021 [83]. Latin America's "Lithium Triangle," comprising Chile, Argentina, and Bolivia, holds around 58% of the world's lithium in the form of lithium-rich brine resources. The resulting lithium carbonate, produced from the evaporation of the salars, or brine ponds, is further processed to produce lithium hydroxide monohydrate, which is currently the desired precursor for lithium-ion cell manufacturers. Mineral-based lithium resources like the Australian spodumene ores are generally preferred as they contain up to 8% $Li_2O$ by mass and can be refined to lithium carbonate (used typically in NMC622) or lithium hydroxide monohydrate (used in NMC811), supposedly at a cheaper cost than the lithium extracted from brine [82], [85]. Sedimentary lithium-clay sources are in various stages of development in Mexico and the United States [83]. Thacker Pass in Humboldt County, Nevada, 100% owned by Lithium Americas (LAC), has mineral reserves of 3.7 million tonnes of lithium carbonate equivalent (LCE) with an estimated mine life of 40 years. LAC projects its average operating costs (production scenario) of battery-grade lithium carbonate per year for about $6,700 per tonne [86]. LAC and General Motors (GM) are collaborating to develop U.S.-sourced lithium production through a $650 million Equity Investment and Supply Agreement, where GM is LAC's largest shareholder [87].

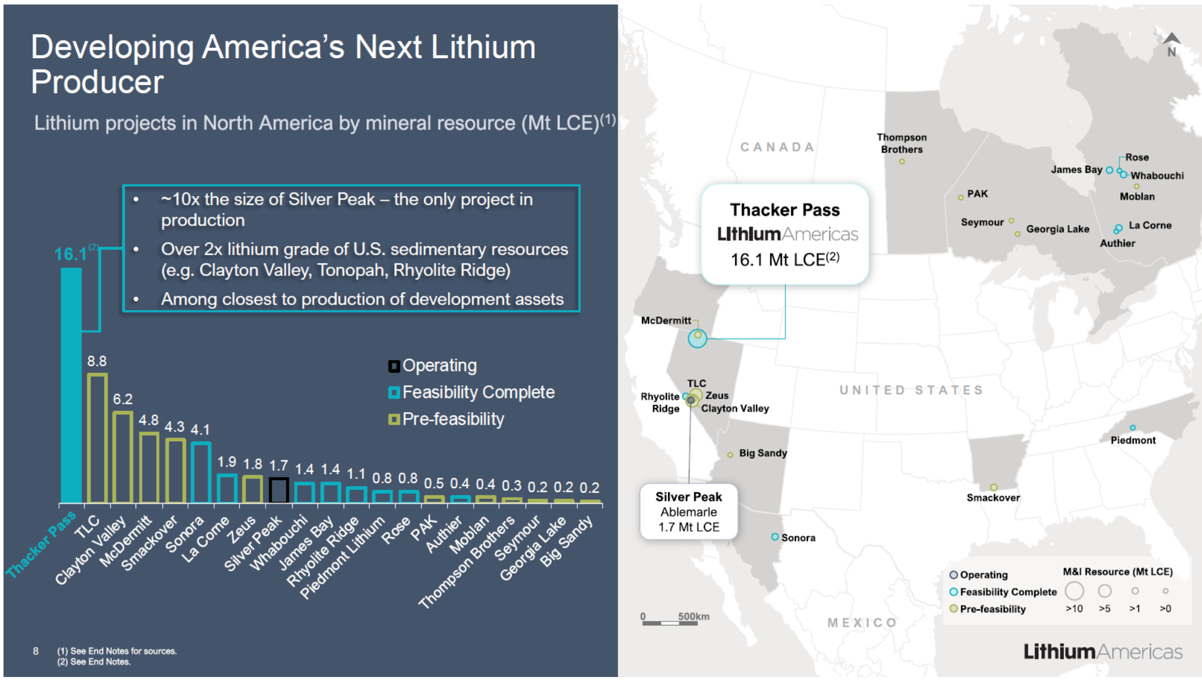


**Figure 27: Lithium projects in North America. Image Source: Lithium Americas Investor Presentation** [87]**.**

Compared to the large physical footprint of brine salars, as shown in Figure 28, and open-pit mines of spodumene or clay, alternative promising technologies of closed-loop direct lithium extraction (DLE) and direct lithium to product (DLP) are being explored to tap the vast reserves of lithium-rich geothermal brines, estimated at around 600,000 tonne LCE per year, in the Salton Sea region of southern California [82], [88]. GM in 2021, and Stellantis in 2022, formed a strategic investment and commercial collaboration with Controlled Thermal Resources, which has set up the Hell's Kitchen geothermal project around the Salton Sea, to secure low-cost lithium produced using the DLE technology [89], [90].

**Figure 28: Cauchari-Olaroz project jointly operated by Lithium Americas (LAC) and Ganfeng Lithium in Argentina. Source: Lithium Americas** [86]

The identified lithium resources increased from 89 million metric tons in 2021 to 98 million metric tons in 2022 as a result of further exploration, which was encouraged by rising commodity prices and demand for lithium. Additionally, India [91] and Iran [92] announced the discovery of lithium deposits estimated at 5.9 million metric tons and 8.5 million metric tons, respectively. These discoveries result in a 26% increase in worldwide Lithium resources from 2021 to 2022. From 2021 to 2022, these finds lead to a 26% increase in the world's lithium supplies. The amount of lithium that can be mined globally with current technology and economic viability grew by 18%, from 22 to 26 million metric tons.

### 3.1.2.2 Cobalt

70% of the world's cobalt requirements are being met by the mines in the Democratic Republic of the Congo [83]. Cobalt has often been a preferred material as it provides structural stability and boosts energy density and battery life [93]. China was the world's leading producer and consumer of refined cobalt, with most of it being used by their rechargeable battery industry [83]. Cobalt is mined as a by-product of copper (55%), nickel (29%), and other mineral ore sources (16%), except at Bou Azzer ophiolite mines in Morocco [20], [94]. Large-scale mining (LSM) and artisanal and small-scale mining (ASM) have a share of 87% and 13%, respectively [95]. Additionally, cobalt ores in various forms can be found in Zambia, Australia, and nearby island countries, Cuba, Canada, Russia, and the United States [83]. Furthermore, the seabed of the Atlantic, Indian, and Pacific Oceans hosts abundant regions of cobalt crusts, estimated to be more than 120 million tons [83], some as big as Europe in the western Pacific [96]. However, given the technical and environmental challenges, economical methods of deep-sea mining are still being explored and are in the early stages [97].

#### 3.1.2.3 Nickel

One of the long-term objectives per the National Blueprint for Lithium Batteries prepared by FCAB is to eliminate nickel and cobalt in LIBs [98]. High-purity Class 1 nickel (> 99%) found in sulfide deposits is used in its sulfate form in cell manufacturing [61]. Low-purity Class 2 nickel is found in laterite deposits. However, both grades of nickel can be used to produce nickel sulfate for batteries. Nickel has been traditionally used in NiMH and NiCd batteries, most notably in the Prius. However, modern-day EV LIBs use layered oxides of high nickel in the NMC and NCA cathodes to boost their energy density and specific capacity at the cost of thermal stability [12]. This has a direct effect on the cost savings of the battery as it cuts down on the cobalt required while improving the energy density [12]. As with cobalt, nickel resources are also found on the ocean floor [83]. Currently, Indonesia, the Philippines, Australia, Russia, China, and Brazil, in addition to other countries in a smaller percentage, lead in terms of mining and have identified reserves of nickel [83]. In November 2021, nickel was added to the U.S. critical minerals list [83].

#### 3.1.2.4 Graphite

LIBs use graphite-based anodes, as their layered structure allows for intercalation and deintercalation [12]. They are ubiquitous in EV batteries. Naturally occurring graphite in flake form or artificial/synthetic graphite derived from petroleum coke is used as the anode active material [20]. In 2021, China was the world's top graphite producer with an estimated production of 820,000 metric tons amounting to ≈79% of total world output, followed by Brazil at 68,000 metric tons [83]. Due to its superior performance and purity, synthetic graphite is the preferred choice of EV cell manufacturers, despite being twice as expensive as natural graphite [12]. The fast charging of EVs is limited due to lithium-ion diffusion within the graphite anode due to the risk of lithium plating [99]. Several technologies, like the introduction of silicon to produce high-capacity silicon anodes, are being explored to increase energy density. However, silicon's volumetric changes during charge and discharge cycles are a challenge as they end up introducing cracks in the electrode interface [12], [100]. Self-healing or auto-repair mechanisms in batteries are being explored to address this issue [100].

In North America, Syrah Resources' Vidalia Active Anode Material Facility based out of Louisiana is projected to have a capacity of 11,250 metric tons of anode active material when it starts production in Q3 2023. Syrah operates graphite mines in Australia and Mozambique. The current capacity can support the production of about 7.5 GWh of lithium-ion batteries. Canada was the 7th largest producer of Graphite (15,000 tonnes) in 2022 [23] with the 9th largest graphite reserves [102]. Canada would become a crucial source of graphite that could meet the sourcing requirements of critical minerals.

#### 3.1.2.5 Manganese

In 2021, South Africa, Gabon, and Australia led the production of manganese ores [83]. Manganese is one of the most overlooked materials in the battery world and is now poised to grow as an alternative to nickel and cobalt. Argonne National Laboratory is developing an array of low-cobalt, manganese-rich cathodes, including layered-type structures, spinel-type structures, rocksalt-type structures, and combinations thereof. They have higher capacities due to lithium-rich cathodes, higher power due to their spinel structure, and stability-enhancing characteristics concerning the surface stability, rate capability, and cycling stability of electrodes, which leads to increased electrode energy capacity [101]. Given the trends in the EV space, cell manufacturers and/or automotive OEMs may migrate to high-manganese cathode chemistry that is free from nickel and cobalt. If it happens, then one of the earth's most abundant metals could provide a safer and cheaper alternative to cobalt-laden chemistries [102].

### 3.1.3 Overview of Battery Production

Per SNE Research's news release in February 2022, China was the leading producer of cells with a 47% market share in 2021, followed by South Korea at 30% and Japan at 14%, with other regions including the U.S. and Europe at 9% [103]. It is estimated that 296.8 GWh worth of batteries were deployed across EVs [103]. As shown in Figure 29, Contemporary Amperex Technology Co., Limited (CATL) is the world's biggest EV battery manufacturer, with 32.6% of the market, followed by LG Energy Solutions at 20.3% market share and Panasonic at 12.2%, with other companies trailing them in single digits [103].

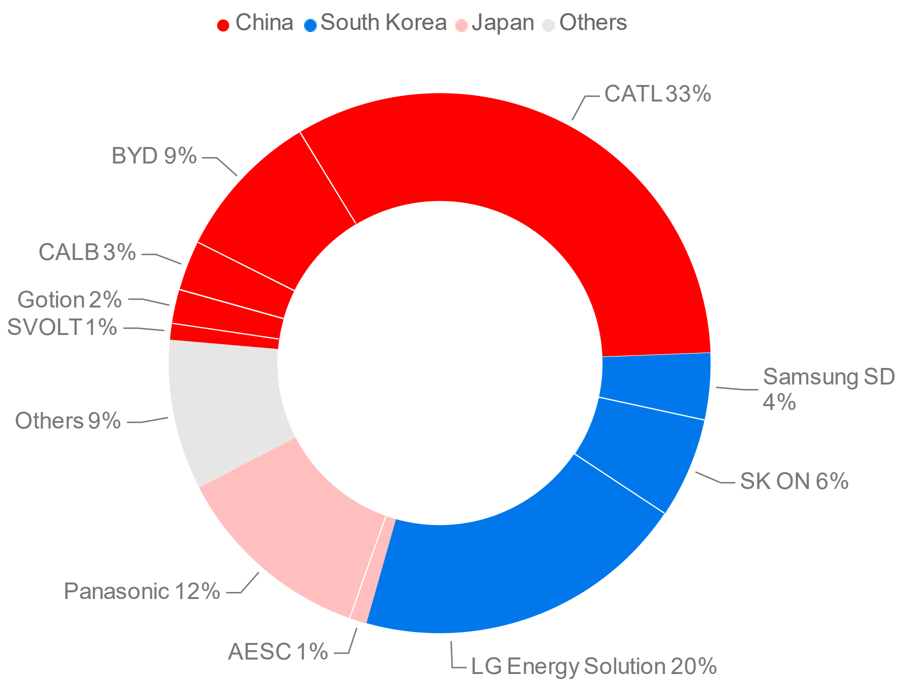


**Figure 29: Top 10 EV battery manufacturers in 2021 based on data from SNE Research** [103]

The U.S. government has taken aggressive steps to accelerate and strengthen the domestic battery chain to transition to a clean-energy economy while maintaining the automotive industry's competitiveness [98]. One recent example is the significant incentives provided by the Inflation Reduction Act of 2022, as discussed in further detail in Section 6.

| | 2022e EV Li-ion market share | 34% | 14% | 12% | 10% | 7% | 5% | 4% | 3% | 11% | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Auto OEM | CATL | LGES | BYD | Panasonic | SKI | SDI | CALB | Gotion | Others | Most common form factor |
| U.S.A. | Tesla | ✓ | ✓ | ✓ | ✓ | | | | | | Mostly cylindrical, prismatic |
| | GM | ✓ | ✓ | | | | | | | | Pouch |
| | Ford | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | Pouch & Prismatic |
| | Rivian | | P | | | | ✓ | | P | | Cylindrical |
| Europe | BMW | ✓ | | | | | ✓ | | | | Prismatic, cylindrical |
| | Mercedes-Benz | ✓ | ✓ | ✓ | | | ✓ | ✓ | | | Pouch, prismatic, cylindrical |
| | VW Group | ✓ | ✓ | | | ✓ | ✓ | | ✓ | | Mostly prismatic |
| | Stellantis | ✓ | ✓ | | | ✓ | | | | | Pouch and Prismatic |
| Asia | BYD | | | ✓ | | | | | | | Prismatic |
| | Toyota | ✓ | | ✓ | ✓ | | | ✓ | | | Prismatic, cylindrical, pouch |
| | Honda | ✓ | ✓ | | ✓ | | | | | | Pouch |
| | Nissan | ✓ | ✓ | | ✓ | | | | | | |
| | Hyundai/Kia | ✓ | ✓ | | | ✓ | | | | | Pouch and Prismatic |
| | SAIC | ✓ | | | | | | ✓ | ✓ | | Prismatic |

Legend: ✓ Current battery supply relationship; P Potential battery supply

*not exhaustive list

**Figure 30: Current and potential JVs between OEMs and battery suppliers. Source: Volta Foundation** [104]

In recent times, there has been a spate of announcements by prominent automakers like Tesla, GM, Ford, Stellantis, Toyota, and Volkswagen towards collaborating and building gigafactories within the U.S., as shown in Figure 30 and Figure 31, to cut down on costs and secure an assured supply of batteries to meet the growing demand for EVs. It is expected that when these projects come to fruition, they will continue to support electrification in the U.S. and position the North American region as a dominant force in the clean-energy sector [105]. A large number of startups are also working on the next generation of batteries, promising to revolutionize the sector [105], [106].

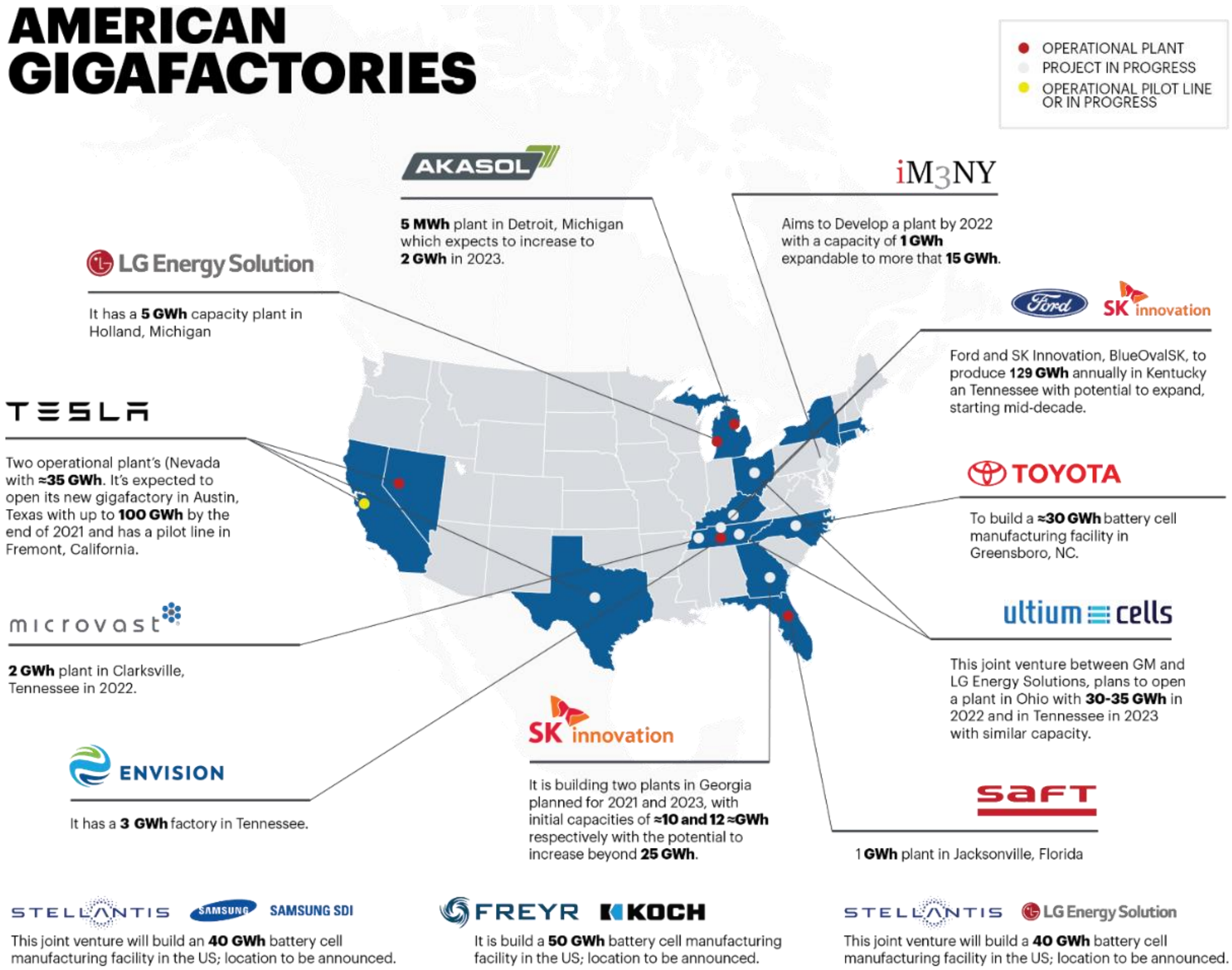


**Figure 31: Major announcements made in the U.S. Source as of March 2022: PIEDMONT Lithium** [107]

### 3.1.4 Recycling

Unlike the fossil fuel used to power ICEVs, the LIB in BEVs is not consumed during operation. This fundamental difference in power generation places LIBs in a unique position to be recycled and reused to build a circular economy. The U.S. Department of Energy-United States Advanced Battery Consortium (USABC) has defined the energy storage system performance targets for EVs in the Battery Test Manual for Electric Vehicles [108]. End-of-life is defined as a condition in which a battery is no longer capable of meeting targets when its state-of-health (SOH) falls to 80% or loses 20% of its original usable capacity, which typically takes 15 years or 1000 cycles [108], [109]. Towards the end of this decade, with the proliferation of EVs, thousands, if not millions, of EV batteries will be at the end of their lives and can be reused, repurposed, or recycled. Creating a circular supply chain economy, as shown in Figure 32, is the way forward to reduce dependence on critical raw materials and mitigate the associated environmental impact [98], [100], [110].

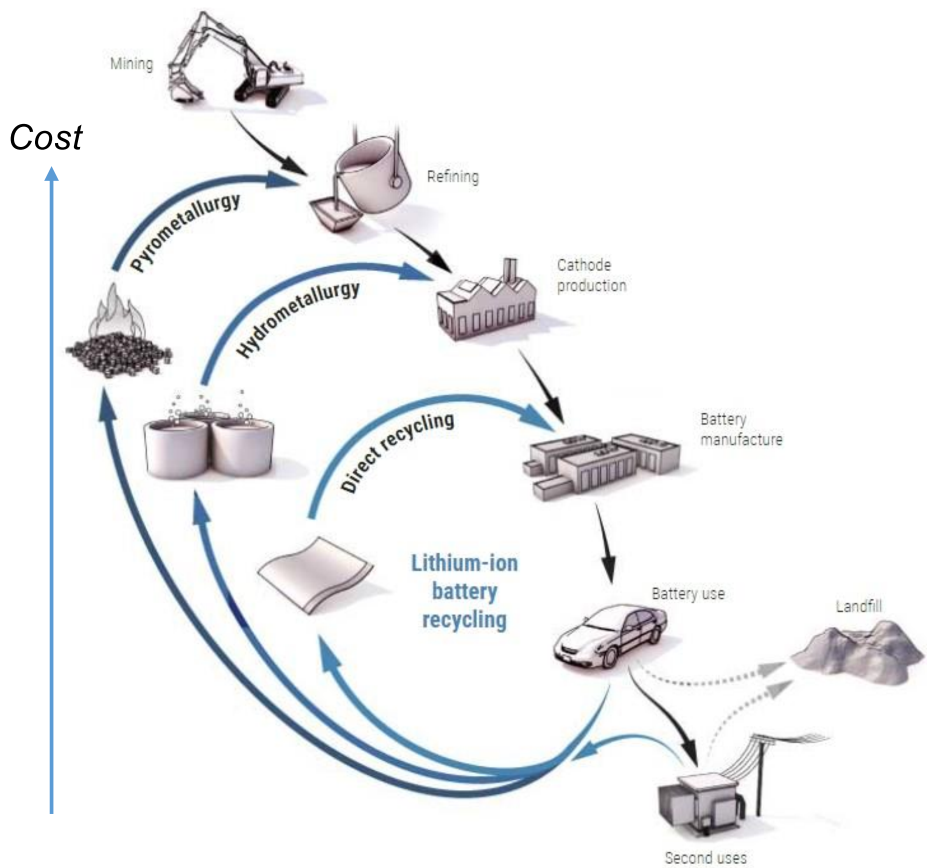


**Figure 32: Potential LIB recycling practices from a cost and efficiency perspective to create a circular supply chain. Image Source: Science** [111]

Repurposing of second-life batteries (SLB) for other applications, such as less demanding stationary energy storage applications, is underway, but technical challenges remain

[109], [112]. LCO is one of the most widely used cathode chemistries in consumer electronics, making mobile phones and similar devices one of the largest cobalt resources [78]. By recycling these readily available dense concentrations of cobalt and feeding them to industry, recyclers can create lasting positive social, environmental, and economic impacts. Compared to virgin metal mining, recycling is a relatively low-carbon pathway, as depicted in Figure 33. Creating and scaling the EV supply value chain presents challenges due to a gap in raw materials and know-how. In the future, with increased penetration of EVs, the recycling and reprocessing industry is expected to become bigger than the mining industry. Recycling and reprocessing are poised to play a decisive role in sustaining the EV industry.

For instance, Redwood Materials, based in Nevada, is one of the largest battery recyclers in the United States. They recycled 500,000 lbs of batteries and recovered more than 95% of lithium, cobalt, nickel, copper, and other metals in the first year of operation of their pilot battery recycling facility in Nevada in March 2023 [113]. ANL's Materials Research Group verified the performance of high-nickel cathodes (NMC-811) in 2022 using cathode precursors from Redwood's recycling process[114]. Redwood expects to finish qualifying their NMC cathode materials in 2023.

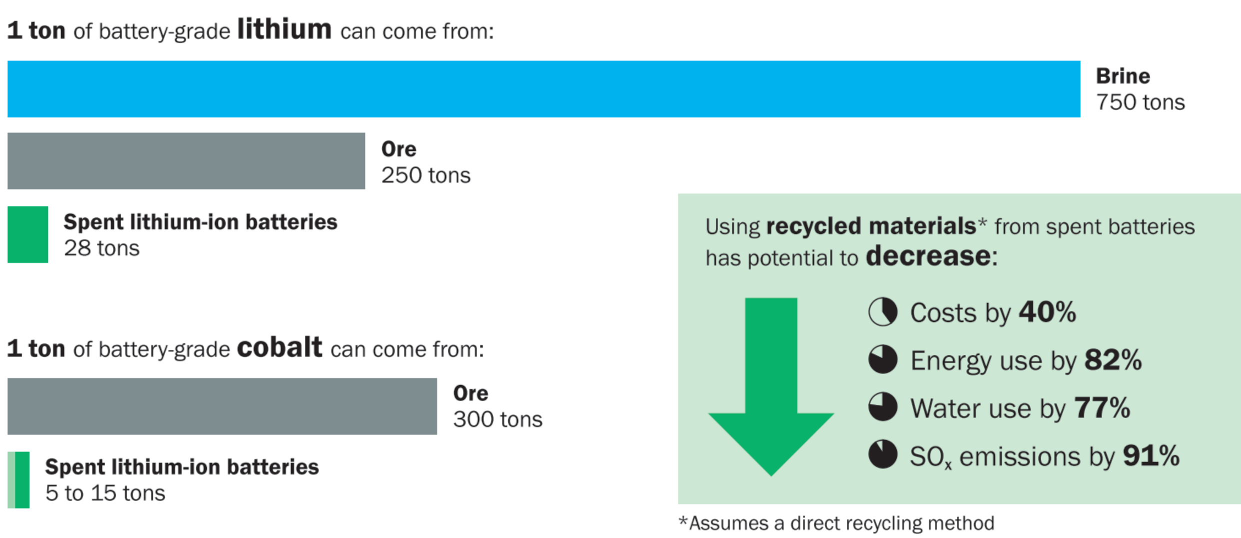


**Figure 33: Batteries have a high elemental concentration of critical materials compared to naturally available resources, making recycling them an attractive prospect** [98], [110]

The cost of recycling, the variety of cathode chemistries used, and the cell design in use, as shown in Figure 34, are a few of the current primary barriers to recycling. ANL’s ReCell Center, which is a collaboration of national laboratories and universities, is working on developing cost-effective and sustainable processes to recycle LIBs [115].

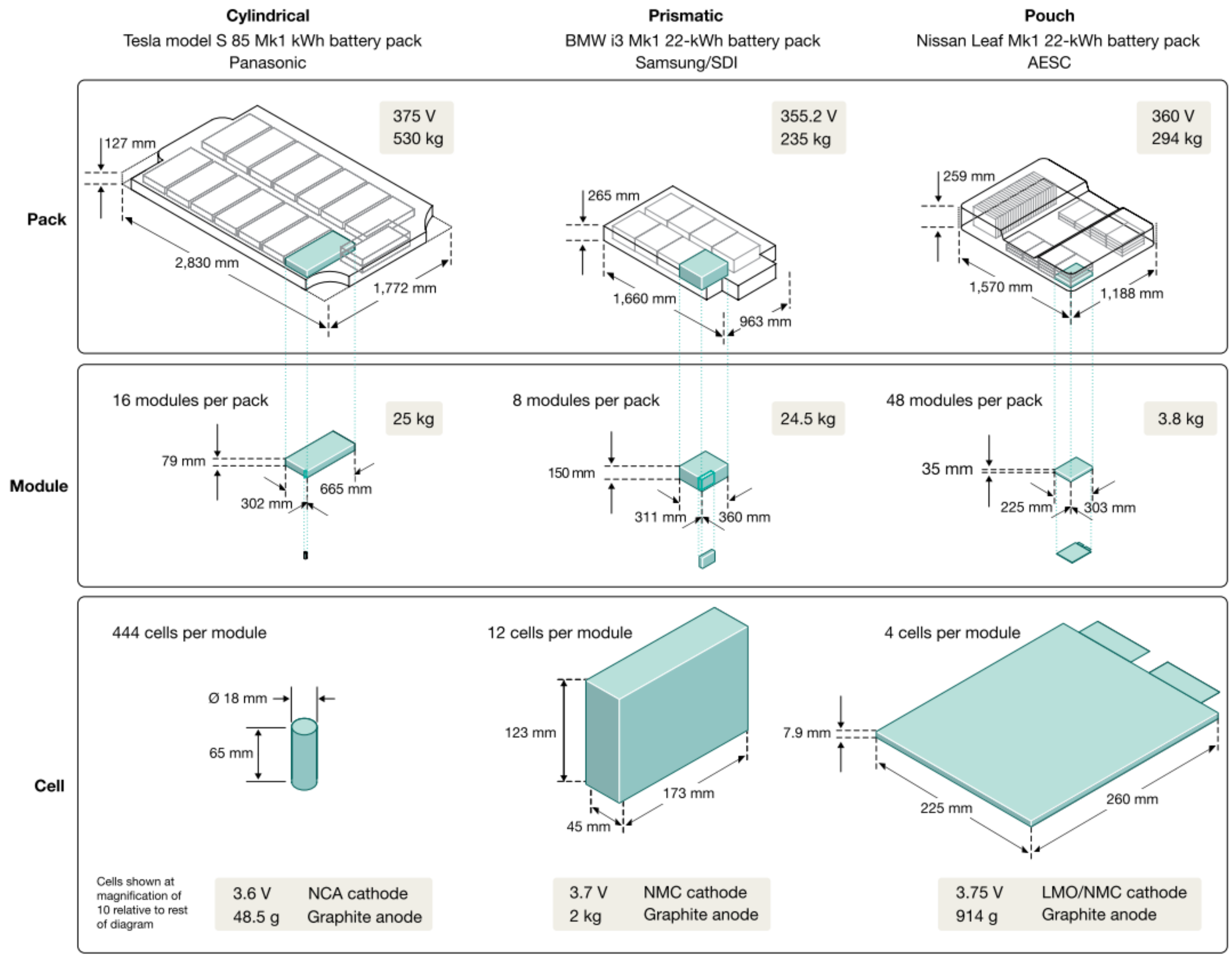


**Figure 34: Different battery pack configurations currently pose a challenge to recyclers** [116]

In addition to bringing costs down, the efforts of ANL's ReCell Center are focused on minimizing the consumption of limited resources, strengthening national security, and creating a robust battery supply chain [117]. ANL also developed EverBatt, a closed-loop battery recycling cost and environmental impacts model, to help evaluate recycling technologies and their challenges [118]. The tool provides the stakeholder with a holistic view when deciding whether to produce LIBs using virgin materials or recycled ones and enables estimation and analysis of various costs. Other efforts are being made by the private and public sectors to develop new processes and recycle battery materials in order to create a circular supply chain. The metallurgical processing of these LIBs is complicated; per ANL, the cost to recycle is estimated to be around 5%–15% of a new battery's cost [119].

Currently, there are three primary methods of recycling: pyrometallurgical recycling, hydrometallurgical recycling, and direct cathode recycling, or direct recycling [118], as shown in Figure 35. Each of these processes has tradeoffs and cost implications due to the varied unit operations adopted to recover the metals. Reverse logistics—collection and transportation—and dismantling of these spent batteries, due to their varied configurations, is currently a challenge, as can be seen in Figure 34 and Table 21. However, implementing a standardized and cost-effective recycling system in the future will make recycling a key component of the battery supply chain.

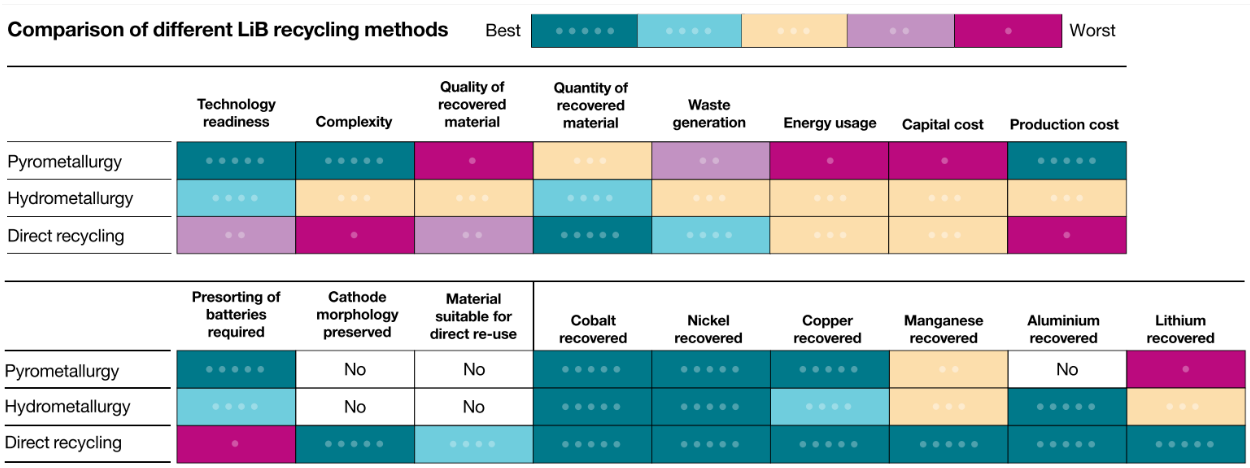


**Figure 35: Comparison of recycling methods** [116]

### 3.1.4.1 Pyrometallurgical Recycling

In pyrometallurgical recycling, LIBs, upon arrival at the facility, are sorted and organized based on their size, shape, and chemistries. The battery packs are disassembled into modules and cells and then sent into a high-temperature furnace, either shredded or intact, to be smelted [111], [116], [118]. The electrolytic salts and plastics burn off, leaving behind metallic alloy fractions and slag. Cobalt, nickel, copper, and iron make up the matte, a denser molten phase, which is further processed for separation using hydrometallurgical processes like acid leaching [116], [118]. Lithium, manganese, and aluminum typically end up in the slag, which can also be potentially recovered using hydrometallurgical processes [116], [120]. The mixed alloy goes through a series of extraction processes to produce precursor salts for cathode production. The recoverable materials are compounds of copper, iron, lithium, cobalt, and nickel [116], [118], [120]. Pyrometallurgical recycling requires the most energy and results in the lowest recovery rates.

### 3.1.4.2 Hydrometallurgical Recycling

In hydrometallurgical recycling, batteries are separated based on their physical properties, pretreated and shredded, followed by low-temperature calcination [118], [120]. These steps are followed by acid leaching or biological leaching and reduction [120]. The remaining materials, known as "black mass," go through a series of acid leaching, precipitation, and extraction steps before they are recoverable. Copper, steel, aluminum, graphite, plastics, lithium carbonate, cobalt, nickel manganese, electrolyte solvents, and salts are potentially recoverable materials [118]. The current cell designs bonded with glue make it difficult to dismantle and discharge safely before recycling them using the pyro- or hydro-metallurgical processes [111], [116]. The presence of costly metals like cobalt or nickel in the cathode structure makes ternary cathodes attractive to recyclers.

**Table 21: Medium-size EV with a 60 kWh battery with materials accounting for about 160 kg. Electrolyte, binder, separator, and casing weights are not shown** [121]**.**

| Mass (kg) | 2020 Average | NMC523 | NMC622 | NMC811 | NCA+ | LFP |
|---|---|---|---|---|---|---|
| Lithium | 6 | 7 | 6 | 5 | 6 | 5 |
| Cobalt | 8 | 11 | 11 | 5 | 2 | – |
| Manganese | 10 | 16 | 10 | 5 | – | – |
| Copper | 20 | 20 | 19 | 18 | 17 | 26 |
| Nickel | 29 | 28 | 32 | 39 | 43 | – |
| Aluminum | 35 | 35 | 33 | 30 | 30 | 44 |
| Graphite | 52 | 53 | 50 | 45 | 44 | 66 |

The recycling industry is exploring novel ways to recycle batteries using hydrometallurgy. For instance, Li-Cycle Corp, a Toronto-based battery recycling startup, launched their latest battery recycling facility in Alabama in October 2022, with a capacity to recycle 10,000 tonnes of LIB materials per year. They claim to be able to recycle and directly process full EV battery packs without dismantling using a proprietary submerged shredding process. Their four facilities in Kingston, Ontario, Rochester, New York, Gilbert, Arizona, and Tuscaloosa, Alabama, have a combined capacity of 30,000 tonnes of batteries, which is equivalent to batteries from approximately 60,000 EVs [122].

### 3.1.4.3 Direct Recycling

Direct recycling is one of the most promising methods as it can keep the cathode crystal structure intact [110]. After the electrolyte, binders, and solvents are removed using special extraction techniques, the cells are shredded. The remaining material, cathode, and anode are separated using a flotation technique [118]. A study to produce 1 kg of NMC111 by ReCell Center suggests that direct recycling can result in 27%–46% cost savings compared to production using virgin materials [110]. It has the lowest carbon emissions of the three recycling pathways and offers greater savings compared to the pyro- and hydro-metallurgical processes. Research is being conducted to achieve scale and invent new ways to upcycle the cathode chemistry [110]. Due to the rapidly evolving field of battery chemistry, the current cathodes (all below the NMC6- series) will be redundant in the next 10–15 years; hence, upgrading the chemistry by tweaking the stoichiometric ratios can make it an attractive choice as a precursor for the NMC8- or

NMC9-series. Additional work remains to be done in this field to meet the desired electrochemical performance and improve lithium recovery.

### 3.1.5 Battery Chemistries

Several incremental and breakthrough technologies could lead to a significant reduction in battery raw material and manufacturing costs. The industry is moving towards battery chemistries that reduce or eliminate the use of nickel and cobalt and reduce the impact of their increasing commodity prices. Process improvements in the manufacture of cathode active material, such as Nano One's one-pot process, reduce cost, energy usage, and the amount of waste generated [123]. Cell manufacturing processes such as the dry battery electrode process can reduce cell manufacturing costs by cutting battery line capital expenditure and energy consumption by 50%. Solid-state electrolytes would increase cycle life, make batteries safer, and enable lithium metal anodes that will increase energy density and reduce the environmental footprint of mining naturally occurring graphite or producing synthetic graphite [124]. Sodium-ion technology is improving so quickly that it might displace lithium as the dominant technology by the end of the decade.

Due to the rapid pace of innovation, it is difficult to accurately predict the timeline of introduction, scaling, and cost implications of new chemistries and manufacturing process improvements. This section of the report attempts to capture the current state of the art, future battery chemistries, and advancements in battery manufacturing.

#### 3.1.5.1 Lithium-ion Battery (Cathode) Chemistries in Production

##### 3.1.5.1.1 Lithium Iron (Ferro) Phosphate (LFP)

LFP chemistry is the fastest-growing chemistry for use in electric vehicles. Tesla during its Q1 earnings call in 2022 stated that 50% of all its vehicles sold worldwide had LFP battery packs. LFP batteries have a cost advantage over other lithium chemistries (NMC, LMNO) because they do not use cobalt or nickel, significantly reducing the raw material cost and risk of supply chain disruptions. The current LFP manufacturing process is more expensive because of the complexity of its production, as it requires a reducing atmosphere and a carbon coating step to reach the end product [55]. However, new, simpler manufacturing processes such as Nano One's "one-pot" process eliminate the need for the iron phosphate intermediate currently used in China and significantly reduce the process cost and waste generated by the manufacturing process [123], [125].

LFP chemistry was initially considered unsuitable for most EV applications due to its low energy density and poor performance at low temperatures (due to high cell internal resistance). However, the energy density of production LFP cells has increased from 120-150 Wh/kg in 2015 to 210 Wh/kg in 2021 (according to Gotion High-Tech, the VW battery partner for the manufacture of the "unified cell concept"). Gotion announced that their new

LFP cells will achieve an energy density of 260 Wh/kg by the end of 2022. Modern thermal management systems with heat pumps can maintain the LFP cells in their optimum operating window with minimal energy overhead.

The use of innovative cell form factors and packaging of the cells directly into the pack (Cell-to-Pack, or CTP) eliminates the use of cell modules, reduces the weight and complexity of the battery pack, and increases its energy density. As shown in Table 22, the BYD "Blade" battery pack uses large form factor prismatic cells and CTP architecture to achieve a higher volumetric energy density and a higher gravimetric energy density [126] than many NCA and NMC packs in production.

**Table 22: Comparison of battery packs in production.**

| Parameters | Units | 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 [127]
[2] Blade battery pack prototype - Source BYD

The cycle life of LFP cells is significantly longer than those of NMC622 and NCA, as shown in Figure 36, at various depths of discharge. The cycle life of NMC and NCA decreases rapidly with the increase in depth of discharge. To increase cycle life, most OEMs set software limits for the minimum and maximum state of charge (SOC) of the pack, with the usable capacity of the pack set at 85%-90% of the gross capacity. The depth of discharge has little effect on the cycle life of an LFP battery, and they need little or no unused buffer capacity to reach cycle life targets. This reduces the difference between the gross and usable battery capacities in an LFP pack, bringing down the effective cost per kWh of usable battery capacity. While most commercial NCA and NMC batteries have a cycle life of up to 3000 cycles, LFP batteries can have a cycle life of over 7000 cycles.

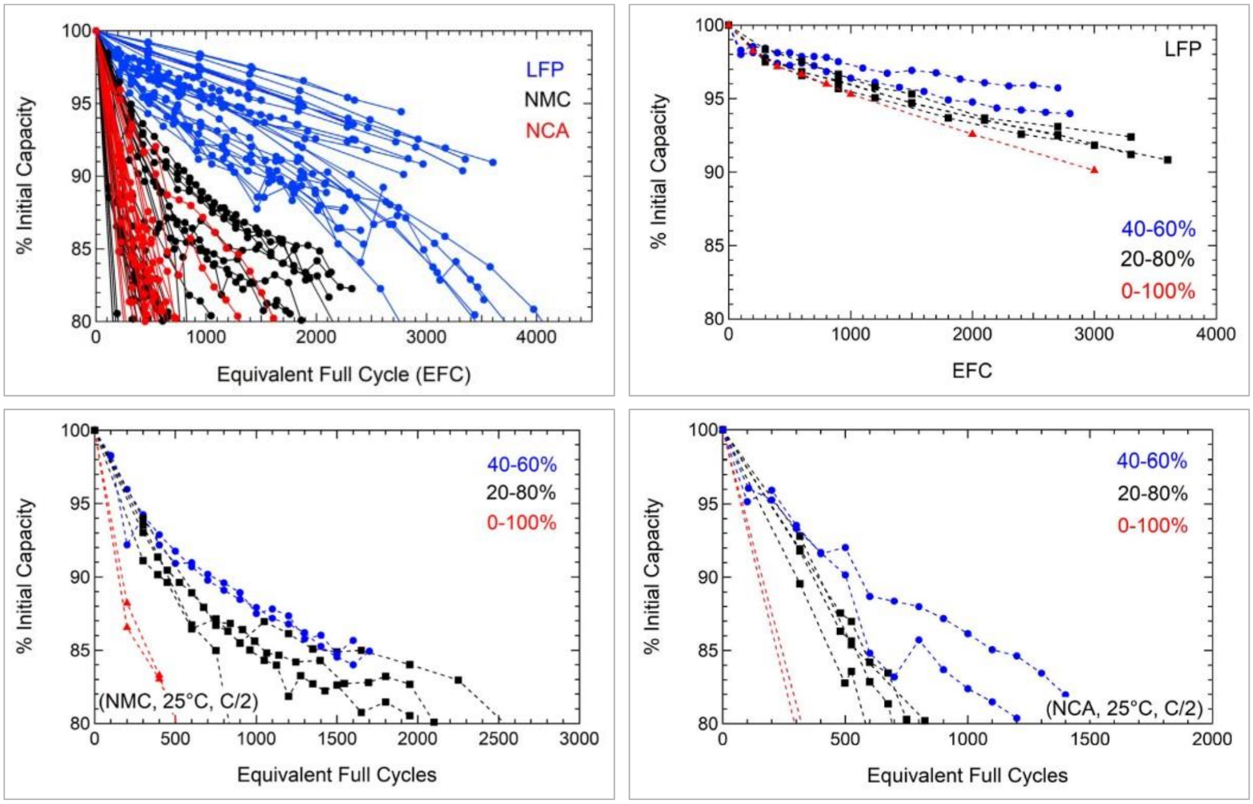


**Figure 36: Capacity retention of various commercially available lithium-ion cells used in light-duty applications (20°C 100% DOD). Effect of depth of discharge on the cycle life of LFP, NMC, and NCA cells. Cycle life = 80% of initial capacity** [128]

### 3.1.5.1.2 Nickel Manganese Cobalt Oxide (NMC or NCM)

NMC in its various forms (622, 811) comprises a large portion of the current BEV market. 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 or eliminating the use of cobalt in EV batteries due to its high cost. 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) soon. The low-cobalt NMC variants have a higher energy density and lower material costs but are more susceptible to thermal runaway.

### 3.1.5.1.3 Nickel Cobalt Aluminum (NCA)

The NCA cathode for mass-market BEVs was pioneered by Tesla and Panasonic with the launch of the Tesla Model S in 2012. Today, Tesla remains the only large automotive OEM that uses NCA in high-volume production cars such as the Model 3 and Y vehicles. Panasonic’s NCA chemistry used lower amounts of cobalt (8-10%) when compared to mature NMC chemistries five years ago, giving them a cost advantage [129][130]. NCA chemistry has a shorter cycle life (1000-1500 cycles) when compared to NMC and NCMA cathodes (Figure 37) [128]. NCA batteries have a higher energy density than NMC batteries but are more susceptible to thermal runaway and require precise monitoring by the battery management system (BMS).

#### 3.1.5.1.4 Nickel Cobalt Manganese Aluminum Oxide (NCMA)

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 a significantly higher cycle life compared to NCA and NMC (NCM) chemistries [131], as shown in Figure 37. LG cells will initially be used in GM (Ultium™ batteries) EVs.

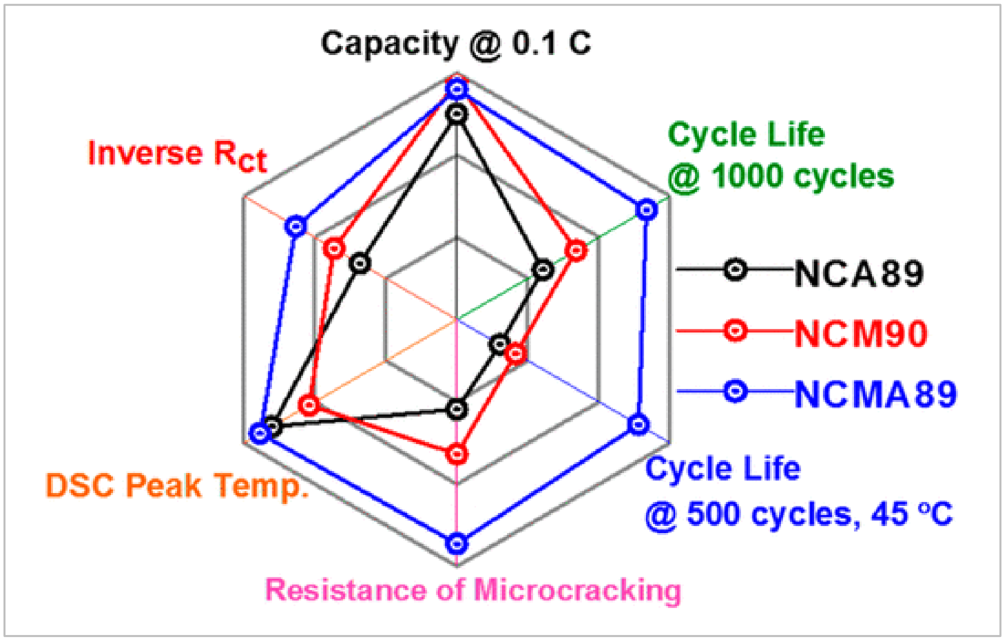


**Figure 37: Comparison of NCMA89 chemistry with NCA89 and NCM90** [131]

### 3.1.5.2 Emerging Technologies

LIBs suffer from various degradation modes, such as loss of lithium inventory, loss of anode active material, and loss of cathode active material, which result in capacity fade and power fade [132]. The causal factors that affect its thermodynamics, i.e., its open-circuit voltage (not kinetic behavior), are time, temperature variation, current load, and mechanical stresses. As shown in Figure 38, these factors, in combination with each other, can lead to the decomposition of solid electrolyte interphase (SEI) and electrolyte, affect the growth of SEI, cause lithium plating and dendrite formation, and cause structural issues related to the cathode, anode, and current collectors.

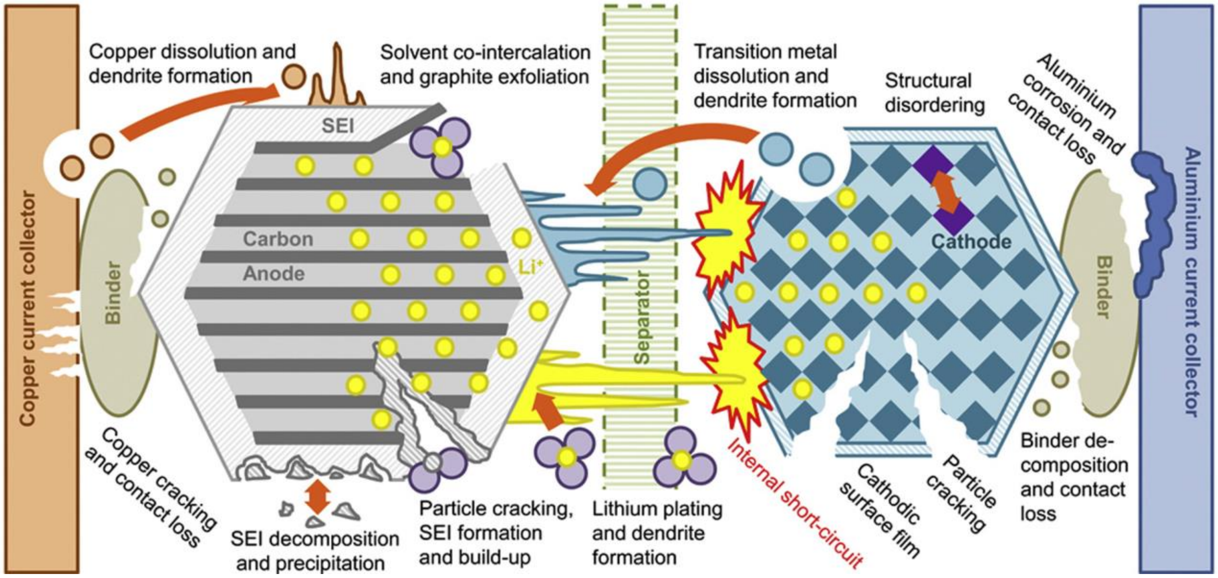


**Figure 38: Modes of degradation in lithium-ion cells** [132]

There is significant improvement potential in the complex world of state-of-the-art lithium-ion cells to make them more energy-dense, safer, and cost-effective, and to allow faster charging. Multi-pronged efforts are being made, spanning atomic levels to mesoscale architectures. Many of these technological and performance breakthroughs are focused on reducing potential resource constraints while forging novel, scalable, and sustainable pathways. In the following sections, an attempt is made to describe the emerging battery technologies that can help the world transition to EVs.

#### 3.1.5.2.1 Lithium Metal Anodes

Anodes composed of graphite and lithium titanium oxide have been considered a safety stop-gap since their introduction; using a pure element anode would be the ideal solution [133]. Theoretically, lithium can store 10 times more energy than graphite and would be an ideal anode [12]. However, it suffers from plating issues, dendrite formations, and low coulombic efficiency. These dendrites can puncture the polymer separator and cause a short circuit, resulting in thermal runaway. Current R&D efforts are targeted to improve their safety, cycle life, and energy density, with the key challenge being to find plating metals that do not form dendrites or mossy metals [12], [133].

#### 3.1.5.2.2 Silicon Anodes

As with a lithium metal anode, silicon has a capacity 10 times greater than graphite [12] but suffers from volumetric expansion and calendar life issues [72]. Volume changes, up to 300%, contribute to side reactions and end up cracking the solid electrolyte interphase (SEI), leading to loss of cyclable lithium and electrical isolation of silicon, resulting in capacity fade [134]. Silicon is usually included in small amounts (<8%) in the graphite anode to boost the energy density without affecting the cycle life [12].

#### 3.1.5.2.3 All-Solid-State Batteries

All-solid-state batteries (ASSB) have a promising future and could make a significant impact as early as 2025. Toyota has plans to deploy ASSB in its vehicles by 2025 [135], with other OEMs lining up portfolios of these chemistries for their vehicles in the 2027–2035 timeframe. Per the Nissan Ambition 2030 plan, Nissan intends to launch a BEV with its proprietary all-solid-state batteries (ASSB) with an estimated pack cost of $75/kWh by the fiscal year 2028 and aims to achieve $65/kWh [136]. As shown in Figure 39, ASSBs represent the next frontier in the LIB world by replacing the flammable liquid electrolyte with a non-flammable solid electrolyte, allowing the use of energy-dense anodes and supporting fast charging [12], [137].

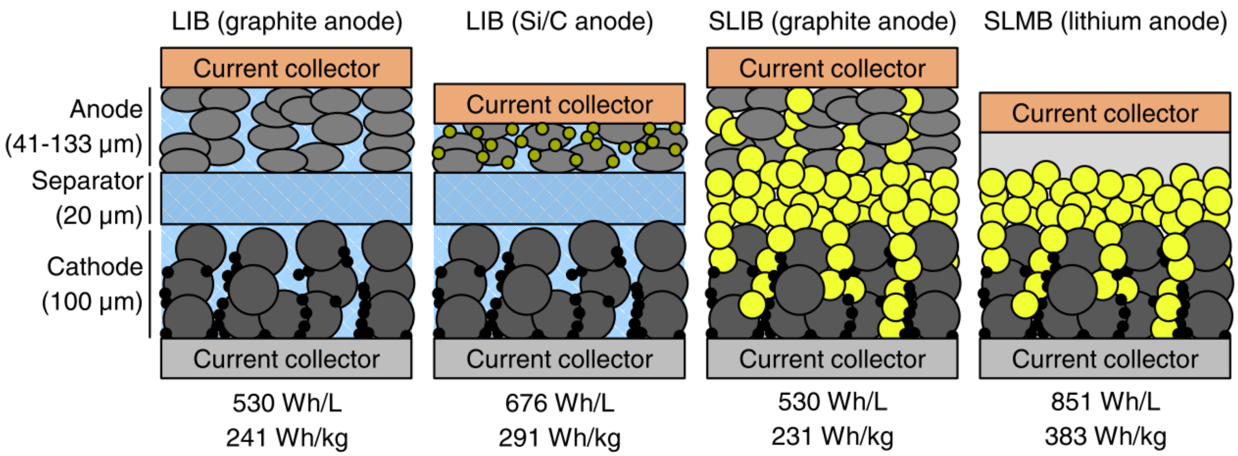


**Figure 39: Cell design for different types of LIBs and ASSBs** [137]

The introduction of a solid electrolyte comparable in technical characteristics to a liquid one decreases the cell volume and provides greater energy density. Of the polymer-, metal oxide- (ceramic-), and sulfide-based solid electrolytes, the latter promises to be a better option due to better performance characteristics, in addition to being cost-effective from a manufacturing perspective [12], [137], [138]. The mitigation of the formation of dendrites, operability over a wide temperature range (in some cases better than the current LIBs), and reduced cooling requirements make the ASSBs a potential successor to the current liquid-based LIBs. However, the main factors hindering the use of ASSBs are mechanical stability and poor cycle life. Special additives are required for the electrochemical stability of the interfaces, which increases the cost and complexity of the active material manufacturing process [12], [137].

#### 3.1.5.2.4 Other Lithium Battery Chemistries

There are several other promising battery technologies at various levels of technological readiness, each with various advantages and limitations, as shown in Figure 40. Most of them are lithium-based and focused on using lower-cost, more abundant raw materials for their cathodes. Almost all of them eliminate the use of cobalt. Some of these may include nickel-iron aluminum oxide (NFA) and nickel-manganese aluminum oxide (NMA). Some of these technologies may never be adopted for volume production unless their economics and terms of licensing their intellectual property are attractive to suppliers. Also, they will most certainly need backing from a major OEM for large, assured volumes to start production. Their development is too early to know if their technical performance and cost are competitive with other options. To date, no OEM has committed to them. Still, these chemistries may play an important role in the EV ecosystem in the future.

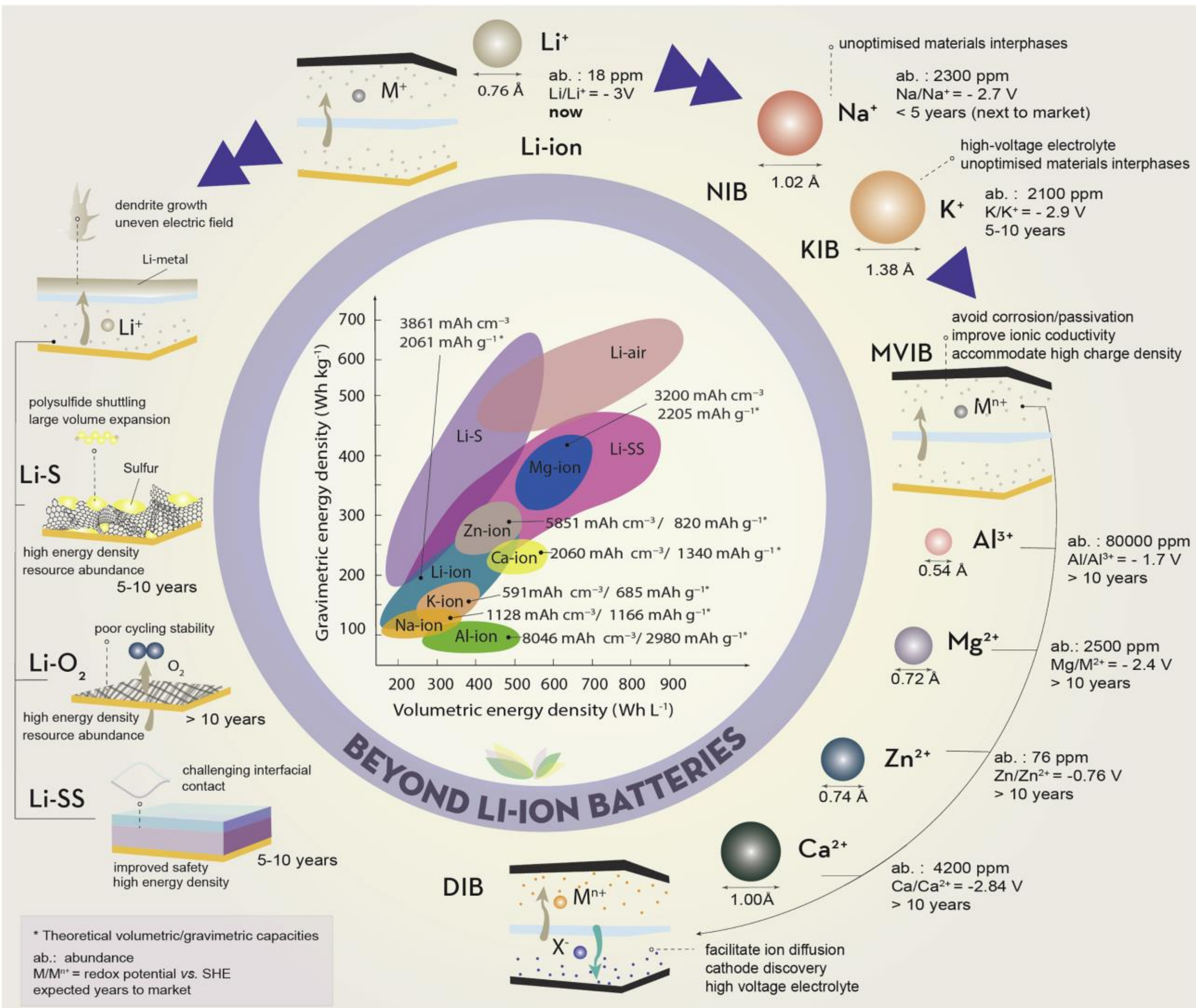


**Figure 40: Snapshot of beyond lithium-ion batteries with their status and challenges** [138]

### 3.1.5.3 Beyond Lithium-ion Chemistries

Sodium is a viable alternative to lithium in nickel-manganese-cobalt oxide ternary cathodes. Argonne National Lab published a unique cathode material manufacturing process that allows a battery to be charged to 4.5 V, increasing the energy density between 20% and 40% in a $NaNi_{0.4}Mn_{0.4}Co_{0.2}O_2$ cathode [139]. In 2021, Faradion UK unveiled a prototype cell based on $Na.Ni_{(1-x-y-z)}.Mn_x.Mg_y.T_zi O_2$ cathode [140] with an energy density of 140 Wh/kg. However, in the long run, sodium-ion batteries that use NMC cathodes will probably not offer significant savings in cost or environmental impact compared to lithium NMC batteries.

CATL unveiled the first generation of a sodium-ion battery with a carbon anode and Prussian White cathode in July 2021, slated for mass production in 2023 [126]. 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 sodium-ion battery uses raw materials that are cheaper, more abundant, and free from supply constraints, resulting in a promising substitute for lithium-based chemistries. Figure 41 shows CATL's comparison of its sodium-ion and LFP technologies. Assuming a 90% gravimetric cell-to-pack ratio achieved by advanced pack architectures, a 200 Wh/kg cell equates to a pack-level energy density of 180 Wh/kg making it more energy dense than most EVs on sale in the US in 2022.

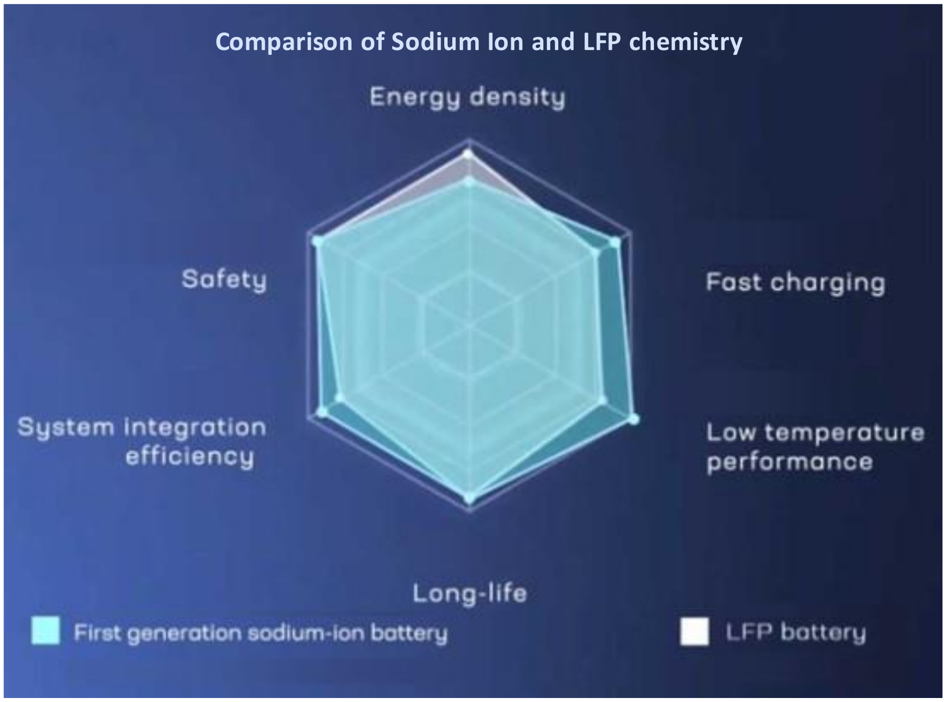


**Figure 41: First-generation sodium-ion compared to LFP. CATL 2021** [126]

As shown in Figure 40, apart from sodium-ion, other elements like magnesium, potassium, and calcium are being looked at as potential candidates in the beyond-lithium class of batteries [133], [138]. Each of these chemistries has its own hurdles and limitations before it can reach a comparable stage to that of a state-of-the-art LIB. In addition to their electrochemical performance, other factors like manufacturing, safety, and cost would play a decisive role in their adoption.

### 3.1.6 High-Cycle Life Batteries

For a BEV with 150 miles of range, a 600,000-mile life can be achieved in 4000 100% DOD cycles or 5000 80% DOD cycles. This is significantly more than the average vehicle in classes 2b and 3, given the annual VMT and a 12-year life cycle.

State-of-the-art LFP cells have a cycle life of 5000-7000 cycles, as shown in Figure 36 [128], which is enough to comfortably exceed the longest lifetime mileage requirements. For class 2b and 3 vehicles with a 150-250 mile driving range, LFP chemistry, with its lower energy density when compared to NMC and NCA, can be used. A high-energy-density battery pack is only required for applications like class 3 pickup trucks that are used for towing and may require a range of 300-400 miles (when not towing).

Technologies can significantly increase the cycle life of high-energy-density NMC cells, well beyond the state-of-the-art LFP cells.

#### 3.1.6.1 Fast Ionic Conductor (FIC) Coated Cathode

The cycle life of NMC batteries with various fast ionic conductor coatings on the cathode particles has been significantly increased [141], [142] [143]. 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, such as the range of the vehicle, number of cycles, and 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 [144], [145].

#### 3.1.6.2 Single Crystal Cathode Materials

Using 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% [146]. The industry defines a cell or pack's end-of-life as 80% of its initial capacity. This paves the way for semi trucks with over 2 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 [147]. Single-crystal cathode materials are compatible with commercial battery chemistries, with no change required to the cell manufacturing process or equipment.

Figure 42 (right) [148] 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 a 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. With such a long cycle life, vehicle-to-grid (V2G) technology can be implemented without affecting vehicle battery life significantly. 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 the vehicle's electricity (fuel) costs. A large number of vehicles with V2G capabilities will allow the grid to transition to renewables at a much faster pace and lower cost. The TCO implications of V2G technologies are not part of this study.

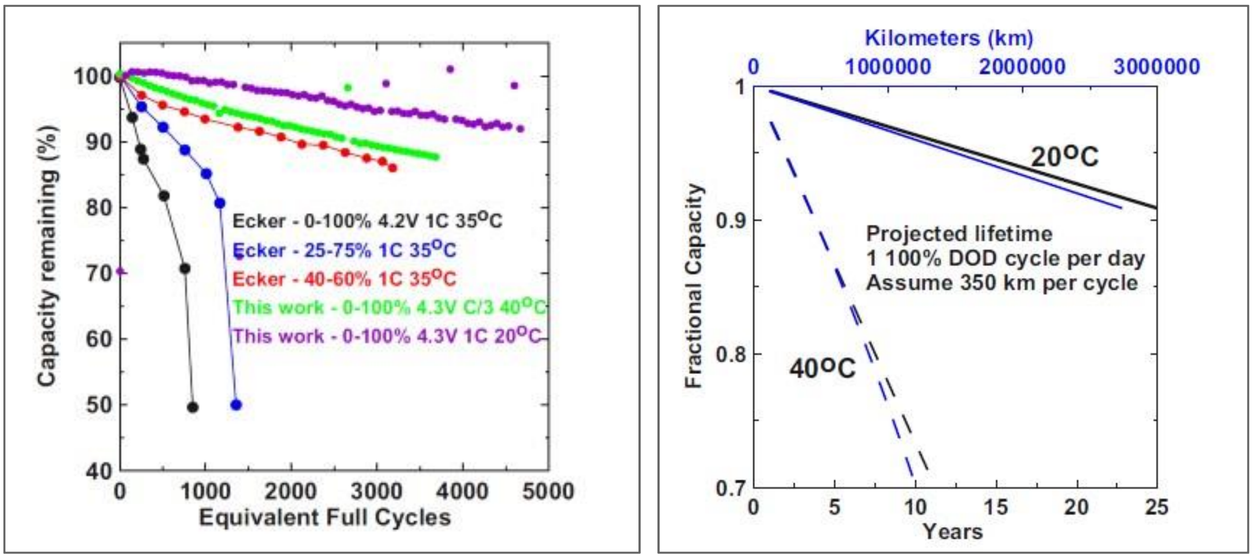


**Figure 42: Left: Long-term cycling data plotted as percent initial capacity (left), Right: Worst-case scenario lifetime and total driving range projections for the NMC532/graphite cells 6-hour 100% DOD cycle per day and 350 km initial driving range per cycle** [148]

### 3.1.7 Advances in Battery Cell and Pack Manufacturing

#### 3.1.7.1 Dry Battery Electrode (DBE) Process

Figure 43 shows the schematic of the typical lithium-ion battery manufacturing process. Currently, most commercial lithium-ion battery manufacturing processes use "slurry casting" to coat the electrode (anode and cathode) material onto the metal foil. A slurry is made by mixing the electrode active material, binder, and conductive additives into a solvent. This slurry is coated onto a metal foil and then dried in an oven, and the solvent is recovered [149]. This accounts for significant floor space requirements, capital expenditure, and energy consumption, and is the bottleneck limiting the output of a battery line. Slurry mixing, coating, and solvent recovery together account for about 27% of the cost and close to 50% of the energy consumption of the manufacturing process [150].

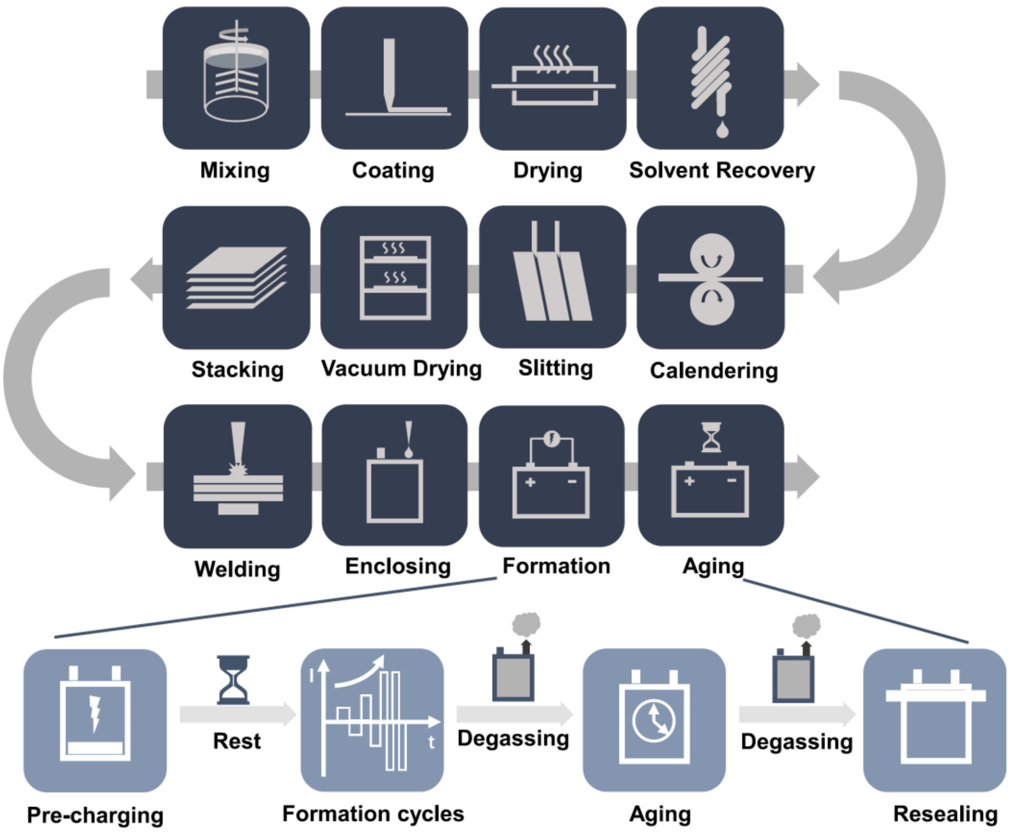


**Figure 43: Schematic of lithium-ion battery manufacturing processes** [150]

The DBE process eliminates these steps, significantly reducing the cost and GHG emissions from the battery manufacturing process, as shown in Figure 44. Based on their 10 GWh pilot plant, Tesla estimates the DBE process will result in an 18% cost saving [151]. VW estimates that the dry electrode coating process will result in a 50% reduction in the footprint of the cell manufacturing plant and a 30% reduction in CAPEX [68]. DBE also has a higher cell energy density due to a higher active-to-inactive (binder) material ratio and longer cycle life. The process also results in lower cell resistance, improving the power density. Alternatively, due to lower cell internal resistance, thicker electrodes can be fabricated for improved energy density.

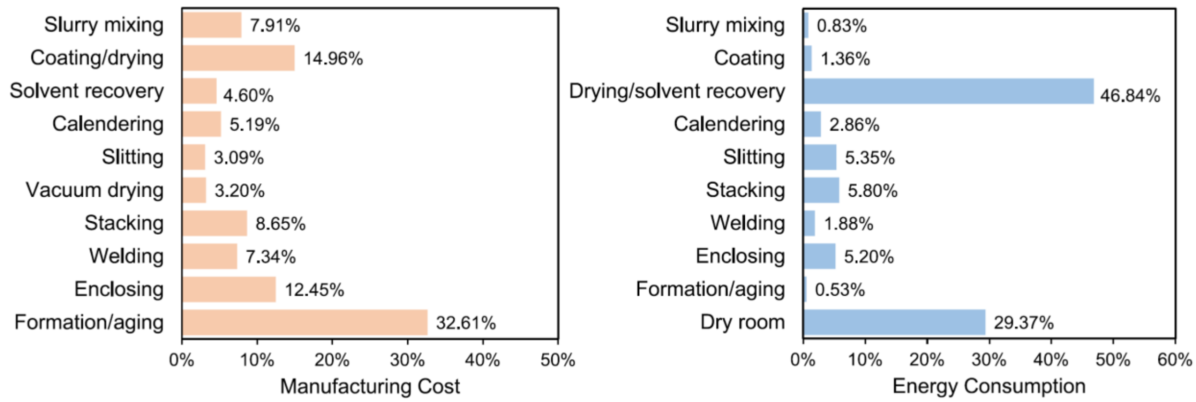


**Figure 44: Dry battery electrode (DBE) processing process (left) and the cost and energy consumption breakdown for the conventional wet slurry cell manufacturing process (right)** [150]

#### 3.1.7.2 Cell to Pack

Most vehicles today have cells grouped into modules, and multiple modules are 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 45, left—GM Ultium battery pack).

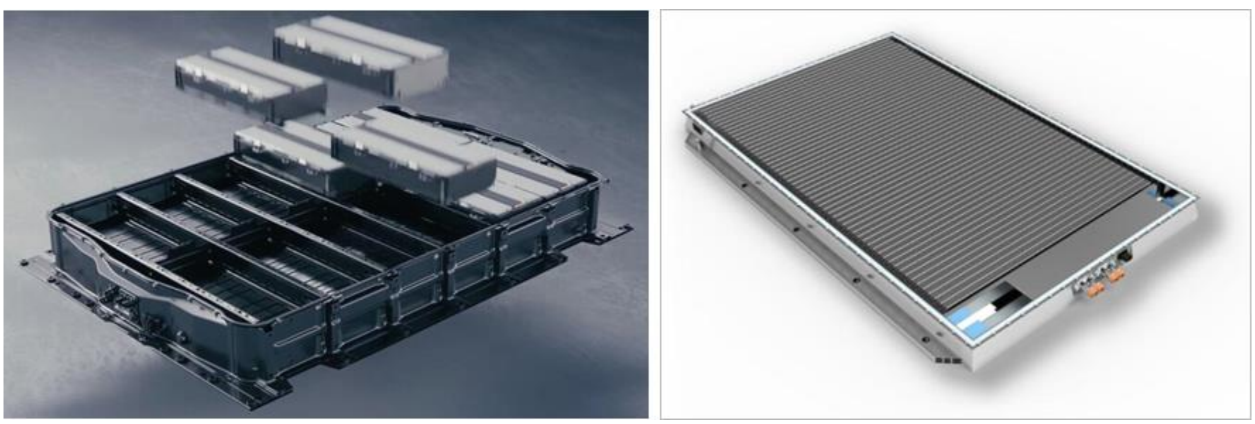

**Figure 45: GM Ultium battery pack** [152]**. BYD Tang "cell to pack" battery pack** [153]

This architecture arose from the idea that any faulty module could be replaced without having to replace the entire pack. However, this adds weight and complexity and reduces the GCTP and VCTP. With improving quality and reliability of cell manufacturing, 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 45) that does away with individual modules, reducing the associated cost and complexity, and increasing the GCTP and VCTP.

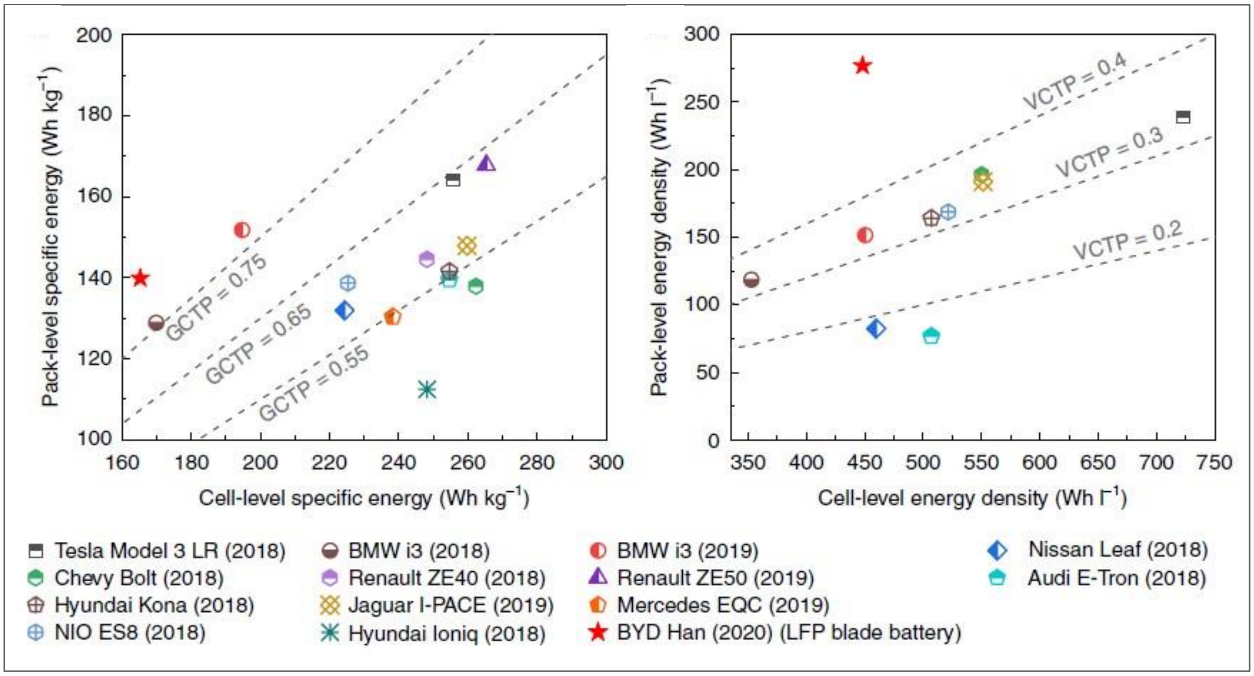


**Figure 46: Gravimetric energy density and volumetric energy density of the battery packs in production EVs** [126]

Figure 46 shows the gravimetric energy density (left) and volumetric energy density (right) at the cell and pack levels for various production BEVs. Even though it uses LFP chemistry cells with a lower energy density, the cell-to-pack BYD blade battery achieves a gravimetric and volumetric packing density greater than 0.85, making the pack energy density competitive with NMC and NCA packs [126].

#### 3.1.7.3 Structural Battery Pack

In traditional BEVs, the structural loads are mostly taken by the vehicle's monocoque. Some of the loads may be transmitted through the battery pack enclosure, but the cells themselves are isolated from any stresses. If the battery pack is constructed to transmit structural loads, the stiffness and weight of the rest of the unibody can be significantly reduced. Tesla is starting to mass-produce the Model Y with a structural battery pack at their Austin factory. The battery forms the floor of the unibody, making it significantly lighter. In 2020, Tesla estimated that the vehicle would have 370 fewer parts, a 10% reduction in mass, and a 14% improvement in its range [151].

### 3.2 Traction Motors

Figure 47 shows the different types of motors used in production BEVs and OEMs or production applications.

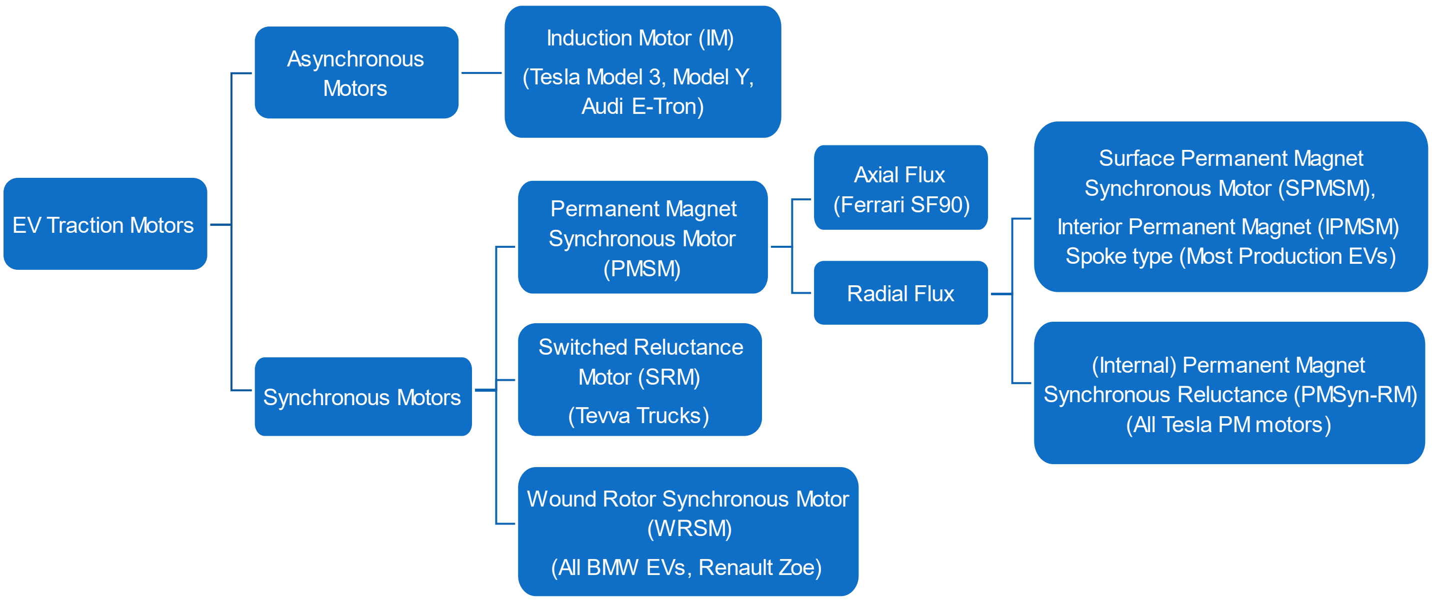


**Figure 47: Different types of traction motors in production battery electric vehicles**

#### 3.2.1 Permanent Magnet Synchronous Motor (PMSM) and Permanent Magnet Assisted Synchronous Reluctance Motor (PM Syn-RM)

PMSM currently has the highest peak efficiency among the different types of traction motors and is used in most light-, medium-, and heavy-duty applications. PMSMs 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 energy density generated. Some of these magnets also contain heavy rare earth metals such as dysprosium and terbium.

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 for expensive permanent magnet (PM) material. Table 23 compares the internal PMSM used in the 2020 VW ID3 to the rear PMSyn-RM used in the 2018 Tesla Model 3 Dual Motor Long Range. On a kg per kW basis, Tesla uses 33% fewer magnets by weight when compared to VW. 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 23: Comparison of VW ID3 motor and Tesla Model 3 rear motor**

| Parameters | Units | 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 (NdFeB) weight-rotor | Kg | 2.5 | 1.8 |
| Magnet (NdFeB) 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** [154] | | | |

### 3.2.2 Induction Motors

Induction motors (IM) have a lower peak efficiency when compared to PMSM but are attractive due to their significantly lower cost per kilowatt and designs that eliminate the need for rare-earth permanent magnets. Replacing the copper conductors in the rotor with aluminum brings costs down further. The 158 kW induction motor that drives the front axle of the Tesla Model 3 and Model Y costs $2.5 per kW for the Tesla Model 3/Y front motor, compared to >$4 per kW for PMSMs and PMSyn-RM. Audi (Figure 48), and VW are some of the other manufacturers that use induction motors. Induction motors with high power densities require liquid cooling of the rotors, which adds cost and complexity but is still cheaper than a comparable PMSM.

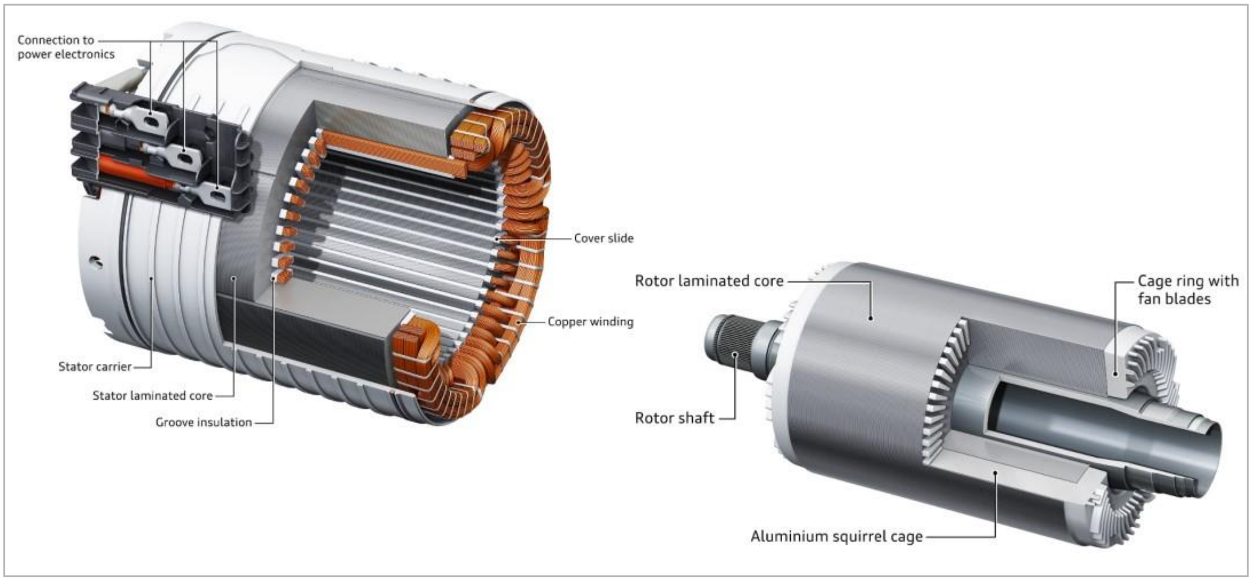


**Figure 48: Audi APA250 induction motor with cast aluminum rotor conductors (125kW).** [155]

### 3.2.3 Wound Rotor Synchronous Motor (WRSM)

Wound rotor synchronous motors (also called electrically excited synchronous motors or separately excited synchronous motors) use electromagnets in place of the permanent magnets used in PMSMs. The power to magnetize the rotor coils is transmitted wirelessly by inductive (a rotating transformer) or capacitive methods. The manufacturing cost of a WRSM is higher than a PMSM due to the added complexity of the rotor coils and wireless power transmission to the rotor, but material costs are lower owing to the elimination of NdFeB magnets. The peak efficiency of a WRSM is marginally lower than a PMSM but because of 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 49 shows a WRSM powertrain (motor, inverter, and reduction gearbox), part of BMW's "5th generation E-drive technology" family of motors. BMW uses WRSMs in all of its EVs.

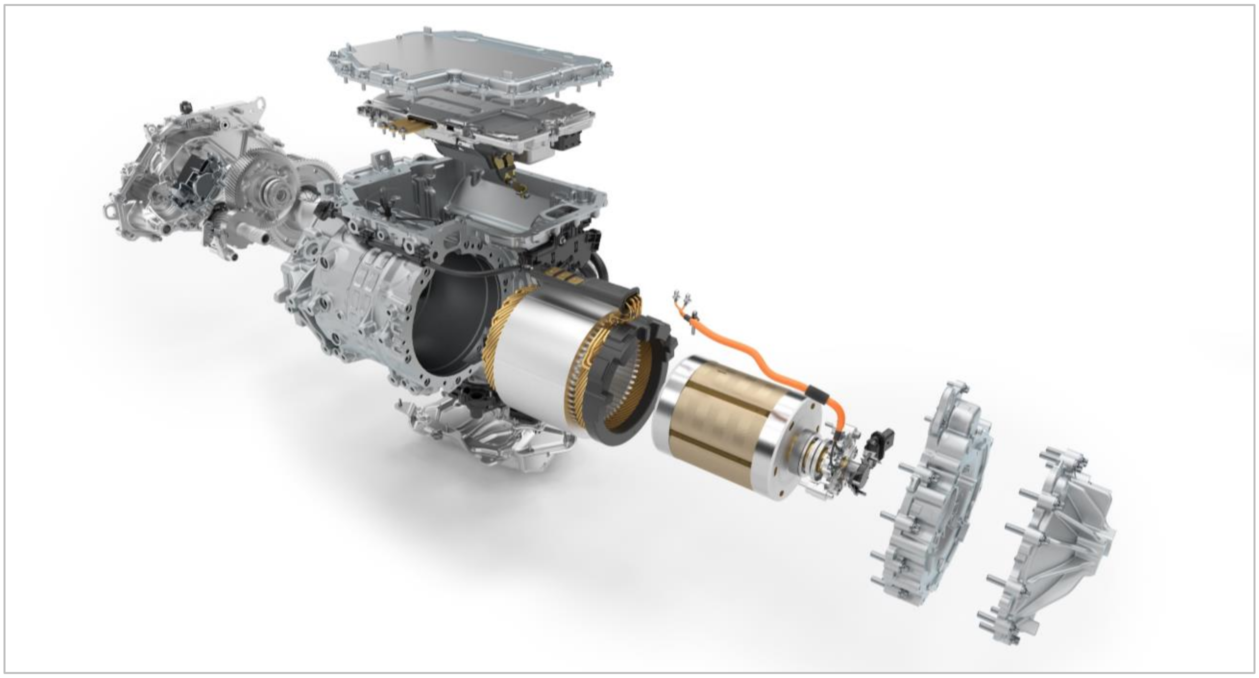

**Figure 49: BMW "5th Gen E-drive Technology" employing a wound rotor synchronous rotor. The new BMW iX3 – Drivetrain** [156]

### 3.2.4 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 and being available for OEMs to test and integrate into their new product programs.

### 3.2.5 Optimizing the Cost and Performance of Electric Motors

Figure 50 shows the results of the motor teardown studies done by Munro & Associates on mass-produced light-duty BEV motors [44]. The cost of PMSMs is in the range of $4-5 per kW. The 190 kW Tesla Model 3 and Y rear motor (PM-SynRM) is $4.2 per kW. The aluminum-conductor rotor induction motor (Tesla Model 3—front motor) is significantly cheaper, with a cost of less than $3 per kW.

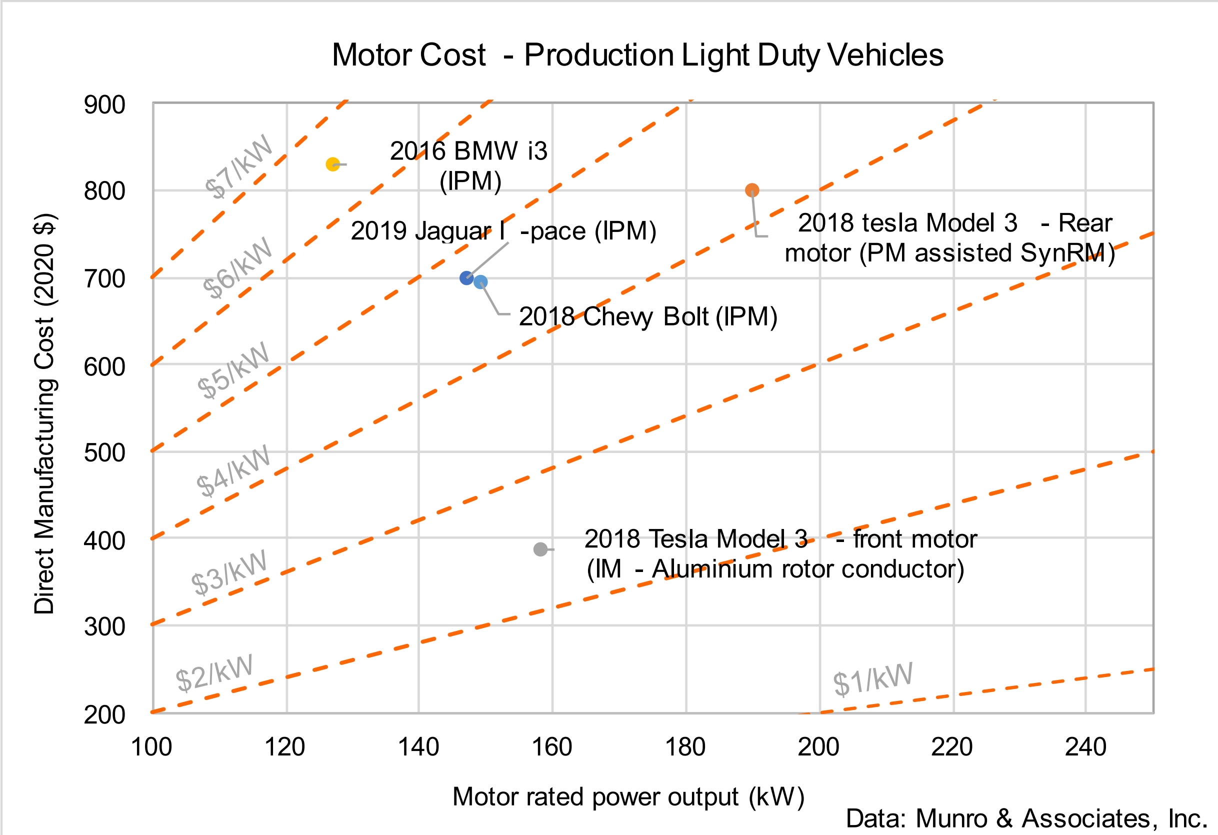


**Figure 50: Production light-duty BEV motor cost [9]**

Figure 51 shows the materials (commodity prices of raw materials, $/kg in 2020 and 2022) used in the construction of the various parts of the different types of electric motors. With the increased demand for rare earth magnets, the commodity price of neodymium has tripled from 2020 to 2022 (Figure 51). The mining and processing of rare-earth metals can have a large environmental footprint, and the materials are subject to price volatility with increasing demand. Also, China currently provides 85% of rare-earth metals, putting its supply at risk from geopolitical developments. Hence, there is a huge incentive to reduce or eliminate the use of rare-earth magnets in motors.

Several vehicles from OEMs (Tesla, VW Group, etc.) that offer AWD BEVs use a combination of PMSM in the rear and IM in the front. The IM is typically used in situations with high wheel torque demand (accelerating or regenerative braking) or limited traction. The front axle IM is freewheeling under normal driving conditions. This enables the rear PMSM to operate at higher average loads and efficiencies. Unlike the PMSM, the IM has no parasitic losses when freewheeling due to the absence of cogging torque. This combination of PMSM on the rear axle and IM on the front axle reduces the average cost ($/kW) of the total traction motor output and increases the efficiency (Wh/mile) of the BEV.

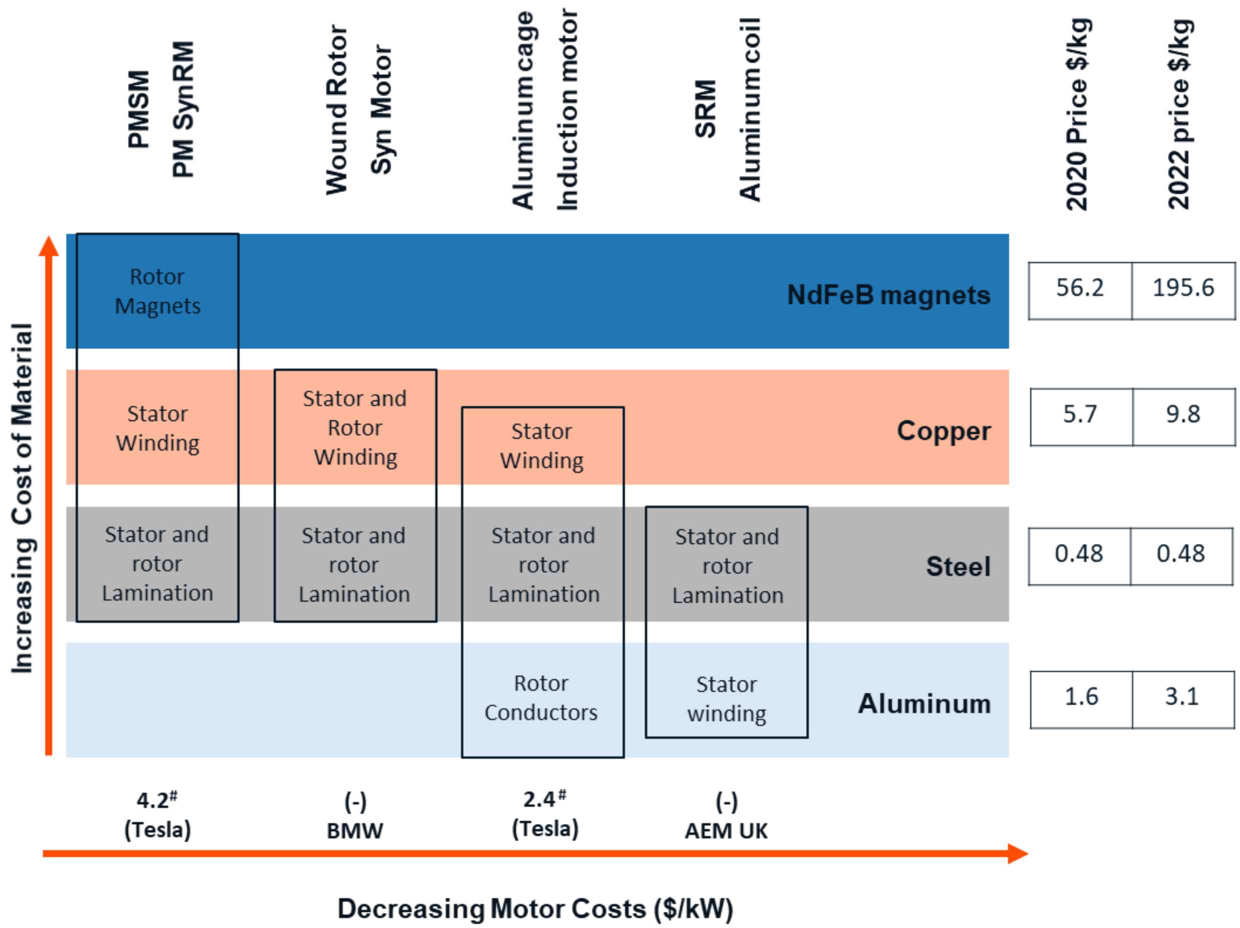


**Figure 51: Different types of electric motors and materials used in different parts of their construction. #costs from Munro and Associates Motor teardown report** [44]

The increasing price volatility of NdFeB magnets has pushed some automotive manufacturers to use other types of traction motors in their BEVs. For example, BMW uses WRSMs in all their vehicles, while Audi uses induction motors (in the e-tron Quattro and the Q4 e-tron Quattro). In summary, traction motors can be made out of significantly cheaper materials without any appreciable reduction in performance or efficiency. This provides automakers with alternative technology pathways to reduce motor costs in the event of supply chain constraints or an increase in the price of rare earth (NdFeB) magnets or copper.

### 3.2.6 Reducing the Material Costs of Electric Motors

#### 3.2.6.1 Reducing/Eliminating the use of Rare-Earth Materials for Magnets

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 ($\alpha''$-$Fe_{16}N_2$) are a promising technology that can replace rare earth magnets. With a magnetic energy density of approximately 2.5 times that of NdFeB magnets, the technology promises cheaper, more compact, and more powerful electric motors while maintaining the sustainability of electric vehicles in the long term. In November 2022, Niron Magnetics secured a $17.5 million SCALEUP grant [157]. The SCALEUP program is aimed at helping a disruptive technology to transition from proof-of-concept prototypes to a commercially scalable and deployable version and be well-positioned for investment from the private sector [158].

#### 3.2.6.2 Replacing Copper Stator Coils with Aluminum

The Tesla Model 3/Y and the VW ID3 use 6.8 kg of copper in their rear motor Table 23. Copper commodity prices increased from $1.85 in 2000 to $9.3 per kg in 2022 and are projected to rise above $15 per kg by 2025. By 2030, the global demand for copper is expected to increase by 900%, which could result in a significantly higher price for the metal [159].

Pre-compressed wound aluminum coils, as shown in Figure 52 (A and B), can be used in place of copper stator windings. These have demonstrated a slot fill factor of 77% and the ability to match the efficiency and performance of a copper stator winding [160]. Advanced Electric Machines Ltd. (UK) offers a switched-reluctance motor that uses pre-compressed aluminum windings.

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, as shown in Figure 52 (C and D).

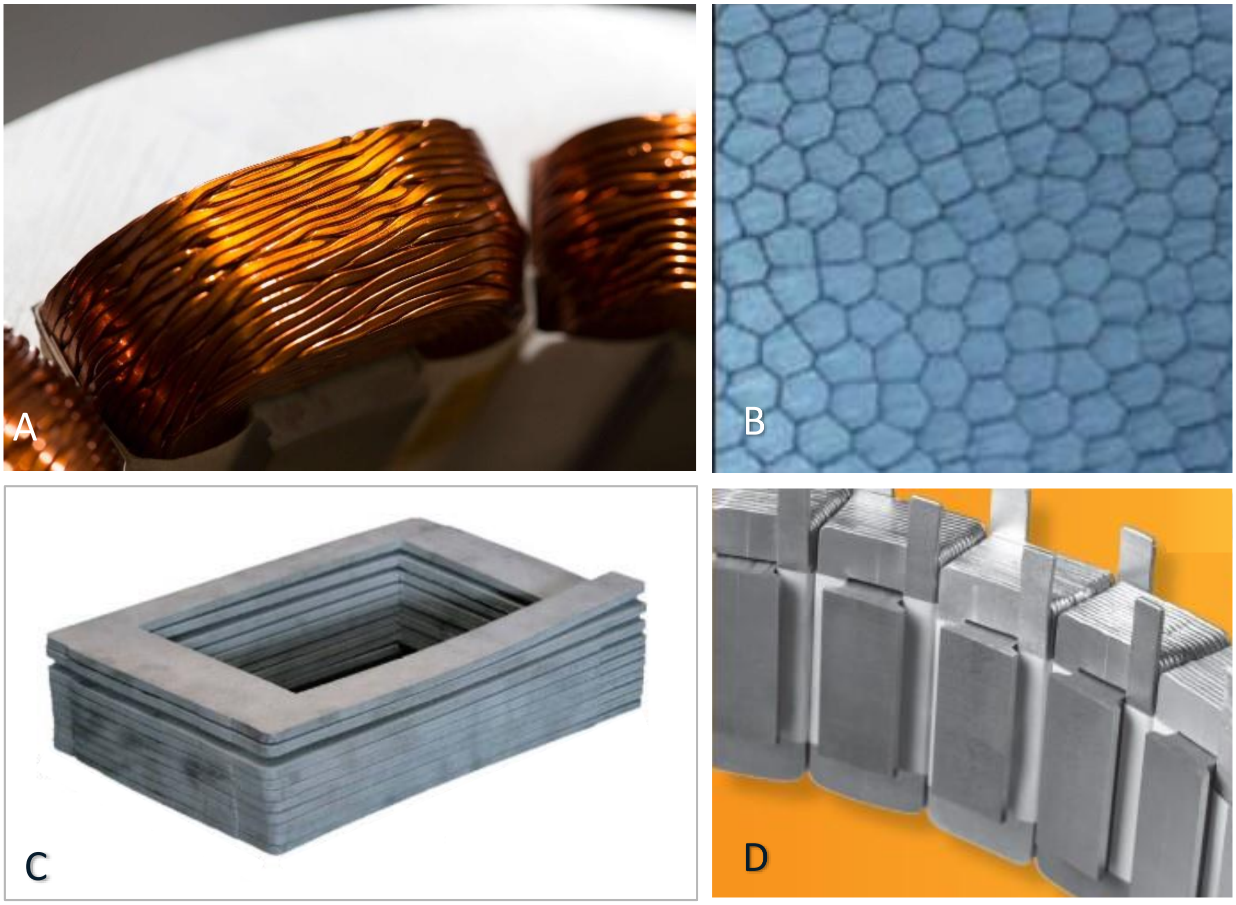


**Figure 52: A: Compressed aluminum stator coil (AEM UK), and B), B: cross-section of the compressed aluminum coil, Cand D: die-cast aluminum coils C and D**

### 3.3 Power Electronics

The three major components of power electronics are the traction inverter, the DC-to-DC converter, and the onboard charger. These technologies are quite mature, owing to industry efforts to improve performance and efficiency while lowering size and costs [12].

a) **Traction Inverter**: A traction inverter is an electronic device used in EVs to convert the direct current (DC) from the high voltage (HV) battery into an alternating current (AC) to power the traction motor that drives the wheels. The traction inverter typically consists of power electronics (insulated gate bipolar transistors or IGBTs), control logic, and a cooling system. The primary function of a traction inverter is to control the speed and torque of the electric motor in response to the driver's inputs and other operating conditions. The inverter accomplishes this by adjusting the frequency, voltage, and current of the AC output to match the traction motor's requirements. Traction inverters are a critical component of EVs, as they determine the vehicle's performance, efficiency, and reliability.

Silicon IGBT inverters are a common type of traction inverter used in EVs. Many popular BEVs use Si IGBT inverters in their powertrain systems. Some examples of BEVs that use Si IGBT inverters include Tesla Model S and Model X (early models), Nissan Leaf (2010-2017 models), BMW i3, Volkswagen e-Golf, Ford Focus Electric, Chevrolet Spark EV, Kia Soul EV, and Hyundai Ioniq Electric. It's worth mentioning that the use of Si IGBTs in BEV inverters is dwindling as newer, more efficient power electronics technologies like Silicon Carbide (SiC) and Gallium Nitride (GaN), known as wide-bandgap (WBG) materials (shown in Figure 53), become more widely available and cost-effective. These newer technologies outperform traditional Si IGBTs in terms of power density, switching speed, and loss, making them appealing to electric car makers [12], [46], [60], [161]. SiC traction inverters are used in the Tesla Model 3 and Model Y, as well as the Porsche Taycan, Lucid Air, and Chevrolet Bolt EUV. According to reports, the usage of SiC technology allows for quicker charging and increased efficiency [12], [60], [161]. SiC technology is projected to play an increasingly crucial role in the development of high-performance, efficient electric cars as it advances and becomes more generally available. In 2020, Toyota announced that it had developed a prototype electric vehicle powertrain system that uses a GaN inverter [162]. Other companies, such as Infineon and Panasonic, are also working on GaN-based power electronics for electric vehicles. These variants were not factored in this study.

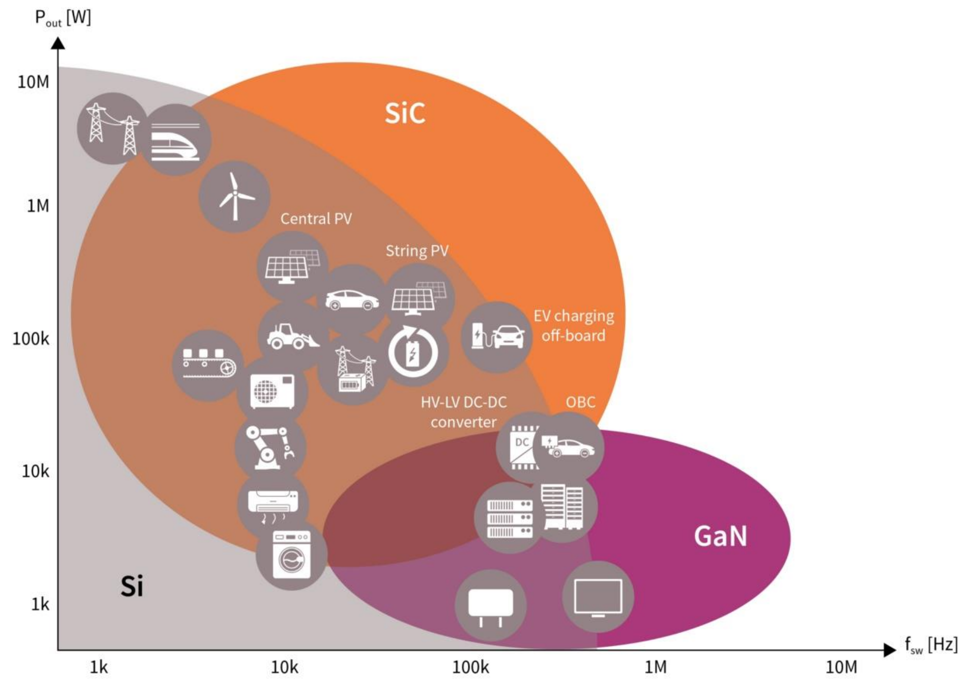


**Figure 53: Wide-bandgap semiconductor applications. Source: Infineon** [163]

b) **DC-to-DC converter**: DC-DC converters are an essential component of EV power electronics systems. The high-voltage DC output (400–750 V) from the EV's battery pack (250–360 V) must be converted to the lower-voltage DC required to power the auxiliary systems and subsystems such as lights, infotainment systems, steering, advanced driver assistance systems (ADAS), and air conditioning, which is typically 12–48 V. DC-DC converters are typically non-isolated or isolated and come in various configurations [164].

   DC-DC converters can significantly impact the efficiency and performance of an EV, as they must convert DC output voltages to appropriate levels while minimizing energy losses. As the industry transitions to higher voltage specs 800 V and beyond to achieve more efficient motor operation and extreme fast charging technology, WBG-based architecture would be prevalent. Higher-efficiency converters can reduce the amount of energy wasted as heat and improve the overall range of the vehicle. DC-DC converters are advancing to high switching speeds to reduce power losses in passive components, and hence the SiC (in use) and GaN (not mature) are explored as possible solutions to overcome the limitations of Si-based devices [12], [164].

c) **On-board charger (OBC)**: It is responsible for converting the input AC power from an external source such as a charging station or wall outlet into DC power. This DC power is required to charge the EV battery. It can be integrated into the traction motor housing, thereby reducing costs. There are different types of OBCs, such as single-phase or three-phase chargers, depending on the AC power source and the charging speed. A single-phase charger typically has a lower charging speed, while a three-phase charger can provide faster charging rates. They typically range from 3.7 kW to 22 kW [165]. With the advent of fast charging technology, some electric vehicles can charge from empty to 80% in under an hour. Figure 54 provides an overview of trends in OBC design and the solutions they offer.

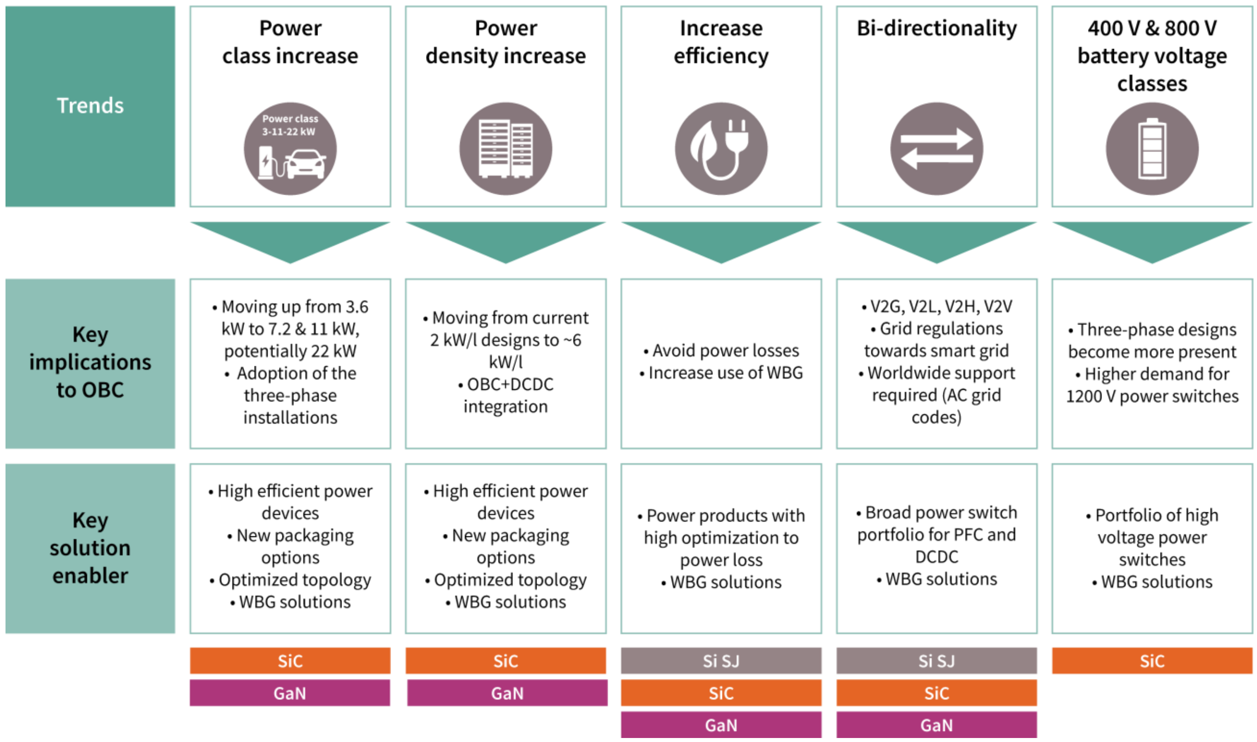


**Figure 54: Developments in on-board charger (OBC) design. Source: Power Electronics News** [165]

## 3.4 Charging

An overview of the EV charging infrastructure is presented in Figure 55, where Type 1 and 2 charging require the vehicle's onboard charger to convert AC power to high voltage DC to charge the battery pack. The maximum charge rate is dependent on the AC connection rating and the throughput of the OBC. While AC charging is the most cost-effective way to charge an EV, due to the low cost of a type 2 AC charger, minimal upgrades to the site infrastructure, and the low cost of electricity, especially during off-peak hours, DC Fast chargers (DCFC) offer much higher power than AC charging. Companies such as Electrify America and EVgo provide charge rates up to 350 kW, but the equipment and site preparation costs for DCFCs are considerably higher than for level 2 AC chargers.

| Supply type to the charger | Output AC/DC | Rated power* | Time to charge 10 kWh | Time to charge 30 kWh |
|---|---|---|---|---|
| Single phase 16 A | AC | 3.7 kW | 2 h 40 min | 8 hours |
| Single phase 32 A or 3 phase, 16 per phase** | AC | 7.4kW | 1 h 20 min | 4 hours |
| 3 phase, 16 A per phase** | AC | 11 kW | 55 min | 2 hours 45 min |
| 3 phase, 32 A per phase | AC | 22 kW | 27 min | 1 hour 22 min |
| 3 phase/ DC | DC | 50 kW | 12 min | 36 min |
| 3 phase/ DC | DC | 350 kW | < 2 min | 5 min |

* Simplistically (ignoring Power Factor correction):
- For single phase 230 V connections, Power (kW) = **Amps (A) x 230 V*0.001**
- For 3 phase 400 V connections, Power (kW) = **1.732*Ampsper phase (A) x 400 V*0.001**

** Depending on the country

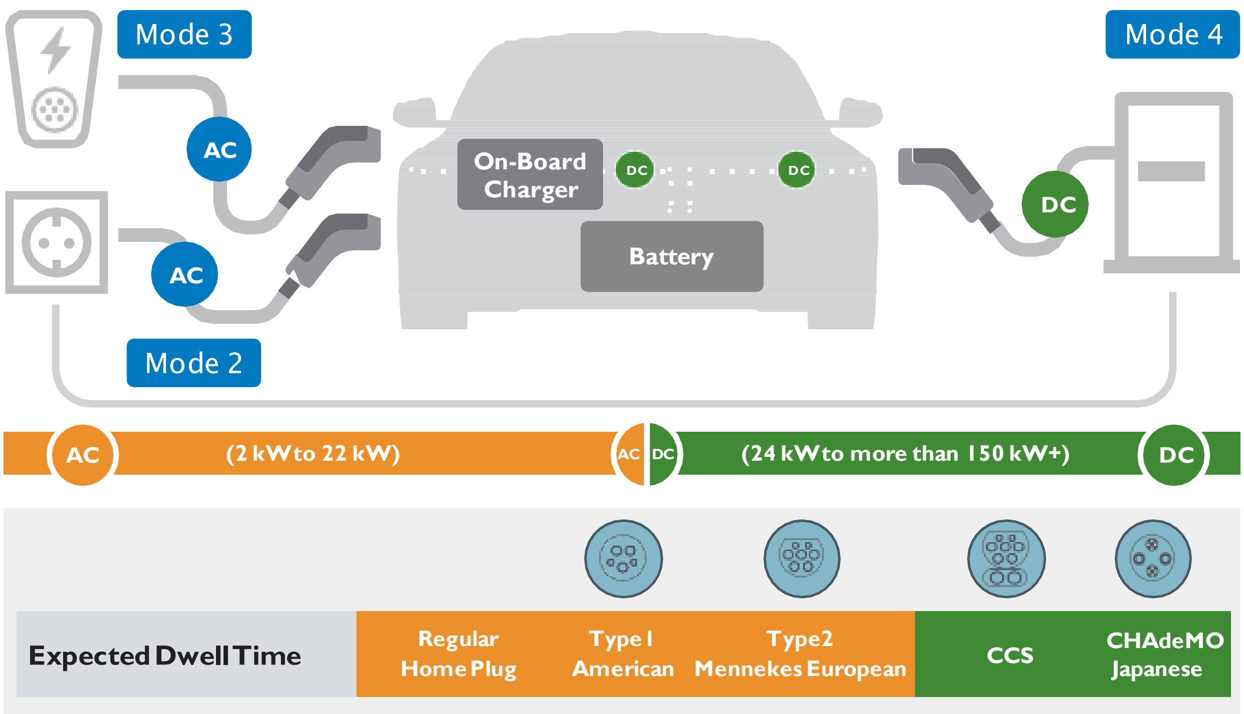


**Figure 55: Overview of the EV charging infrastructure. Source: Eaton** [166]

According to available literature [8], [60], the cost of charger equipment for a DC fast-charging site typically ranges from $150,000 to $200,000 per dispenser. However, standardized modular components and larger manufacturing scales have the potential to considerably decrease this cost. Grant applications for DCFC equipment as part of the Texas Volkswagen Environmental Mitigation Program (TxVEMP) [167] in 2022 showed that cost reductions were achievable. The program allowed applicants to request up to $150,000 per DCFC charging unit installed, not exceeding 70% of the DCFC equipment's cost, with a maximum of $600,000 per project site [168]. Most applicants requested

$150,000 per DCFC unit, which translated to a cost per unit of $215,000. Tesla, on the other hand, requested $500,000 for a 17-unit site and $383,438 for a 9-unit site, which indicates that the cost of Tesla supercharger (DCFC) equipment ranges from about $42,000 to $61,000 per charger [169].

Figure 56 displays a Tesla supercharger location built from prefabricated components, such as a power cabinet and 4 DCFC dispensers mounted on a cast concrete footing, which can significantly reduce the construction cost of DCFC sites. Tesla has two manufacturing facilities for supercharger (DCFC) equipment manufacturing, one in China which produces 10,000 units per year, and the other in Buffalo, NY.

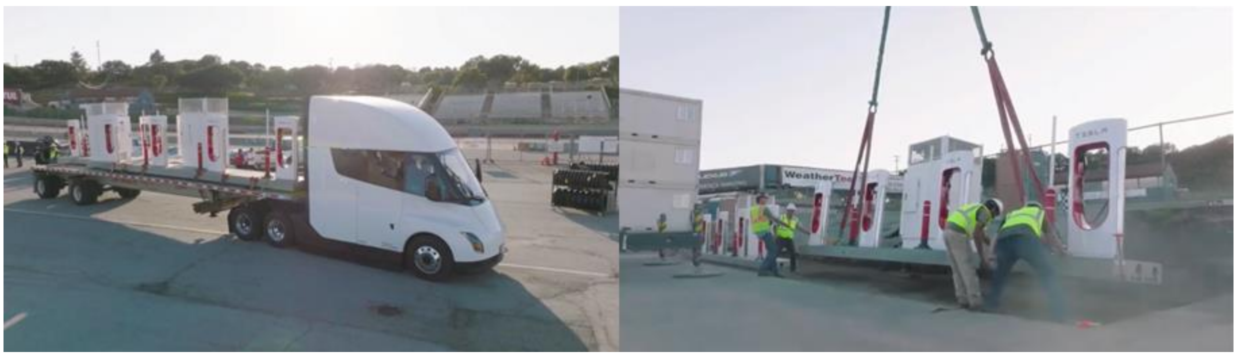

**Figure 56: Tesla supercharger station built with prefabricated components** [170]

### 3.4.1 State-of-the-Art Charging

Figure 57 depicts the charging rate to add real-world 100 miles that were collated by Car and Driver when testing EVs for an *EV of the Year* contender [171]. Vehicles in the top-right quadrant can accept high charging rates, which adds to their range in a short time. Most OEMs have been launching BEVs that can charge from 10% to 80% within 15 minutes. Usually, the batteries are significantly derated beyond 80-90% and take more time to charge.

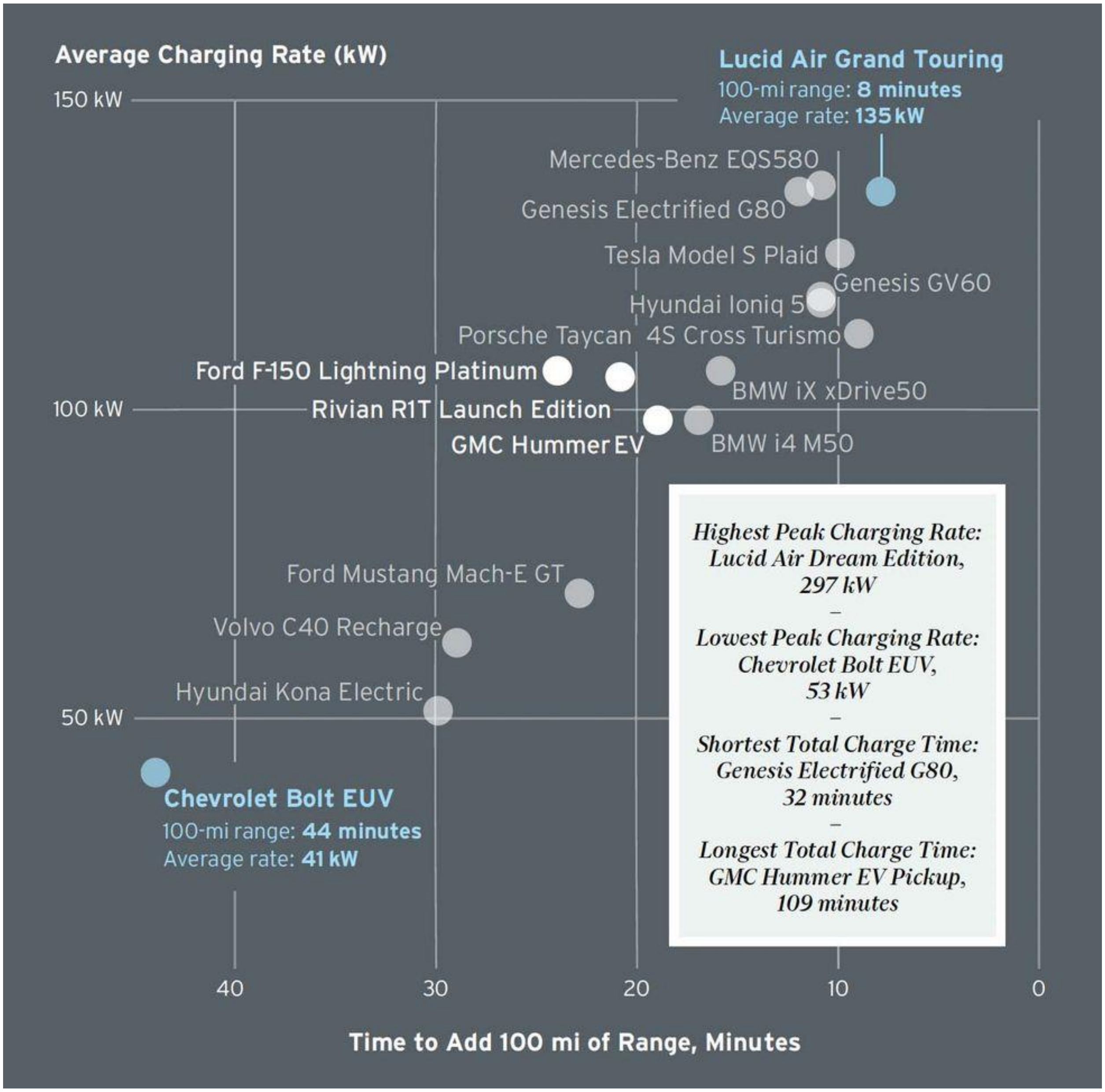


**Figure 57: Average charging rate to add 100 real-world highway miles. Source: CAR AND DRIVER** [171]

### 3.4.2 Charging Stations with Energy Storage

Figure 58 shows Freewire's Boost Charger™ 200 [172] for businesses and fleets. The all-in-one unit integrates all the necessary power electronics and 160 kWh of battery storage. The unit is connected to the commonly available 240V 3-phase AC connection, but the battery buffer enables it to provide DC fast charging at 200 KW (10 times the input-to-output power ratio). This removes the necessity for an expensive specialized high-power connection from the utility, expensive on-site construction to set up power cabinets, and costly electricity rates during periods of high demand.

**Figure 58: Freewire's Boost Charger™ 200. Source: Freewire Technologies**

Many Electrify America and Tesla DC fast charging locations with multiple chargers feature battery storage to reduce peak demand tariffs. Incorporating energy storage into DCFC charging solutions can reduce or eliminate peak demand tariffs and will, in the long run, reduce the $ per kWh charge at DCFCs.

# 4. Results

This section presents the overall results of the incremental cost and TCO analysis for a BEV against an ICEV for the considered class 2b–3 vehicle types in the 2027–2030 timeframe. The incremental costs of each powertrain type are calculated to determine if purchasing a BEV over an ICEV in the 2027 and 2030 timeframes is an economically attractive option for an individual or fleet owner. The projected incremental costs presented are conservative estimates for MYs 2027 and 2030. The powertrain costs considered for class 2b–3 vehicles are appended in Section 9.1.

## 4.1 Incremental Cost of Electrification with RPE

Figure 59 depicts the projected incremental retail costs of a BEV powertrain over a comparable ICE powertrain for each electrification scenario. A negative number implies that the retail cost of a BEV powertrain is cheaper than the retail cost of a comparable ICE powertrain in 2027 and 2030. The incremental cost of a BEV powertrain varies according to battery cost scenarios and ICE powertrain type. Switching from a high-cost ICE powertrain such as a SHEVP2 or CI with advanced DEAC (DSLIAD) to a low-cost BEV powertrain with an LFP battery pack (Scenario 1) results in the lowest incremental cost of electrification. Switching from a low-cost ICE powertrain (conventional NA SI) to a BEV with a high-cost battery pack (10% premium on the projected NMC811 cost) (Scenario 3) results in the highest incremental cost of electrification. Scenario 2 compares a medium-cost ICEV to a medium-cost BEV. The following can be observed with respect to the initial vehicle purchase price (operating cost savings are not considered):

a) MYs 2027 and 2030 BEV150s across Scenarios 1 and 2 across all vehicle types are cheaper than their ICEV counterparts.
b) By MY 2030 BEV150s across all vehicle types in Scenario 3 will be cheaper than their ICEV counterparts.
c) MYs 2027 and 2030 BEV150s and BEV250s across all vehicle types in Scenario 1 are cheaper than their ICEV counterparts.
d) Except for MY 2030 pickup BEV300 in Scenario 1, in MYs 2027 and 2030, both pickups BEV300 and BEV400 are costlier than their ICEV counterparts across all three scenarios. This is primarily due to larger battery packs.
e) MYs 2027 and 2030 BEV250s and above are all costlier than their ICEV counterparts in Scenarios 2 and 3.

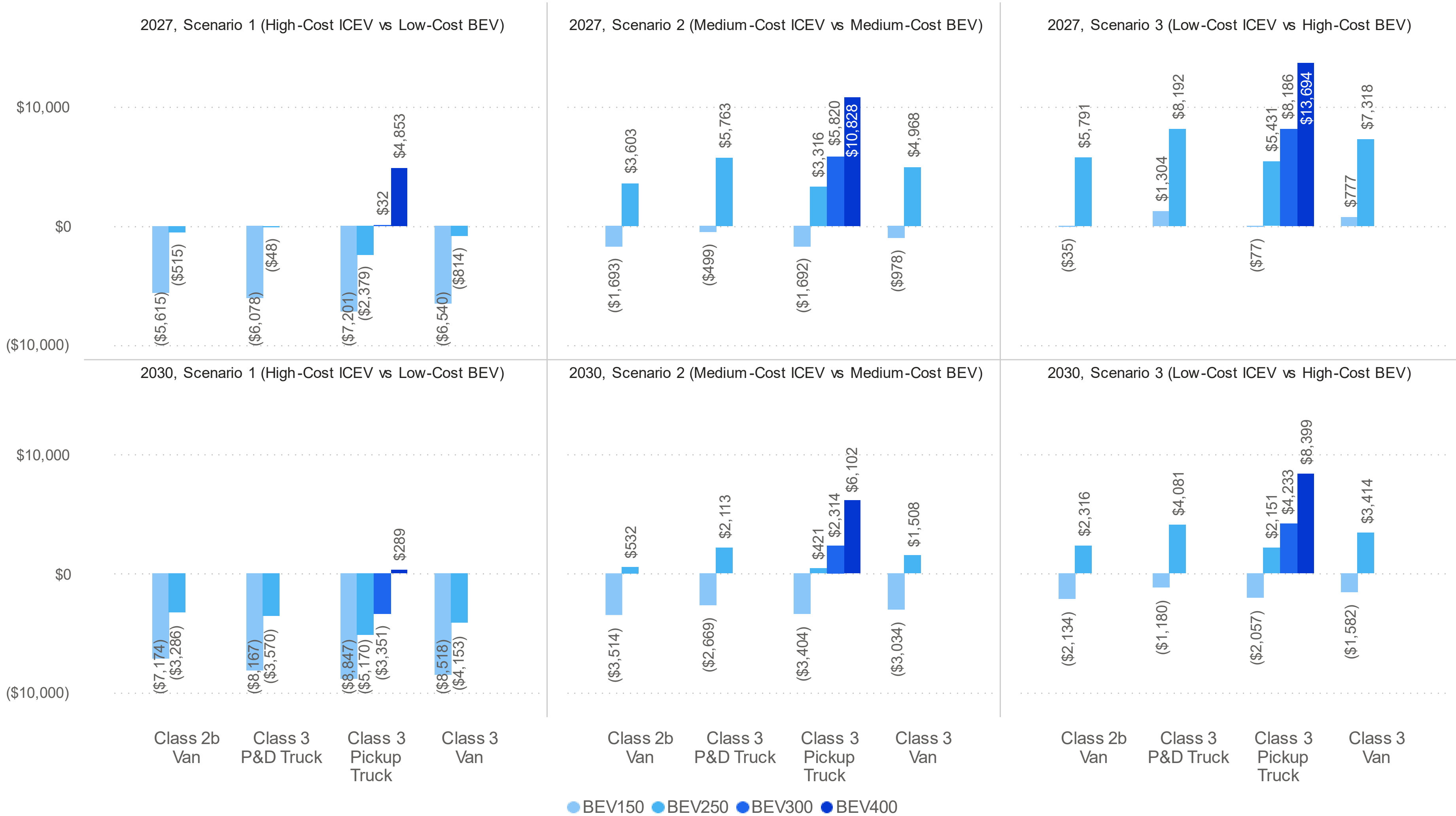


**Figure 59: Projected incremental cost of BEV over ICEV with their respective RPEs in 2027 and 2030.**

We project that most vehicles with a 150-250-mile range will use the cheaper LFP battery packs in 2027 and 2030 i.e., the incremental costs shown for Scenario 1. Only a small subset of vehicles, such as class 3 pickup trucks that are used for towing (with a range of 300-400 miles), will need larger and more expensive large-capacity batteries, and, hence, the probable incremental costs will be positive in the timeframe evaluated.

### 4.2 Time to Reach TCO Parity

A total cost of ownership analysis, considering both the initial purchase price and subsequent operating costs, was also performed. Table 24 summarizes the time to achieve TCO parity (i.e., to have BEV ownership costs equal and subsequently drop below ICEV ownership costs) in the residential-type charging scenario across all vehicle types and segments in the 2027 and 2030 purchase timeframes. The results indicate that:

a) In Scenario 1,
   i) All MY 2027 vehicles achieve parity within the first year of ownership except for the BEV400, which would achieve parity after 1 year of ownership.
   ii) All MY 2030 vehicles achieve parity within the first year of ownership upon purchase.

b) In Scenario 2,
   i) All MY 2027 BEV150s would achieve parity within the first year of ownership; BEV250 and above could take up to 6 years to achieve parity.
   ii) All MY 2030 BEV150s achieve parity within the first year of ownership, while BEV250s and above achieve parity within 3 years.

c) In Scenario 3,
   i) MY 2027 BEV150s take up to 4 years to achieve parity, while BEV250 and above may not achieve parity in the assumed lifetime of 12 years. Exceptions are seen in the case of the class 3 pickup trucks BEV250 and BEV300, which could take 6 years and 9 years, respectively, to achieve parity.
   ii) All MY 2030 BEV150s would achieve parity within the first year of ownership, while BEV250 and above could take 2–7 years to achieve parity.

**Table 24: Time to achieve parity for class 2b–3 BEVs with a 2027 and 2030 purchase timeframe.**

| Vehicle Type | BEV Segment | 2027 | | | 2030 | | |
|---|---|---|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | <1 | <1 | 2 | <1 | <1 | <1 |
| | BEV250 | <1 | 4 | End of Life | <1 | 1 | 4 |
| Class 3 Pickup Truck | BEV150 | <1 | <1 | 1 | <1 | <1 | <1 |
| | BEV250 | <1 | 2 | 6 | <1 | <1 | 2 |
| | BEV300 | <1 | 4 | 9 | <1 | 1 | 4 |
| | BEV400 | 1 | 6 | End of Life | <1 | 3 | 7 |
| Class 3 Package & Delivery Truck | BEV150 | <1 | <1 | 4 | <1 | <1 | <1 |
| | BEV250 | <1 | 4 | End of Life | <1 | 2 | 5 |
| Class 3 Van | BEV150 | <1 | <1 | 4 | <1 | <1 | <1 |
| | BEV250 | <1 | 5 | End of Life | <1 | 2 | 6 |

## 4.3 Total Cost of Ownership (TCO)

In addition to their powertrain architecture, BEVs and ICEVs also vary in their purchase price and operating expenses incurred throughout the lifetime of ownership. The TCO accounts for the upfront purchase price and factors in the charger cost, energy or fuel cost, and M&R cost over the assumed life of 12 years for vehicles purchased in 2027 (and operated through 2038) and 2030 (and operated through 2041).

To account for charging cost sensitivity, two scenarios have been developed: residential-type charging and commercial charging. We have considered residential-type and commercial charging scenarios that encompass the broad spectrum of users, which span from a typical single-vehicle user to a fleet owner. The latter scenario is covered separately as a what-if scenario in Section 5 wherein tiered charging infrastructure costs have been considered as a sensitivity input in Scenario 2. The residential-type charging scenario, split as 90:10 between residential-type charging and requirement-based public charging, is considered in the analysis to calculate the time to achieve parity with 2027 and 2030 vehicle purchases. We assume that residential-type charging will be the preferred choice of users of class 2b–3 vehicles since it serves a mixed purpose of personal and commercial vehicles. An upfront cost of $1,800 for a 19.2 kW non-networked level 2 charger is considered for the residential-type charging scenario.

Figure 60 shows the projected range of TCO per mile for purchases made in MYs 2027 and 2030 for ICEVs and BEVs, respectively. The total sum of the vehicle purchase price and the operating costs (discounted by 3% on an annual basis for the lifetime of 12 years) for the ICEVs and BEVs results in a discounted cumulative TCO. TCO per mile is calculated by dividing the cumulative TCO by the lifetime miles traveled (annual VMT × 12 years). TCO per mile of an ICEV is higher, and its range is wider than that of a comparable BEV due to a wide variation in projected fuel prices. For example, in the case of class 3 vehicles, in Scenario 1, the high diesel price and low fuel economy of a conventional diesel powertrain add to the spread of the TCO per mile of an ICEV compared to a BEV, where the battery sizing in conjunction with the inexpensive electricity prices (and thereby charging rates) provides a tight, accurate range of TCO. Despite considering a high public charging rate of $0.43/kWh for 10% of the use case, the energy costs of a BEV are less expensive than a comparable ICEV. On average across all vehicle types and three scenarios of electrification, the TCO of BEVs is about 20% lower than that of ICEVs.

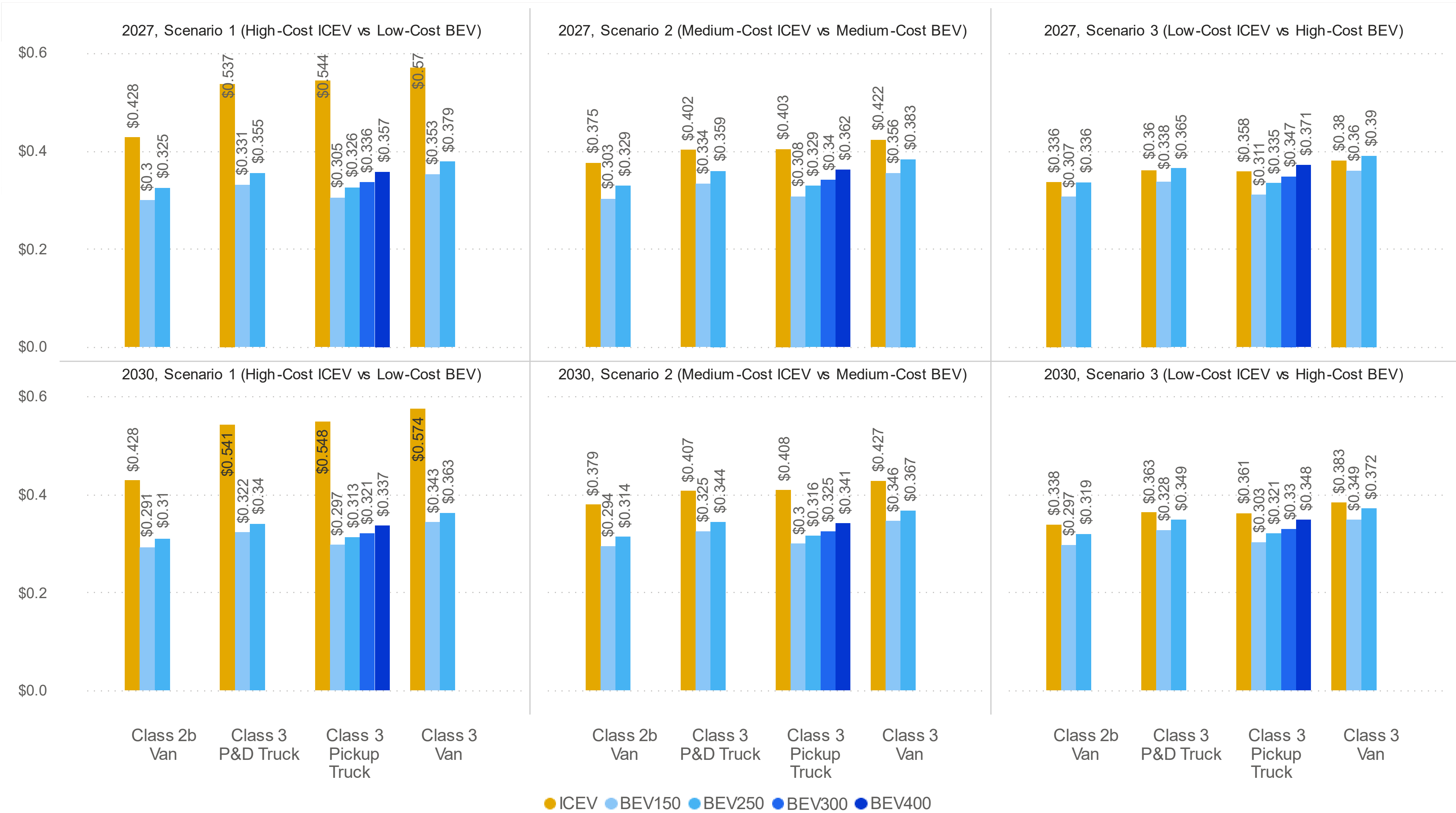


**Figure 60: Projected range of total cost of ownership (TCO) per mile for MYs 2027 and 2030.**

The contributions of the purchase price and operating expenses of a vehicle to TCO scenarios have been depicted using ring charts in sections 4.3.1 and 4.3.2 for vehicles purchased in MYs 2027 and 2030, respectively. The non-purchase costs are discounted to “purchase year” equivalents. Also, in each chart, BEV is the inner ring and ICEV is the outer ring. The energy and maintenance costs of BEVs are lower than their ICEV counterparts across all vehicle types in MYs 2027 and 2030. For most fleet owners that have vehicles with longer fleet lives, energy and maintenance costs are critical decision-making metrics. They would find BEVs attractive due to lower energy and maintenance costs.

### 4.3.1 TCO breakdown of MY 2027 Vehicles

#### 4.3.1.1 Class 2b Van

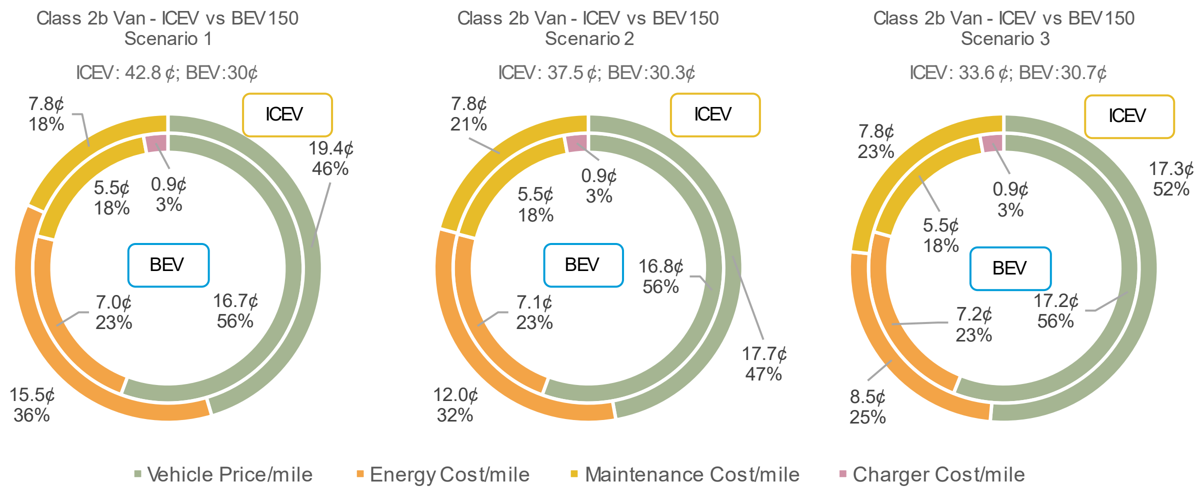


**Figure 61: MY 2027 Class 2b Van ICEV and BEV150 contributions to TCO scenarios.**

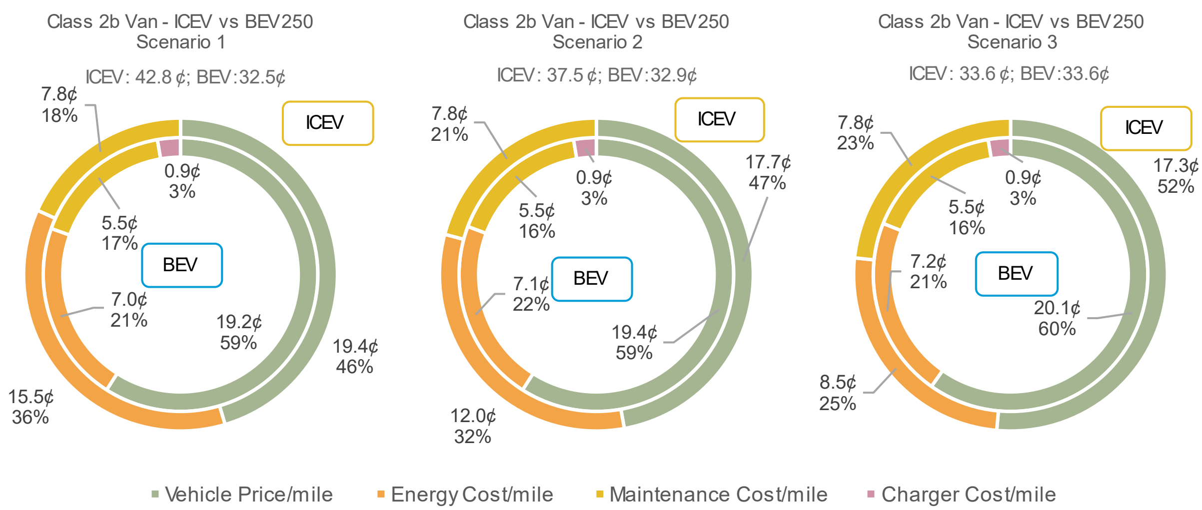


**Figure 62: MY 2027 Class 2b Van ICEV and BEV250 contributions to TCO scenarios.**

### 4.3.1.2 Class 3 Pickup

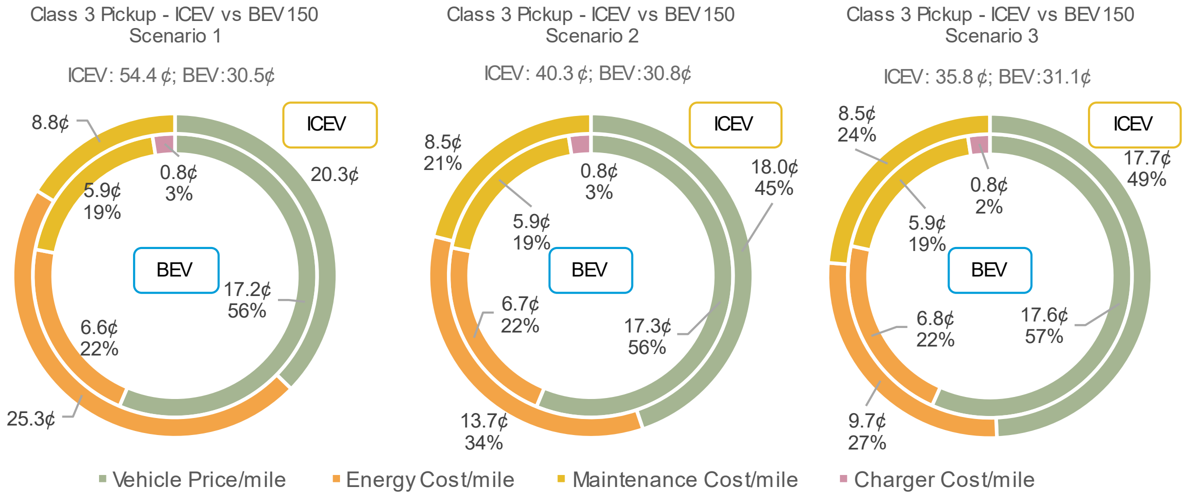


**Figure 63: MY 2027 Class 3 Pickup ICEV and BEV150 contributions to TCO scenarios.**

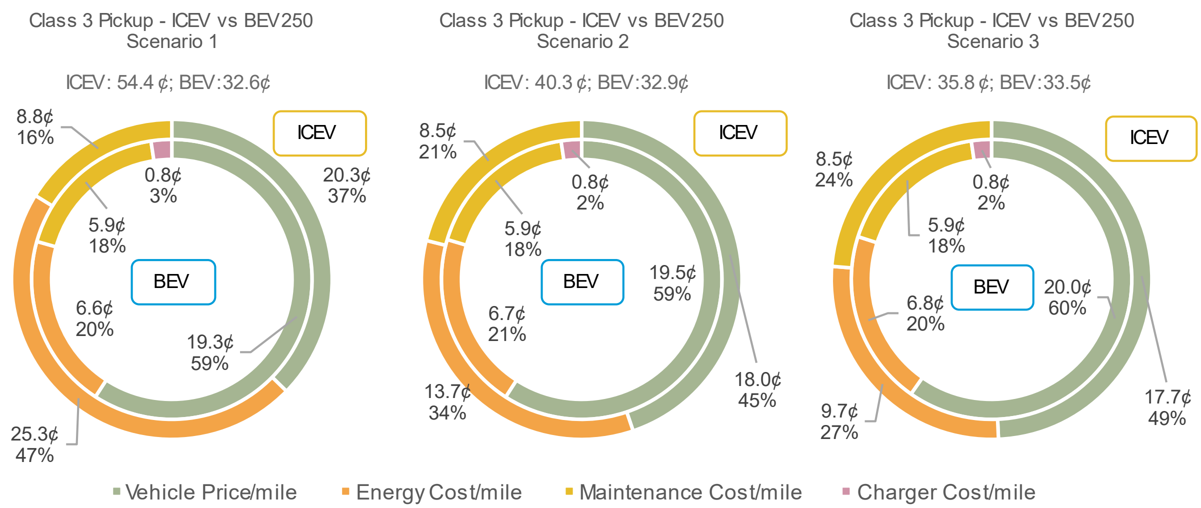


**Figure 64: MY 2027 Class 3 Pickup ICEV and BEV250 contributions to TCO scenarios.**

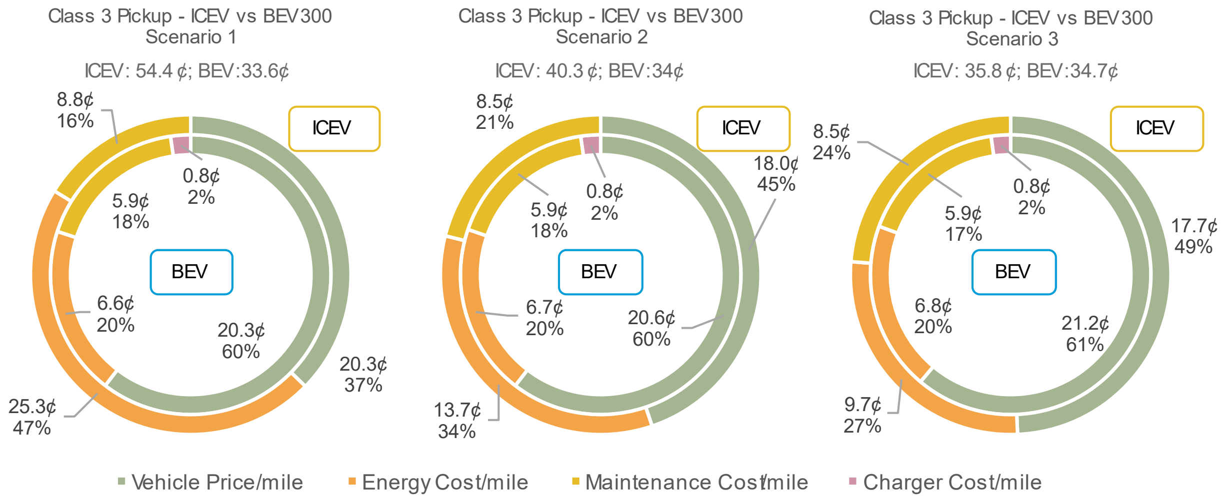


**Figure 65: MY 2027 Class 3 Pickup ICEV and BEV300 contributions to TCO scenarios.**

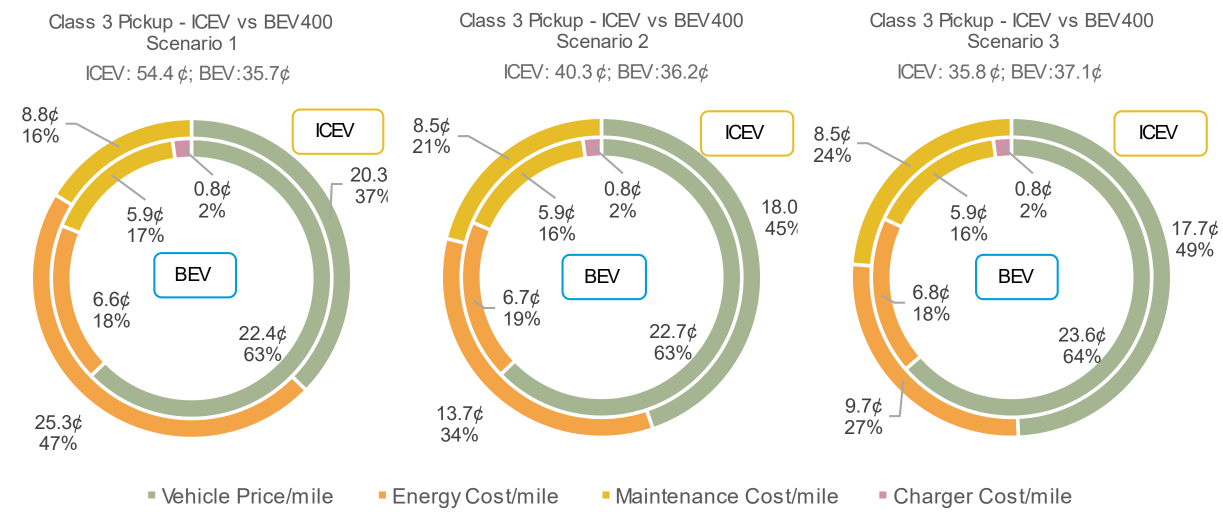


**Figure 66: MY 2027 Class 3 Pickup ICEV and BEV400 contributions to TCO scenarios.**

#### 4.3.1.3 Class 3 P&D Truck

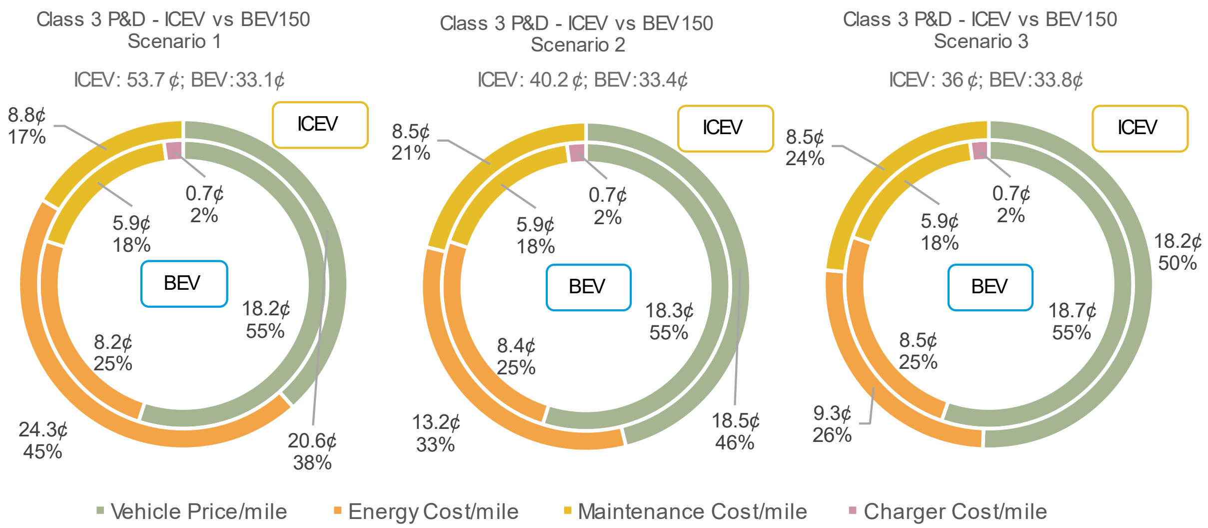


**Figure 67: MY 2027 Class 3 P&D ICEV and BEV150 contributions to TCO scenarios.**

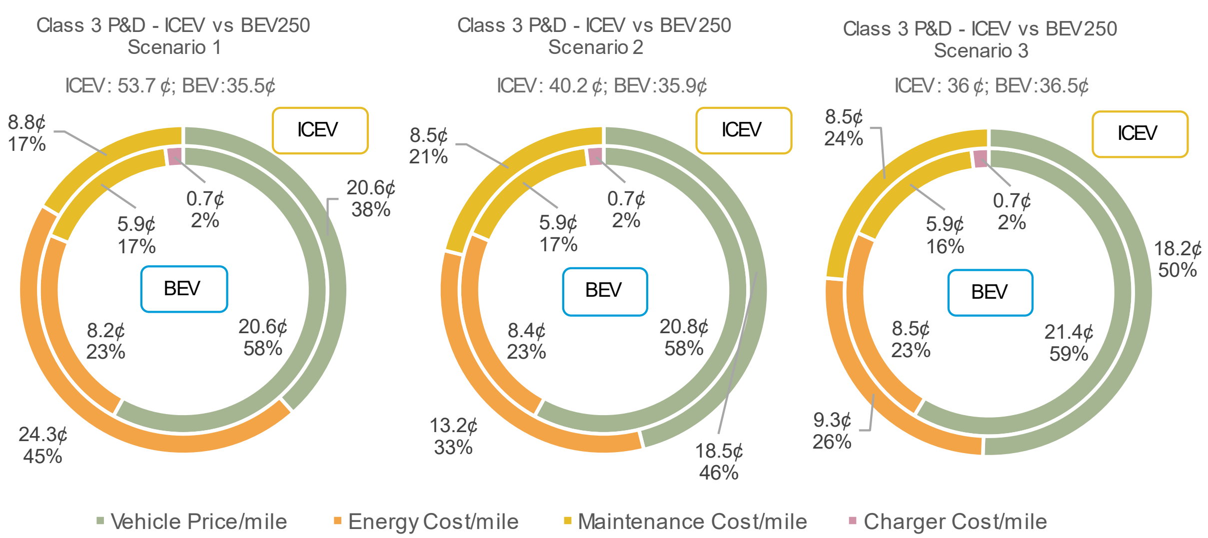


**Figure 68: MY 2027 Class 3 P&D ICEV and BEV250 contributions to TCO scenarios.**

#### 4.3.1.4 Class 3 Van

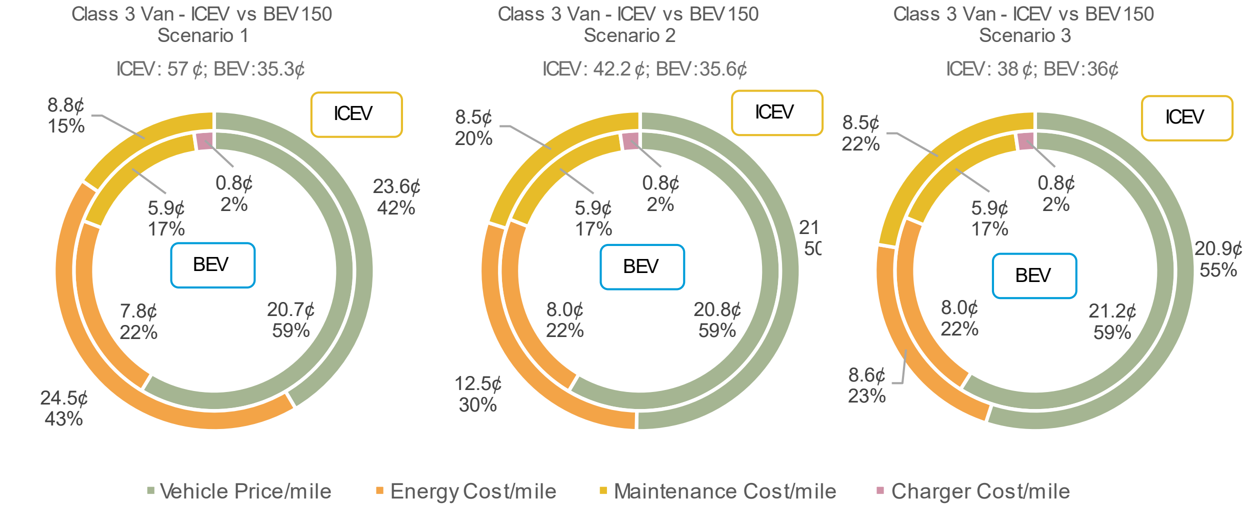


**Figure 69: MY 2027 Class 3 Van ICEV and BEV150 contributions to TCO scenarios.**

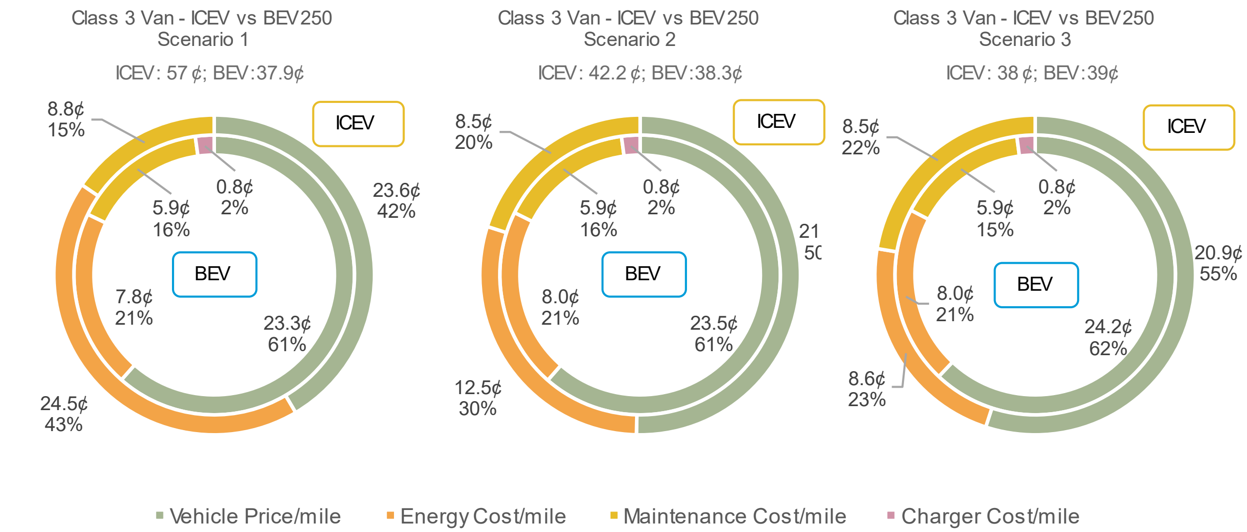


**Figure 70: MY 2027 Class 3 Van ICEV and BEV250 contributions to TCO scenarios.**

## 4.3.2 TCO breakdown of MY 2030 Vehicles

### 4.3.2.1 Class 2b Van

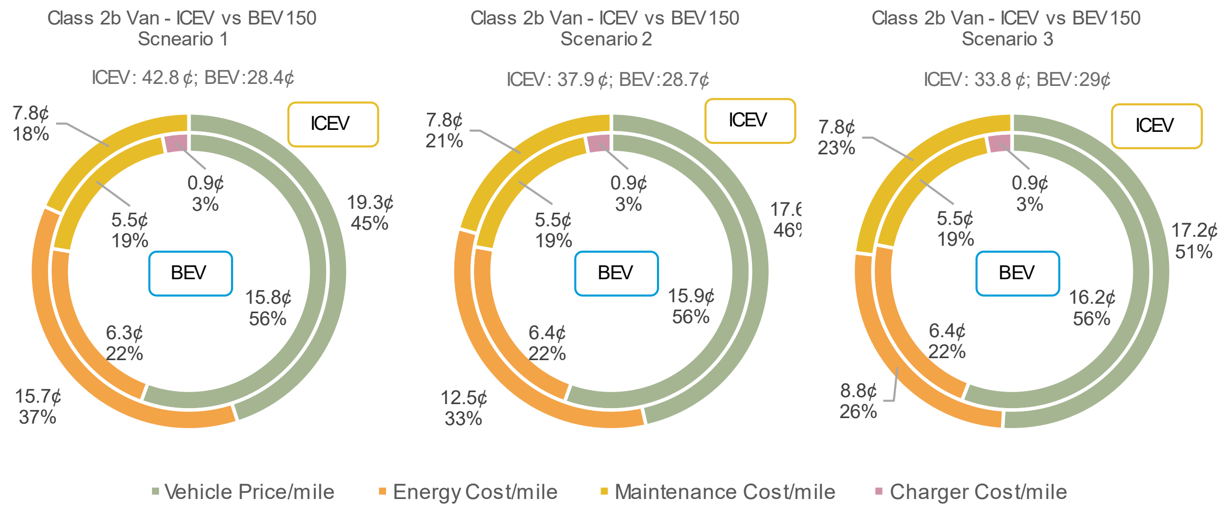


**Figure 71: MY 2030 Class 2b Van ICEV and BEV150 contributions to TCO scenarios.**

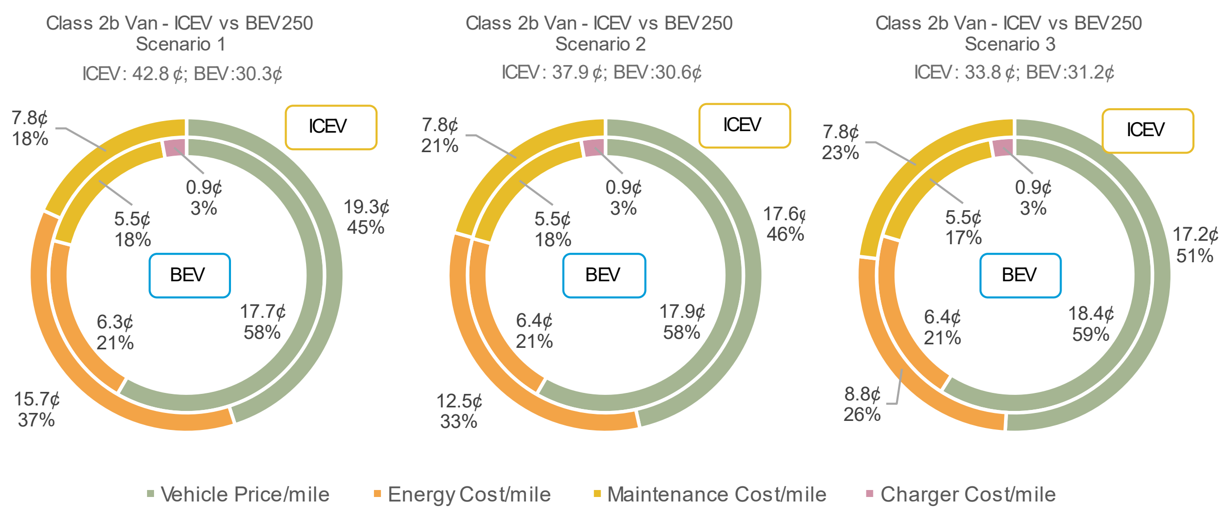


**Figure 72: MY 2030 Class 2b Van ICEV and BEV250 contributions to TCO scenarios.**

### 4.3.2.2 Class 3 Pickup

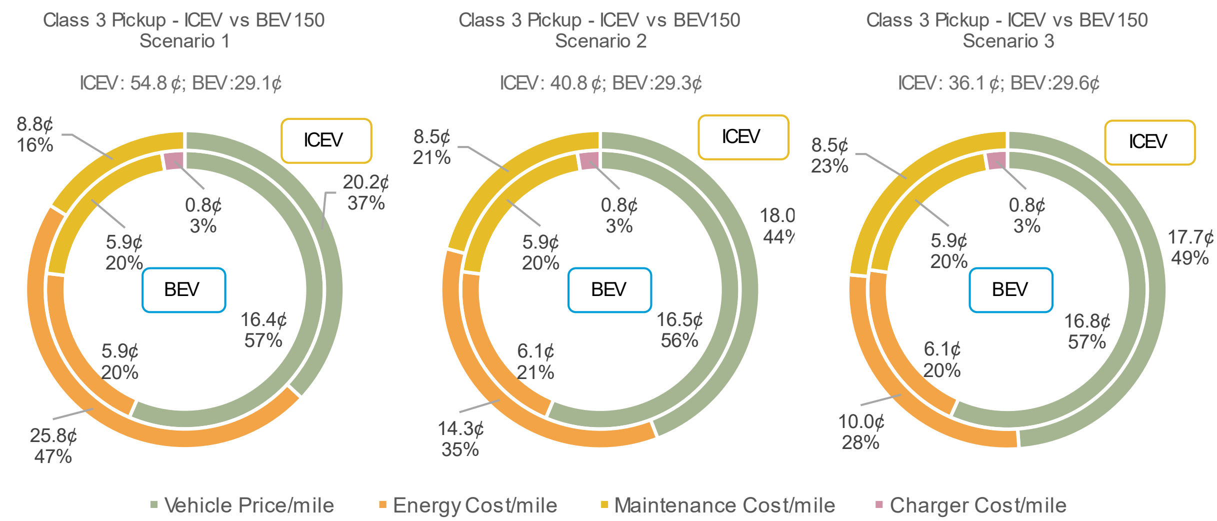


**Figure 73: MY 2030 Class 3 Pickup ICEV and BEV150 contributions to TCO scenarios.**

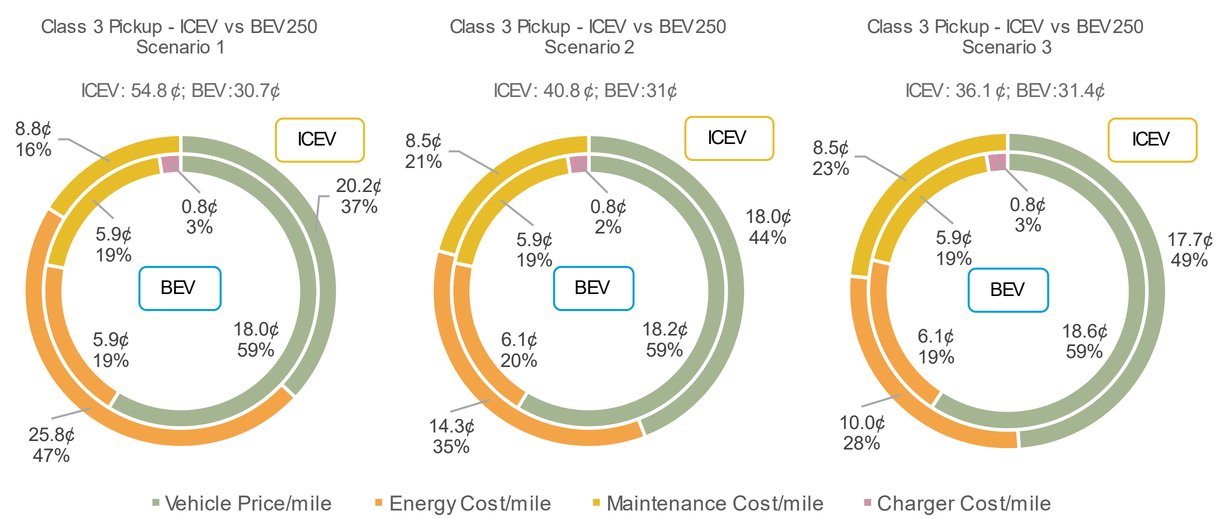


**Figure 74: MY 2030 Class 3 Pickup ICEV and BEV250 contributions to TCO scenarios.**

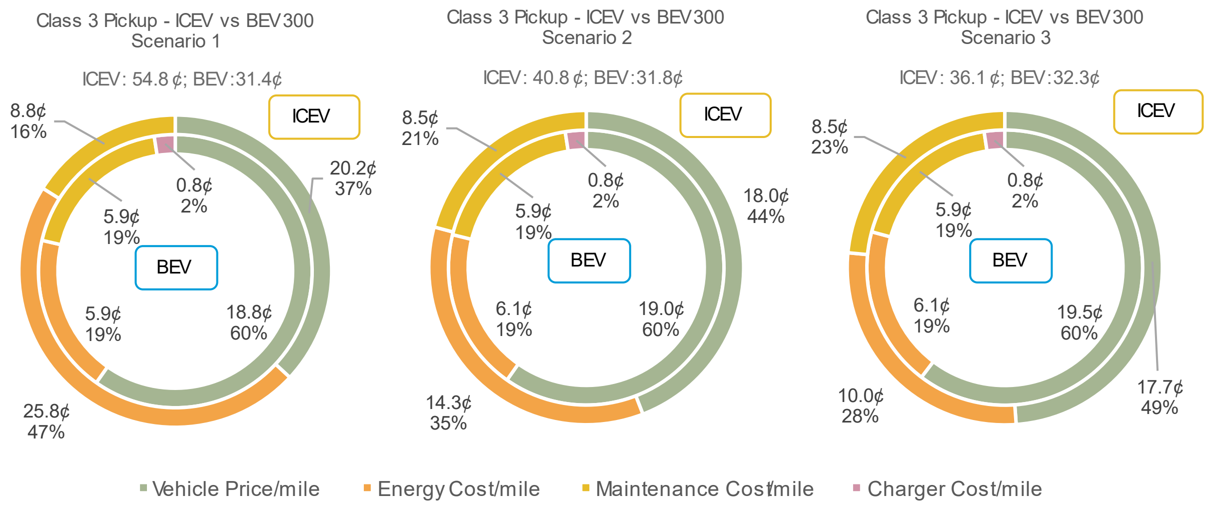


**Figure 75: MY 2030 Class 3 Pickup ICEV and BEV300 contributions to TCO scenarios.**

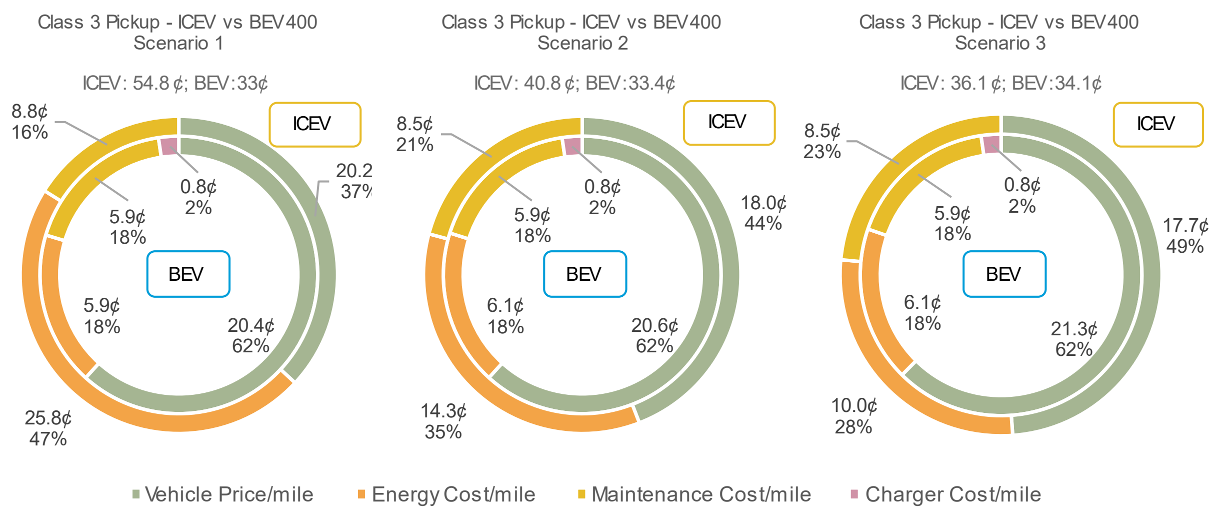


**Figure 76: MY 2030 Class 3 Pickup ICEV and BEV400 contributions to TCO scenarios.**

### 4.3.2.3 Class 3 P&D Truck

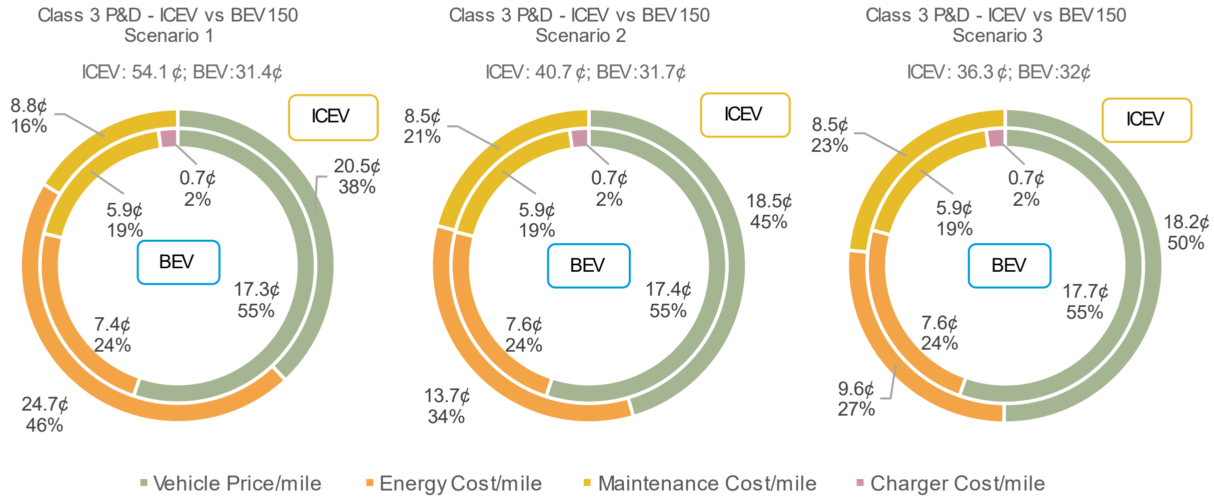


**Figure 77: MY 2030 Class 3 P&D ICEV and BEV150 contributions to TCO scenarios.**

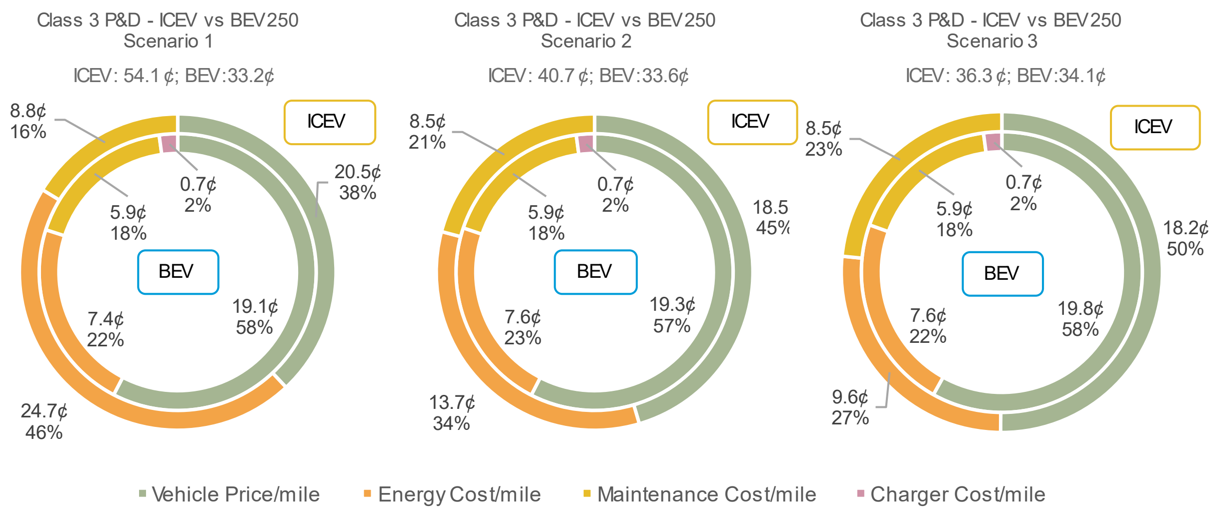


**Figure 78: MY 2030 Class 3 P&D ICEV and BEV250 contributions to TCO scenarios.**

#### 4.3.2.4 Class 3 Van

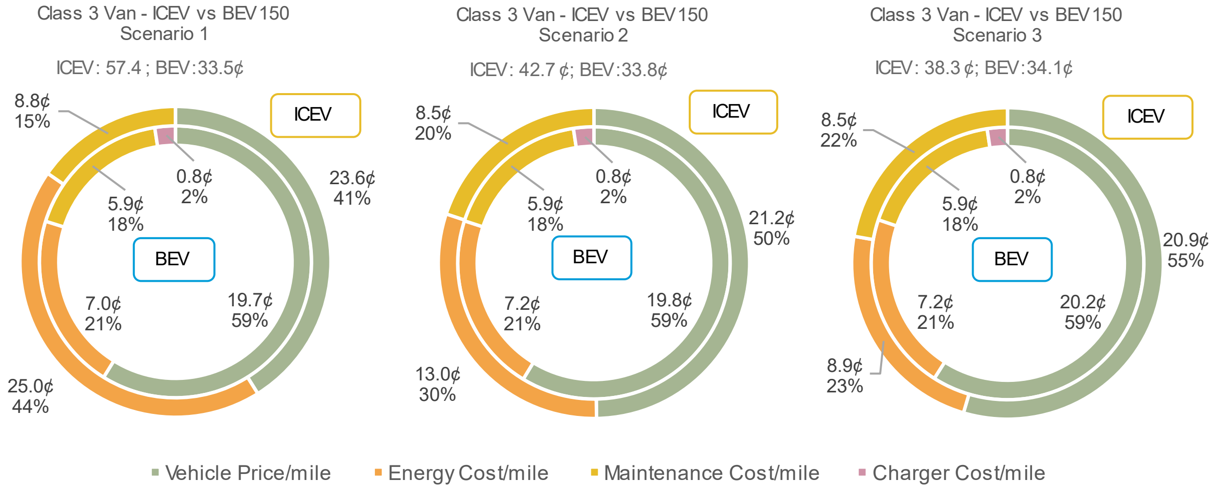


**Figure 79: MY 2030 Class 3 Van ICEV and BEV150 contributions to TCO scenarios.**

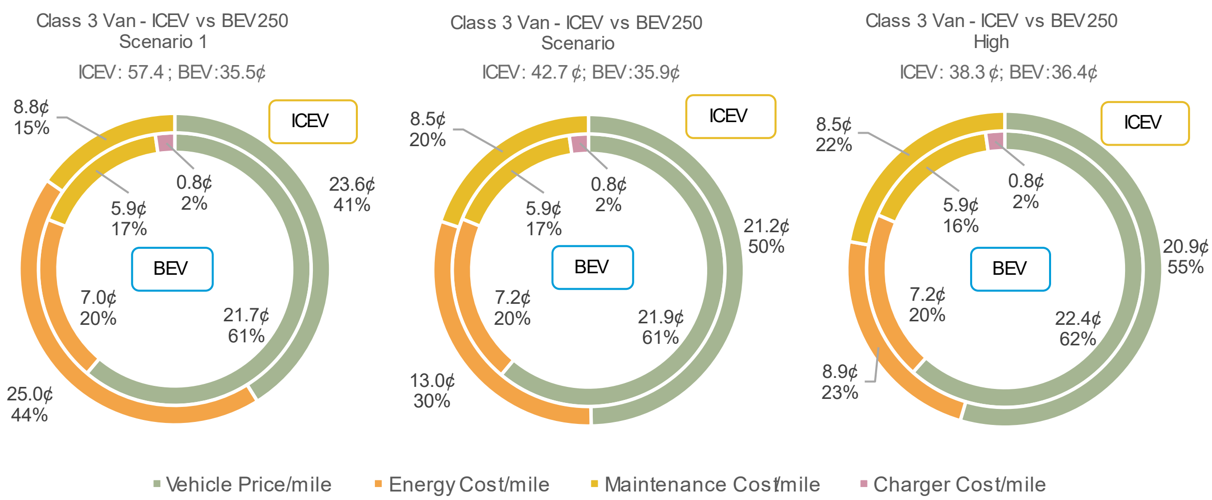


**Figure 80: MY 2030 Class 3 Van ICEV and BEV250 contributions to TCO scenarios.**

### 4.4 Cumulative Net Savings

Figure 81 depicts the cumulative net savings achieved by BEVs over ICEVs during their assumed lifetime of 12 years. Scenario 1 has the highest savings when migrating from a high-cost ICEV to a low-cost BEV, and vice versa for Scenario 3. Except for MY 2027 BEV400 pickup truck, BEV250 class 2b van, BEV250 P&D, and BEV250 class 3 van under Scenario 3, all BEVs across the two model years and three scenarios demonstrate considerable savings with BEV ownership compared to an ICEV. On average, consumers can save about $20,000 and $25,000 in MYs 2027 and 2030, respectively, by purchasing BEVs (given an assumed lifetime of 12 years).

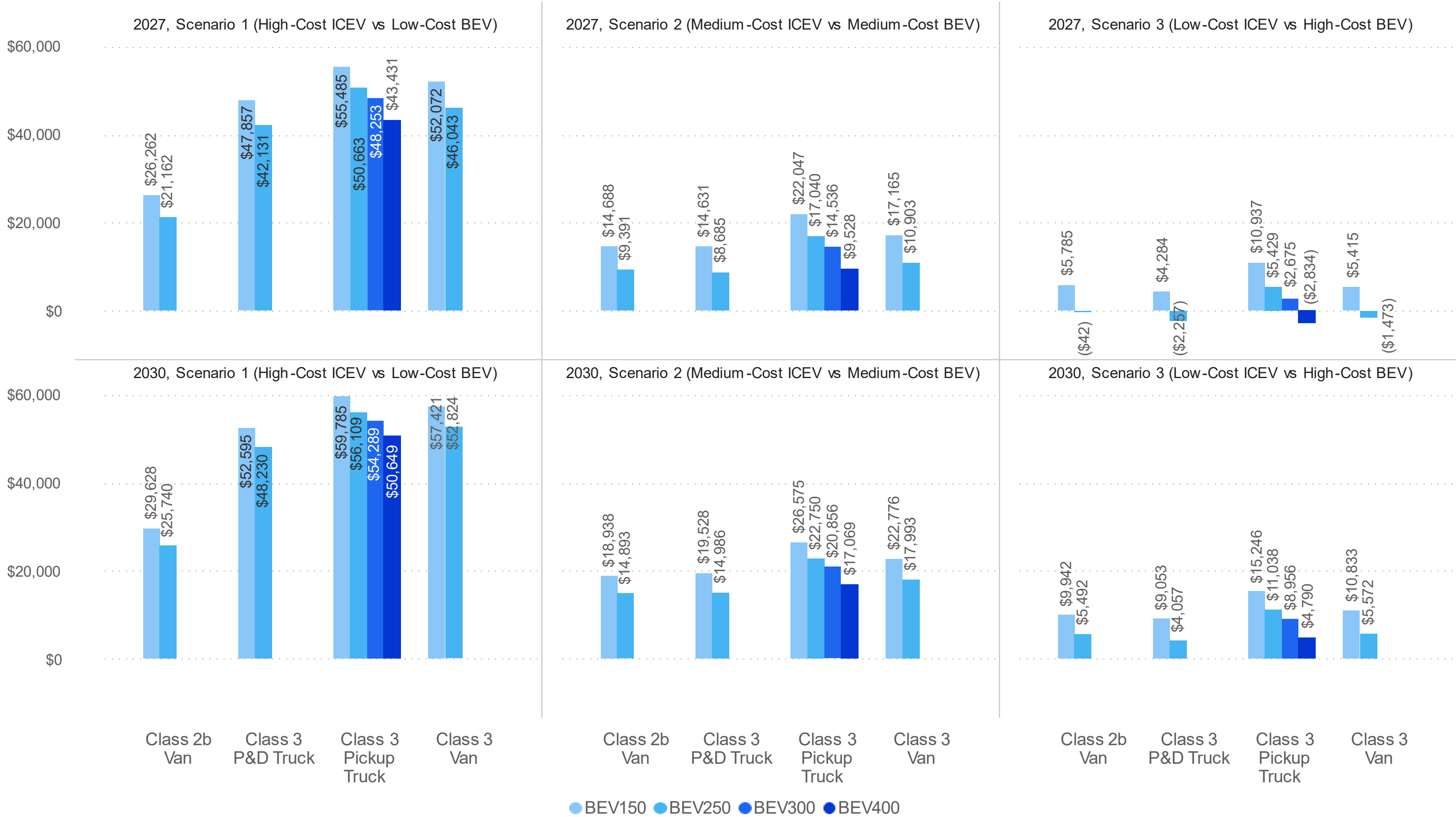


**Figure 81: Projected cumulative net savings of a BEV over ICEV during its lifetime for MYs 2027 and 2030.**

### 4.5 Key Takeaway

The key finding of this analysis is that, over the life of ownership of class 2b–3 vehicles, a BEV is less expensive to own and operate than a comparable ICEV. The TCO per mile on average across all vehicle classes and scenarios is 42.6¢ for an MY 2027 ICEV and 43¢ for an MY 2030 ICEV. For BEVs, the average TCO per mile for MYs 2027 and 2030 is 34.1¢ and 32¢, respectively. Comparing the averages for MYs 2027 and 2030, the TCO per mile for a BEV is ~20% and ~25% lower than for an ICEV, respectively. Moreover, under all but the most pessimistic scenarios, BEVs reach cost parity with ICEVs during the first five years of ownership. In many cases, parity is achieved during the first year. The analysis demonstrates that over the lifecycle of ownership of a vehicle, owning a BEV could result in significant savings for a typical consumer. This total cost of ownership analysis does not consider any subsidies, tax cuts, or other economic incentives that may further lower the cost of BEVs; nor does it consider the vehicle performance benefits.

# 5. What-if Scenario

## 5.1 Commercial Charging

As an exploratory exercise to examine a scenario more specific to fleet owners, we developed a what-if scenario considering 100% on-site commercial charging, which assumes that business entities bear the high, upfront capital cost of charger installation, and use commercial electricity for charging purposes. Scenario 2 (the middle-cost scenario) is used to develop three commercial charging cases that are differentiated based on 19.2 kW level 2 charger hardware and installation costs of $4,000, $6,000, and $15,000. The charger costs remain the same as considered in the primary analysis, but the additional costs go toward installation. The differentiation in the installation costs encompasses the various factors that go into the development of a given charger installation site, such as parking spaces, underground boring, mounting piers, cable tunneling, bollards, etc. [7], [8]. Commercial electricity prices projected by the EIA AEO2022 [6] are considered for estimating energy costs. Table 25 summarizes the time to achieve TCO parity across all vehicle types and segments with 2027–2030 purchase timeframes in this commercial charging scenario.

**Table 25: Cumulative TCO parity of BEVs purchased in 2027 and 2030 in commercial charging scenario.**

| Vehicle Type | BEV Segment | 2027 | | | 2030 | | |
|---|---|---|---|---|---|---|---|
| | | Low charger cost $4,000 | Medium charger cost $6,000 | High charger cost $15,000 | Low charger cost $4,000 | Medium charger cost $6,000 | High charger cost $15,000 |
| Class 2b Van | BEV150 | 1 | 2 | 7 | <1 | 1 | 6 |
| | BEV250 | 4 | 5 | 11 | 2 | 3 | 8 |
| Class 3 Pickup Truck | BEV150 | <1 | 1 | 5 | <1 | <1 | 4 |
| | BEV250 | 3 | 3 | 7 | 1 | 2 | 5 |
| | BEV300 | 4 | 4 | 8 | 2 | 3 | 6 |
| | BEV400 | 6 | 7 | 11 | 3 | 4 | 8 |
| Class 3 Package & Delivery Truck | BEV150 | 1 | 2 | 6 | <1 | 1 | 4 |
| | BEV250 | 4 | 5 | 9 | 2 | 3 | 6 |
| Class 3 Van | BEV150 | 1 | 2 | 7 | <1 | 1 | 5 |
| | BEV250 | 4 | 5 | 11 | 2 | 3 | 8 |

Figure 82 shows the projected range of TCO per mile for MYs 2027 and 2030 for ICEVs and BEVs.

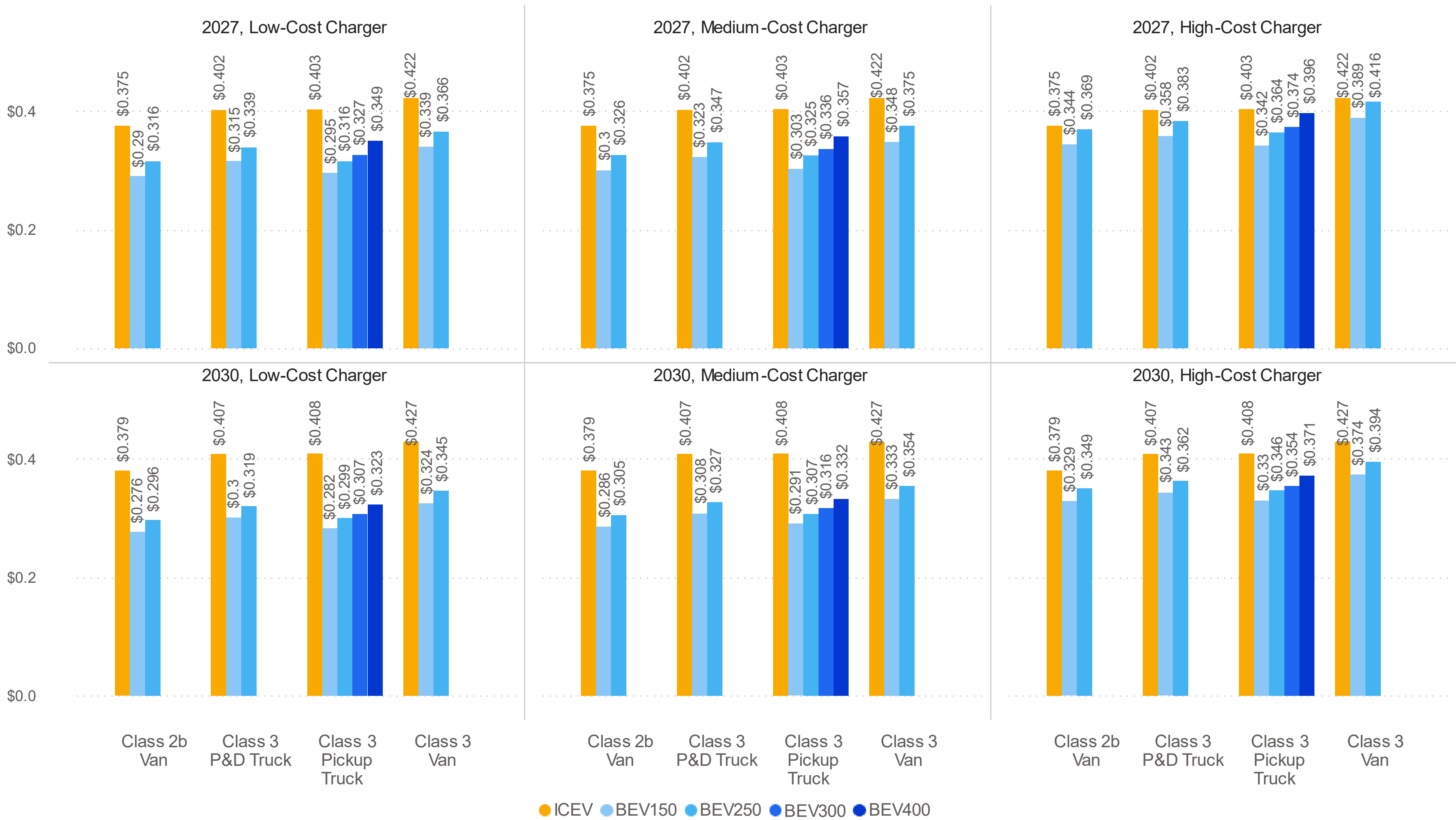


**Figure 82: Projected range of Total Cost of Ownership (TCO) per mile for MYs 2027 and 2030 in commercial charging scenario.**

Figure 83 depicts the cumulative net savings of BEVs over ICEVs during their lifetime of 12 years in this commercial charging scenario. The low charger cost scenario has the highest savings when migrating from a medium-cost ICEV to a medium-cost BEV, and vice versa for Scenario 2. On average, consumers can save about $13,000 and about $18,000 when they purchase MY 2027 and MY 2030 BEVs, respectively, during their assumed lifetime of 12 years. It is essential to note that even though the capital costs can be higher than those of an ICEV for some longer-range vehicle purchases, the BEVs are cheaper to own and operate compared to ICEVs across all the vehicle classes. This is due to the less expensive commercial electricity prices as compared to gasoline prices [6]. Despite the high installation costs of chargers, BEVs are financially attractive and economical to operate for fleet owners. Furthermore, the infrastructure upgrade costs are a one-time investment that would last years beyond the assumed lifetime of a BEV, allowing the fleet owner to reap greater benefits on future BEV purchases. Additionally, with the availability of flexible and off-peak charging rates, the cost of owning a BEV could be even lower than we have found in this analysis.

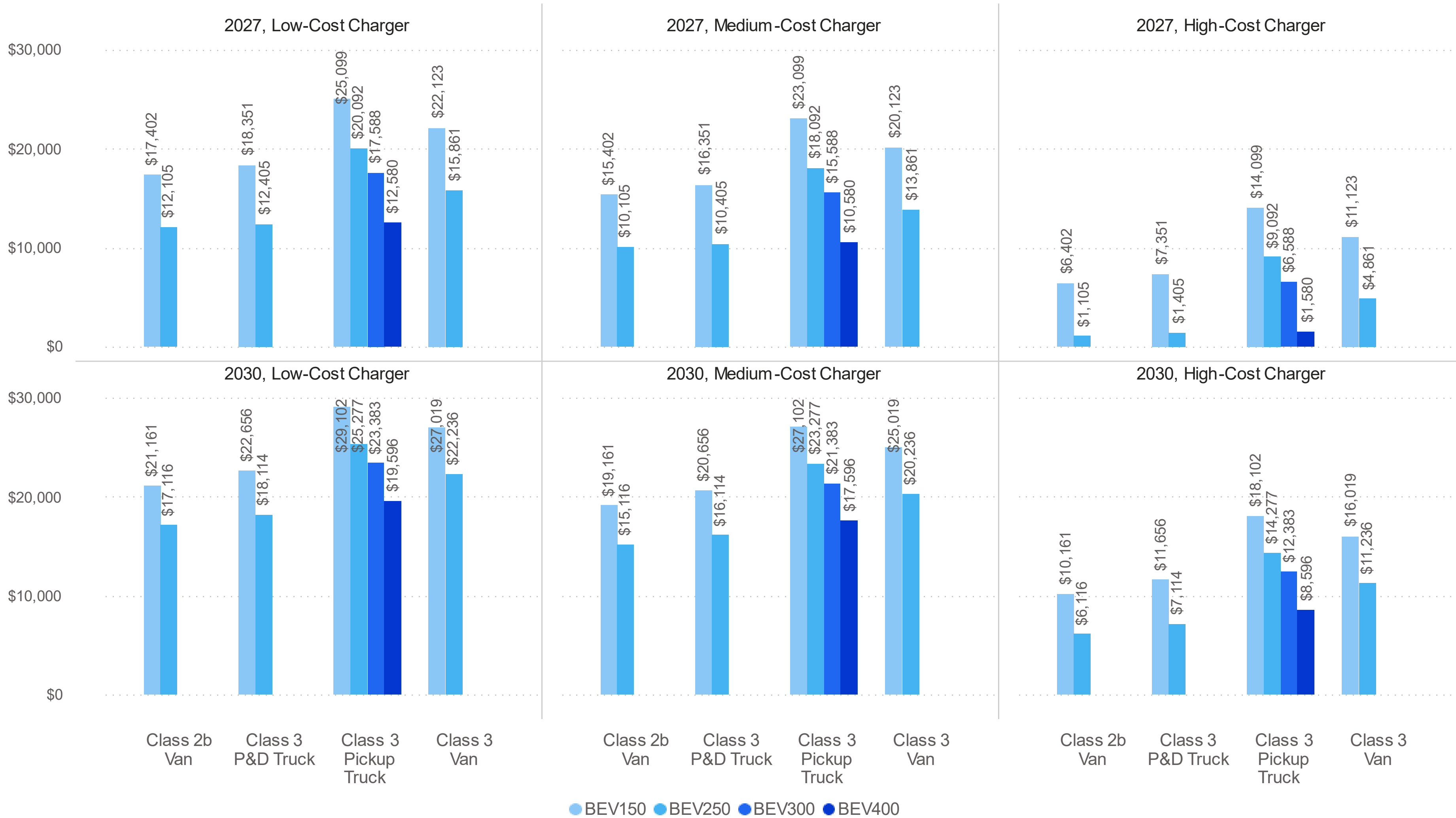


**Figure 83: Projected cumulative net savings of a BEV over ICEV during its lifetime for MYs 2027 and 2030 in a commercial charging scenario.**

## 5.2 Fuel Price Sensitivity

It is difficult to accurately forecast oil prices and to determine if the EIA projected prices per AEO 2022 used in this study are a good measure of future energy costs for ICEVs. As an exploratory what-if scenario, the highest all-time gasoline and diesel retail prices are used as a sensitivity input for ICEVs in all three scenarios of electrification to determine their effect on TCO and parity timeline. Oil prices reached historical all-time highs in 2022, as shown in Figure 84 and Figure 85. In June 2022, California had the highest retail gasoline price at $6.294 per gallon, and the highest diesel retail price in the United States was $5.754 per gallon. We did not include fuel prices that were this high in our primary analysis, so we conducted a sensitivity analysis to determine the potential effects of such price spikes. We used $5.18 per gallon for diesel and $5.80 per gallon for gasoline, without taxes, as sensitivity inputs to estimate the impact of such prices on the findings of this report.

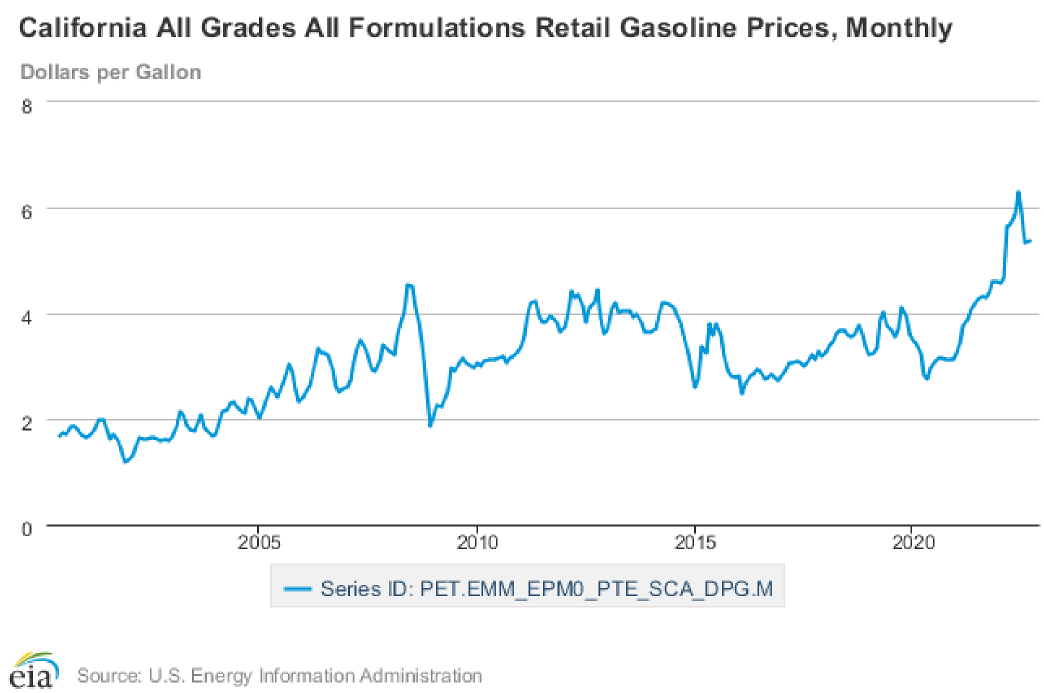


**Figure 84: Highest retail price of gasoline was recorded in California in June 2022 at $6.294. Source: EIA.**

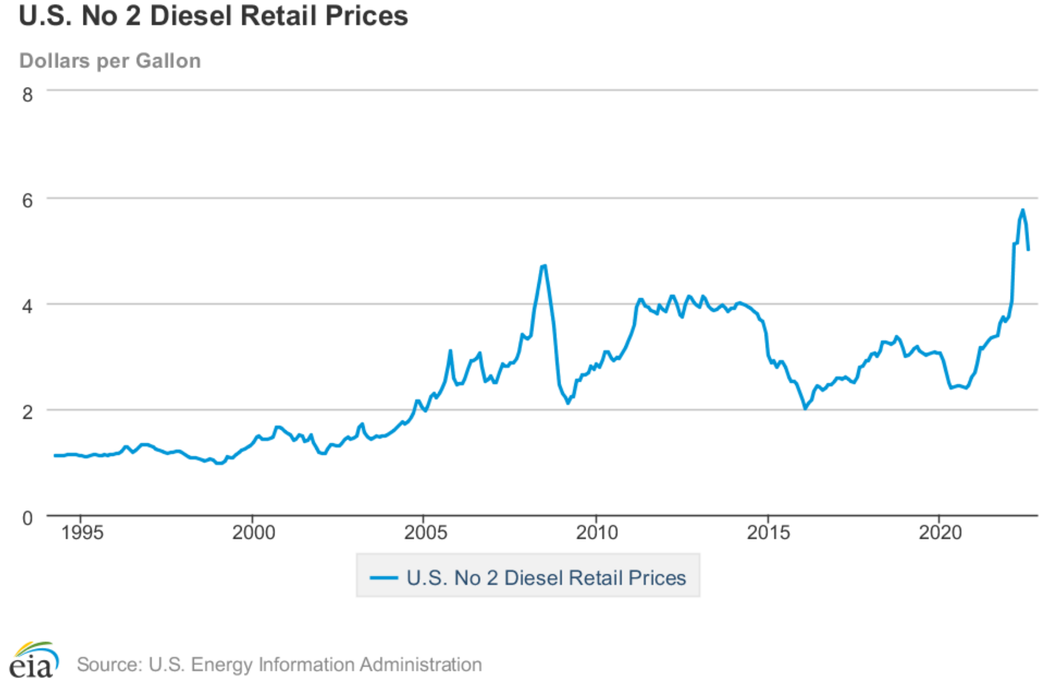


**Figure 85: Historical U.S. diesel retail price. Source: EIA**

As shown in Figure 86, in this high fuel price scenario, on average across all vehicle types and electrification scenarios, the TCO per mile of MYs 2027 and 2030 ICEVs is 58% and 55% higher than that of comparable BEVs, respectively. These results indicate the large cumulative savings achieved by BEV ownership compared to ICEVs ownership.

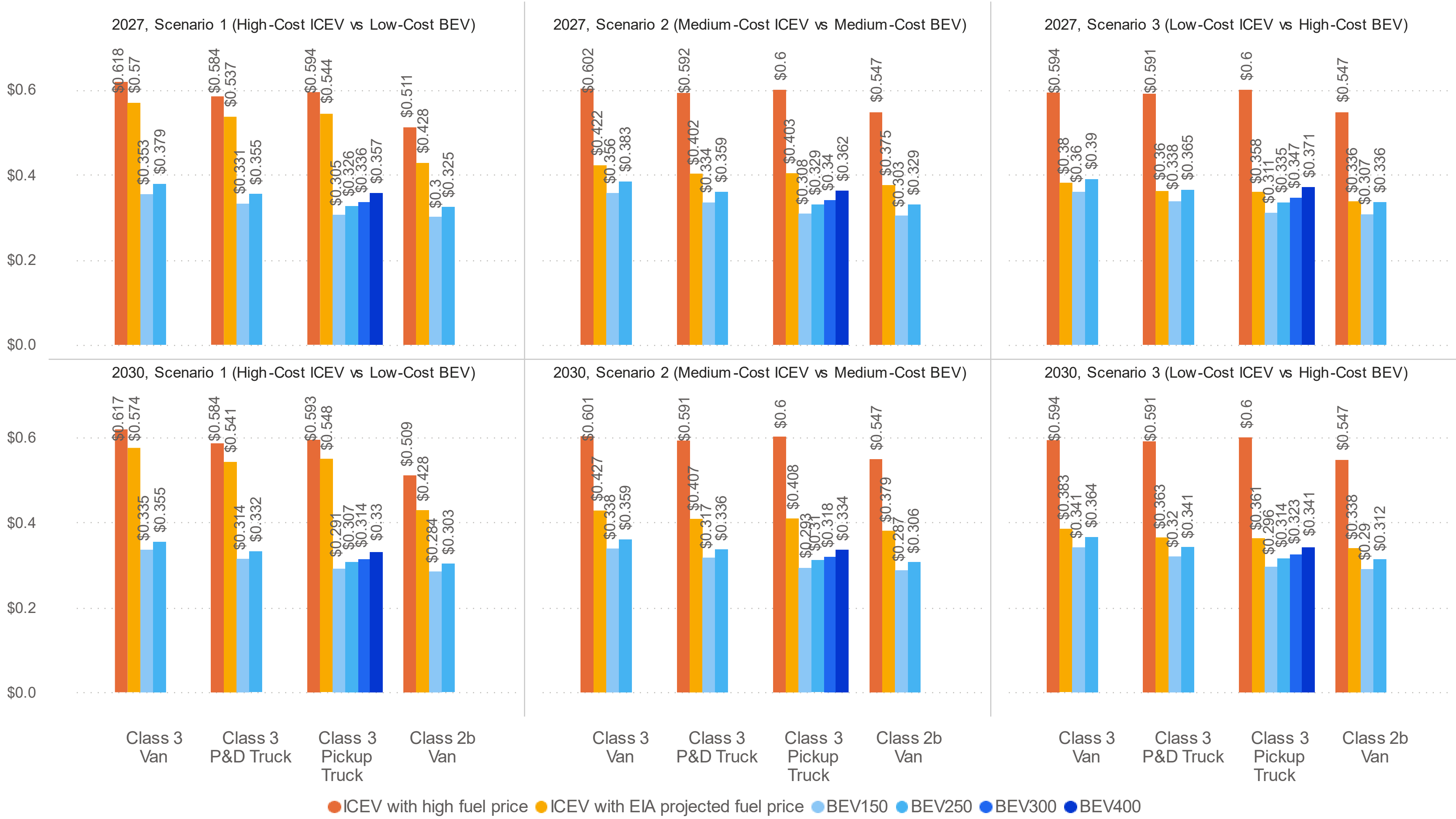


**Figure 86: Projected range of Total Cost of Ownership (TCO) in a high fuel price scenario.**

Table 26 summarizes the time required to achieve TCO parity in a high fuel price scenario across all vehicle types and segments, with purchase timeframes of 2027–2030. It provides a compelling glimpse of the sensitivity of real-world oil prices to the cost of ownership of an ICEV in comparison to a comparable BEV.

**Table 26: Time to achieve parity for MYs 2027 and 2030 BEVs in high fuel price scenario.**

| Vehicle Type | BEV Segment | 2027 | | | 2030 | | |
|---|---|---|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | <1 | <1 | <1 | <1 | <1 | <1 |
| | BEV250 | <1 | 1 | 1 | <1 | <1 | <1 |
| Class 3 Pickup Truck | BEV150 | <1 | <1 | <1 | <1 | <1 | <1 |
| | BEV250 | <1 | <1 | 1 | <1 | <1 | <1 |
| | BEV300 | <1 | 1 | 1 | <1 | <1 | <1 |
| | BEV400 | 1 | 1 | 2 | <1 | 1 | 1 |
| Class 3 Package & Delivery Truck | BEV150 | <1 | <1 | <1 | <1 | <1 | <1 |
| | BEV250 | <1 | 1 | 1 | <1 | <1 | <1 |
| Class 3 Van | BEV150 | <1 | <1 | <1 | <1 | <1 | <1 |
| | BEV250 | <1 | 1 | 1 | <1 | <1 | <1 |

The cost of fuel is a major factor that impacts the cumulative savings achieved by BEVs compared to ICEVs and the time it takes to achieve parity. As can be seen in Figure 87, in this high fuel cost scenario, BEVs offer significant savings of several tens of thousands of dollars across all classes, with an average savings of about $56,000 and $60,000 for MYs 2027 and 2030, respectively.

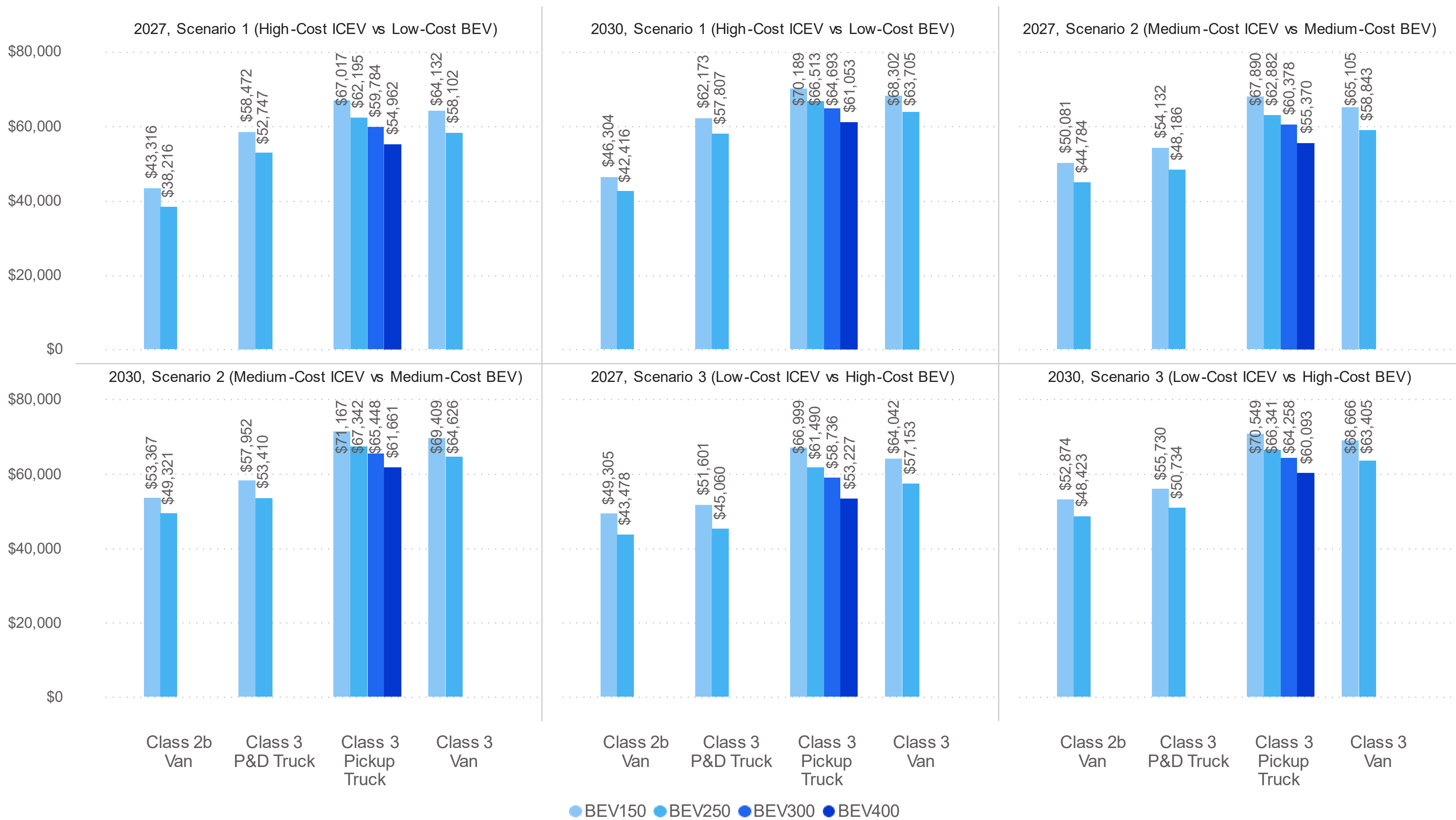


**Figure 87: Projected cumulative net savings of BEV over ICEV in a high fuel price scenario.**

## 5.3 Electricity Price Sensitivity

As a further exploratory exercise, we examined real-world state-specific electricity prices, which show a wider variation over time than average national prices, and estimated their impact on the three incremental costs of electrification scenarios. The average state-specific price of residential electricity from January 2022 to July 2022, as shown in Figure 88, is evaluated to determine the prices for each of the three scenarios. Average residential electricity prices in California, New York, and Michigan are selected as inputs to Scenarios 3, 2, and 1 of electrification, with the rates being 26.26¢, 21.38¢, and 17.63¢, respectively. These represent three distinct takes on “high” residential electricity rates: very high, high, and somewhat high. These three states capture the spread of residential electricity prices from the west coast to the east coast and are much higher than the average electricity prices for other states and the future price projections in EIA AEO 2022.

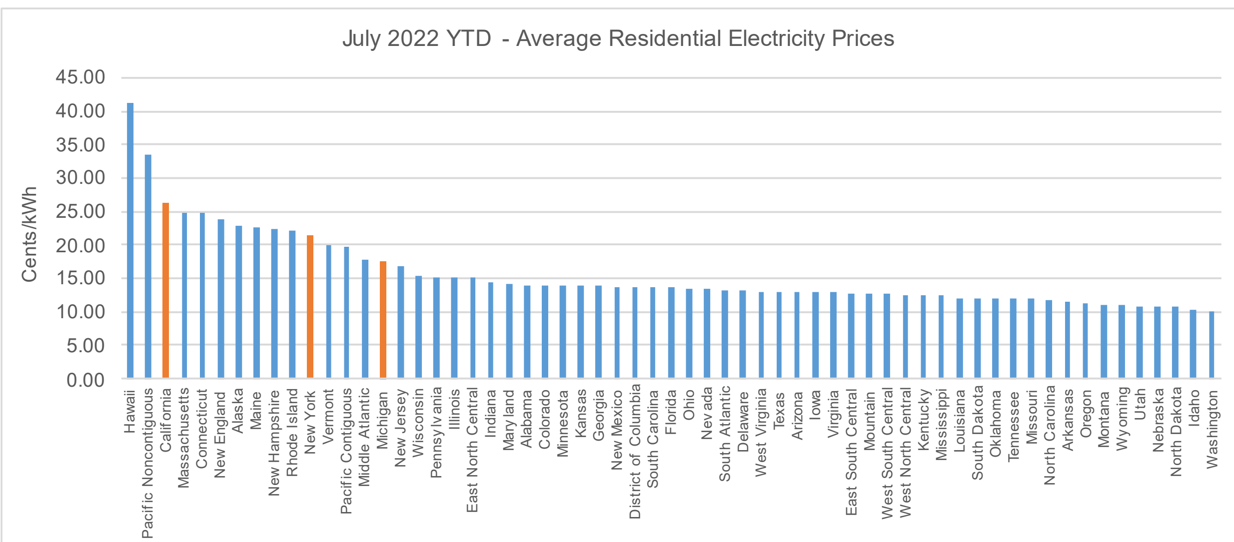


**Figure 88: Average Price of Residential Electricity, by State, from January 2022 to July 2022 (¢/kWh). The orange columns are sensitivity inputs for our analysis. Source: EIA.**

As shown in Figure 89, the average TCO per mile across all vehicles and electrification scenarios for MYs 2027 and 2030 ICEVs is still 18% and 11% higher than a comparable BEV, respectively, even under the assumed high electricity prices considered in this sensitivity analysis. Despite factoring in the real-world state electricity prices, which are much higher than the EIA AEO 2022 projections, the BEVs are still cheaper to operate than a comparable ICEV, except in Scenario 3 of electrification, where California-specific electricity prices are more than double the national average prices.

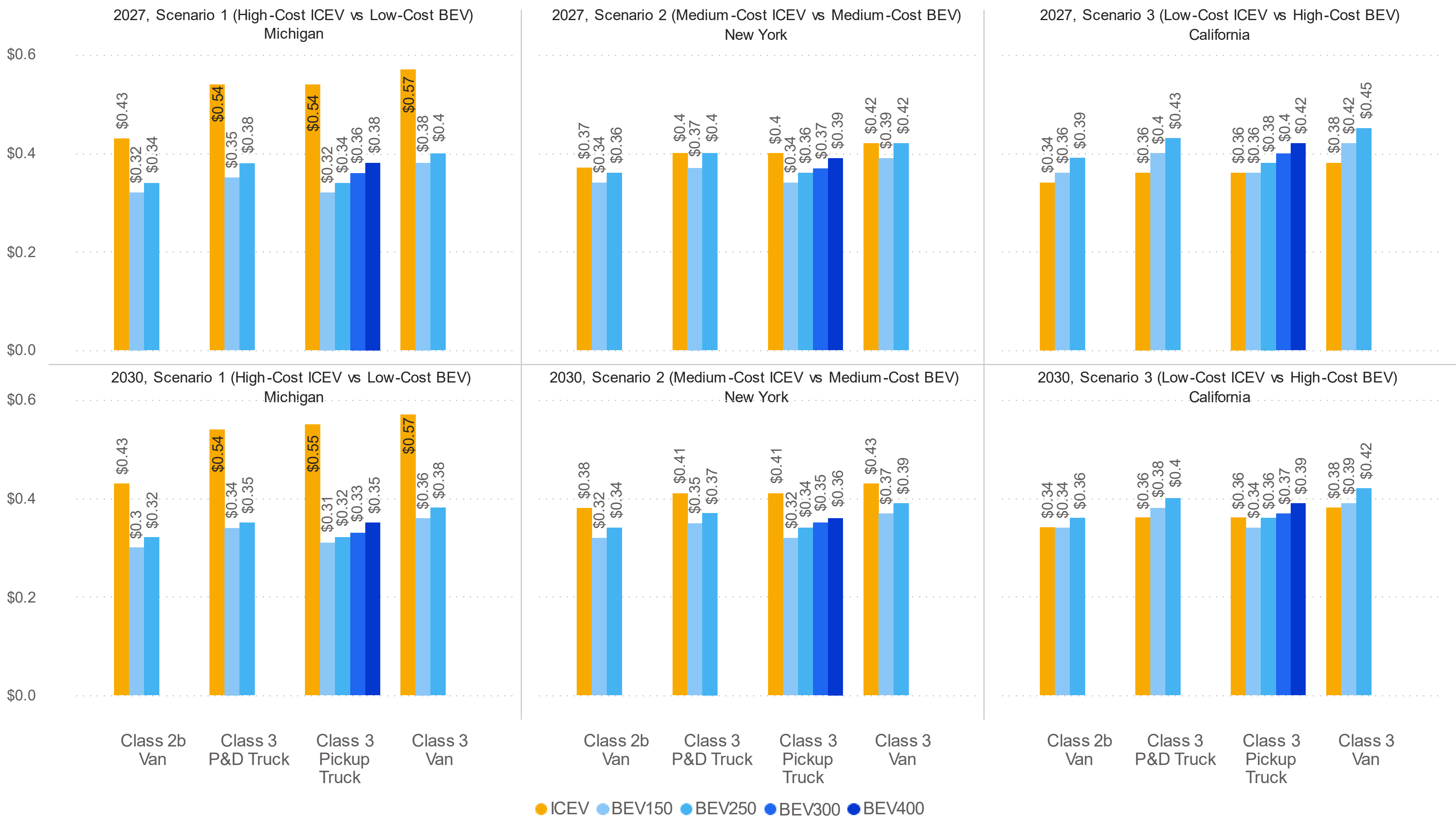


**Figure 89: Projected range of Total Cost of Ownership (TCO) in a high energy price scenario.**

Table 27 summarizes the time required to achieve TCO parity in this electricity price sensitivity analysis across all vehicle types and segments for MY 2027 and MY 2030.

**Table 27: Time required to achieve parity for MYs 2027 and 2030 BEVs with electricity price sensitivity.**

| Vehicle Type | BEV Segment | 2027 | | | 2030 | | |
|---|---|---|---|---|---|---|---|
| | | Scenario 1 (Michigan) | Scenario 2 (New York) | Scenario 3 (California) | Scenario 1 (Michigan) | Scenario 2 (New York) | Scenario 3 (California) |
| Class 2b Van | BEV150 | <1 | <1 | End of Life | <1 | <1 | <1 |
| | BEV250 | <1 | 8 | End of Life | <1 | 2 | End of Life |
| Class 3 Pickup Truck | BEV150 | <1 | <1 | End of Life | <1 | <1 | <1 |
| | BEV250 | <1 | 4 | End of Life | <1 | 1 | 10 |
| | BEV300 | <1 | 6 | End of Life | <1 | 2 | End of Life |
| | BEV400 | 1 | 10 | End of Life | <1 | 4 | End of Life |
| Class 3 Package & Delivery Truck | BEV150 | <1 | 2 | End of Life | <1 | <1 | End of Life |
| | BEV250 | <1 | 10 | End of Life | <1 | 3 | End of Life |
| Class 3 Van | BEV150 | <1 | 1 | End of Life | <1 | <1 | End of Life |
| | BEV250 | <1 | 11 | End of Life | <1 | 3 | End of Life |

As illustrated in Figure 90, BEVs provide significant savings across all vehicle types in Scenarios 1 and 2. Only the MY 2030 class 2b van BEV150 and class 3 pickup truck BEV150 and BEV250 offer savings in Scenario 3, while the other vehicle types in Scenario 3 do not.

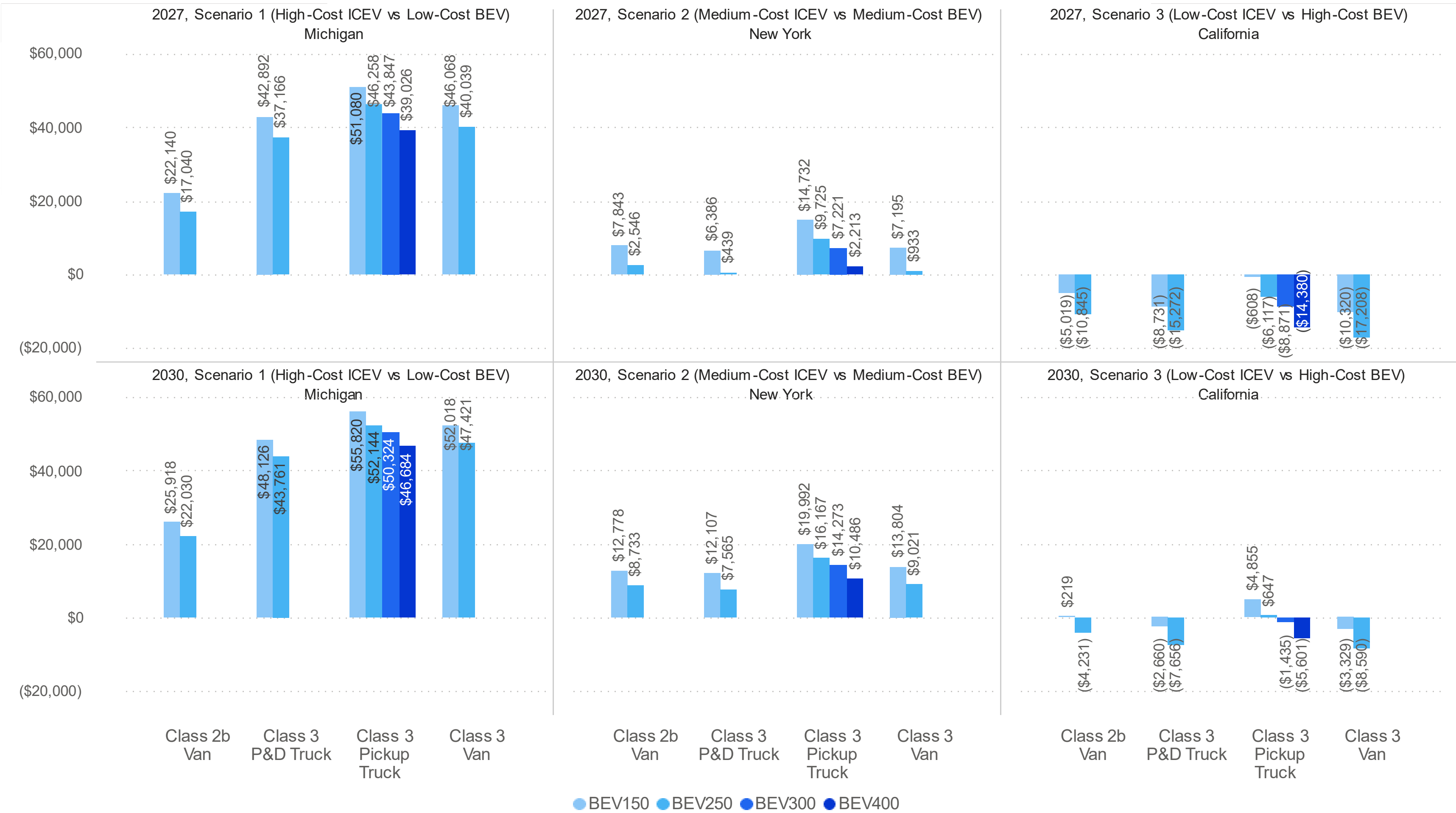


**Figure 90: Projected cumulative net savings of BEVs over ICEVs with state-specific electricity prices.**

## 6. Impact Analysis of the Inflation Reduction Act of 2022

On August 16, 2022, the Inflation Reduction Act of 2022 (IRA) was signed into law. It contains multiple provisions regarding the adoption and deployment of clean transportation technology. Many of the provisions in the Act provide incentives, tax credits, and funding for various programs designed to electrify the transportation sector. The U.S. Department of the Treasury has begun the process of promulgating rules and guidance to implement the IRA. Treasury's actions over the coming months will provide additional clarity on many of the IRA provisions discussed in this report. This section analyzes the effect of these provisions on the class 2b–3 segment and attempts to quantify those effects on the purchase price of a BEV, the price of a vehicle charger, and the TCO of the vehicle. Furthermore, this section also examines the qualitative impact of IRA provisions on the class 2b–3/medium-duty ecosystem from upstream to downstream.

This section projects impacts based on electrification Scenario 2 (the medium-cost scenario). The originally estimated incremental cost of electrification (pre-IRA) for MYs 2022 and 2027 has been used as a baseline to analyze the impact of IRA tax incentives. To assess the near-term effects, the costs of MY 2022 have been used as a substitute for the projections of MY 2023 since the tax provision for the purchase price will not be effective until after December 31, 2022. IRA vehicle purchase and charging equipment credits have been addressed quantitatively, while the other aspects of the law have been addressed qualitatively. As stated earlier, this impact analysis does not factor in potential geopolitical risks to the battery supply chain and any associated rising raw material costs. This study assumes that the long-term raw material supply grows simultaneously with BEV demand, without any shortages.

### 6.1 Impact Analysis

This IRA impact analysis is broadly divided into two sections: quantitative impact and qualitative impact. The quantitative impact assessment evaluates the IRA vehicle purchase price and charging infrastructure tax incentives to ascertain the cost-benefit to the end user. The qualitative impact assessment delves into the various funding and financing programs, grants, rebates, and emission reduction programs that will stimulate and encourage the adoption of BEVs over comparable ICEVs in the MD/HD segment. The intent is to present the results generated from the theoretical application of these provisions in the class 2b–3 segment and to gauge impacts related to the electrification of class 2b–3 vehicles. Given the difficulty in quantifying some IRA effects, there may be certain scenarios where the impact on electrification of the class 2b–3 segment could be greater than estimated here.

## 6.2 Quantitative Impact

To assess and quantify the IRA's direct impact on the class 2b–3 segment, vehicle purchase price credits and charging equipment credits are applied to Scenario 2 (medium cost) developed in the primary (i.e., non-IRA) analysis. Broadly speaking, there are two IRA vehicle-level tax credits that purchasers of class 2b–3 vehicles would be able to choose from: the clean vehicle credit and the qualified commercial clean vehicle credit. Individuals and business entities may also be able to claim a tax credit for the installation of charging equipment. The following sections detail the applicability of these credits.

### 6.2.1 Clean Vehicle Credit – 26 U.S.C. §30D

This section of the IRA amends the tax credit provisions for plug-in electric vehicles under 26 U.S.C. §30D, while also expanding eligibility to fuel cell vehicles (FCVs), which had a previous tax credit under 26 U.S.C. §30B that expired on December 31, 2021. The provision defines "clean vehicles" as those propelled primarily by electricity with a battery capacity of at least 7 kWh and capable of being recharged from an external source of electricity; the definition is also expanded to include hydrogen FCVs. The maximum allowable credit per vehicle is capped at $7,500 for vehicles with a gross vehicle weight rating (GVWR) of less than 14,000 lbs., which would include class 2b–3 vehicles. The provision establishes income and price limits to qualify for the credit. Qualifying vehicles must also meet:

a) North American final assembly requirements,
b) Critical minerals sourcing requirements, and
c) Battery component manufacturing requirements.

This provision also eliminates the previous per-manufacturer cap of 200,000 vehicles qualifying for credits, a cap that was already exceeded by OEMs such as Tesla and GM. Sellers are required to provide taxpayer and vehicle information to the Department of Treasury for tax credit-eligible vehicles. Only vehicles manufactured by qualified manufacturers who have signed written agreements with Treasury and submit periodic reports may be eligible. Figure 91 lists the vehicle credit provisions in the pre- and post-IRA periods.

| | Pre-IRA 2022 | | Post-IRA 2022 | | |
|---|---|---|---|---|---|
| | Plug-in EV Credit | Fuel Cell Vehicle Credit | Clean Vehicles Credit | Credit for Previously-Owned Clean Vehicles | Credit for Commercial Clean Vehicles |
| Maximum Amount | $7,500 base amount of $2,500 plus $417 for each kWh of capacity above 5 kWh (up to $5,000) | $8,000 or $40,000 base amount of $4,000 plus up to $4,000 additional based on fuel economy; credit of up to $40,000 for heavy vehicles | $7,500 $3,750 for vehicles meeting the critical minerals requirement; $3,750 for vehicles meeting the battery components requirement | $4,000 limited to 30% of the sales price | $7,500 or $40,000 credit is limited to the lesser of 15% of the vehicle's cost (30% for vehicles not gasoline or diesel powered) or the incremental cost of the vehicle, as compared to vehicles powered with a gasoline or diesel ICE; credit of up to $40,000 for heavy vehicles |
| Qualifying Vehicles | battery with 4 kWh of capacity with external charging | vehicles propelled by fuel cells | battery with 7 kWh of capacity with external charging; vehicles propelled by fuel cells; after 2024, no credits allowed for batteries containing critical minerals sourced from a foreign entity of concern; after 2023, no credit for batteries with components sourced from a foreign entity of concern | previously-owned clean vehicles having a model year that is two years earlier than the calendar year; credit can only be claimed on the first transfer of the vehicle; vehicle must be purchased from a dealer | clean vehicles and mobile machinery; larger EVs required to have a battery with 15 kWh of capacity; vehicle must be subject to a depreciation allowance (i.e., for business use), except in the case of vehicles used by tax-exempt entities |
| Manufacturering Location Requirements | n.a. | n.a. | final assembly must occur within North America (effective 8/16/2022) | n.a. | n.a. |
| Manufacturer Limitations | phaseout after 200,000 plug-in EVs manufactured | n.a. | n.a. | n.a. | n.a. |
| Eligible Taxpayers | individuals & businesses; for tax-exempt entities seller can claim credit | | individuals & businesses | individuals (limited to one credit every 3 years) | businesses & tax-exempt entities; tax-exempt entities could receive credit as direct pay |
| Price Limits | n.a. | n.a. | no credit allowed for vans, SUVs, pickup trucks with MSRP > $80,000; other vehicles with an MSRP > $55,000 | no credit allowed if the sales price is $25,000 or more | n.a. |
| Income Limits | n.a. | n.a. | no credit if MAGI > $300,000 (married filing jointly); MAGI > $225,000 (head of household); MAGI > $150,000 (single); income thresholds apply to the lesser of current year or prior year MAGI | no credit if MAGI > $150,000 (married filing jointly); MAGI > $112,500 (head of household); MAGI > $75,000 (single); income thresholds apply to the lesser of current year or prior year MAGI | n.a. |
| VIN Reporting Requirements | n.a. | n.a. | seller must report VIN to the Treasury; taxpayers must report VIN on tax return | | taxpayers must report VIN on tax return |
| Transferability | only for tax-exempt entities | only for tax-exempt entities | taxpayers can elect to transfer credit to dealer (effective after 12/31/2023) | taxpayers can elect to transfer credit to dealer (effective after 12/31/2023) | n.a. |
| Expiration | none | 12/31/2021 | 12/31/2032 | 12/31/2032 | 12/31/2032 |

**EV** = electric vehicle; **kWh** = kilowatt hour; **MAGI** = modified adjusted gross income; **MSRP** = manufacturer's suggested retail price; **SUV** = sport utility vehicle; **ICE** = internal combustion engine; **VIN=** vehicle identification number; **n.a.** = not applicable

**Figure 91: Clean Vehicle Credits in the Inflation Reduction Act of 2022. Source: CRS analysis of P.L. 117-169.**

Starting in 2023 and upon the adoption of Treasury guidance, EVs qualify for a total credit of up to $7,500 only if the vehicle's battery meets threshold percentages for critical mineral sourcing and battery component manufacturing or assembly, as listed in Table 28. Each of these two conditions carries a credit of $3,750. Vehicles can qualify for one or both $3,750 credits.

**Table 28: Applicable minimum percentage of critical mineral and battery component requirements.**

<table>
<tr><th>Service date</th><th>Critical Mineral ($3,750)</th><th>Battery Component ($3,750)</th></tr>
<tr><td>Placed in service before January 1, 2024</td><td>40%</td><td>50%</td></tr>
<tr><td>Placed in service during the calendar year 2024</td><td>50%</td><td rowspan="2">60%</td></tr>
<tr><td>Placed in service during the calendar year 2025</td><td>60%</td></tr>
<tr><td>Placed in service during the calendar year 2026</td><td>70%</td><td>70%</td></tr>
<tr><td>Placed in service during the calendar year 2027</td><td rowspan="3">80%</td><td>80%</td></tr>
<tr><td>Placed in service during the calendar year 2028</td><td>90%</td></tr>
<tr><td>Placed in service after 2028</td><td>100%</td></tr>
</table>

To qualify for the $3,750 critical minerals portion of the credit, at least 40% of the value of the battery's applicable critical minerals must have been extracted or processed in the United States or in a country with which the United States has a free trade agreement, or from critical minerals recycled in North America. Beginning in 2024, the required threshold percentage increases by 10% every year until it reaches 80% for vehicles placed in service in 2027 and thereafter.

Similarly, to qualify for the $3,750 battery component portion of the credit, at least 50% of the value of the battery's components must have been manufactured or assembled in North America. Beginning in 2024, the threshold percentage rises to 60%, then 10% per year after that until it reaches 100% for vehicles placed in service in 2029 and later.

Figure 92 provides an overview of the sourcing and production criteria for §30D and §45X (§45X is covered in detail below). The green color indicates the geographic areas from which critical minerals and battery component manufacturing must be sourced for vehicles to qualify for applicable credits. The yellow color indicates the geographic areas that do not qualify for §30D credits. The dark blue shading for §45X indicates that only eligible components manufactured in the United States qualify for applicable credits. An "X" indicates that vehicles using batteries recycled or sourced from these areas do not qualify for credits.

| IRA Credits | | Conditions | United States | North America | FTA partner | Foreign Entity of Concern |
|---|---|---|---|---|---|---|
| §30D Clean Vehicle Credit<br>(all 3 conditions to be met to define qualifying vehicle) | $3,750 to Consumer | Ia. Critical Minerals Extraction or Processing | Applicable % to be met from 2023 | | | Vehicle does not qualify for any credit after **2024** |
| | | Ib. Critical Minerals Recycling | | | X | X |
| | $3,750 to Consumer | II. Battery Components | Applicable % to be met from 2023 | | X | Vehicle does not qualify for any credit after **2023** |
| | | III. Final Assembly | | | X | X |
| §45X Advanced Manufacturing Production Credit | Variable $$ to OEM | Covered in detail in Section 6.3.1.2 | | X | X | X |

**Figure 92: Applicability of tax credits under §30D and §45X under the IRA of 2022.**

Vehicles are ineligible for the credit if: (i) after 2023, they contain battery components manufactured or assembled by a foreign entity of concern (as defined in U.S.C. 18741(a)(5)); or (ii) after 2024, the battery contains critical minerals that were extracted, processed, or recycled by a foreign entity of concern. All credit provisions, regardless of source or component content, expire on December 31, 2032. Before that time, credit is only allowed for vehicles that do not exceed the following manufacturer's suggested retail price (MSRP):

a) Vans: $80,000
b) SUVs: $80,000
c) Pick-up Trucks: $80,000
d) Any other vehicle: $55,000

The vehicle purchaser can elect to transfer tax credits to the vehicle dealer at the point of sale beginning in 2024, once the Department of Treasury and IRS finalize a credit transfer mechanism. All credit eligibility requirements will still apply.

For this analysis, the provisions described above are used to determine the applicable purchase price credits for each of the considered vehicle classes. To determine the potential impact of the IRA, the full credit amount of $7,500 is applied to BEV MSRPs for 2023 and 2027 vehicles. The primary restrictions affecting class 2b–3 vehicles' qualification for the clean vehicle credit are: a) battery production and battery component sourcing requirements, and b) vehicle price limitations.

### 6.2.2 Qualified Commercial Clean Vehicles – 26 U.S.C. §45W

This provision of the IRA creates a new tax credit for purchases of qualified commercial electric vehicles for all vehicle classes spanning from LDVs to MD/HDVs. It adds a new section, 26 U.S.C. §45W, which takes effect after December 31, 2022, and applies until its expiration on December 31, 2032.

The amount of the credit is the lesser of:

a) 15% of the vehicle's cost (30% for vehicles not powered by a gasoline or diesel internal combustion engine); or
b) the vehicle's incremental (excess) cost in comparison to a comparable gasoline- or diesel-powered vehicle.

The maximum credit is $7,500 for vehicles with a GVWR of less than 14,000 lbs., or $40,000 otherwise. Eligible vehicles must be charged by an external source of electricity and have a battery capacity of not less than:

a) 7 kWh in the case of vehicles with a GVWR of less than 14,000 pounds (i.e., light-duty vehicles (LDVs) and class 2b–3 vehicles).
b) 15 kWh in the case of other classes (i.e., class 4 and larger vehicles).

For this analysis, these provisions are used to determine the applicable purchase price credits for each of the considered vehicle classes. The battery size requirement is not restricting for the BEVs being evaluated in this study. Since class 2b–3 vehicles have a GVWR of less than 14,000 lbs., the credit is capped at $7,500. The limitation that the credit cannot exceed 30% of the vehicle's cost is inapplicable for our purposes, as it would only limit the credit for vehicles costing less than $25,000 (which is less expensive than all class 2b–3 BEVs considered in this analysis). However, the credit would be less than $7,500 if the incremental cost of the BEV over a comparable ICEV is less than this amount, which is sometimes the case for the vehicles considered in our analysis. These provisions are applied to the MY 2023 and 2027 BEVs analyzed above to determine potential IRA impacts on the economics of electrification.

### 6.2.3 Alternative Fuel Vehicle Refueling Property Credit – 26 U.S.C. §30C

This provision of the IRA extends and modifies the available credits in 26 U.S.C. §30C for alternative fuel vehicle refueling property (as related to charging infrastructure for this analysis). A tax credit for the cost of any qualified alternative fuel vehicle refueling property installed by a business or at a taxpayer's principal residence was in existence until 2021 and is extended by the IRA. The credit is equal to 30% of property costs, capped at $1,000 for residences. For business property, the credit is extended at a rate of 6% of the property costs (30% if prevailing wage and registered apprenticeship requirements are met), capped at $100,000. The credit expires on December 31, 2032, but starting in 2023, charging or refueling property is only eligible if it is placed in service within a low-income or rural census tract.

In this analysis, a 19.2 kW level 2 residential charger is assumed to cost $1,800 ($1000 for equipment and $800 for installation). Due to the wide variation in charger installation expenses across different regions, we have applied the credits only to the charger unit resulting in a conservative estimate. We assumed a flat 30% credit on the cost of the charger unit, which is equivalent to $300. As a result, total charger costs effectively decline from $1,800 to $1,500 in the case of a residential charging scenario. While some charger units will not qualify for this credit due to the census tract limitations, we applied the credit here because our analysis aims to evaluate the impacts of the IRA under favorable conditions.

## 6.3 Qualitative Impact

We also assessed the qualitative impact of the IRA on the class 2b–3 segment. The IRA provisions we considered can be broadly divided into three categories: tax incentives, loans and grants, and other clean transportation incentives. The provisions of the IRA are discussed under each of these general headings based on their indirect effect on the electrification of the class 2b–3 segment.

### 6.3.1 Tax Incentives

#### 6.3.1.1 Extension of the Advanced Energy Project Credit – 26 U.S.C. §48C

This provision extends the 26 U.S.C. §48C advanced energy project credit, starting in 2023. It provides additional allocations of the qualified advanced energy manufacturing tax credit, a 30% tax credit for investments in projects that reequip, expand, or establish certain energy manufacturing facilities. An additional $10 billion is earmarked to provide credits for advanced energy projects. The term “qualifying advanced energy project” includes the following three project types:

a) A project that re-equips, expands, or establishes an industrial or manufacturing facility for the production or recycling of one of the following nine property types:
   i) Property designed to be used to produce energy from the sun, water, wind, geothermal deposits, or other renewable resources.
   ii) Fuel cells, microturbines, or energy storage systems and components.
   iii) Electric grid modernization equipment or components.
   iv) Property designed to capture, remove, use, or sequester carbon oxide emissions.
   v) Equipment designed to refine, electrolyze, or blend any fuel, chemical, or renewable product or low-carbon and low-emission.
   vi) Property designed to produce energy conservation technologies (including residential, commercial, and industrial applications).

vii) Light, medium, or heavy-duty electric or fuel cell vehicles, as well as technologies, components, or materials for such vehicles, and associated charging or refueling infrastructure.
viii) Hybrid vehicles with a gross vehicle weight rating of not less than 14,000 lbs., as well as technologies, components, or materials for such vehicles.
ix) Advanced energy property designed to reduce greenhouse gas emissions.

b) A project that re-equips an industrial or manufacturing facility with equipment designed to reduce greenhouse gas emissions by at least 20% through the installation of
   i) Low- or zero-carbon process heat systems,
   ii) Carbon capture, transport, utilization, and storage systems,
   iii) Energy efficiency and reduction in waste from industrial processes, or
   iv) Any other industrial technology designed to reduce greenhouse gas emissions.
c) A project that re-equips, expands, or establishes an industrial facility for the processing, refining, or recycling of critical materials (as defined in § 7002(a) of the Energy Act of 2020 (30 USC § 1606(a)).

Projects receive a base credit rate of 6% of the total cost or a bonus rate of 30% if the projects meet prevailing wage and registered apprenticeship requirements.

#### 6.3.1.2 Advanced Manufacturing Production Credit – 26 U.S.C. §45X

This provision creates a new production tax credit, 26 U.S.C. §45X, that could be claimed for domestic battery production. The following credits apply to cell material or production:

a) A credit of 10% of the cost of production is available for the domestic production of critical minerals. Per the USGS, a “critical mineral” is a non-fuel mineral or mineral material essential to the economic or national security of the U.S. and which has a supply chain vulnerable to disruption. Critical minerals are also characterized as serving an essential function in the manufacturing of a product, the absence of which would have significant consequences for the economy or national security. A list of critical minerals per 26 U.S.C. §45X can be found in Appendix 9.7 for reference.
b) For electrode active materials, the credit is 10% of the production cost. The term “electrode active material” means cathode materials, anode materials, anode foils, and electrochemically active materials, including solvents, additives, and electrolyte salts that contribute to the electrochemical processes necessary for energy storage.
c) Battery cells could qualify for a credit of $35/kWh, and battery modules could qualify for a credit of $10/kWh. The term “battery cell” means an electrochemical cell,
   i) comprised of 1 or more positive electrodes and 1 or more negative electrodes,
   ii) with an energy density of not less than 100 Wh/liter, and
   iii) capable of storing at least 12 Wh of energy.
d) Battery modules that do not use battery cells qualify for a credit of $45/kWh. The term “battery module” means a module,

i) (aa) in the case of a module using battery cells, with 2 or more battery cells which are configured electrically, in series or parallel, to create voltage or current, as appropriate, to specified end use, or (bb) with no battery cells, and

ii) with an aggregate capacity of not less than 7 kWh (or, in the case of a module for a hydrogen fuel cell vehicle, not less than 1 kWh).

The sales of eligible components are considered only if their production is within the US or a US territory (including continental shelf areas). Full credits are provided for eligible components produced and sold before January 1, 2030. The credit begins to phase out for eligible components sold at a fixed rate of 25% each year, i.e., 75%, 50%, and 25% of the credits described above are available in 2030, 2031, and 2032, respectively. No credit is available for components sold after December 31, 2032. The phaseout does not apply to the production of critical minerals. Table 29 illustrates the applicability of credits specific to battery-related components and materials.

**Table 29: Advanced Manufacturing Production Credit applicable battery materials.**

| Manufacturing production credit to batteries | *Credits remain same* | | | | | | | | *Most credits phase-out* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 |
| Electrode active materials | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 7.5% | 5% | 2.5% | - |
| Cells ($/kWh) | $35 | $35 | $35 | $35 | $35 | $35 | $35 | $35 | $26.3 | $17.5 | $8.8 | - |
| Modules ($/kWh) | $10 | $10 | $10 | $10 | $10 | $10 | $10 | $10 | $7.5 | $5 | $2.5 | - |
| Modules that don't use cells ($/kWh) | $45 | $45 | $45 | $45 | $45 | $45 | $45 | $45 | $33.8 | $22.5 | $11.3 | - |
| Production of Critical Minerals *(Credits do not phase out)* | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% | 10% |

Provision §45X contains some ambiguity regarding the following issues, which will be clarified through Treasury actions[1].

a) **Critical minerals**:

i) Since critical minerals go through several transformation steps and the allocated capital is amortized over several years, determining the incurred costs in the production of critical minerals and electrode active materials is ambiguous. It is unclear if the definition of production costs includes overhead costs (such as the cost of consumables), upfront costs, and indirect production-related costs.

ii) Moreover, it is unclear whether the requirement for sourcing, extraction, or processing of critical minerals from a non-foreign entity of concern is required—that is, whether the critical mineral requirement in this section aligns with the definition in §30D.

iii) Furthermore, the provision does not state whether the critical minerals must be converted and purified into battery-grade material.

[1] This report was drafted in 2022 and early 2023 before the release of the prepublication draft Treasury guidance.

iv) The eligibility of recycled critical minerals is unclear.

b) **Electrode active materials**: Whether other common battery materials or those under development, such as conductive additives (for example, carbon black), binder materials (fluoropolymers), ionically conductive separators, carbon nanotubes, pouches, cathode foils, solid electrolytes, tabs, tapes, adhesives and the raw materials used to make them, would be included in the definition of electrode active materials for credit eligibility.

c) **Module production tax credit**: If the battery pack is eligible for the module production tax credit in the absence of a module configuration in a cell-to-pack or cell-to-chassis configuration, or if combining multiple modules to form larger modules to form a pack would be considered individually for the credit.

d) The impact of clauses such as "sale of components to a related and unrelated person" and "integrated, incorporated or assembled" on credit applicability are unclear.

#### 6.3.1.3 Clean Electricity Production Credit and Investment Credit

The provisions add a new §45Y known as the clean energy production credit and §48E known as the clean electricity investment credit. These provisions bolster the energy generation sector by providing credits to clean energy producers, with a choice to use the credits either upfront to reduce their required investment or during production. The IRA extends, expands, and modifies the 26 U.S.C. §45 production tax credit (PTC) and the 26 U.S.C. §48 investment tax credit (ITC) through 2024. After this point, the IRA introduces new investment and production credits: §45Y, known as the clean energy production credit, and §48E, known as the clean electricity investment credit. These provisions bolster the energy generation sector by providing credits to clean energy producers, with a choice to use the credits either upfront to reduce their required investment or during production. Producers can choose between a PTC under §45Y or an ITC under §48D, which is provided based on the carbon emissions of the electricity generated – measured as grams of carbon dioxide equivalents ($CO_2e$) emitted per kWh generated. The provisions create an emissions-based incentive that would be neutral and flexible between clean electricity technologies. The credits would end after 2032, or when the emission targets are achieved (i.e., when the electric power sector emits an amount equal to or less than 25% of their 2022 levels). In that case, the incentives will be phased out over 3 years.

These credits could have an impact on BEV adoption and economic appeal as a result of reduced charging rates, as these credits allow energy producers to offset a portion of their investment and production costs.

### 6.3.2 Federal Funding and Financing Opportunities

#### 6.3.2.1 Funding for the Department of Energy Loan Programs Office

The IRA provides $40 billion in additional commitment authority for eligible projects under Title XVII section 1703 through Sept. 30, 2026. This funding will be available for existing eligible projects and will expand the eligibility for projects that increase the domestic supply of critical minerals through the production, processing, manufacturing, recycling, or fabrication of mineral alternatives. Additionally, the provision will provide $3.6 billion in credit subsidy costs through September 30, 2026. It also establishes a time-limited (available through FY2026), $250 billion Title XVII loan guarantee commitment authority—Section 1706—for "Energy Infrastructure Reinvestment Financing." This loan guarantee program includes fossil fuel energy infrastructure facilities and electricity generation and transmission energy infrastructure, encouraging them to reduce GHG emissions.

DOE would provide access to debt capital for large-scale energy projects that use innovative technology. The IRA, in conjunction with the Infrastructure Investment and Jobs Act, also supports projects involving critical minerals processing, manufacturing, and recycling.

#### 6.3.2.2 Advanced Technology Vehicle Manufacturing (ATVM)

The IRA of 2022 eliminated the loan program cap of $25 billion on the total amount of ATVM loans established under the Energy Independence and Security Act of 2007. The ATVM direct loan program finances U.S. auto manufacturing across the value chain as long as the projects meet stipulated criteria. Under the IRA, the program's total loan capacity is no longer limited, as long as credit subsidies are available to offset the cost of those loans. The IRA provides $3 billion through September 30, 2028, to the Advanced Technology Vehicles Manufacturing (ATVM) Loan Program for re-equipping, expanding, or establishing a manufacturing facility in the United States to produce, or for engineering integration performed in the U.S., low- or zero-emission vehicles. According to DOE, eligible borrowers can be one of the following:

a) Manufacturers of advanced technology vehicles that achieve defined fuel economy targets. Eligible vehicles are light-duty vehicles that meet or exceed a 25% improvement in fuel efficiency beyond a MY 2005 baseline of comparably-sized vehicles; and/or ultra-efficient vehicles that achieve a fuel efficiency of 75 miles per gallon equivalent.
b) Manufacturers of components or materials that support eligible vehicles' fuel economy performance. Examples of eligible components include:
    i) Advanced engines & powertrain components including electrified powertrains, batteries, and electronics;
    ii) Materials for light-weighting such as aluminum, advanced steels, composites, and fuel-efficient tires;

iii) Electric Vehicle Charging & Alternative Fuel Vehicle Fueling Infrastructure Components. For example, associated hardware and software for fuel cell hydrogen fueling stations;
iv) May also be able to support projects that include the processing or manufacturing of critical minerals in support of eligible vehicles.

According to 42 U.S.C. §17013(a)(1), the term "advanced technology vehicle" means—

a) an ultra-efficient vehicle or a light-duty vehicle that meets—
   i) the Bin 5 Tier II emission standard established in regulations issued by the Administrator of the Environmental Protection Agency under section 202(i) of the Clean Air Act (42 U.S.C. 7521(i)), or a lower-numbered Bin emission standard;
   ii) any new emission standard in effect for fine particulate matter prescribed by the Administrator under that Act (42 U.S.C. 7401); and
   iii) at least 125% of the average base year combined fuel economy for vehicles with substantially similar attributes.
b) a medium-duty vehicle or a heavy-duty vehicle that exceeds 125% of the greenhouse gas emissions and fuel efficiency standards established by the final rule of the Environmental Protection Agency entitled "Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles—Phase 2" (81 Fed. Reg. 73478 (October 25, 2016));
c) a train or locomotive;
d) a maritime vessel;
e) an aircraft; and
f) hyperloop technology.

The ATVM loan program has benefitted automakers like Ford, Nissan, Tesla, Redwood Materials, and Li-Cycle, to name a few. According to the U.S. DOE Loans Program Office:
a) Ford received a direct loan of $5.9 billion to retool its manufacturing facilities, which aided the production of 13 separate models with electric, hybrid, or improved conventional powertrains and the introduction of a family of Ford EcoBoost™ engines;
b) Nissan was awarded a loan of $1.45 billion to retool its plant to build BEVs and for a LIB manufacturing plant that aided the Nissan LEAF BEV;
c) Tesla received a $465 million loan to develop the Fremont manufacturing facility to produce the Model S.
d) In July 2022, DOE issued a $102.1 million loan to Syrah Technologies LLC to expand its Syrah-Vidalia facility, which processes battery-grade natural graphite.
e) In November 2022, DOE issued a direct loan of $2.5 billion to Ultium Cells, LLC to help finance the construction of new lithium-ion battery cell manufacturing facilities in Ohio, Tennessee, and Michigan. Ultium Cells is a joint venture between General Motors and

LG Energy Solution that will manufacture nickel-cobalt-manganese-aluminum (NCMA) based large format, pouch-type cells for EVs.

f) In 2023, Redwood Materials received a $2 billion conditional commitment from DOE under the ATVM program. In March 2023, Redwood Materials broke ground on a new facility in Charleston, South Carolina that will recycle, refine, and manufacture anode and cathode components for 100 GWh of lithium-ion batteries.
g) In 2023 Li-Cycle secured a conditional commitment for a $375 million loan to expand its Rochester, New York facility [173].

Elimination of the loan program cap and the additional funding to ATVM could prove beneficial to various producers and manufacturers in the EV ecosystem, as essentially all EV technology would qualify for this credit. This $3 billion in IRA funding is expected to support an additional ~$40 billion (under Title XVII) in loan authority, bringing the total estimated available loan authority under the ATVM to about $55.1 billion.

#### 6.3.2.3 Domestic Manufacturing Conversion Grants

This provision appropriates $2 billion to remain available through September 30, 2031, as grants and loan guarantees under 42 U.S.C. §16062 to automobile manufacturers and suppliers and hybrid component manufacturers to encourage domestic production of efficient hybrid, plug-in electric hybrid (PHEV), plug-in electric drive (PEV), and hydrogen fuel cell electric vehicles (FCEV). Priority shall be given to the refurbishment or retooling of manufacturing facilities that have recently ceased operation or will cease operation in the near future.

#### 6.3.2.4 Energy Infrastructure Reinvestment Financing

This provision appropriates $5 billion through September 30, 2026, to be leveraged for up to $250 billion in loan guarantees. Energy Infrastructure Reinvestment (EIR) will guarantee loans to projects that retool, repower, repurpose, or replace energy infrastructure that has ceased operations, or that enable operating energy infrastructure to avoid, reduce, utilize, or sequester air pollutants or anthropogenic emissions of greenhouse gases. Potential projects could include repurposing shuttered fossil energy facilities for clean energy production, retooling infrastructure from power plants that have ceased operations for new clean energy uses, or updating operating energy infrastructure with emissions control technologies, including carbon capture, utilization, and storage (CCUS). It adds section 1706 to 42 U.S.C. §16516. As defined in the bill, energy infrastructure would include:

a) Electricity generation and transmission, or
b) Production, processing, and delivery of fossil fuels, petroleum-derived fuels, or petrochemical feedstocks.

#### 6.3.2.5 Advanced Industrial Facilities Deployment Program

The IRA provides $5.812 billion under 42 U.S.C. §17113(c) through September 30, 2026, to create a new program within the Office of Clean Energy Demonstrations (OCED) to invest in projects aimed at reducing emissions from energy-intensive industries. It will provide financial assistance to projects for—

a) The purchase and installation, or implementation, of advanced industrial technology at an eligible facility;
b) Retrofits, upgrades to, or operational improvements at an eligible facility to install or implement advanced industrial technology; or
c) Engineering studies and other work needed to prepare an eligible facility for activities as described in paragraphs (a) or (b).

Iron and steel producers serving the automotive industry may benefit from this appropriation.

### 6.3.3 Other Clean Transportation Initiatives

#### 6.3.3.1 Clean Heavy-Duty Vehicles

The IRA provides $1 billion to the EPA to establish a program to award grants and rebates to states, local governments, and nonprofit school transportation associations to replace Class 6 and Class 7 heavy-duty vehicles with zero-emission vehicles, and to provide the necessary infrastructure and workforce development, until September 30, 2031. The bill requires that 40% of funding ($400 million) be for communities located in nonattainment areas (i.e., areas with high levels of air pollution).

#### 6.3.3.2 Grants to Reduce Air Pollution at Ports

The IRA provides $3 billion to the EPA over the next 5 years to establish a program to award grants and rebates for the purchase and installation of zero-emission equipment and technology at ports. The bill allocates 25% of the funding ($750,000) for investments made at ports in nonattainment areas.

This new funding builds on EPA’s Ports Initiative and would aid the electrification of cargo-fuel handling equipment like drayage trucks.

#### 6.3.3.3 Greenhouse Gas Reduction Fund

The IRA will provide $7 billion to the EPA for a new GHG Reduction Fund to make competitive grants to states, municipalities, tribal governments, and eligible recipients to provide financing and technical assistance to enable low-income and disadvantaged communities to deploy or benefit from zero-emission technologies, including distributed technologies on residential rooftops, and to carry out other GHG emission reduction activities; $11.97 billion for general assistance; $8 billion for low-income and disadvantaged communities; and $30 million for EPA administrative costs.

The program would also stimulate and promote the electrification of the medium-duty segment.

#### 6.3.3.4 Diesel Emissions Reductions

The IRA provides the EPA with $60 million for Diesel Emissions Reduction Act (DERA) grants to identify and reduce diesel emissions at goods movement facilities (e.g., airports, railyards, and distribution centers), and from vehicles servicing goods movement facilities in low-income and disadvantaged communities, in order to address the health impacts of emissions on those communities.

## 6.4 Results of This Analysis with Consideration of IRA Credits

The purchase price credits under the IRA's clean vehicle credit provision (§30D) and qualified commercial clean vehicle credit provision (§45W) have been applied to the vehicles evaluated in this analysis to determine potential purchase price reductions in 2023 and 2027. Additionally, the 30% alternative fuel infrastructure credit provision has been applied to charger purchase costs (only to the charger unit itself and not to its installation). The RPE multiplier for MY 2023 vehicles has been kept the same as the equivalent ICEVs at 1.5 to recognize the nascent market for Class 2b–3 BEVs. For simplification of the 2023 TCO analysis, operating expenses for 2023 BEVs are kept the same as such expenses for MY 2027 BEVs. The figures in the following sections illustrate the effect of potential IRA credits on purchase parity and TCO parity in electrification Scenario 2 (the medium cost scenario) for each vehicle class in MYs 2023 and 2027. Results for the other two scenarios can be found in Appendix 9.8.

### 6.4.1 Clean Vehicle Credits (§30D)

A flat $7,500 credit has been applied to all vehicle subclasses purchased in 2023 and 2027. Assuming the consumer qualifies for the entire $7,500 purchase credit, the possible benefits could manifest as greater savings or increased affordability (e.g., using the credit to upgrade to a more expensive vehicle with, for example, a larger battery option or a greater range). It is possible that no or few of the vehicles will be eligible for the entire credit of $7,500 for MY 2023 (and possibly MY 2027) due to the difficulty of meeting the critical mineral sourcing and battery component manufacturing criteria. It may take some years for the industry to ramp up production, regionalize, and strengthen the battery supply chain. However, as we intended to evaluate the full range of potential effects of the IRA under favorable conditions and a robust market, we applied the full $7,500 credit for this analysis.

#### 6.4.1.1 Purchase Price Parity

This section demonstrates the impact of IRA purchase credits and their effect on purchase price parity. Except for the MY 2023 class 3 BEV400 pickup, which is priced above $80,000 (making it ineligible for clean vehicle credits), all the other vehicles have been assigned a $7,500 credit. In the case of MY 2027, all vehicles in Scenario 2 achieve purchase price parity within the first year of ownership, except the class 3 BEV400 pickup where the BEV MSRP is still expensive by $3,328. Figure 93 through Figure 96 illustrate the impacts on evaluated MYs 2023 and 2027.

##### 6.4.1.1.1 Class 2b Van

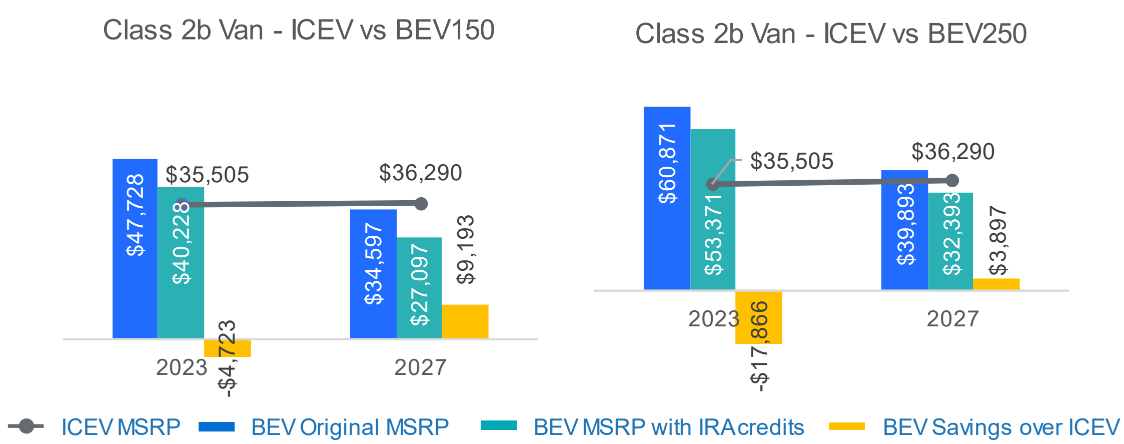


**Figure 93: Comparison of purchase price parity of MYs 2023 and 2027 class 2b van, without and with §30D credits under scenario 2.**

#### 6.4.1.1.2 Class 3 Pickup

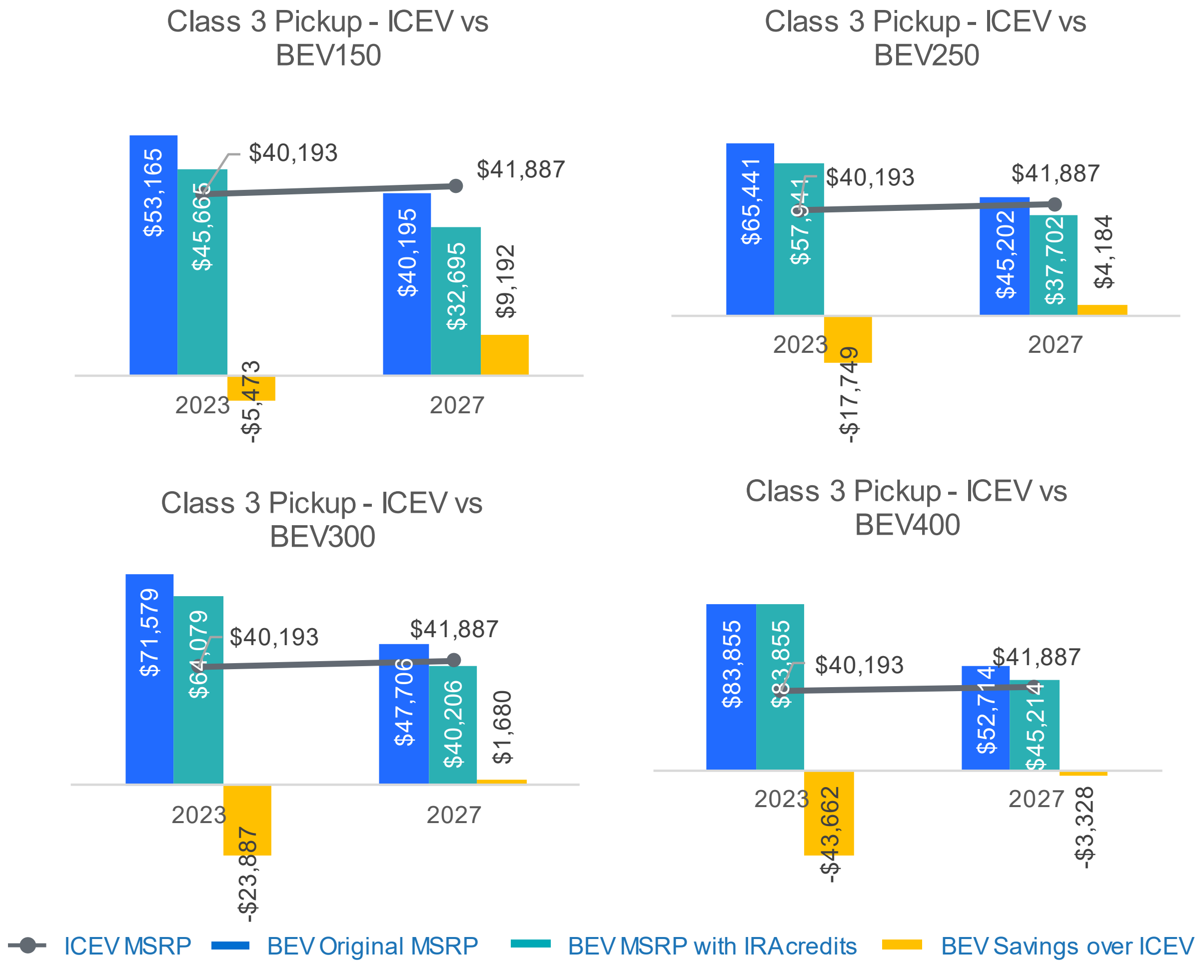


**Figure 94: Comparison of purchase price parity of MYs 2023 and 2027 class 3 pickups, without and with §30D credits under scenario 2.**

#### 6.4.1.1.3 Class 3 P&D Truck

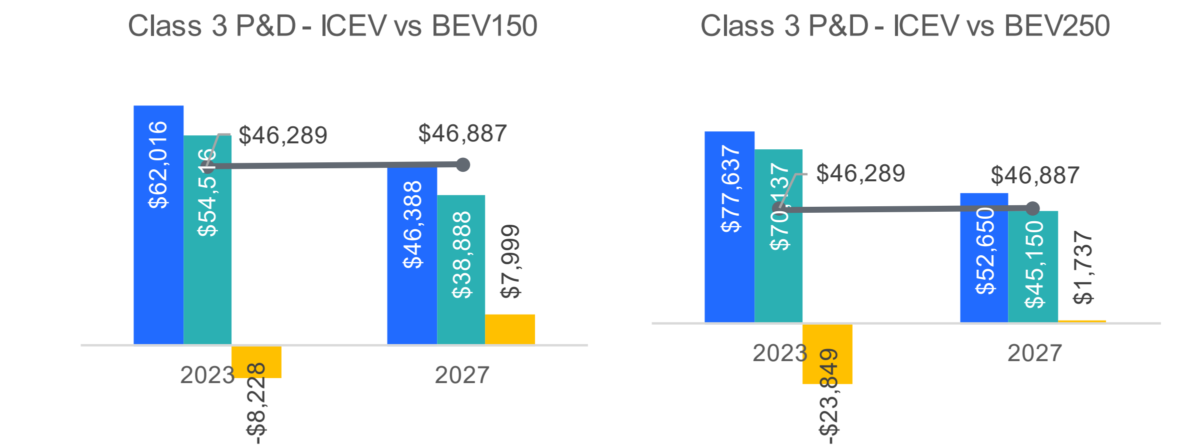


**Figure 95: Comparison of purchase price parity of MYs 2023 and 2027 class 3 P&D trucks, without and with §30D credits under scenario 2.**

#### 6.4.1.1.4 Class 3 Van

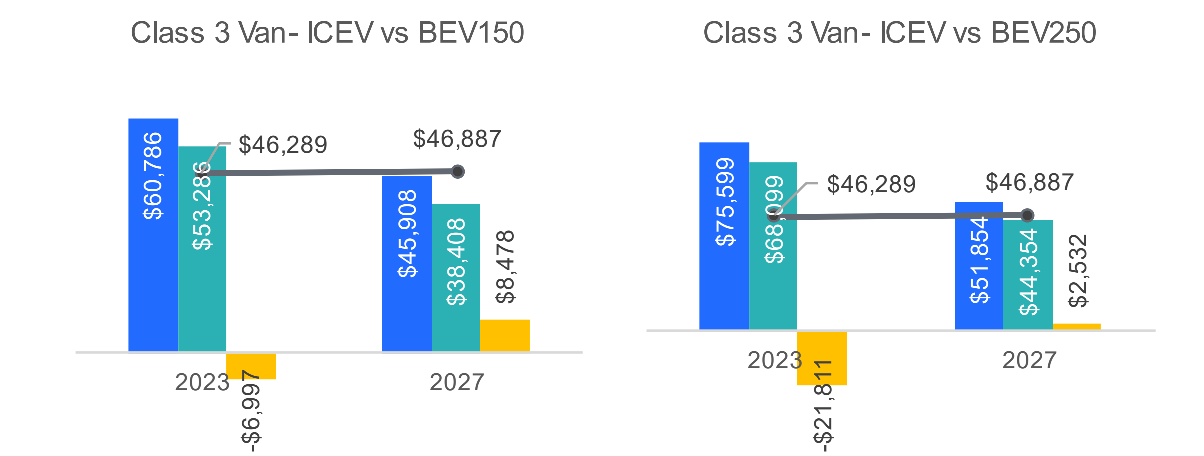


**Figure 96: Comparison of purchase price parity of MYs 2023 and 2027 class 3 vans, without and with §30D credits under scenario 2.**

### 6.4.1.2 Time to Reach TCO Parity

Table 30 lists the year TCO parity is reached for a BEV purchased in 2023 and 2027 with and without the application of IRA credits. Note that here, the applicable tax credits include both the vehicle credit of $7,500 and the charger credit of $300. Due to the high upfront purchase price of BEVs in 2023, it takes longer to reach parity compared to a 2027 purchase. Longer range MY 2023 BEVs (BEV250 and above) do not achieve parity in their assumed lifetime of 12 years, except for the class 3 pickup BEV250, which achieves parity in the 10th year of ownership; shorter range MY 2023 BEVs reach parity within three to six years with the IRA credits. Parity acceleration is seen in MY 2027 BEVs, with all vehicles achieving parity within the first two years of ownership.

**Table 30: Time to achieve TCO parity with IRA §30D credits for MYs 2023 and 2027 under Scenario 2.**

| Vehicle Type | BEV Range | 2023 | | 2027 | |
|---|---|---|---|---|---|
| | | Original | With IRA Credits | Original | With IRA Credits |
| | | Scenario 2 | Scenario 2 | Scenario 2 | Scenario 2 |
| Class 2b Van | BEV150 | 11 | 4 | <1 | <1 |
| | BEV250 | End of Life | End of Life | 4 | <1 |
| Class 3 Pickup Truck | BEV150 | 7 | 3 | <1 | <1 |
| | BEV250 | End of Life | 10 | 2 | <1 |
| | BEV300 | End of Life | End of Life | 4 | <1 |
| | BEV400 | End of Life | End of Life | 6 | 2 |
| Class 3 P&D Truck | BEV150 | 11 | 6 | <1 | <1 |
| | BEV250 | End of Life | End of Life | 4 | <1 |
| Class 3 Van | BEV150 | End of Life | 6 | <1 | <1 |
| | BEV250 | End of Life | End of Life | 5 | <1 |

#### 6.4.1.3 Cumulative Net Savings

To quantify the overall benefit to consumers in terms of the relative savings offered by the purchase of a BEV as compared to a comparable ICEV, net savings in purchase years 2023 and 2027, with and without application of the IRA credits, are depicted in Figure 97. An intra-year comparison indicates that with the application of credits, the relative net savings remain the same at $7,800 due to the clean vehicle and charger credits, except in the case of the MY 2023 class 3 BEV400 pickup with charger-related savings of only $300. The reduction in IRA savings for the BEV400 pickup is because its purchase price exceeds the cap imposed on eligibility for the $7,500 vehicle tax credit.

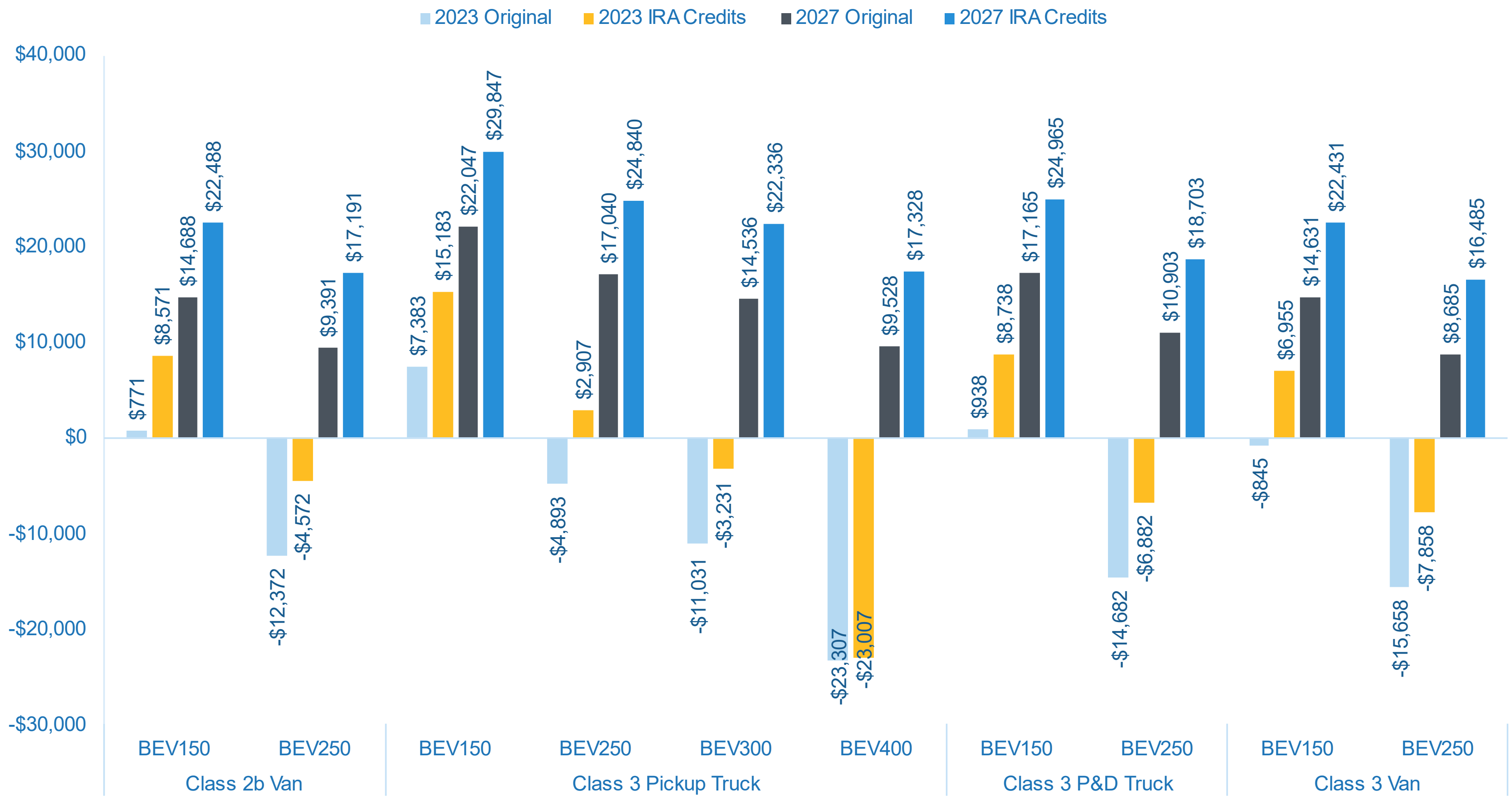


**Figure 97: Cumulative lifetime savings of MYs 2023 and 2027 BEVs over equivalent ICEVs with IRA §30D credits under Scenario 2.**

### 6.4.2 Qualified Commercial Clean Vehicle Credits (§45W)

In our analysis, all MY2023 BEVs receive the maximum purchase credit of $7,500 as the purchase price of all exceeds that of a comparable ICEV by more than $7,500. Despite receiving the maximum possible purchase credits, MY 2023 BEVs do not achieve purchase parity within the first year of ownership due to their high purchase price.

However, by MY 2027, all BEVs except the BEV400 pickup will be priced at or below the price of a comparable ICEV with the application of IRA credits, achieving immediate purchase parity. In our analysis, MY 2027 BEV150s across all vehicle types are priced lower than their ICEV counterparts before the application of IRA credits. As a result, they would not qualify for the IRA's qualified commercial clean vehicle credit. In the case of MY 2027 BEV250s, BEV300s, and BEV400s, all receive a credit equal to the difference between the price of a comparable ICEV and the price of a non-credit BEV (with credits ranging from $3,315 through $5,819), except the BEV400 pickup, which receives the maximum credit of $7,500 (due to a purchase price differential that exceeds that value).

Figure 98 through Figure 101 illustrate the impact of §45W on MYs 2023 and 2027 BEVs.

#### 6.4.2.1 Purchase Price Parity

##### 6.4.2.1.1 Class 2b Van

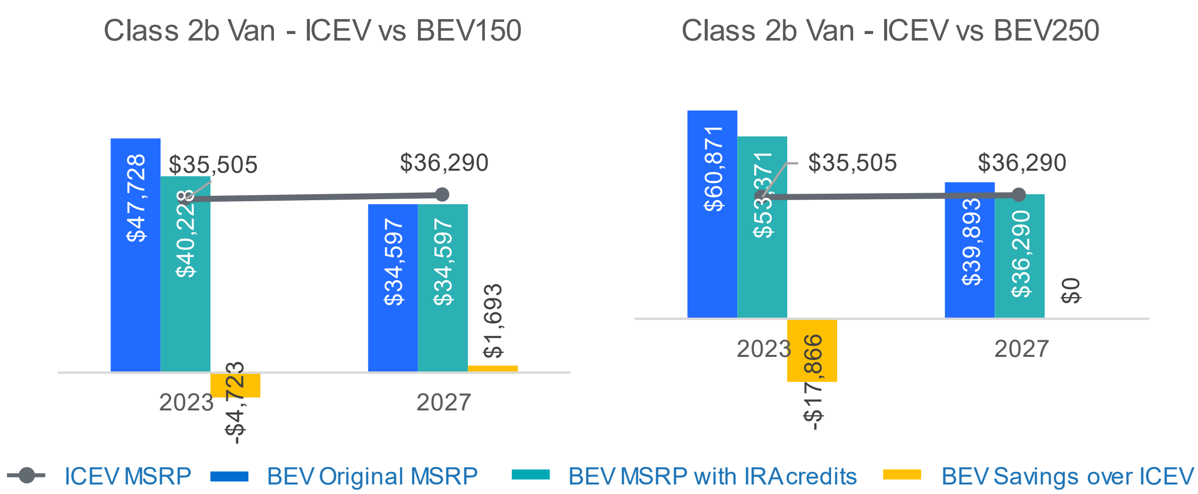


**Figure 98: Comparison of purchase price parity of MYs 2023 and 2027 class 2b vans, without and with §45W credits under Scenario 2.**

#### 6.4.2.1.2 Class 3 Pickup


**Figure 99: Comparison of purchase price parity of MYs 2023 and 2027 class 3 pickups, without and with §45W credits under Scenario 2.**

#### 6.4.2.1.3 Class 3 P&D Truck

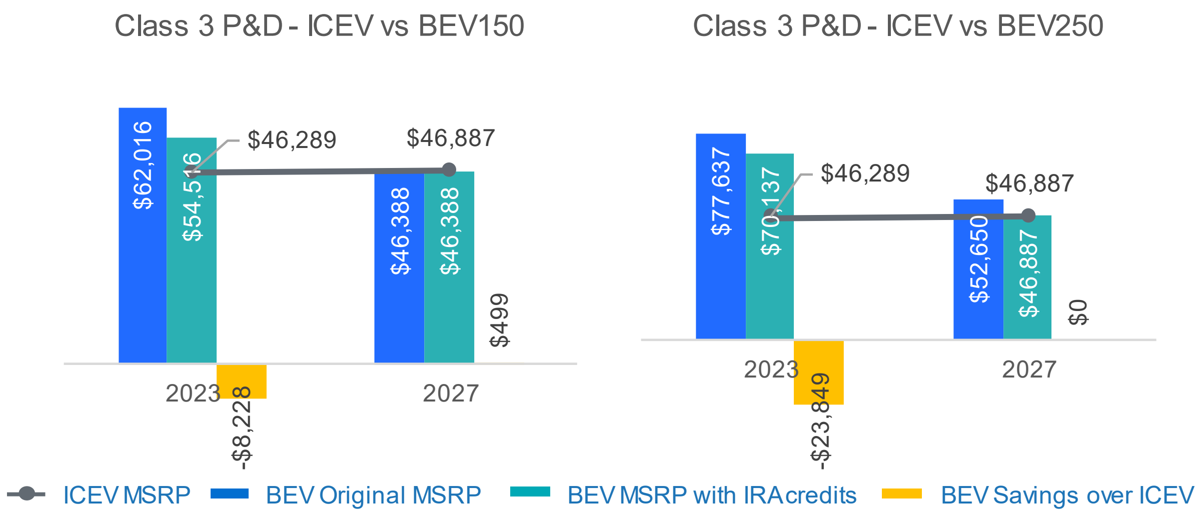


**Figure 100: Comparison of purchase price parity of MYs 2023 and 2027 class 3 P&D trucks, without and with §45W credits under Scenario 2.**

#### 6.4.2.1.4 Class 3 Van

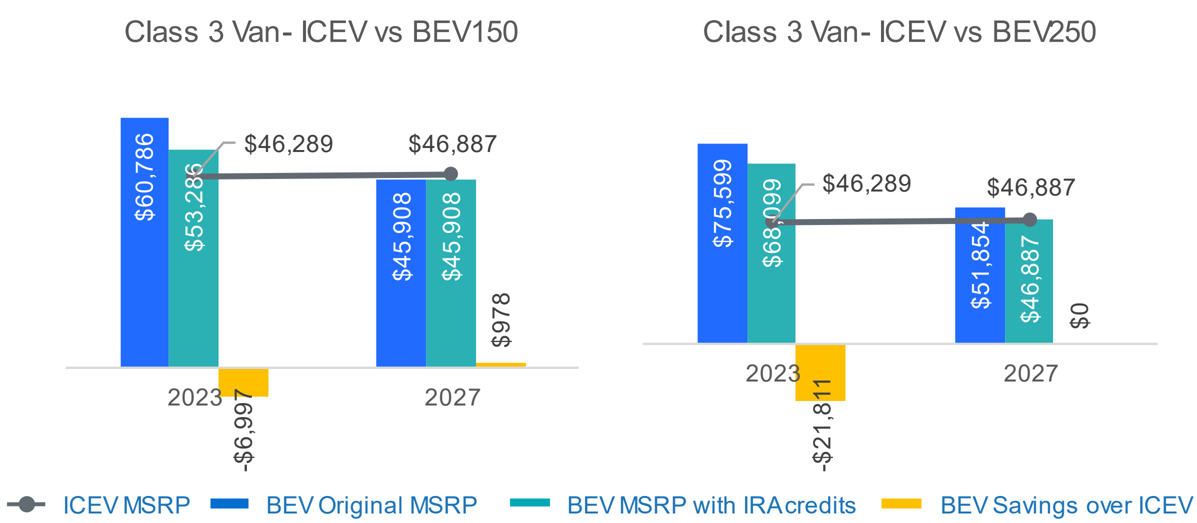


**Figure 101: Comparison of purchase price parity of MYs 2023 and 2027 class 3 vans, without and with §45W credits under Scenario 2.**

### 6.4.2.2 Time to Reach Parity

Table 31 lists the year parity is reached when a BEV is purchased in MYs 2023 and 2027, considering the application of qualified commercial clean vehicle credits. Due to the high upfront purchase price of BEVs in MY 2023, it takes longer to reach parity compared to an MY 2027 purchase. MY 2023 BEV250 and above do not achieve parity in their 12-year assumed lifetime, except for the class 3 BEV250 pickup, which achieves parity in the 10th year of ownership. MY 2027 BEVs experience parity acceleration, with all vehicles achieving parity within the first two years of ownership.

**Table 31: Time to achieve parity with IRA §45W credits for MYs 2023 and 2027**

| Vehicle Type | BEV Range | 2023 | | 2027 | |
|---|---|---|---|---|---|
| | | Original | With IRA Credits | Original | With IRA Credits |
| | | Scenario 2 | Scenario 2 | Scenario 2 | Scenario 2 |
| Class 2b Van | BEV150 | 11 | 4 | <1 | <1 |
| | BEV250 | End of Life | End of Life | 4 | 1 |
| Class 3 Pickup Truck | BEV150 | 7 | 3 | <1 | <1 |
| | BEV250 | End of Life | 10 | 2 | <1 |
| | BEV300 | End of Life | End of Life | 4 | <1 |
| | BEV400 | End of Life | End of Life | 6 | 2 |
| Class 3 P&D Truck | BEV150 | 11 | 6 | <1 | <1 |
| | BEV250 | End of Life | End of Life | 4 | <1 |
| Class 3 Van | BEV150 | End of Life | 6 | <1 | <1 |
| | BEV250 | End of Life | End of Life | 5 | 1 |

#### 6.4.2.3 Cumulative Net Savings

To quantify the overall benefit to consumers in terms of the relative savings offered by the purchase of a BEV as compared to a comparable ICEV, net savings in purchase years 2023 and 2027, with and without application of the IRA §45W credits, are depicted in Figure 102. Overall, only MY 2023 BEV150s and all MY 2027 BEVs demonstrate greater savings due to the IRA credits. For fleet owners whose operational requirements can be met by using BEV150, it is currently financially beneficial for them to electrify their fleets. By 2027, BEVs will be economically attractive in all operational configurations.

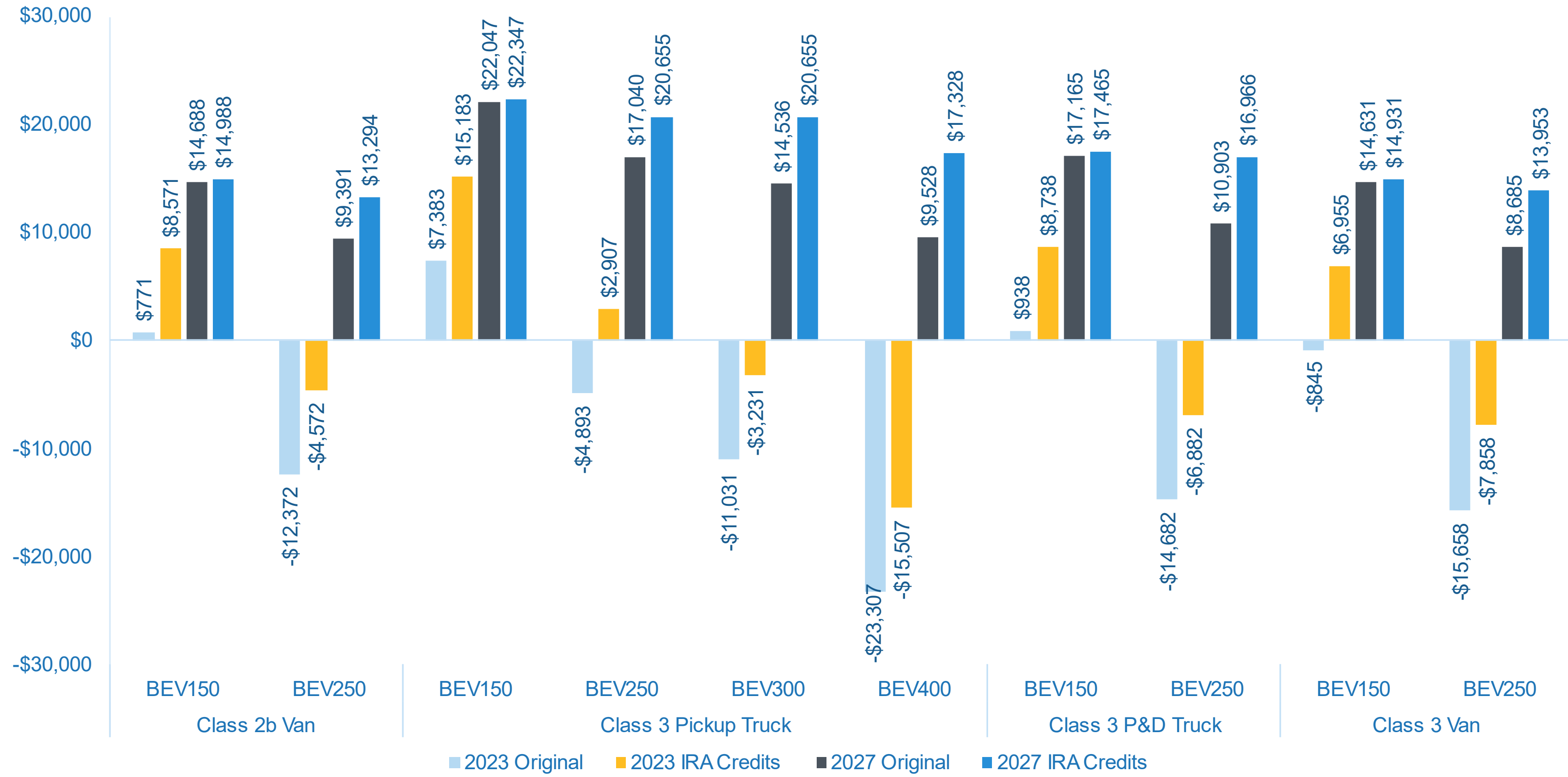


**Figure 102: Cumulative lifetime savings of MYs 2023 and 2027 BEVs over equivalent ICEVs with IRA §45W credits.**

### 6.4.3 Hypothetical Application of Credits to Establish Battery Pack Cost Ceiling

To evaluate the potential impact of advanced manufacturing production and purchase credits on both automaker OEMs and the consumer, we ran a hypothetical exercise that applies such credits to an MY 2027 BEV150 class 2b van and assesses the maximum battery pack cost that would still be economically attractive (as illustrated in Figure 103). The objective is to ascertain how high the market-driven pack cost could be and still allow the end consumer to achieve purchase price parity with the first year of ownership (with the IRA credit).

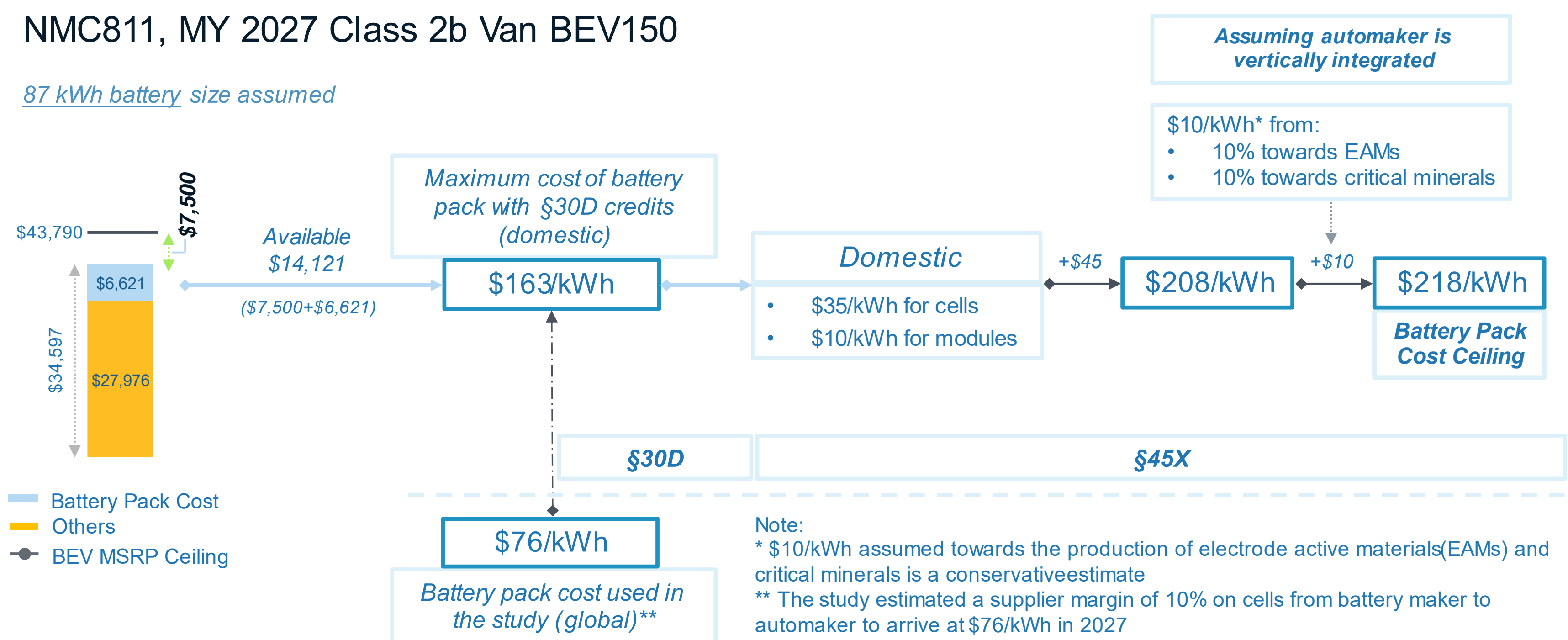


**Figure 103: Hypothetical application of purchase credit (§30D) and advanced manufacturing production credit (§45X) to determine the maximum battery pack cost of an 87 kWh battery pack sized for MY 2027 BEV150 class 2b van.**

The primary analysis assumes that a BEV150 class 2b van with an 87 kWh battery will have a pack cost of $76/kWh, with the battery constituting $6,621 of the vehicle price. Assuming that the automaker marks up the vehicle purchase price by $7,500 to offset a hypothetical increase in battery costs, the cost of the 87 kWh battery pack could go up to $14,121, equal to a pack cost of $163/kWh. In effect, the IRA purchase price credit provides a 114% buffer of $87/kWh on top of the robust market estimate of $76/kWh. There are, however, additional manufacturing credits that provide even more market security.

If we assume that a manufacturer meets all the requirements for an advanced manufacturing production credit (§45X), the following credits apply:

a) $35/kWh for cells;
b) $10/kWh for modules (assuming the manufacturer does not make cell-to-pack or cell-to-chassis configurations);
c) $10/kWh (assumed $/kWh) from 10% towards both the production of electrode active materials and the processing of battery-associated critical minerals.

With the application of these credits, the maximum pack cost of a domestically manufactured battery could be $218/kWh under a cost parity scenario, almost 187% more than the estimated pack cost of $76/kWh.

In addition, for any taxable year, there is a qualifying advanced energy project credit (§48C) equal to 30% of the qualified investment in an eligible property:

a) which re-equips, expands, or establishes an industrial or manufacturing facility for the production or recycling of light-, medium-, or heavy-duty electric or fuel cell vehicles, as well as technologies, components, or materials for such vehicles, as well as associated charging or refueling infrastructure; or
b) which re-equips, expands, or establishes an industrial facility for the processing, refining, or recycling of critical materials.

The advanced manufacturing production credit (§45X) cannot be claimed for components produced at a facility (or property) for which a credit was claimed under §48C (i.e., double dipping is not allowed). A wide range of projects are eligible for credits under §48C, but the following scenarios may shed more light on their potential impact on battery pack cost:

a) In cases where the automaker is essentially a vehicle integrator, i.e., sourcing a battery pack from a battery producer, then the tax incentives under §48C can be claimed by the automaker, while the credits under §45X can be claimed by the battery producer, allowing "stacking" of credits. Multiple automakers have joint ventures with battery producers, and most are anticipated to carry out the integration of batteries on a pack level in their BEVs. This allows them to claim the 30% tax incentive under §48C for an

EV manufacturing facility; however, it is difficult to estimate the effect of §48C credits on the battery cost on a per kWh basis. Such incentives greatly benefit the EV value chain.

b) In cases where the automaker is vertically integrated, then they can claim the credits under §48C and §45X as long as the battery-related manufacturing activities and vehicle manufacturing or pack integration are done on separate properties. Battery and BEV production encompasses a wide range of activities, and as long as "double benefit" is not claimed, the OEM would be able to use these credits to their advantage to produce cost-effective BEVs by lowering battery costs.

The battery value chain is incredibly complex, with segmented supply chains involving numerous components and raw materials and spanning multiple vendors from various regions. This exercise attempts to demonstrate the cost buffer provided to various stakeholders in the battery ecosystem that are able to take advantage of all of the available IRA credits by satisfying the eligibility requirements. This is a simplified view of battery production, and numerous additional factors and elements influence the price of a battery. We recognize that we have made generous assumptions to arrive at the battery pack cost ceiling, and it is up to the automaker as to how they apportion the credits, such as §48C. Furthermore, since the 30% tax credit under §48C is for a manufacturing or industrial facility, the capital cost per unit of production could be much lower. However, if the automakers were to use these credits towards mitigating battery price volatility by securing long-term strategic supply contracts, then it could directly impact the battery prices; however, we have not stacked them onto the battery cost in this analysis. It is also worth noting that the credits have been stacked on the estimated battery pack cost, which was calculated in the primary analysis before the IRA of 2022 became law, without taking into account the restrictions it imposes. Onshoring of battery manufacturing-related activities (upstream and midstream) could result in significantly higher battery pack costs than the one used here ($76/kWh). Nevertheless, it is a first-order attempt to illustrate the potential "calming" effect that IRA credits could have on a potentially volatile battery supply chain.

Figure 104 shows the maximum cost a battery pack can reach in the case of the other vehicles evaluated in this analysis with the application of IRA credits (except the class 3 BEV400 pickup truck, which does not achieve purchase price parity in the core analysis). The maximum cost of the pack is determined by the size of the battery as well as the availability and magnitude of credits for the costed vehicles. As stated, this is purely a hypothetical, theoretical exercise that applies all credits toward battery pack costs and is in no way a projection of expected battery pack costs. Similarly, we recognize that the OEMs would prioritize profits while still producing cost-effective BEVs and that some of the effects of the IRA credits may not be passed on to the benefit of end consumers. Market conditions, as they develop, will ultimately determine how IRA credits are apportioned.

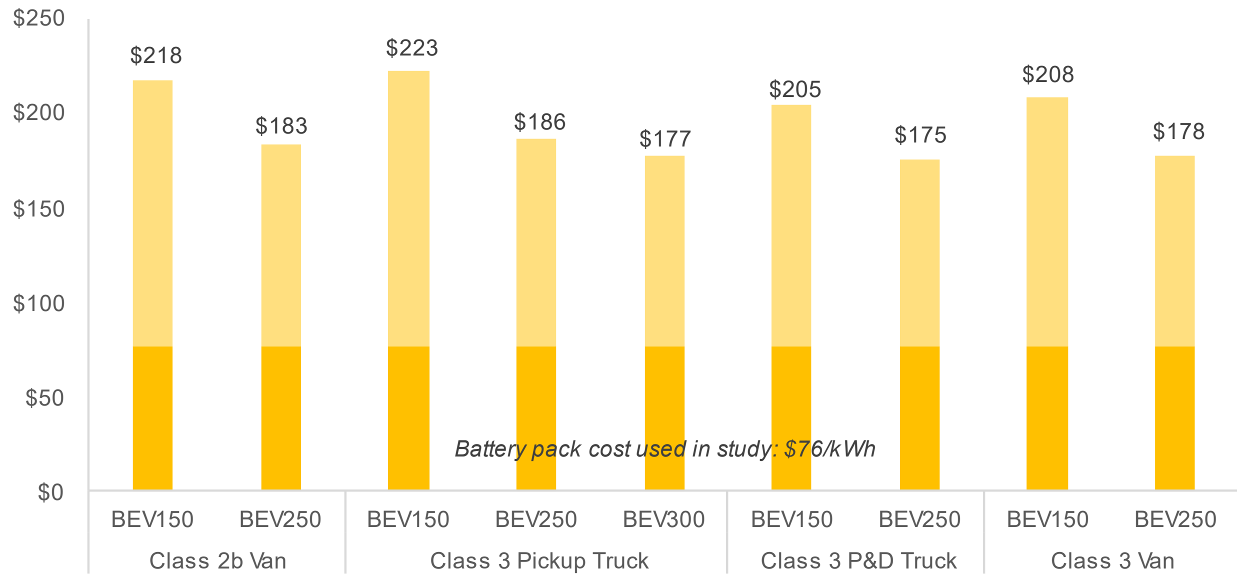


**Figure 104: Hypothetical application of purchase and advanced manufacturing production credits to determine the maximum price-parity cost of a battery pack for class 2b–3 vehicles.**

## 7. Conclusion

This study was conducted to project and compare the incremental purchase price and TCO of class 2b–3 BEVs with comparable ICEVs in the 2027–2030 purchase timeframe. Additionally, the study analyzes the effect of IRA provisions on BEVs purchased in the 2023–2027 timeframe and attempts to quantify the effects of IRA credits on the purchase price of a BEV, associated charging equipment, and the TCO of the vehicle. Class 2b–3 vehicles are used for both private and commercial purposes and have widely varying operational characteristics. Class 2b vehicles have been evaluated for three gasoline powertrains with varying levels of hybridization options: a low-cost non-electrified NA SI engine, a medium-cost mild hybrid NA SI engine with BISG, and a high-cost strong hybrid NA SI SHEVP2. Class 3 vehicles have similar low- and medium-cost options, but the high-cost strong hybrid is replaced with a CI powertrain. The selection of powertrain technologies is based on the current mix of vehicles offered on the market today, various future vehicles under development, and general technology trends. The different powertrain combinations are used to compute three electrification scenarios that are then used to analyze the total cost of ownership across vehicle classes and segments, relative to the cost of equivalent BEVs.

While purchase price differences are an important consideration, operating costs are also a significant determinant in ascertaining the economic viability of BEVs relative to equivalent ICEVs. This analysis evaluates both upfront and operational costs. We include several evaluation years, as BEV component costs have dropped dramatically over the last several years and are expected to continue to do so. The analysis assumes that the current trajectory of costs, technological advancements, and supporting infrastructure development continues into the evaluated near future timeframe.

Switching from a high-cost ICE powertrain with high fuel prices, such as a gasoline SHEVP2 or a diesel CI with advanced DEAC (DSLIAD), to a low-cost BEV powertrain with low electricity prices and an LFP battery pack represents the lowest electrification cost scenario and is evaluated as Scenario 1. Switching from a low-cost ICE powertrain with low fuel prices (conventional NA SI) to a BEV with a high-cost battery pack (10% premium on projected NMC811 cost) and high electricity prices results in the highest electrification cost scenario and is evaluated as Scenario 3. A medium-cost electrification scenario is evaluated as Scenario 2. The results of this study indicate that class 2b–3 ICEVs are generally well-positioned for the transition to BEVs and that consumers would benefit by switching to them, as evidenced by the following analysis results.

a) In Scenario 1, the purchase prices of all BEVs except the very long-range class 3 BEV400 pickup are cheaper than a comparable ICEV in the 2027–2030 timeframe.

b) BEV150 purchase prices in MY 2027 are lower than their ICEV counterparts under both Scenario 1 and Scenario 2.
c) Under all three scenarios, the purchase prices of BEV150s in MY 2030 are lower than those of ICEVs.
d) Longer-range BEVs have a more expensive powertrain than a comparable ICEV in Scenario 2 and Scenario 3, but these costs are based on NMC811 battery technology, and several technologies are currently being developed to support higher efficiency and lower production costs in the near future.
e) Despite considering a high public charging price of $0.43/kWh for 10% of the charging that is assumed to be accomplished at retail commercial facilities, the energy costs of a BEV are less expensive than those of a comparable ICEV. The associated fuel savings offset nearly all of the estimated incremental purchase prices of longer-range BEVs. While the economics vary based on several factors, on average across the evaluated vehicle types and scenarios, the TCO of BEVs is about 20% lower than that of ICEVs.
f) In terms of the time to achieve TCO parity:
    i) In Scenario 1,
        a. All MY 2027 BEVs achieve parity within the first year of ownership, except BEV400 pickups, which achieve parity after 1 year of ownership.
        b. All MY 2030 vehicles achieve parity within the first year of ownership.
    ii) In Scenario 2,
        a. All MY 2027 BEV150s achieve parity within the first year of ownership; longer-range BEVs may take up to 6 years to achieve parity.
        b. All MY 2030 BEV150s achieve parity within the first year of ownership, while longer-range BEVs achieve parity within 3 years.
    iii) In Scenario 3,
        a. MY 2027 BEV150s take up to 4 years to achieve parity, while longer-range BEVs may take from 6 to over 12 years to achieve parity.
        b. All MY 2030 BEV150s achieve parity within the first year of ownership, while longer-range BEVs may take from 2 to 7 years to achieve parity.
g) BEVs have significantly lower operating and maintenance costs due to lower electricity rates (compared to liquid fuels) and fewer moving parts, making them economically attractive over a lifetime of ownership.
h) On average, consumers can save about $20,000 with a MY 2027 BEV purchase and $25,000 with a MY 2030 BEV purchase during the vehicle's assumed lifetime of 12 years.
i) This analysis supports the conclusion that the total MY 2027 and MY 2030 BEV operating costs are largely indifferent to typical variations in charging infrastructure costs and electricity prices.
j) After applying for IRA credits under §30D and §45W, a significant acceleration in parity is observed for MY 2027 BEVs across all classes and electrification scenarios. For MY

2023 BEVs, acceleration is observed across all classes in Scenario 1. In Scenarios 2 and 3, parity acceleration is observed only in BEV150 (across all vehicle types).

k) Applying the IRA's clean vehicle credits (§30D) and charger credits, the cumulative net average savings for MY 2023 and MY 2027 BEVs are about $5,000 and $27,000, respectively. Furthermore, the TCO of BEVs will be about $0.40 per mile and $0.31 per mile, which is less than comparable ICEVs averaging at $0.42 per mile and $0.43 per mile in MYs 2023 and 2027, respectively.

l) Applying the IRA's qualified commercial clean vehicle (§45W) and charger credits, the cumulative net average savings for MY 2023 and MY 2027 BEVs are about $6,000 and $23,000, respectively. Furthermore, the TCO of BEVs will be about $0.40 per mile in MY 2023 and $0.33 per mile in MY 2027, which is less than comparable ICEVs (averaging at $0.42 per mile in MY 2023 and $0.43 per mile in 2027).

m) Considering recent real-world high fossil fuel prices (as opposed to the more conservative prices used in the core analysis), the majority of the BEVs achieve parity with the first year of ownership. Even the class 3 BEV400 pickup achieves parity within 1-2 years of ownership. Furthermore, switching to BEVs results in an average lifetime net savings of about $56,000 and $60,000 for MY 2027 and MY 2030 purchases, respectively. The high operating expenses of ICEVs make a compelling case to switch to BEVs.

n) Various studies and technology indicators project a continuing reduction in the cost of battery packs, the development of a superior charging infrastructure enabling faster charging, and tighter emission and fuel economy regulations for ICEVs, which would facilitate both an even more compelling economic case and a more rapid transition to BEVs. With the likely influx and adoption of Rivian's EDV series, Ford's E-Transit, and GM's Brightdrop, there is a strong basis for the electrification of class 2b–3 vehicles.

There are also a substantial number of external benefits to BEV adoption, including environmental benefits through the reduction of PM and NOx emissions, as well as a reduction in noise in congested environments. While these benefits are not included in this analysis, they further improve the case for BEV adoption.

## 8. References

[1] N. R. C. 2015, *Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*. Washington, D.C.: National Academies Press, 2015. doi: 10.17226/21744.

[2] U.S. National Highway Traffic Safety Administration (NHTSA), *Technical Support Document : Final Rulemaking for Model Years 2024-2026 Light- Duty Vehicle Corporate Average Fuel Economy Standards March 2022 Table of Contents*, no. March. 2022.

[3] U.S. National Highway Traffic Safety Administration, "Draft CAFE Model Documentation," no. July, 2018.

[4] U.S. Environmental Protection Agency, "Facts," 2021. [Online]. Available: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

[5] "2022 Final Rule for Model Years 2024-2026 Passenger Cars and Light Trucks," 2022. https://www.nhtsa.gov/corporate-average-fuel-economy/cafe-compliance-and-effects-modeling-system (accessed Apr. 04, 2022).

[6] U S Energy Information Administration, "Annual Energy Outlook 2022 AEO2022 Highlights," 2022. doi: EIA, AEO2022 National Energy Modeling System run ref2022.d011222a.

[7] E. Incorporated, C. C. of C. N. York, and I.-T. C. T. Council, "Tompkins County Plug-in Electric Vehicle Infrastructure Plan: Charging Station Installation Analysis," 2017.

[8] California Air Resources Board, "Draft Advanced Clean Fleets Total Cost of Ownership Discussion Document," pp. 1–68, 2021.

[9] M. Wentker, M. Greenwood, J. Leker, M. Wentker, and J. Leker, "A bottom-up approach to lithium-ion battery cost modeling with a focus on cathode active materials," *Energies*, vol. 12, no. 3, pp. 1–18, 2019, doi: 10.3390/en12030504.

[10] N. Bloomberg, "Hitting the EV inflection point," *Transp. Environ.*, vol. 19, no. May, p. 58, 2021, [Online]. Available: https://www.transportenvironment.org/publications/hitting-ev-inflection-point

[11] NIST, "The Future is Charged: National Electric Vehicle Infrastructure (NEVI) Formula Program | NIST," 2022. https://www.nist.gov/news-events/news/2022/03/future-charged-national-electric-vehicle-infrastructure-nevi-formula (accessed May 04, 2022).

[12] and M. N. A. of S. Engineering, "Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy-2025-2035," The National Academies Press, Washington, D.C., 2021. doi: 10.17226/26092.

[13] D. Lowell and J. Culkin, "Medium- & Heavy-Duty Vehicles," 2021.

[14] United States Environmental Protection Agency, "Motor Vehicle Emission Simulator (MOVES) | US EPA," 2022. https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves#download (accessed Jun. 22, 2022).

[15] California Air Resources Board, "Staff Report: Initial Statement of Reasons, Public Hearing To Consider the Proposed Advanced Clean Cars Regulation," 2022, [Online]. Available: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/isor.pdf

[16] The White House, "FACT SHEET: President Biden Announces Steps to Drive American Leadership Forward on Clean Cars and Trucks | The White House," 2021.

https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/05/fact-sheet-president-biden-announces-steps-to-drive-american-leadership-forward-on-clean-cars-and-trucks/ (accessed May 05, 2022).

[17] FHWA, "Federal Funding is Available For Electric Vehicle Charging Infrastructure On the National Highway System," 2021.

[18] U. S. D. of ENergy, "Alternative Fuels Data Center: Emissions from Hybrid and Plug-In Electric Vehicles." https://afdc.energy.gov/vehicles/electric_emissions.html (accessed Apr. 29, 2022).

[19] P. Chakraborty *et al.*, "Addressing the range anxiety of battery electric vehicles with charging en route," *Sci. Reports 2022 121*, vol. 12, no. 1, pp. 1–15, Apr. 2022, doi: 10.1038/s41598-022-08942-2.

[20] R. Pell *et al.*, "Towards sustainable extraction of technology materials through integrated approaches," *Nat. Rev. Earth Environ.*, vol. 2, no. 10, pp. 665–679, 2021, doi: 10.1038/s43017-021-00211-6.

[21] International Energy Agency (IEA), "The Role of Critical Minerals in Clean Energy Transitions," *world energy outlook Spec. Rep.*, 2021.

[22] U.S. Department of Defense, "Defense Production Act Title III Presidential Determination for Critical Materials in Large-Capacity Batteries - U.S. Department of Defense - Release," 2022. https://www.defense.gov/News/Releases/Release/Article/2989973/defense-production-act-title-iii-presidential-determination-for-critical-materi/ (accessed Apr. 29, 2022).

[23] U.S. Geological Survey, "Mineral Commodity Summaries 2023," 2023. [Online]. Available: https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries

[24] Ford Media Center, "Ford Accelerating Transformation: Forming Distinct Auto Units to Scale EVs, Strengthen Operations, Unlock Value | Ford Media Center," 2022. https://media.ford.com/content/fordmedia/fna/us/en/news/2022/03/02/ford-accelerating-transformation.html (accessed May 05, 2022).

[25] S&P Global Commodity Insights, "INSIGHT: Regionalization of battery supply chains advances, but challenges persist | S&P Global Commodity Insights," 2021. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/093021-insight-regionalization-of-battery-supply-chains-advances-but-challenges-persist (accessed May 02, 2022).

[26] A. Birky, M. Laughlin, K. Tartaglia, R. Price, B. Lim, and Z. Lin, "Electrification Beyond Light Duty: Class 2b-3 Commercial Vehicles," Oak Ridge, TN (United States), Dec. 2017. doi: 10.2172/1427632.

[27] Ford Media Center, "2022 Ford Transit Full-Size Cargo Van | Photos, Colors & 360° Views." https://www.ford.com/commercial-trucks/transit-cargo-van/gallery/?gnav=vhpnav-gallery (accessed May 24, 2022).

[28] FCA Media Center, "2022 Ram ProMaster® | Crew Van Package | Ram Van." https://www.ramtrucks.com/ram-promaster.html (accessed May 24, 2022).

[29] Fedex trucks for sale, "Ford P700 Stepvan - BTL," 2022. https://www.fedextrucksforsale.com/truck/ford-p700-stepvan-utilimaster/ (accessed May 24, 2022).

[30] NHTSA, "Technical Support Document: Proposed Rulemaking for Model Years

2024-2026 Light- Duty Vehicle Corporate Average Fuel Economy Standards," no. August, 2021, [Online]. Available: https://www.nhtsa.gov/sites/nhtsa.gov/files/2021-08/CAFE-NHTSA-2127-AM34-TSD-Complete-web-tag.pdf

[31] ENVIRONMENTAL PROTECTION AGENCY, *81 FR 73478 - Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles-Phase 2*, vol. 81, no. 206. 2016, pp. 73478–74274. [Online]. Available: https://www.govinfo.gov/app/details/FR-2016-10-25/2016-21203

[32] U.S. Environmental Protection Agency and U.S. National Highway Traffic Safety Administration (NHTSA), "Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2 Regulatory Impact Analysis," 2016. [Online]. Available: https://nepis.epa.gov/Exe/ZyPDF.cgi/P100P7NS.PDF?Dockey=P100P7NS.PDF

[33] E. Islam *et al.*, "A Detailed Vehicle Modeling & Simulation Study Quantifying Energy Consumption and Cost Reduction of Advanced Vehicle Technologies Through 2050," Argonne, IL (United States), Oct. 2021. doi: 10.2172/1866349.

[34] K. Ranch, K. T. Plant, and O. A. Plant, "2021 FORD F-SERIES SUPER DUTY Technical Specification," 2021. https://media.ford.com/content/dam/fordmedia/North America/US/product/2021/super-duty/21-Super-Duty-Pickup-Tech-Specs.pdf

[35] NHTSA, "2022 Final Rule for Model Years 2024-2026 Passenger Cars and Light Trucks," 2022. Accessed: Apr. 04, 2022. [Online]. Available: https://www.nhtsa.gov/corporate-average-fuel-economy/cafe-compliance-and-effects-modeling-system

[36] Ford Media Center, "Ford F-150 V8 vs Turbo Towing MPG Test | If You Want The Best F-150 Fuel Economy Buy THIS Truck! - YouTube," *YouTube*, 2019. https://www.youtube.com/watch?v=bgi01ednxXM (accessed May 19, 2022).

[37] L. Ntziachristos *et al.*, "Euro 7 Impact Assessment Study," Publications Office of the European Union, 2022. doi: 10.2873/249061.

[38] U. EPA, "Control of Air Pollution from Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards Final Rule Regulatory Impact Analysis," *Epa Usa*, p. 619, 2014.

[39] A. L. Brown *et al.*, *Driving California' s Transportation Emissions to Zero*. 2021. doi: 10.7922/G2MC8X9X.

[40] K. Walkowicz, K. Kelly, A. Duran, and E. Burton, "Fleet DNA Project Data," *Natl. Renew. Energy Lab.*, 2019.

[41] E. Mulholland, "Cost of electric commercial vans and pickup trucks in the United States through 2040," no. January, pp. 1–21, 2022, [Online]. Available: www.theicct.org

[42] N. Rick Mihelic, Mike Roeth, "GUIDANCE REPORT: Electric Trucks Where They Make Sense," *Nacfe.*, no. January, 2018.

[43] Ford, "2022 Ford E-Transit | Ford Media Center," *Ford Media Center*, 2022. https://media.ford.com/content/fordmedia/fna/us/en/products/evs/e-transit/2022-ford-e-transit.html (accessed May 24, 2022).

[44] Munro & Associates Inc., "Twelve Motor Teardown and Benchmark Study," 2021. [Online]. Available: https://leandesign.com/teardown-benchmarking/

[45] X. Ding, M. Du, T. Zhou, H. Guo, C. Zhang, and F. Chen, "Comprehensive comparison between SiC-MOSFETs and Si-IGBTs based electric vehicle traction systems under low speed and light load," *Energy Procedia*, vol. 88, pp. 991–997,

2016, doi: 10.1016/j.egypro.2016.06.124.
[46] Munro & Associates Inc., “Inverter Benchmark & Cost Study,” 2021. [Online]. Available: https://leandesign.com/teardown-benchmarking/
[47] U.S. Department of Energy, “Electrical and Electronics Technical Team Roadmap,” *U.S. DRIVE Partnersh.*, no. October, p. 9, 2017, [Online]. Available: https://www.energy.gov/sites/prod/files/2017/11/f39/EETT Roadmap 10-27-17.pdf
[48] International Energy Agency, “Global EV Outlook 2022 Securing supplies for an electric future,” 2022, [Online]. Available: www.iea.org/t&c/
[49] N. Bloomberg, “Battery Pack Prices Fall to an Average of $ 132 / kWh , But Rising Commodity Prices Start to Bite,” 2021, [Online]. Available: https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/
[50] M. Greenwood, M. Wentker, and J. Leker, “A bottom-up performance and cost assessment of lithium-ion battery pouch cells utilizing nickel-rich cathode active materials and silicon-graphite composite anodes,” *J. Power Sources Adv.*, vol. 9, Jun. 2021, doi: 10.1016/j.powera.2021.100055.
[51] A. König, L. Nicoletti, D. Schröder, S. Wolff, A. Waclaw, and M. Lienkamp, “An overview of parameter and cost for battery electric vehicles,” *World Electr. Veh. J.*, vol. 12, no. 1, pp. 1–29, 2021, doi: 10.3390/wevj12010021.
[52] M. Wentker, M. Greenwood, and J. Leker, “A bottom-up approach to lithium-ion battery cost modeling with a focus on cathode active materials,” *Energies*, vol. 12, no. 3, pp. 1–18, 2019, doi: 10.3390/en12030504.
[53] Vehicle Technologies Office, “Batteries | Department of Energy.” https://www.energy.gov/eere/vehicles/batteries (accessed May 17, 2022).
[54] L. Mauler, F. Duffner, W. G. Zeier, and J. Leker, “Battery cost forecasting: A review of methods and results with an outlook to 2050,” *Energy and Environmental Science*, vol. 14, no. 9. Royal Society of Chemistry, pp. 4712–4739, Sep. 01, 2021. doi: 10.1039/d1ee01530c.
[55] P. A. Nelson, S. Ahmed, K. G. Gallagher, and D. W. Dees, “Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, Third Edition,” 2019. doi: https://doi.org/10.2172/1503280.
[56] United States Department of Transportation, “CAFE Compliance and Effects Modeling System, The Volpe Model.” NHTSA, 2022. [Online]. Available: https://www.nhtsa.gov/corporate-average-fuel-economy/cafe-compliance-and-effects-modeling-system
[57] A. Burnham *et al.*, “Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains,” 2021, [Online]. Available: https://www.osti.gov/biblio/1780970
[58] J. Kelly, S. A. Group, and E. S. Division, “Light-Duty Vehicle Cost Markup Analysis : Literature Review and Evaluation,” no. July, 2020.
[59] Tesla, “Tesla, Inc. Form 10-K,” Dec. 2021. Accessed: Oct. 11, 2022. [Online]. Available: https://www.sec.gov/Archives/edgar/data/1318605/000095017022000796/tsla-20211231.htm
[60] V. Nair, S. Stone, and G. Rogers, “Technical Review of Medium and Heavy-Duty Electrification Costs for MY 2027- 2030,” 2022. [Online]. Available:

https://blogs.edf.org/climate411/files/2022/02/EDF-MDHD-Electrification-v1.6_20220209.pdf

[61] H. C. et Al., "The GREET Model Expansion for Well-to-Wheels Analysis of Heavy-Duty Vehicles," *Argonne Natl. Lab.*, vol. 1, no. 1, pp. 1–8, 2018, [Online]. Available: http://dx.doi.org/10.1016/j.cirp.2016.06.001

[62] H. Cai, A. Burnham, M. Wang, W. Hang, and A. Vyas, "The GREET Model Expansion for Well-to-Wheels Analysis of Heavy-Duty Vehicles," Argonne, IL (United States), May 2015. doi: 10.2172/1212730.

[63] Y. D. Costs, "Your driving costs 2021," pp. 1–9, 2021, [Online]. Available: AAA.com

[64] B. Propfe, M. Redelbach, D. J. Santini, and H. Friedrich, "Cost analysis of plug-in hybrid electric vehicles including maintenance & repair costs and resale values," *World Electr. Veh. J.*, vol. 5, no. 4, pp. 886–895, 2012, doi: 10.3390/wevj5040886.

[65] P. Northwest, "Electric Vehicle Charging for Residential and Commercial Energy Codes," no. July, 2021.

[66] A. Chakraborty, D. Buch, and K. Tal, *UC Davis Research Reports Title Cost of Plug-in Electric Vehicle Ownership: The Cost of Transitioning to Five Million Plug-In Vehicles in California Publication Date Data Availability*, no. June. 2021.

[67] C. Nelder and E. Rogers, "Reducing EV Charging Infrastructure Costs - Rocky Mountain Institute," no. January, 2019, [Online]. Available: https://rmi.org/ev-charging-costs.%0Ahttps://rmi.org/insight/reducing-ev-charging-infrastructure-costs

[68] M. Nicholas, "Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas," no. 14, p. 11, 2019, [Online]. Available: https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf

[69] John B. Goodenough – Biographical, *John B. Goodenough, Witness to Grace*. PublishAmerica, 2018. [Online]. Available: https://www.nobelprize.org/prizes/chemistry/2019/goodenough/biographical/

[70] A. Kolesnikova, "State of Charge: EVs, Batteries and Battery Materials," 2021.

[71] Wood Mackenzie, "Global lithium-ion battery capacity to rise five-fold by 2030 | Wood Mackenzie," 2022. https://www.woodmac.com/press-releases/global-lithium-ion-battery-capacity-to-rise-five-fold-by-2030/

[72] The White House, "Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Braod-based Growth: 100-Day Reviews under Executive Order 14017," pp. 1–250, 2021, [Online]. Available: https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf%0Ahttps://www.whitehouse.gov/briefing-room/statements-releases/2021/06/08/fact-sheet-biden-harris-administration-announces-supply-chain-disruptions-task-force-to-

[73] Bloomberg, "'Mr. Lithium' Warns There's Not Enough Battery Metal to Go Around," 2022. https://www.bloombergquint.com/business/mr-lithiumalr-warns-there-s-not-enough-battery-metal-to-go-around (accessed May 02, 2022).

[74] S. LeVine, "Just How Many EVs Can Be Made? Far Fewer Than Expected | Stay ahead of the EV and battery revolutions. by Steve LeVine — The Information Subscriptions," 2022. https://subscriptions.theinformation.com/newsletters/the-electric/archive/just-how-many-evs-can-be-made-far-fewer-than-expected (accessed Apr. 29, 2022).

[75] ETAuto, "Joe Lowry talks global lithium shortage | ET Auto," 2022. Accessed: May 04, 2022. [Online]. Available: https://auto.economictimes.indiatimes.com/videos/joe-lowry-talks-global-lithium-shortage/91230741
[76] McKinsey, "The raw-materials challenge: How the metals and mining sector will be at the core of enabling the energy transition | McKinsey," 2022. Accessed: May 04, 2022. [Online]. Available: https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-raw-materials-challenge-how-the-metals-and-mining-sector-will-be-at-the-core-of-enabling-the-energy-transition
[77] Reuters, "Analysis: Musk's tweets fuel mining industry's hopes of a buyout by Tesla | Reuters," *Reuters*, Apr. 19, 2022. Accessed: May 11, 2022. [Online]. Available: https://www.reuters.com/business/musks-tweets-fuel-mining-industrys-hopes-buyout-by-tesla-2022-04-19/
[78] CERAWeek, "JB Straubel & Daniel Yergin CERAWeek 2022 - YouTube," 2022. https://www.youtube.com/watch?v=_t8-IRKpb-4 (accessed May 05, 2022).
[79] C. Xu, Q. Dai, L. Gaines, M. Hu, A. Tukker, and B. Steubing, "Future material demand for automotive lithium-based batteries," *Commun. Mater.*, vol. 1, no. 1, 2020, doi: 10.1038/s43246-020-00095-x.
[80] Northern Graphite, "BUILDING THE LEADING PUBLIC GRAPHITE COMPANY, Corporate Presentation," 2022.
[81] A. Grant and K. Goodenough, "Is There Enough Lithium to Make All the Batteries?," *BatteryBits*, pp. 1–11, 2021. [Online]. Available: https://medium.com/batterybits/is-there-enough-lithium-to-make-all-the-batteries-c3a522c01498
[82] I. Warren, "Techno-Economic Analysis of Lithium Extraction from Geothermal Brines Techno-Economic Analysis of Lithium Extraction from Geothermal Brines," *Natl. Renew. Energy Lab.*, no. May, p. 48, 2021, [Online]. Available: https://www.nrel.gov/docs/fy21osti/799178.pdf.%0ANREL
[83] U.S. Geological Survey, "Mineral Commodity Summaries 2022," 2022. [Online]. Available: https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries
[84] C. Dessemond, F. Lajoie-Leroux, G. Soucy, N. Laroche, and J. F. Magnan, "Spodumene: The lithium market, resources and processes," *Minerals*, vol. 9, no. 6, 2019, doi: 10.3390/min9060334.
[85] J. C. Kelly, M. Wang, Q. Dai, and O. Winjobi, "Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries," *Resour. Conserv. Recycl.*, vol. 174, no. April, p. 105762, 2021, doi: 10.1016/j.resconrec.2021.105762.
[86] Lithium Americas, "Lithium Americas," 2022. https://www.lithiumamericas.com/usa/thacker-pass/ (accessed May 09, 2022).
[87] Lithium Americas, "GM and Lithium Americas to Develop U.S.-Sourced Lithium Production," 2023. [Online]. Available: https://www.lithiumamericas.com/investors/
[88] McKinsey & Company, "Lithium mining : How new production technologies could fuel the global EV revolution," 2022.
[89] General Motors Co., "News Release Details," *News Release Details*, 2021. https://investor.gm.com/news-releases/news-release-details/gm-source-us-based-lithium-next-generation-ev-batteries-through

[90] Stellantis, "Stellantis Secures Low Emissions Lithium Supply for North American Electric Vehicle Production from Controlled Thermal Resources | Stellantis." https://www.stellantis.com/en/news/press-releases/2022/june/stellantis-secures-low-emissions-lithium-supply-for-north-american-electric-vehicle-production-from-controlled-thermal-resources (accessed Jun. 17, 2022).
[91] "India's lithium discovery could boost green energy but creates problems in the region | PIIE." https://www.piie.com/blogs/realtime-economics/indias-lithium-discovery-could-boost-green-energy-creates-problems-region (accessed Mar. 15, 2023).
[92] "Iran discovers 8.5 million ton lithium deposit - Mining Technology." https://www.mining-technology.com/news/iran-discovers-major-lithium-deposit/ (accessed Mar. 15, 2023).
[93] U.S. Department of Energy, "Reducing Reliance on Cobalt for Lithium-ion Batteries," *Energy.Gov Resour.*, pp. 1–7, 2021, [Online]. Available: https://www.energy.gov/eere/vehicles/articles/reducing-reliance-cobalt-lithium-ion-batteries
[94] Cobalt Institute, "Cobalt Value Chain Mapping," 2022. https://www.cobaltinstitute.org/news/the-cobalt-value-chain-mapping-shaping-the-priorities-for-responsible-sourcing/
[95] Cobalt Institute, "Cobalt Value Chain Mapping," 2022.
[96] World Ocean Review, "Sea-floor mining," *World Ocean Rev. 3*, pp. 54–93, 2014.
[97] The Metals Company, "Home Page - The Metals Company," 2022. https://metals.co/ (accessed May 11, 2022).
[98] F. Consortium for Advanced Batteries, "NATIONAL BLUEPRINT FOR LITHIUM BATTERIES EXECUTIVE SUMMARY," 2021.
[99] M. J. Lain and E. Kendrick, "Understanding the limitations of lithium ion batteries at high rates," *J. Power Sources*, vol. 493, p. 229690, 2021, doi: 10.1016/j.jpowsour.2021.229690.
[100] Battery, "Inventing the sustainable batteries of the future-Battery 2030," 2020.
[101] A. Collaborative and E. Storage, "High-Capacity Cathodes Based in Earth-Abundant Manganese : Scratching the Surface … Or Not ?," 2021.
[102] C. NUNEZ, "Researchers eye manganese as key to safer, cheaper lithium-ion batteries | Argonne National Laboratory," 2020. https://www.anl.gov/article/researchers-eye-manganese-as-key-to-safer-cheaper-lithiumion-batteries (accessed Apr. 21, 2022).
[103] SNE Research, "Global EV battery usage in 2021. All three Korean companies show solid growth.," 2022. http://www.sneresearch.com/_new/html/sub/sub2/sub2_01_view.php?id=95941&s_keyword=&f_date=&t_date=&pg=&cate_id=&type=press
[104] Volta Foundation, "Battery Report 2022," 2023. https://www.volta.foundation/annual-battery-report
[105] C. I. C. Energigune and E. N. E. S. Eu, "NORTH AMERICA ACCELERATES ITS COMMITMENT TO THE DEVELOPMENT OF THE GIGAFACTORY INDUSTRY," 2022. https://cicenergigune.com/en/blog/north-america-accelerates-commitment-development-gigafactory-industry
[106] BatteryBits.org, "The Battery Report 2021," *Report*, pp. 1–132, 2022, [Online]. Available: https://www.batterybrunch.org/battery-

report%0Ahttps://medium.com/batterybits/the-battery-report-2021-442ed2a06324
[107] Piedmont Lithium, “Piedmont Completes Preliminary Economic Assessment for Second U.S. Lithium Hydroxide Plant - Piedmont Lithium,” *Press Release*, 2022. https://piedmontlithium.com/piedmont-completes-preliminary-economic-assessment-for-second-u-s-lithium-hydroxide-plant/ (accessed May 17, 2022).
[108] T. Idaho and E. National, “U . S . Department of Energy Vehicle Technologies Program Battery Test Manual For Electric Vehicles,” no. June, 2015.
[109] J. Zhu *et al.*, “End-of-life or second-life options for retired electric vehicle batteries,” *Cell Reports Phys. Sci.*, vol. 2, no. 8, p. 100537, 2021, doi: 10.1016/j.xcrp.2021.100537.
[110] L. Gaines, Q. Dai, J. T. Vaughey, and S. Gillard, “Direct recycling R&D at the recell center,” *Recycling*, vol. 6, no. 2, pp. 1–18, 2021, doi: 10.3390/recycling6020031.
[111] I. Morse, “A dead battery dilemma,” *Science (80-. ).*, vol. 372, no. 6544, pp. 780–783, 2021, doi: 10.1126/science.372.6544.780.
[112] Y. Kotak *et al.*, “End of electric vehicle batteries: Reuse vs. recycle,” *Energies*, vol. 14, no. 8, pp. 1–15, 2021, doi: 10.3390/en14082217.
[113] “Update on Redwood’s California EV Battery Recycling Program.” https://www.redwoodmaterials.com/news/update-california-ev-battery-recycling-program/ (accessed Mar. 16, 2023).
[114] “U.S. DOE’s Argonne National Laboratory verifies performance of Redwood cathode from recycled content.” https://www.redwoodmaterials.com/news/argonne-national-laboratory-verifies-redwood-cathode-performance/ (accessed Mar. 16, 2023).
[115] ReCell, “Novel Processing and Design Technologies Will Make BATTERY RECYCLING PROFITABLE,” no. February 2019, 2019, [Online]. Available: https://www.anl.gov/sites/www/files/2019-02/ReCell_FS.pdf
[116] G. Harper *et al.*, “Recycling lithium-ion batteries from electric vehicles,” *Nature*, vol. 575, no. 7781, pp. 75–86, 2019, doi: 10.1038/s41586-019-1682-5.
[117] ReCell, “The recell center for advanced battery recycling – fy22 q1 report,” 2022.
[118] Q. Dai, J. Spangenberger, S. Ahmed, L. Gaines, J. C. Kelly, and M. Wang, “EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model,” *Argonne Natl. Lab.*, pp. 1–88, 2019.
[119] ReCell, “Recell – Modeling and Analysis for Recycling,” 2021.
[120] L. F. Zhou, D. Yang, T. Du, H. Gong, and W. Bin Luo, “The Current Process for the Recycling of Spent Lithium Ion Batteries,” *Front. Chem.*, vol. 8, no. December, pp. 1–7, 2020, doi: 10.3389/fchem.2020.578044.
[121] L. Mathieu and Cecilia Mattea, “From dirty oil to clean batteries. Batteries vs oil: a systematic comparison of material requirements,” *Transp. Environ.*, 2021, [Online]. Available: www.transportenvironment.org
[122] “Li-Cycle Opens Lithium-ion Battery Recycling Facility in Alabama - Li-Cycle.” https://li-cycle.com/press-releases/li-cycle-opens-lithium-ion-battery-recycling-facility-in-alabama/ (accessed Mar. 16, 2023).
[123] Nano One, “Nano One Corporate Overview 2022,” 2022.
[124] S. He, S. Huang, S. Wang, I. Mizota, X. Liu, and X. Hou, “Considering Critical Factors of Silicon/Graphite Anode Materials for Practical High-Energy Lithium-Ion Battery Applications,” *Energy and Fuels*, vol. 35, no. 2, pp. 944–964, Jan. 2021, doi: 10.1021/ACS.ENERGYFUELS.0C02948/ASSET/IMAGES/MEDIUM/EF0C02948_0

017.GIF.

[125] Nano One, "Nano One Provides Update on Emerging LFP Opportunity," 2022. https://nanoone.ca/news/news-releases/nano-one-provides-update-on-emerging-lfp-opportunity/ (accessed Mar. 05, 2022).

[126] X. G. Yang, T. Liu, and C. Y. Wang, "Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles," *Nat. Energy*, vol. 6, no. 2, pp. 176–185, 2021, doi: 10.1038/s41560-020-00757-7.

[127] UBS Evidence Lab, "VW ID.3 UBS Vehicle Teardown Full Report," 2020. [Online]. Available: https://www.ubs.com/evidencelab-store/electric-vehicle-and-battery-teardowns-8-full-reports-.html

[128] Y. Preger *et al.*, "Degradation of Commercial Lithium-Ion Cells as a Function of Chemistry and Cycling Conditions," *J. Electrochem. Soc.*, vol. 167, no. 12, p. 120532, 2020, doi: 10.1149/1945-7111/abae37.

[129] Bloomberg, "Battery Metals Outlook," *Bloomberg*, 2021. https://spotlight.bloomberg.com/story/battery-metals-outlook/page/1 (accessed May 12, 2022).

[130] M. Greenwood, M. Wentker, and J. Leker, "A bottom-up performance and cost assessment of lithium-ion battery pouch cells utilizing nickel-rich cathode active materials and silicon-graphite composite anodes," *J. Power Sources Adv.*, vol. 9, no. December 2020, p. 100055, 2021, doi: 10.1016/j.powera.2021.100055.

[131] U. H. Kim, L. Y. Kuo, P. Kaghazchi, C. S. Yoon, and Y. K. Sun, "Quaternary Layered Ni-Rich NCMA Cathode for Lithium-Ion Batteries," *ACS Energy Lett.*, vol. 4, no. 2, pp. 576–582, 2019, doi: 10.1021/acsenergylett.8b02499.

[132] C. R. Birkl, M. R. Roberts, E. McTurk, P. G. Bruce, and D. A. Howey, "Degradation diagnostics for lithium ion cells," *J. Power Sources*, vol. 341, pp. 373–386, Feb. 2017, doi: 10.1016/J.JPOWSOUR.2016.12.011.

[133] M. S. Whittingham, "Special Editorial Perspective: Beyond Li-Ion Battery Chemistry," *Chem. Rev.*, vol. 120, no. 14, pp. 6328–6330, 2020, doi: 10.1021/acs.chemrev.0c00438.

[134] E. Moyassari *et al.*, "Impact of Silicon Content within Silicon-Graphite Anodes on Performance and Li Concentration Profiles of Li-Ion Cells using Neutron Depth Profiling," *J. Electrochem. Soc.*, vol. 168, no. 2, p. 020519, 2021, doi: 10.1149/1945-7111/abe1db.

[135] C. Miller, "First Toyota with Solid-State Batteries Will Be a Hybrid," *Car and Driver Magazine*, 2022. https://www.caranddriver.com/news/a38711469/toyota-solid-state-batteries-2025/ (accessed May 12, 2022).

[136] Nissan Motor Corporation, "Nissan unveils Ambition 2030 vision to empower mobility and beyond," *Official Global Newsroom*, 2021. https://global.nissannews.com/en/releases/nissan-ambition-2030-vision-to-empower-mobility-beyond (accessed May 17, 2022).

[137] J. Schnell, H. Knörzer, A. J. Imbsweiler, and G. Reinhart, "Solid versus Liquid—A Bottom-Up Calculation Model to Analyze the Manufacturing Cost of Future High-Energy Batteries," *Energy Technol.*, vol. 8, no. 3, 2020, doi: 10.1002/ente.201901237.

[138] H. Au, M. Crespo-Ribadeneyra, and M. M. Titirici, "Beyond Li-ion batteries: performance, materials diversification, and sustainability," *One Earth*, vol. 5, no. 3,

pp. 207–211, 2022, doi: 10.1016/j.oneear.2022.02.014.
[139] G. L. Xu *et al.*, "Native lattice strain induced structural earthquake in sodium layered oxide cathodes," *Nat. Commun.*, vol. 13, no. 1, pp. 1–12, 2022, doi: 10.1038/s41467-022-28052-x.
[140] Faradion, "Strong Performance - Faradion," *Media Release*, 2022. https://faradion.co.uk/technology-benefits/strong-performance/ (accessed May 11, 2022).
[141] T. Li, X. Z. Yuan, L. Zhang, D. Song, K. Shi, and C. Bock, *Degradation Mechanisms and Mitigation Strategies of Nickel-Rich NMC-Based Lithium-Ion Batteries*, vol. 3, no. 1. Springer Singapore, 2020. doi: 10.1007/s41918-019-00053-3.
[142] H. Zhang, J. Xu, and J. Zhang, "Surface-Coated LiNi0.8Co0.1Mn0.1O2 (NCM811) Cathode Materials by Al2O3, ZrO2, and Li2O-2B2O3 Thin-Layers for Improving the Performance of Lithium Ion Batteries," *Front. Mater.*, vol. 6, no. November, pp. 1–10, 2019, doi: 10.3389/fmats.2019.00309.
[143] S. Chen *et al.*, "Ni-Rich LiNi0.8Co0.1Mn0.1O2 Oxide Coated by Dual-Conductive Layers as High Performance Cathode Material for Lithium-Ion Batteries," *ACS Appl. Mater. Interfaces*, vol. 9, no. 35, pp. 29732–29743, Sep. 2017, doi: 10.1021/ACSAMI.7B08006/SUPPL_FILE/AM7B08006_SI_001.PDF.
[144] CATL, "Innovative Technology," *Media Release*, 2022. https://www.catl.com/en/research/technology/ (accessed May 27, 2022).
[145] Bloomberg, "A Million-Mile Battery From China Could Power Your Electric Car - Bloomberg," 2020. https://www.bloomberg.com/news/articles/2020-06-07/a-million-mile-battery-from-china-could-power-your-electric-car (accessed May 27, 2022).
[146] Nickel Institute, "Single crystal Ni-containing cathodes - A conversation with Prof. Jeff Dahn | Nickel Institute," 2021. https://nickelinstitute.org/en/blog/2021/january/single-crystal-ni-containing-cathodes-a-conversation-with-prof-jeff-dahn/ (accessed May 27, 2022).
[147] Nano One, "Nano One Introduces a Breakthrough in Longer Lasting Lithium-Ion Cathode Materials | Nano One Materials Corp.," *Media Release*, 2022. https://nanoone.ca/news/news-releases/nano-one-introduces-a-breakthrough-in-longer-lasting-lithium-ion-cathode-materials/ (accessed May 27, 2022).
[148] J. E. Harlow *et al.*, "A Wide Range of Testing Results on an Excellent Lithium-Ion Cell Chemistry to be used as Benchmarks for New Battery Technologies," *J. Electrochem. Soc.*, vol. 166, no. 13, pp. A3031–A3044, 2019, doi: 10.1149/2.0981913jes.
[149] B. J. Ludwig, "Solvent-free additive manufacturing of electrodes for Li-ion batteries," p. 154, 2019.
[150] Y. Liu, R. Zhang, J. Wang, and Y. Wang, "Current and future lithium-ion battery manufacturing," *iScience*, vol. 24, no. 4, p. 102332, 2021, doi: 10.1016/j.isci.2021.102332.
[151] Tesla, "2020 Annual Meeting of Stockholders and Battery Day," 2020. https://www.tesla.com/2020shareholdermeeting (accessed Aug. 04, 2022).
[152] General Motors, "Ultium Battery Powered Electric Vehicles | General Motors," *Media Release*, 2021. https://www.gm.com/ultium?ppc=GOOGLE_700000001980004_71700000090550494_58700007661457492_p69382669543&d_src=313715&d_adsrc=4137267&d_ca

mpaign=71700000090550494&d_site=GOOGLE&d_adgroup=58700007661457492&d_keyword=gm ultium&gclick=Cj0KCQjwspKUBhCvARIsAB2IYu (accessed May 18, 2022).
[153] BYD, "BYD's New Blade Battery Set to Redefine EV Safety Standards - BYD USA," *Media Release*, 2022. https://en.byd.com/news/byds-new-blade-battery-set-to-redefine-ev-safety-standards/ (accessed May 18, 2022).
[154] UBS Evidence Lab, "VW ID.3 UBS Vehicle Teardown Full Report," 2020.
[155] J. Doerr, T. Attensperger, L. Wittmann, and T. Enzinger, "The New Electric Axle Drives from Audi," *ATZelektronik Worldw.*, vol. 13, no. 3, pp. 16–23, 2018, doi: 10.1007/s38314-018-0040-y.
[156] BMW, "The new BMW iX3," *Media Release*, 2022. https://www.press.bmwgroup.com/global/photo/compilation/T0338848EN/the-new-bmw-ix3 (accessed May 18, 2022).
[157] "Niron Magnetics Secures $17.5M SCALEUP Grant from the U.S. Department of Energy's ARPA-E - Niron Magnetics." https://www.nironmagnetics.com/news/niron-magnetics-secures-17-5m-scaleup-grant-from-the-u-s-department-of-energys-arpa-e/ (accessed Mar. 16, 2023).
[158] "The SCALEUP Program | arpa-e.energy.gov." https://arpa-e.energy.gov/technologies/scaleup (accessed Mar. 16, 2023).
[159] "No decarbonisation without copper. After a year of the global pandemic, with its", Accessed: Mar. 16, 2023. [Online]. Available: www.gs.com/research/hedge.html.
[160] J. D. Widmer, R. Martin, and B. C. Mecrow, "Precompressed and Stranded Aluminum Motor Windings for Traction Motors," *IEEE Trans. Ind. Appl.*, vol. 52, no. 3, pp. 2215–2223, 2016, doi: 10.1109/TIA.2016.2528226.
[161] H. Saxena, V. Nair, and S. Pillai, "Electrification Cost Evaluation of Class 2b and Class 3 Vehicles," 2023.
[162] "TECHNOLOGY | ALL GaN VEHICLE FOR FUTURE." https://www.gan-vehicle.jp/product/technology/?=en (accessed Mar. 08, 2023).
[163] "Wide Bandgap Semiconductors (SiC/GaN) - Infineon Technologies." https://www.infineon.com/cms/en/product/technology/wide-bandgap-semiconductors-sic-gan/?utm_source=pen&utm_medium=tech_publications&utm_campaign=202205_glob_en_pss_PSS.P.A.OBC.2122&utm_term=WBG_in_EVs&utm_content=cover_web (accessed Mar. 09, 2023).
[164] R. Islam, S. M. Rafin, and O. A. Mohammed, "Comprehensive Review of Power Electronic Converters in Electric Vehicle Applications," *Forecasting*, vol. 5, no. 1. pp. 22–80, 2023. doi: 10.3390/forecast5010002.
[165] R. Garcia, "WBG Transistors in EV On-Board Chargers - Power Electronics News," *Power Electronics News*, 2022. https://www.powerelectronicsnews.com/wide-bandgap-wbg-transistors-in-on-board-chargers-for-electric-vehicles/ (accessed Mar. 09, 2023).
[166] Eaton, "Essential guide to electric vehicle charging".
[167] "DC Fast Charge - Texas Commission on Environmental Quality - www.tceq.texas.gov." https://www.tceq.texas.gov/agency/trust/dcfch (accessed Mar. 17, 2023).
[168] Tceq, "Light-Duty Zero Emission Vehicle (ZEV) Supply Equipment: Direct Current

Fast Charge (DCFC) & Hydrogen Dispensing Equipment Presentation”.

[169] A. Received, “Texas Commission on Environmental Quality (TCEQ) Texas Volkswagen Environmental Mitigation Program (TxVEMP) Light-Duty Zero Emission Vehicles (ZEV) Supply Equipment Direct Current Fast Chargers (DCFC) and Hydrogen Dispensing Equipment”.

[170] “Installation of prefabricated Tesla Supercharger stations - YouTube.” https://www.youtube.com/watch?v=rZoWvDYITMI (accessed Mar. 17, 2023).

[171] Dave Vanderwerp, “Here’s How Fast the Latest EVs Can Charge,” Aug. 18, 2022. https://www.caranddriver.com/features/a40929408/ev-charging-chart-rates/ (accessed Mar. 17, 2023).

[172] “Boost Charger 200.” https://freewiretech.com/products/dc-boost-charger-200/ (accessed Mar. 17, 2023).

[173] “Li-Cycle Receives Conditional Commitment for $375 Million Loan from the U.S. Department of Energy ATVM Program - Li-Cycle.” https://li-cycle.com/press-releases/li-cycle-receives-conditional-commitment-for-375-million-loan-from-the-u-s-department-of-energy-atvm-program/ (accessed Mar. 16, 2023).

# 9. Appendix

## 9.1 Incremental Powertrain Cost without RPE

This section presents the detailed ICE and BEV powertrain cost calculations that underlie the study analysis. They are expressed as direct manufacturing costs for 2022, 2027, and 2030, and as such do not reflect the application of RPE markups. The green highlight, the red text, and the pink highlight represent the low, medium, and high-cost powertrain options for both ICEVs and BEVs (see Methodology, Section 2 for additional information).

### 9.1.1 Class 2b Van

**Table 32: ICE and BEV powertrain costs for a class 2b van**

| Powertrain | Powertrain Cost ($) | | | Technology | Technology |
|---|---|---|---|---|---|
| | 2022 | 2027 | 2030 | 2022 | 2027 |
| Conventional SI | 7,003 | 6,951 | 6,930 | DOHC + VVT + GDI + AT10L3 | Add ADEAC |
| Mild Hybrid BISG SI | 7,734 | 7,527 | 7,449 | DOHC + VVT + GDI + AT10L3 + BISG | Add ADEAC |
| Conventional SI Turbo | 7,976 | 7,905 | 7,879 | Turbo1 + CEGR + AT10L3 | |
| Mild Hybrid BISG SI Turbo | 8,707 | 8,480 | 8,398 | Turbo1 + CEGR + BISG + AT10L3 | |
| Par HEV SI | 9,547 | 8,960 | 8,758 | HCR1 + AT10L3 + SHEVP2 | |
| Par HEV SI Turbo | 10,562 | 9,944 | 9,733 | Turbo1 + AT10L3 + SHEVP2 | |
| BEV150 - Low | 14,753 | 7,751 | 6,189 | | |
| BEV150 - Medium | 15,152 | 7,997 | 6,383 | | |
| BEV150 - High | 16,466 | 8,659 | 6,884 | | |
| BEV250 - Low | 23,249 | 12,001 | 9,429 | | |
| BEV250 - Medium | 23,914 | 12,411 | 9,755 | | |
| BEV250 - High | 26,104 | 13,515 | 10,592 | | |
| Low cost | (Green highlight) | | | | |
| Medium cost | (Red text) | | | | |
| High cost | (Pink highlight) | | | | |

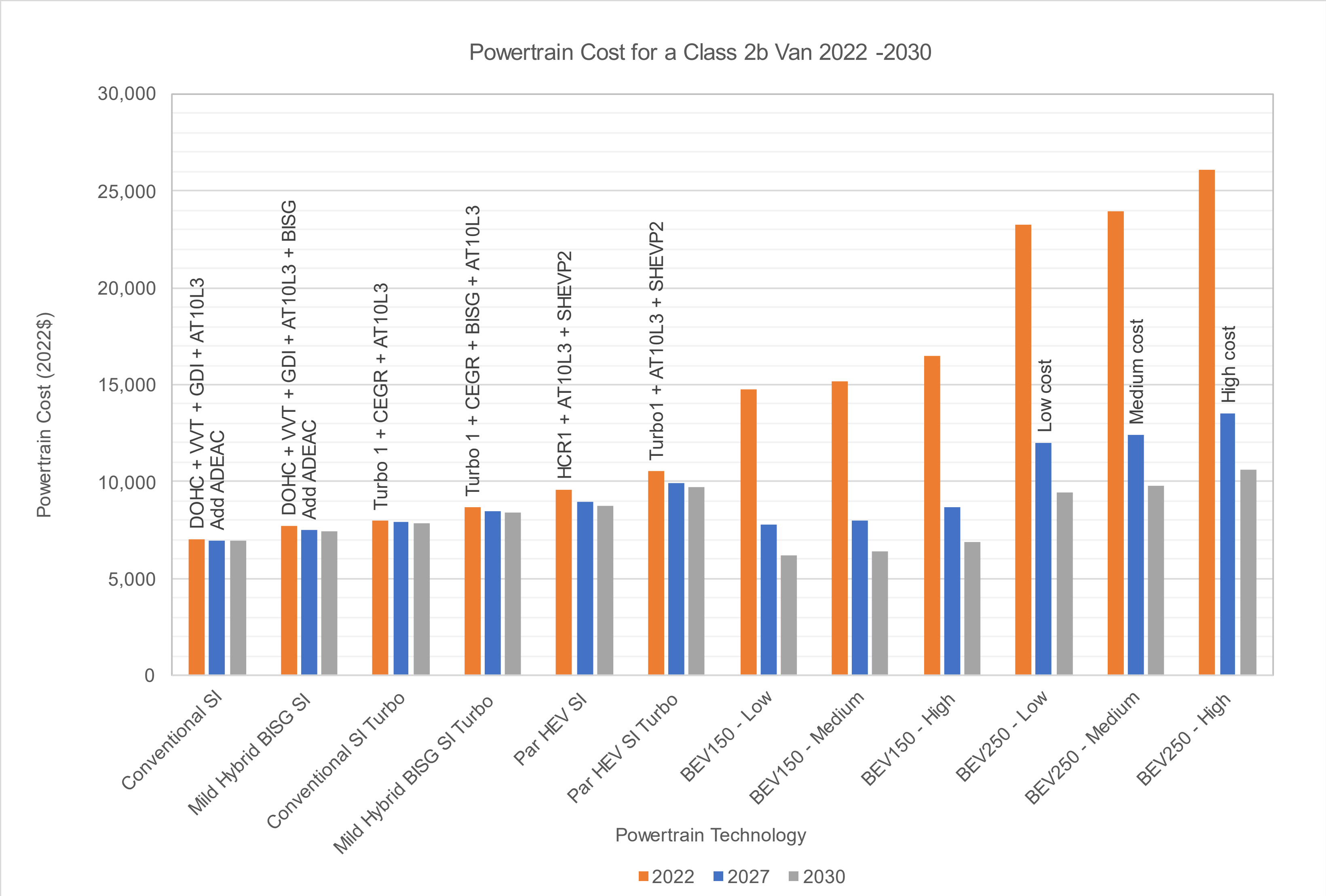


**Figure 105: ICE and BEV powertrain costs for a class 2b Van for 2022, 2027, and 2030**

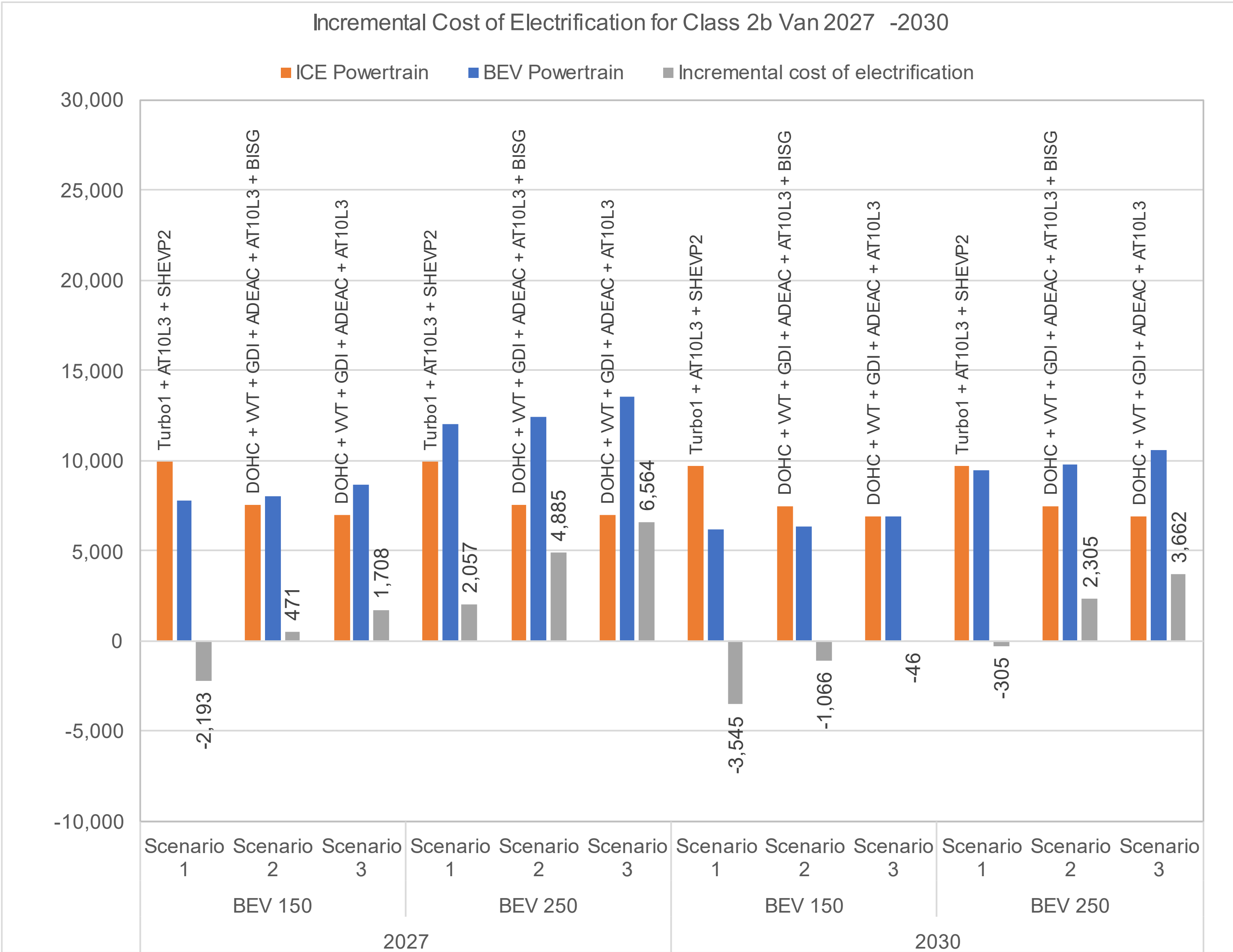


**Figure 106: Class 2b Van ICE and BEV powertrain costs for the three incremental cost scenarios for 2027 and 2030.**

### 9.1.2 Class 3 Pickup

**Table 33: ICE and BEV powertrain costs for a class 3 pickup**

| Powertrain Cost of Class 3 Pickup Truck | | | | | |
|---|---|---|---|---|---|
| **Powertrain** | **Powertrain Cost ($)** | | | **Technology** | **Technology** |
| | **2022** | **2027** | **2030** | **2022** | **2027** |
| Conventional SI | 6,795 | 7,349 | 7,326 | V8 OHV + VVT + AT10L3 | Add GDI + ADEAC |
| Mild Hybrid BISG SI | 7,526 | 7,924 | 7,845 | V8 OHV + VVT + AT10L3 + BISG | Add GDI + ADEAC |
| Par HEV SI | 10,261 | 9,680 | 9,487 | HCR1 + AT10L3 + SHEVP2 | |
| Conventional CI | 10,755 | 11,411 | 11,326 | DSLI + AT10L3 | DSLIAD |
| BEV150 - Low | 15,071 | 8,263 | 6,786 | | |
| BEV150 - Medium | 15,444 | 8,496 | 6,970 | | |
| BEV150 - High | 16,671 | 9,122 | 7,443 | | |
| BEV250 - Low | 23,006 | 12,281 | 9,849 | | |
| BEV250 - Medium | 23,627 | 12,669 | 10,157 | | |
| BEV250 - High | 25,673 | 13,712 | 10,949 | | |
| BEV300 - Low | 26,974 | 14,290 | 11,366 | | |
| BEV300 - Medium | 27,719 | 14,755 | 11,735 | | |
| BEV300 - High | 30,175 | 16,007 | 12,685 | | |
| BEV400 - Low | 34,909 | 18,309 | 14,399 | | |
| BEV400 - Medium | 35,903 | 18,928 | 14,891 | | |
| BEV400 - High | 39,177 | 20,598 | 16,157 | | |
| Low cost | (Green highlight) | | | | |
| Medium cost | (Red text) | | | | |
| High cost | (Pink highlight) | | | | |

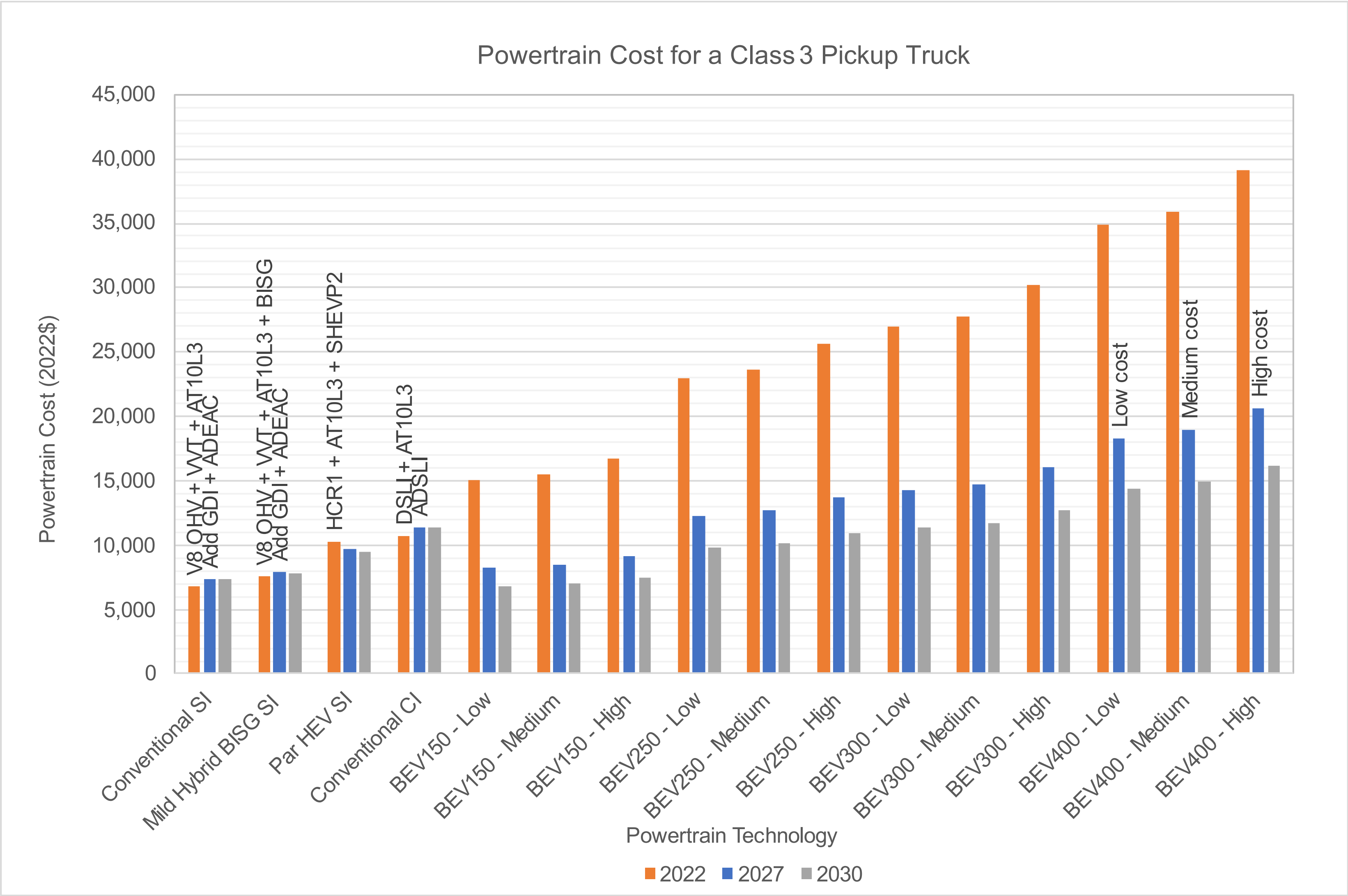


**Figure 107: ICE and BEV powertrain costs for a Class 3 Pickup Truck for 2022, 2027, and 2030**

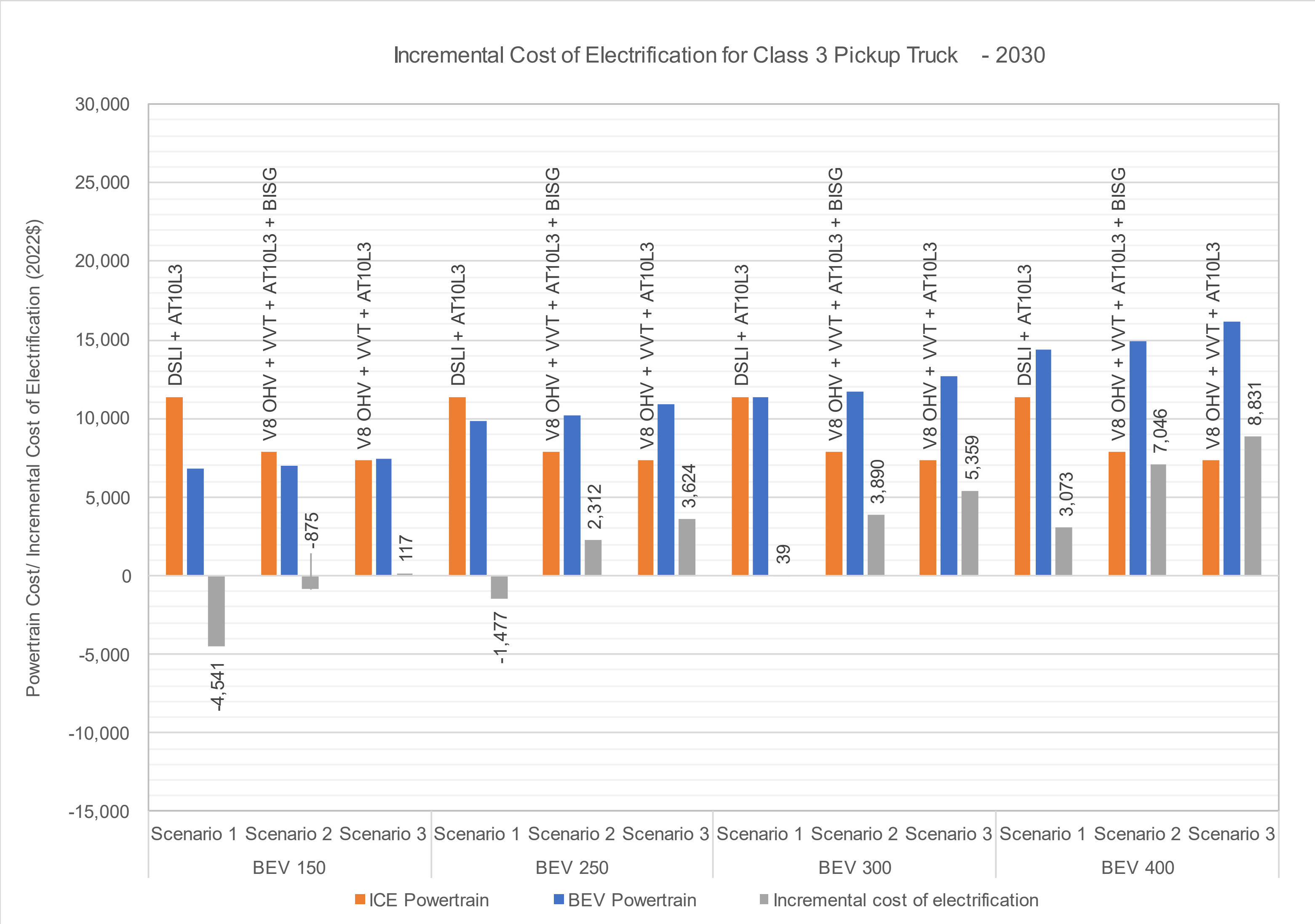


**Figure 108: Class 3 Pickup Truck powertrain costs for the three incremental cost scenarios for 2027 and 2030.**

### 9.1.3 Class 3 Package & Delivery Truck

**Table 34: ICE and BEV powertrain costs for a class 3 package and delivery (P&D) truck**

| Powertrain Cost of Class 3 Package and Delivery Truck | | | | | |
|---|---|---|---|---|---|
| **Powertrain** | **Powertrain Cost ($)** | | | **Technology** | **Technology** |
| | **2022** | **2027** | 2030 | **2022** | **2027** |
| Conventional SI | 6,795 | 7,349 | 7,326 | V8 OHV + VVT + AT10L3 | Add GDI + ADEAC |
| Mild Hybrid BISG SI | 7,526 | 7,924 | 7,845 | V8 OHV + VVT + AT10L3 + BISG | Add GDI + ADEAC |
| Par HEV SI | 10,261 | 9,680 | 9,487 | HCR1 + AT10L3 + SHEVP2 | |
| Conventional CI | 10,755 | 11,411 | 11,326 | DSLI + AT10L3 | DSLIAD |
| BEV150 - Low | 17,536 | 9,199 | 7,352 | | |
| BEV150 - Medium | 18,011 | 9,490 | 7,582 | | |
| BEV150 - High | 19,573 | 10,273 | 8,174 | | |
| BEV250 - Low | 27,634 | 14,224 | 11,182 | | |
| BEV250 - Medium | 28,425 | 14,708 | 11,568 | | |
| BEV250 - High | 31,028 | 16,013 | 12,558 | | |
| Low cost | (Green highlight) | | | | |
| Medium cost | (Red text) | | | | |
| High cost | (Pink highlight) | | | | |

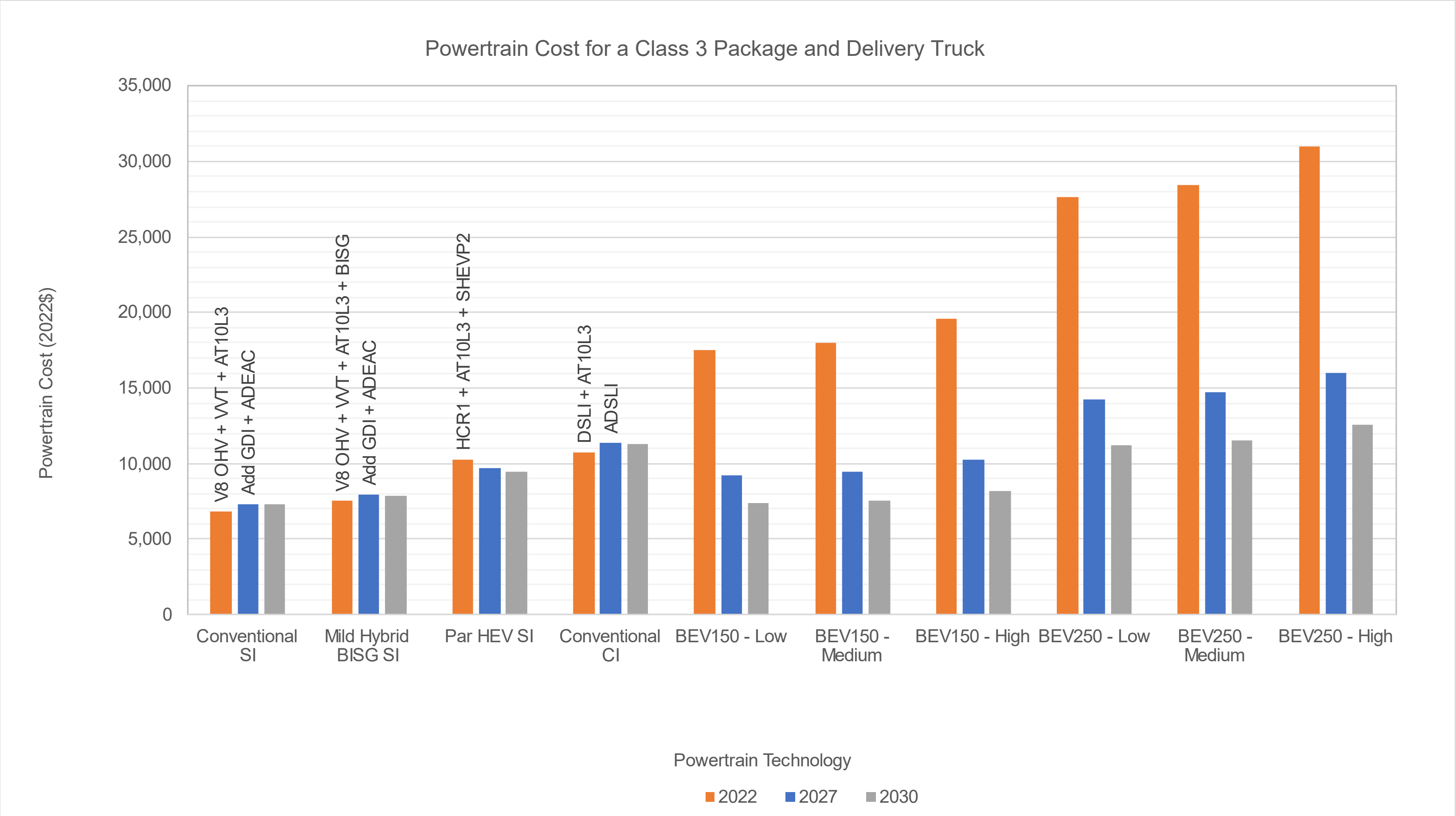


**Figure 109: ICE and BEV powertrain costs for a Class 3 Package and Delivery Truck for 2022, 2027, and 2030.**

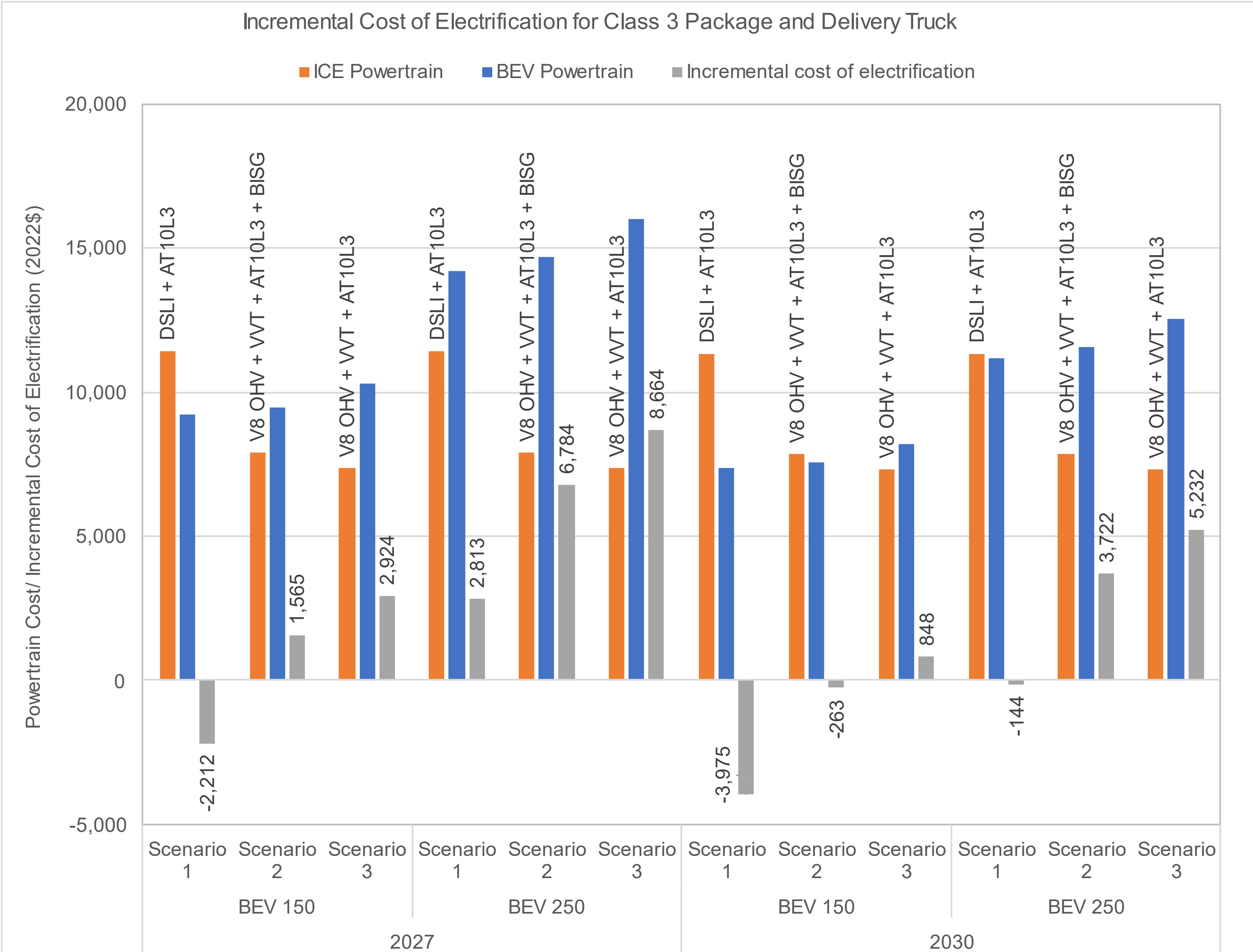


**Figure 110: Class 3 Package and Delivery truck powertrain costs for the three incremental cost scenarios for 2027 and 2030.**

### 9.1.4 Class 3 Van

**Table 35: ICE and BEV powertrain costs for a class 3 van**

| Powertrain Cost of Class 3 Van | | | | | |
|---|---|---|---|---|---|
| **Powertrain** | **Powertrain Cost ($)** | | | **Technology** | **Technology** |
| | **2022** | **2027** | 2030 | **2022** | **2027** |
| Conventional SI | 6,795 | 7,349 | 7,327 | V8 OHV + VVT + AT10L3 | Add GDI + ADEAC |
| Mild Hybrid BISG SI | 7,526 | 7,924 | 7,845 | V8 OHV + VVT + AT10L3 + BISG | Add GDI + ADEAC |
| Par HEV SI | 10,261 | 9,680 | 9,487 | HCR1 + AT10L3 + SHEVP2 | |
| Conventional CI | 10,755 | 11,411 | 11,327 | DSLI + AT10L3 | DSLIAD |
| BEV150 - Low | 16,741 | 8,814 | 7,060 | | |
| BEV150 - Medium | 17,190 | 9,090 | 7,278 | | |
| BEV150 - High | 18,672 | 9,833 | 7,840 | | |
| BEV250 - Low | 26,316 | 13,585 | 10,697 | | |
| BEV250 - Medium | 27,066 | 14,045 | 11,063 | | |
| BEV250 - High | 29,535 | 15,284 | 12,004 | | |
| Low cost | (Green highlight) | | | | |
| Medium cost | (Red text) | | | | |
| High cost | (Pink highlight) | | | | |

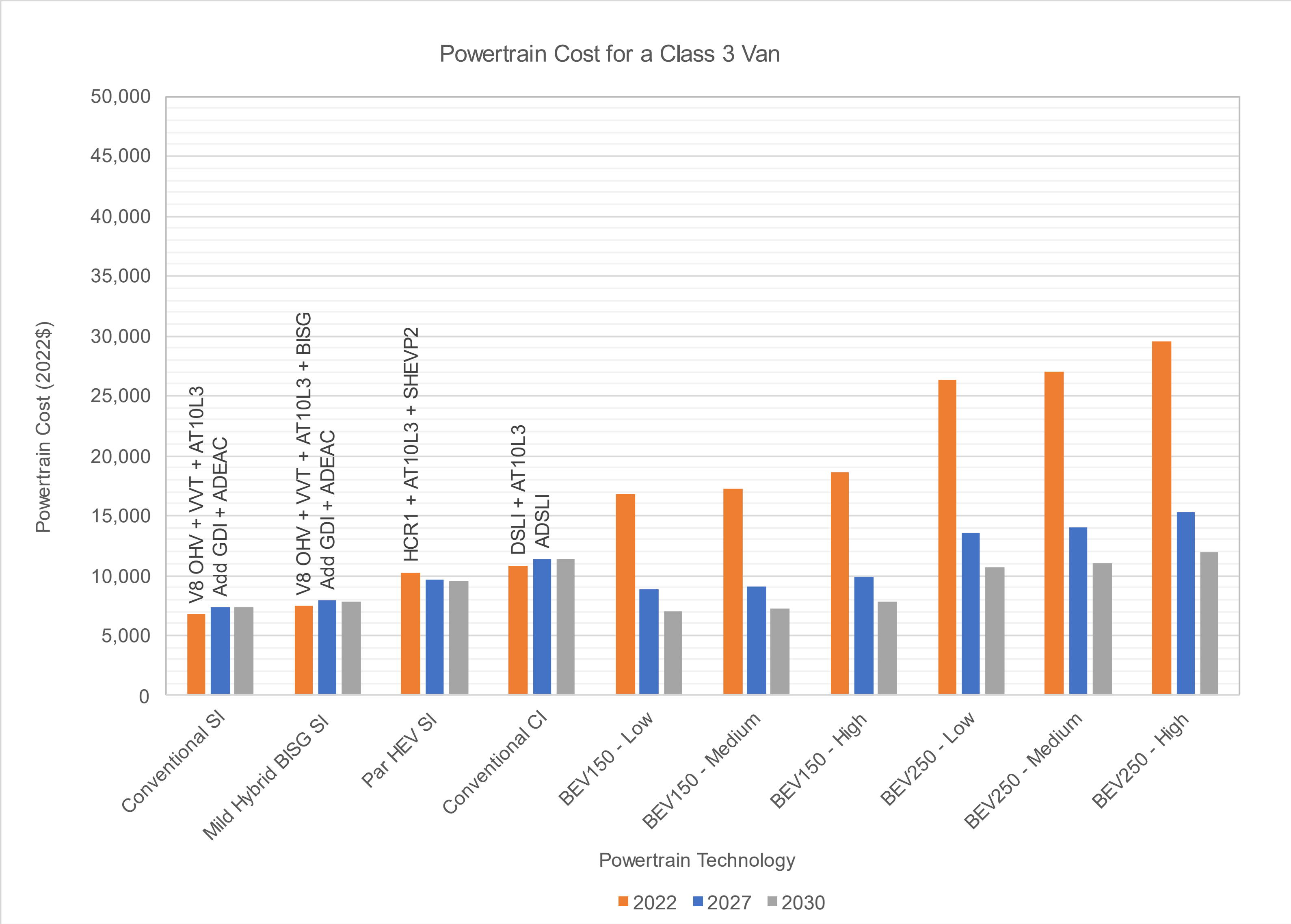


**Figure 111: ICE and BEV powertrain cost for a Class 3 Van for 2022, 2027, and 2030.**

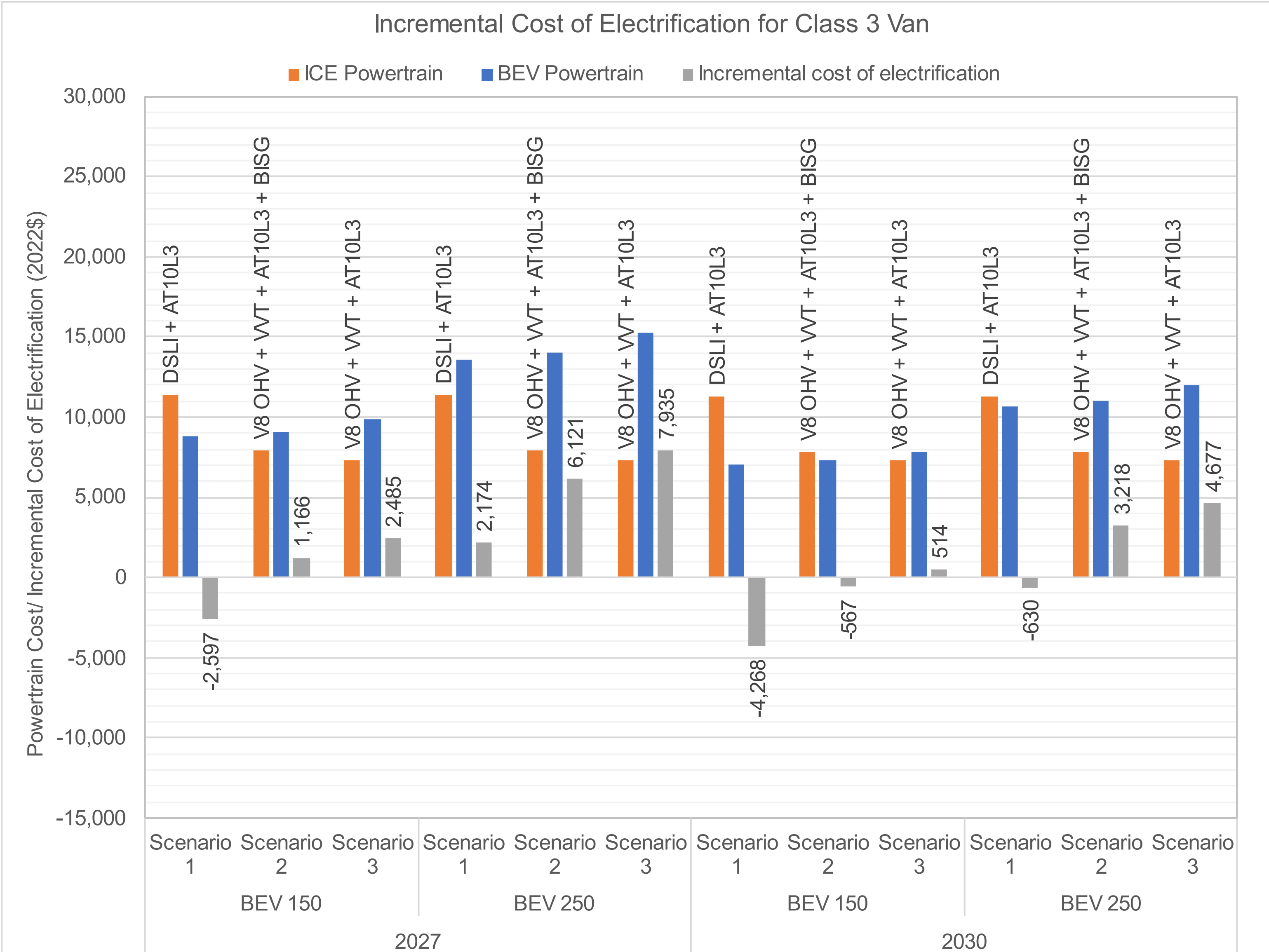


**Figure 112: Class 3 Van ICE and BEV powertrain costs for the three incremental cost scenarios for 2027 and 2030.**

## 9.2 Total Cost of Ownership Energy Inputs

The presented data is sourced from U.S. Energy Information Administration Annual Energy Outlook (AEO) 2022 for the 2027-2038 and 2030-2041 timeframes [6]. The prices have been used as inputs in the respective incremental cost cases included in the column headers.

**Table 36: EIA AEO 2022 fuel ($/gal) and electricity ($/kWh) projections used in this study.**

| Year | Diesel high oil price 2021 $/gal (Scenario 1 case of Class 3 only) | Gasoline High oil price 2021 $/gal (Scenario 1 of Class 2b only) | Gasoline Reference case 2021 $/gal (Scenario 2) | Gasoline Low oil price 2021 $/gal (Scenario 3) | Electricity Residential High oil price $/kWh (Scenario 1 case) | Electricity Residential Reference case $/kWh (Scenario 2) | Electricity Residential Low oil price $/kWh (Scenario 3) | Electricity Commercial Reference case $/kWh (Scenario 1,2,3) |
|---|---|---|---|---|---|---|---|---|
| 2027 | 4.77 | 4.17 | 2.68 | 2.02 | 0.126 | 0.128 | 0.129 | 0.106 |
| 2028 | 4.80 | 4.21 | 2.71 | 2.04 | 0.127 | 0.129 | 0.130 | 0.107 |
| 2029 | 4.85 | 4.23 | 2.73 | 2.05 | 0.127 | 0.129 | 0.130 | 0.107 |
| 2030 | 4.84 | 4.23 | 2.80 | 2.07 | 0.127 | 0.130 | 0.130 | 0.107 |
| 2031 | 4.84 | 4.26 | 2.89 | 2.16 | 0.127 | 0.130 | 0.131 | 0.107 |
| 2032 | 4.86 | 4.29 | 2.91 | 2.17 | 0.127 | 0.131 | 0.131 | 0.107 |
| 2033 | 4.87 | 4.26 | 2.94 | 2.20 | 0.127 | 0.132 | 0.132 | 0.107 |
| 2034 | 4.92 | 4.30 | 2.96 | 2.21 | 0.127 | 0.132 | 0.133 | 0.108 |
| 2035 | 4.97 | 4.34 | 2.97 | 2.24 | 0.126 | 0.132 | 0.133 | 0.107 |
| 2036 | 5.05 | 4.34 | 2.99 | 2.25 | 0.125 | 0.132 | 0.133 | 0.106 |
| 2037 | 5.10 | 4.36 | 3.01 | 2.26 | 0.124 | 0.131 | 0.132 | 0.106 |
| 2038 | 5.08 | 4.36 | 3.04 | 2.27 | 0.124 | 0.131 | 0.132 | 0.105 |
| 2039 | 5.14 | 4.39 | 3.04 | 2.26 | 0.124 | 0.131 | 0.132 | 0.104 |
| 2040 | 5.15 | 4.39 | 3.07 | 2.25 | 0.124 | 0.131 | 0.132 | 0.104 |
| 2041 | 5.15 | 4.37 | 3.09 | 2.24 | 0.124 | 0.130 | 0.132 | 0.104 |

## 9.3 Total Cost of Ownership Parity of MY 2027 BEVs in a Residential-type Charging Scenario

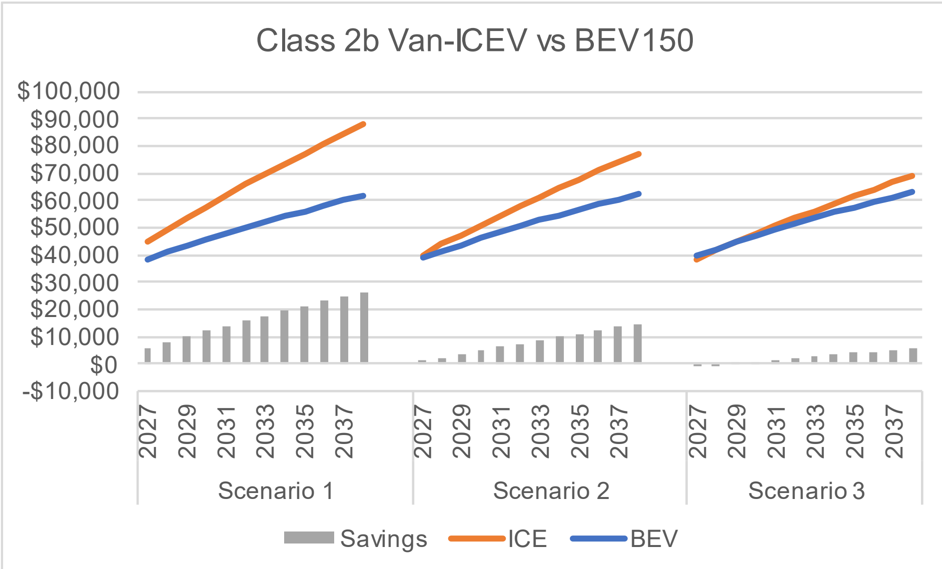


**Figure 113: TCO parity of class 2b van ICEV vs BEV150 with residential-type charging.**

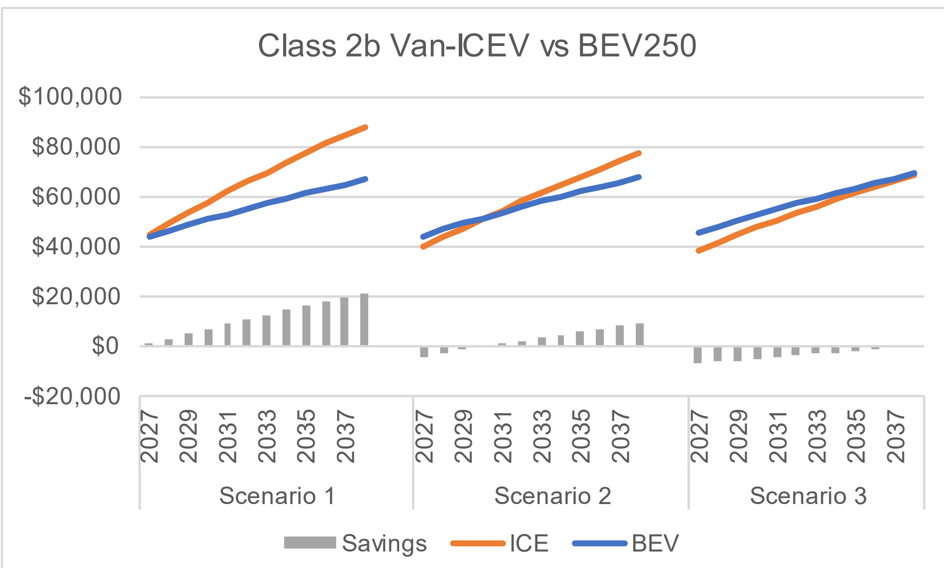


**Figure 114: TCO parity of class 2b van ICEV vs BEV250 with residential-type charging.**

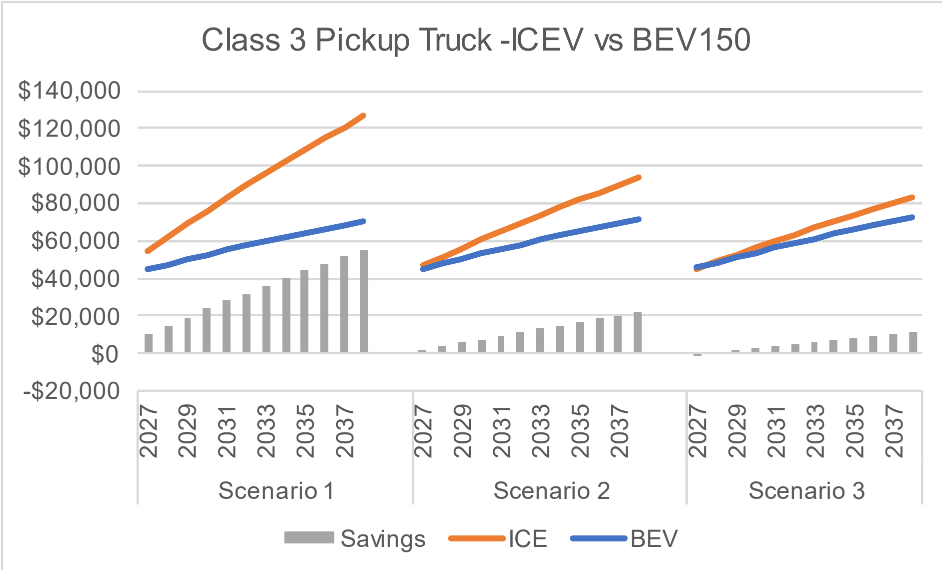


**Figure 115: TCO parity of class 3 pickup truck ICEV vs BEV150 with residential-type charging.**

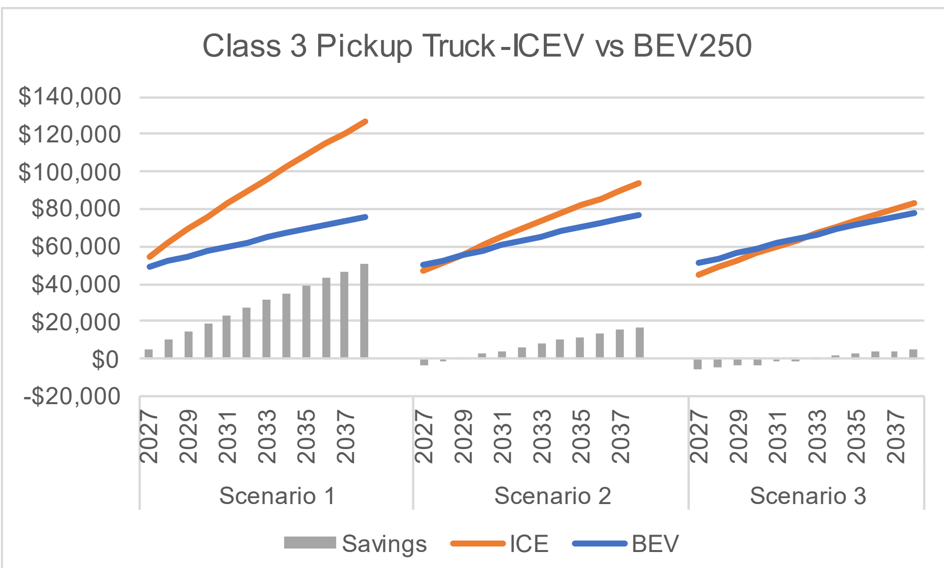


**Figure 116: TCO parity of class 3 pickup truck ICEV vs BEV250 with residential-type charging.**

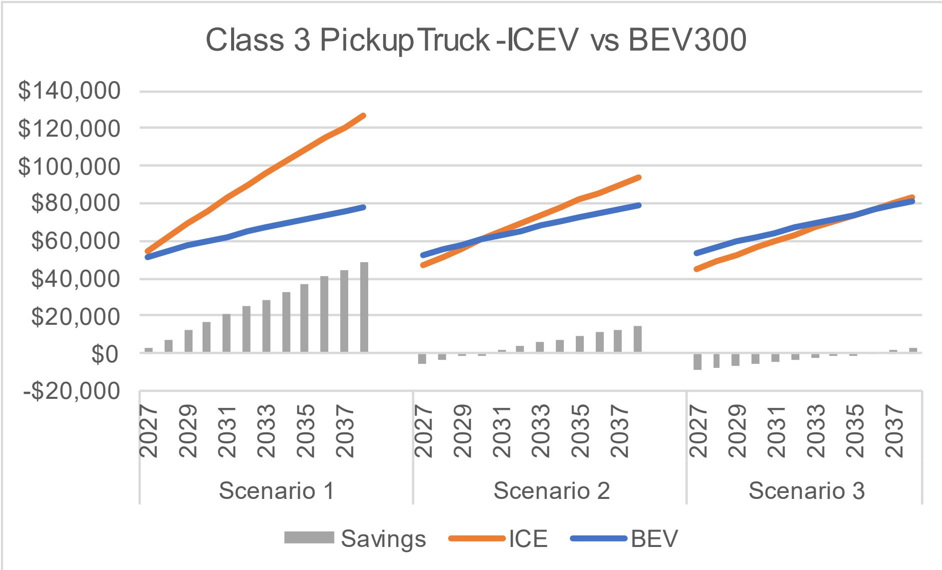


**Figure 117: TCO parity of class 3 pickup truck ICEV vs BEV300 with residential-type charging.**

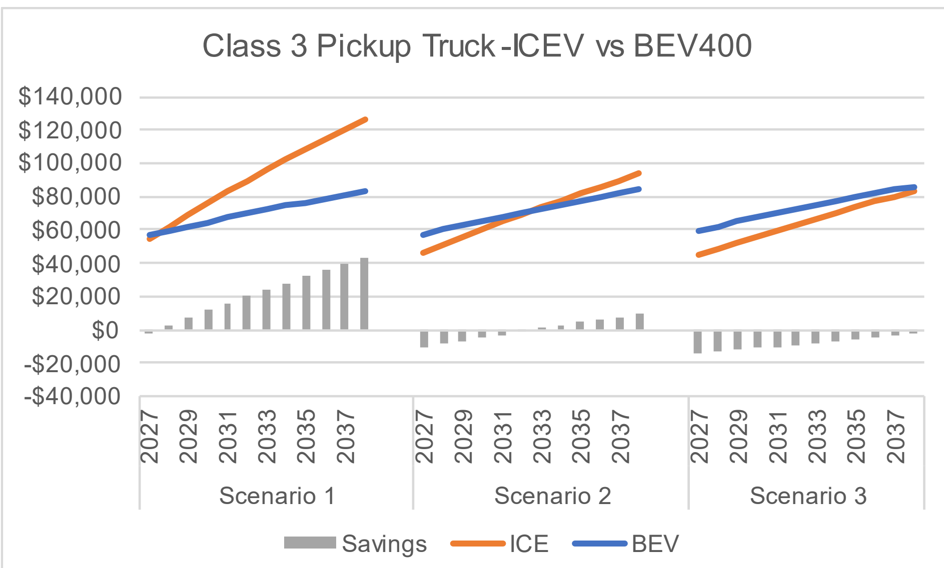


**Figure 118: TCO parity of class 3 pickup truck ICEV vs BEV400 with residential-type charging.**

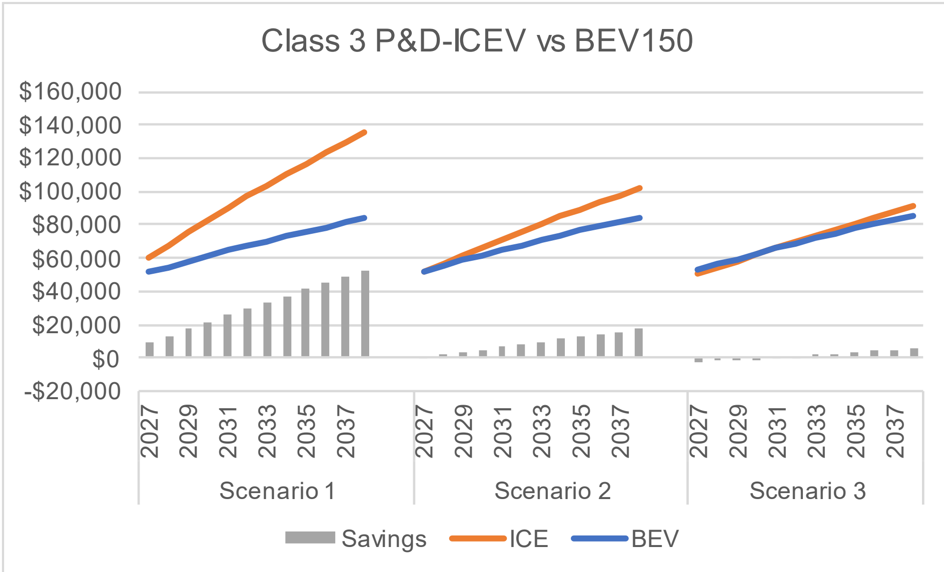


**Figure 119: TCO parity of class 3 package & delivery truck ICEV vs BEV150 with residential-type charging.**

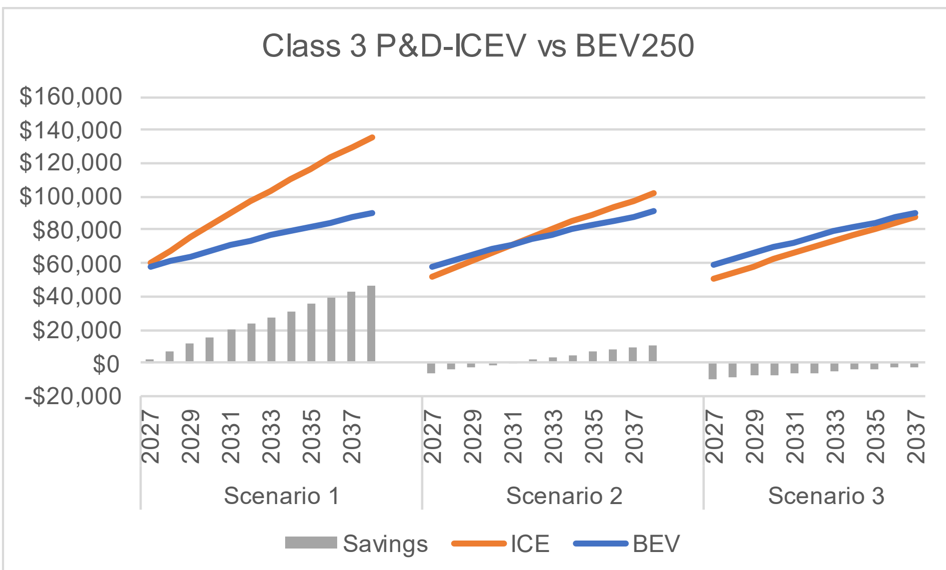


**Figure 120: TCO parity of class 3 package & delivery truck ICEV vs BEV250 with residential-type charging.**

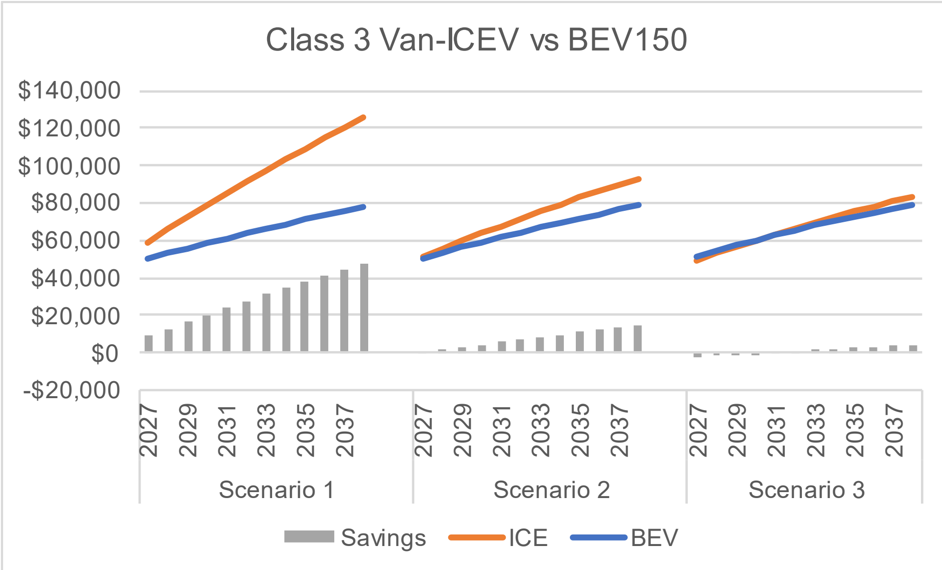


**Figure 121: TCO parity of class 3 van ICEV vs BEV150 with residential-type charging.**

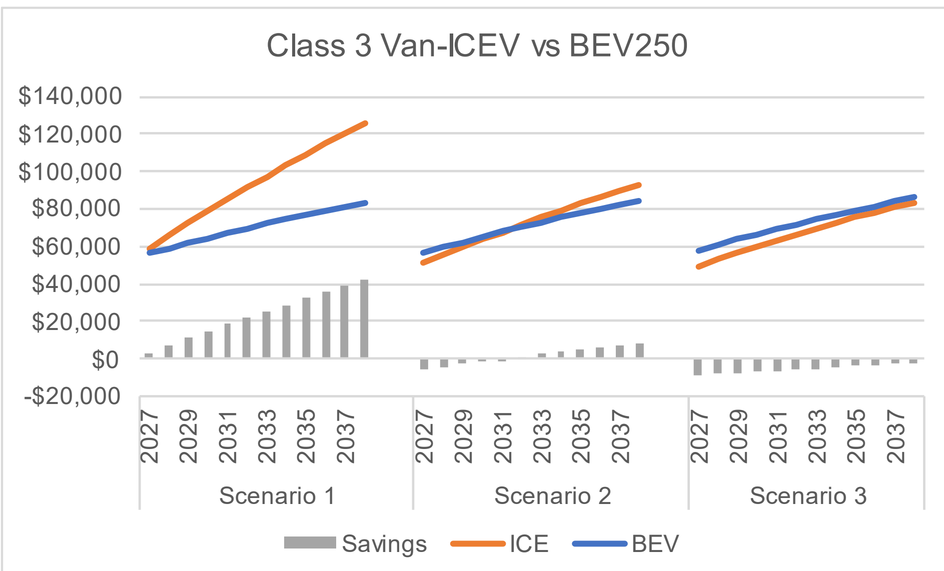


**Figure 122: TCO parity of class 3 van ICEV vs BEV250 with residential-type charging.**

## 9.4 Total Cost of Ownership Parity of MY 2030 BEVs in a Residential-type Charging Scenario

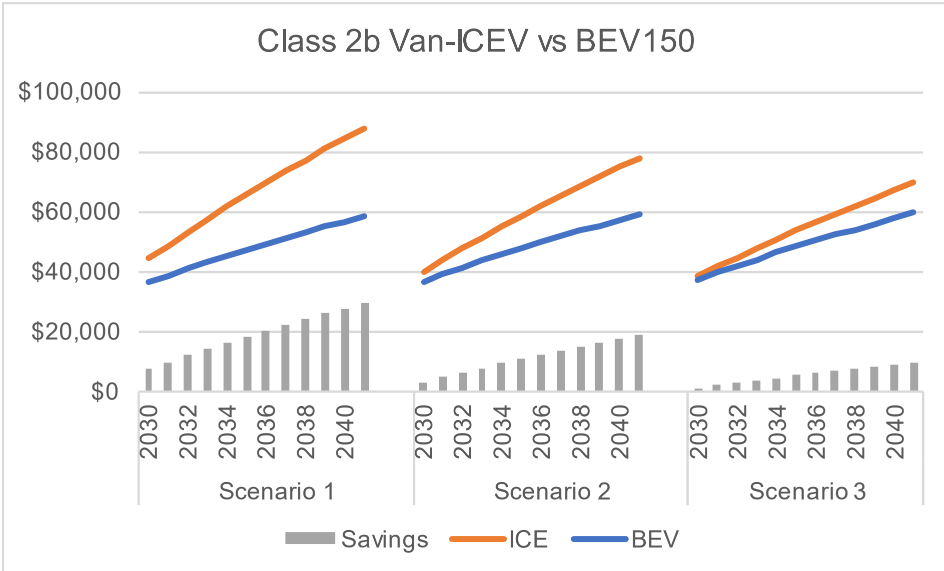


**Figure 123: TCO parity of class 2b van ICEV vs BEV150 with residential-type charging.**

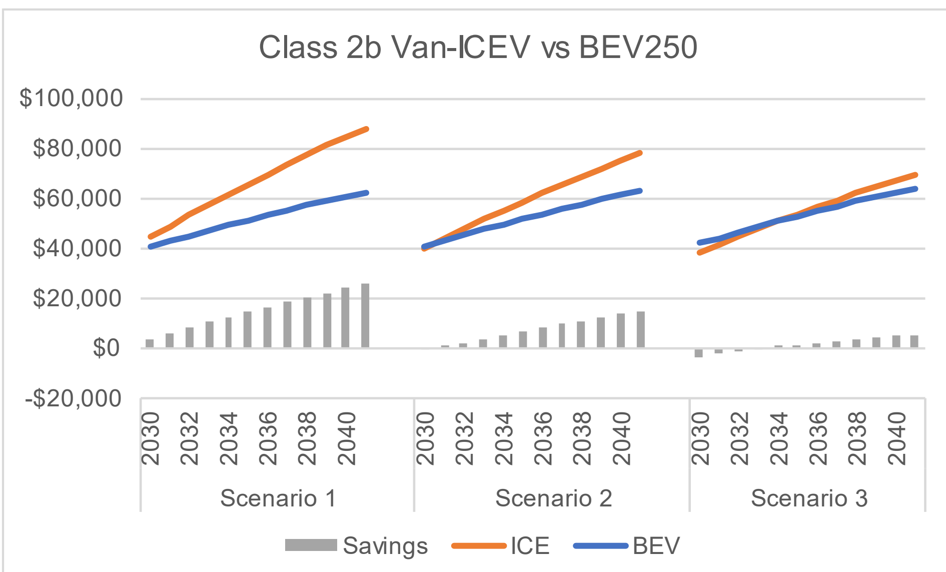


**Figure 124: TCO parity of class 2b van ICEV vs BEV250 with residential-type charging.**

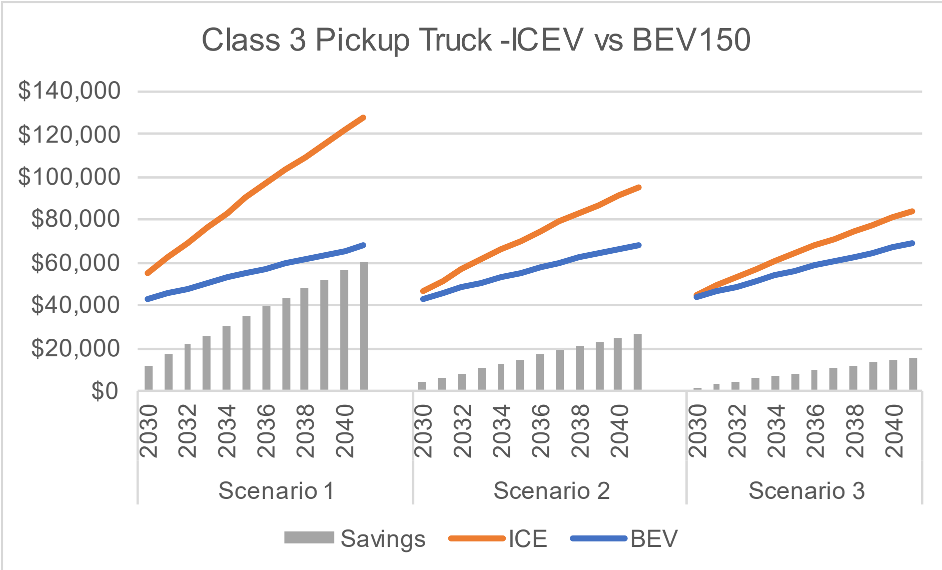


**Figure 125: TCO parity of class 3 pickup truck ICEV vs BEV150 with residential-type charging.**

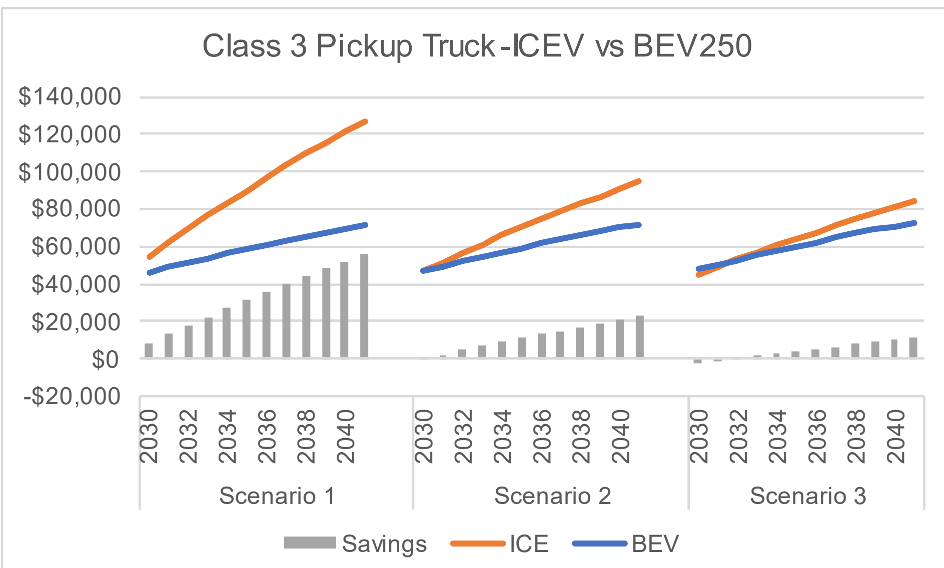


**Figure 126: TCO parity of class 3 pickup truck ICEV vs BEV250 with residential-type charging.**

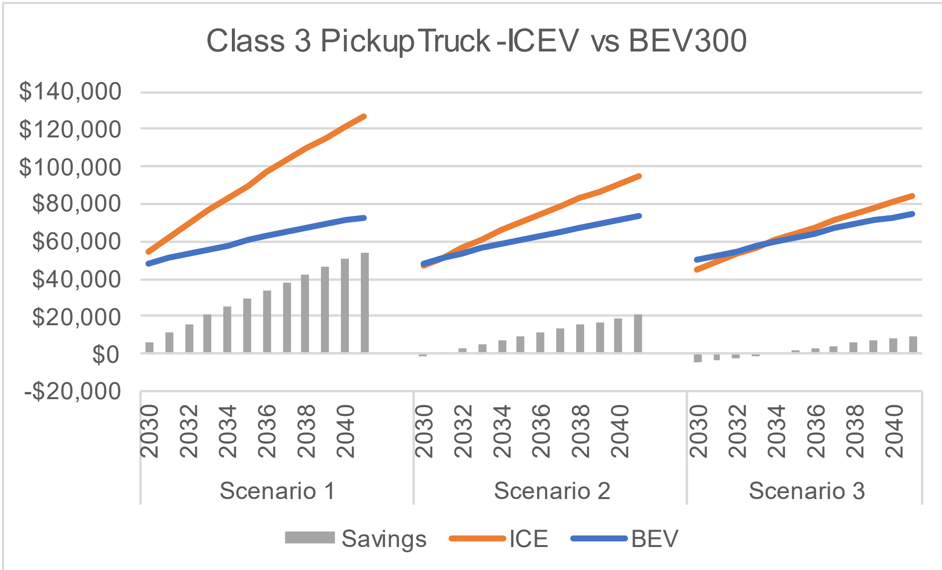


**Figure 127: TCO parity of class 3 pickup truck ICEV vs BEV300 with residential-type charging.**

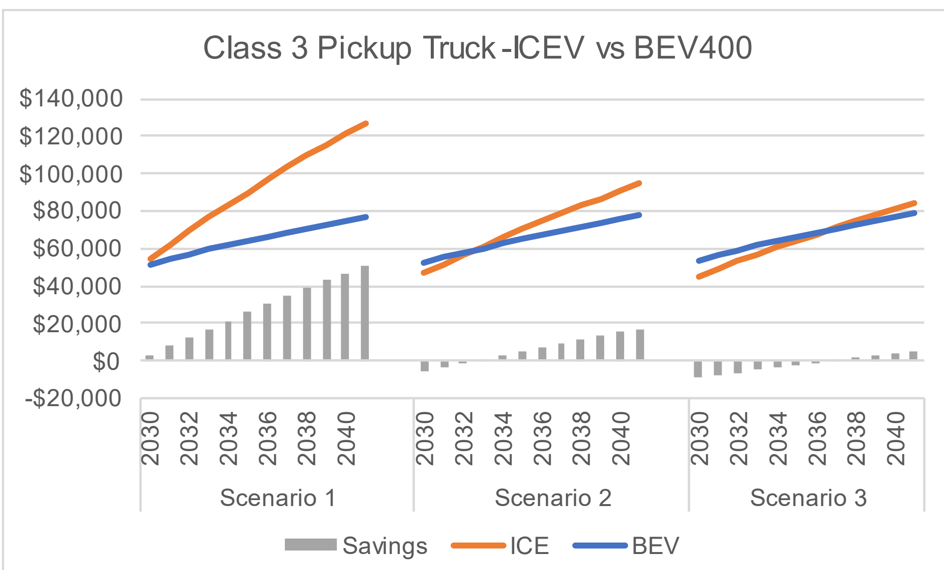


**Figure 128: TCO parity of class 3 pickup truck ICEV vs BEV400 with residential-type charging.**

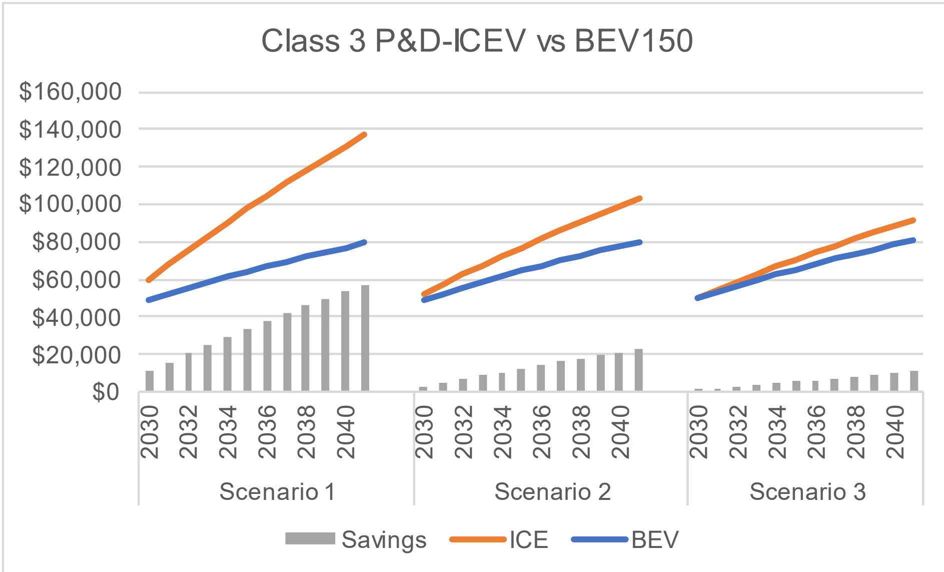


**Figure 129: TCO parity of class 3 package & delivery truck ICEV vs BEV150 with residential-type charging.**

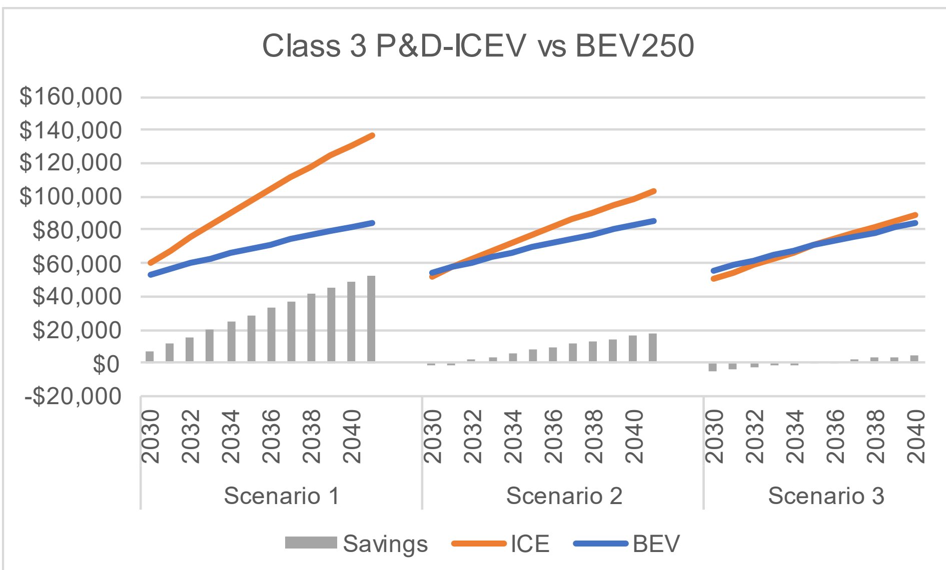


**Figure 130: TCO parity of class 3 package & delivery truck ICEV vs BEV250 with residential-type charging.**

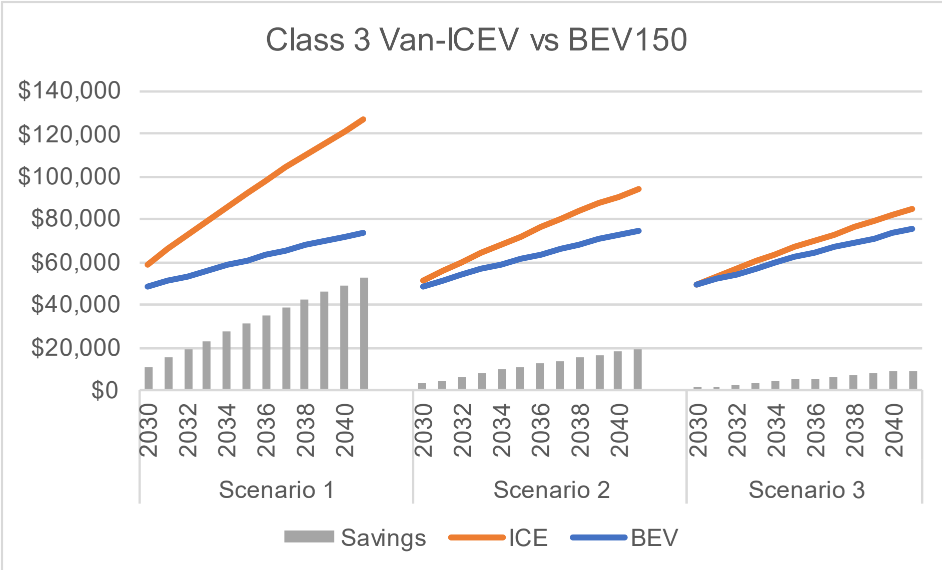


**Figure 131: TCO parity of class 3 van ICEV vs BEV150 with residential-type charging.**

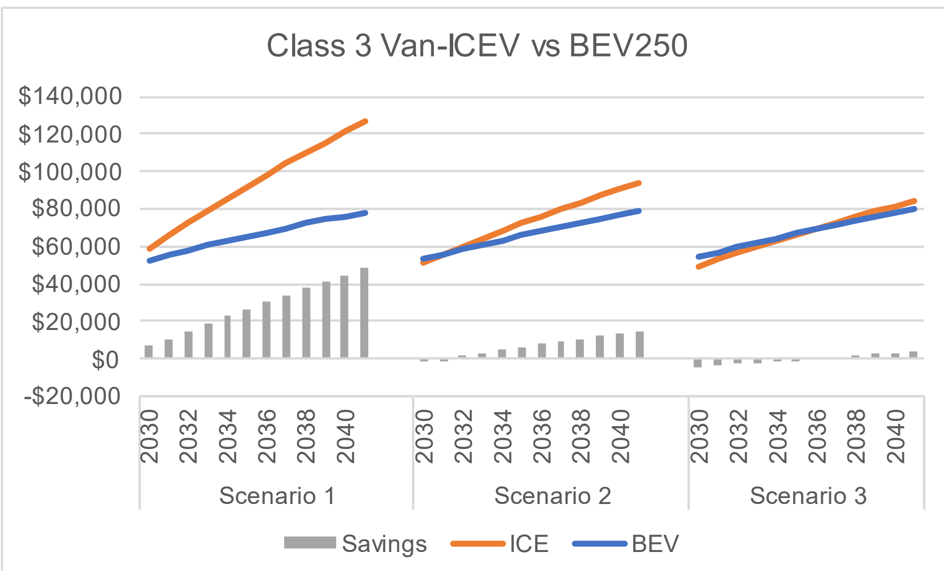


**Figure 132: TCO parity of class 3 van ICEV vs BEV250 with residential-type charging.**

## 9.5 Total Cost of Ownership Parity of MY 2027 BEVs in a Commercial Charging Scenario

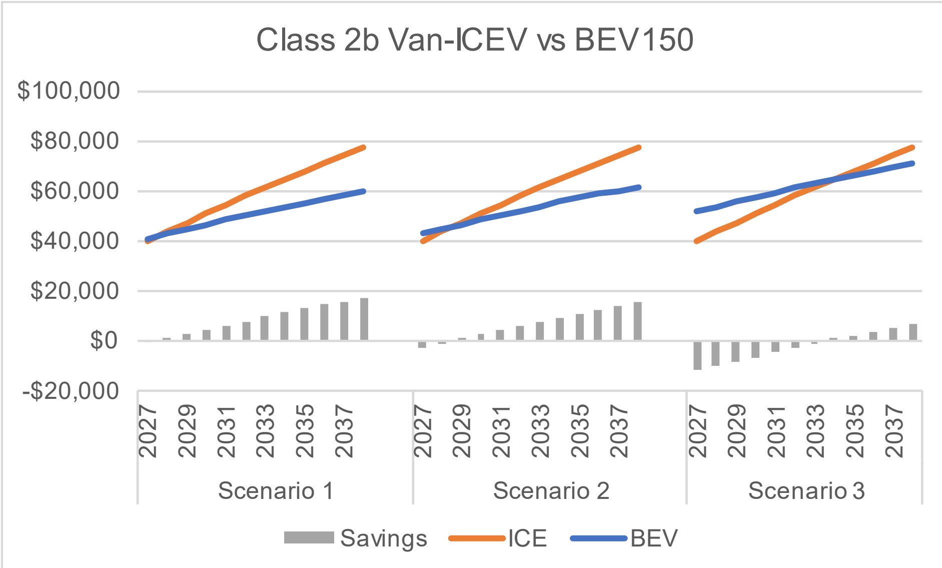


**Figure 133: TCO parity of class 2b van ICEV vs BEV150 with commercial charging.**

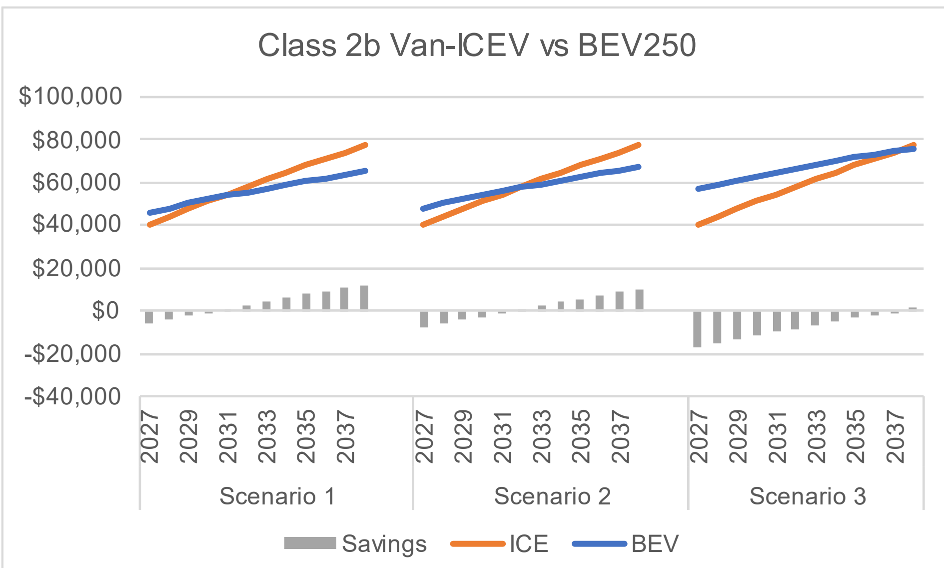


**Figure 134: TCO parity of class 2b van ICEV vs BEV250 with commercial charging.**

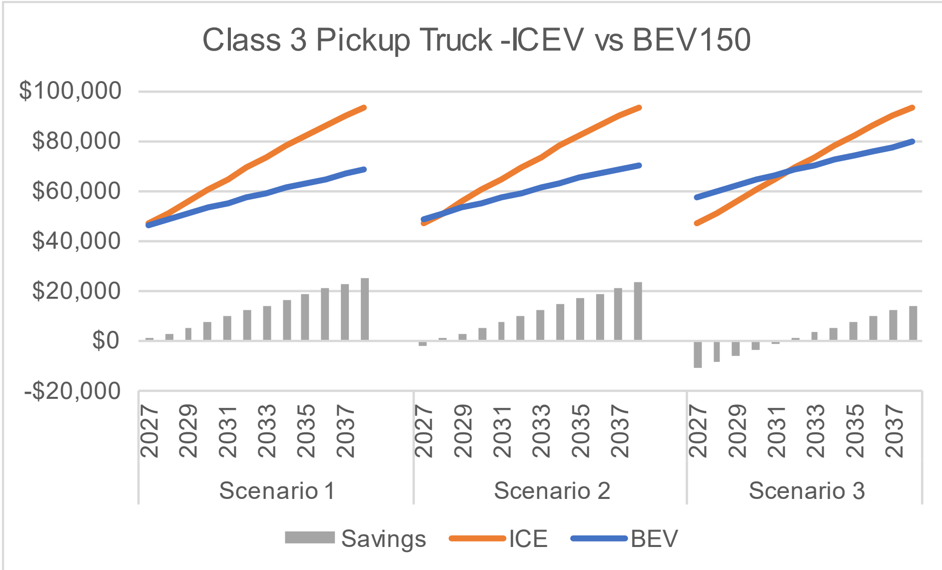


**Figure 135: TCO parity of class 3 pickup truck ICEV vs BEV150 with commercial charging.**

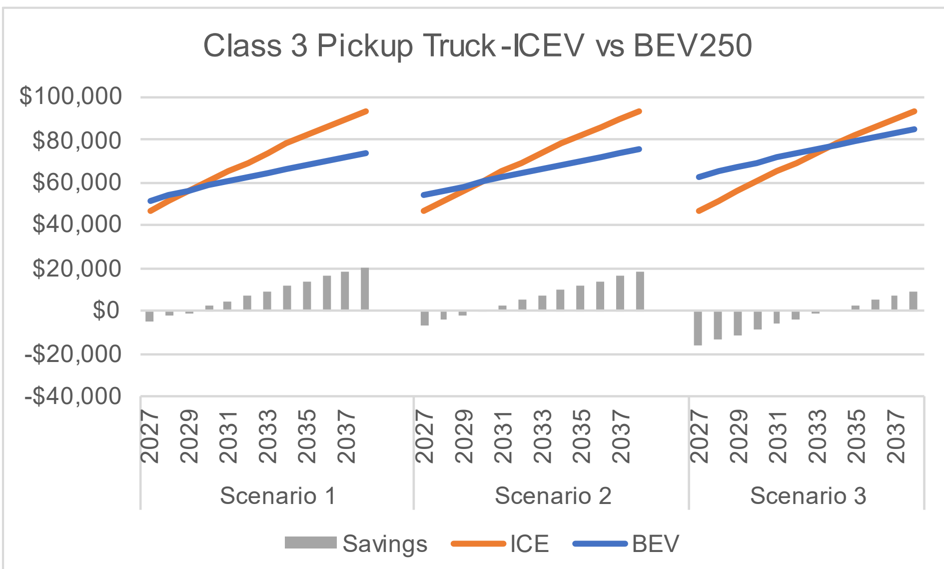


**Figure 136: TCO parity of class 3 pickup truck ICEV vs BEV250 with commercial charging.**

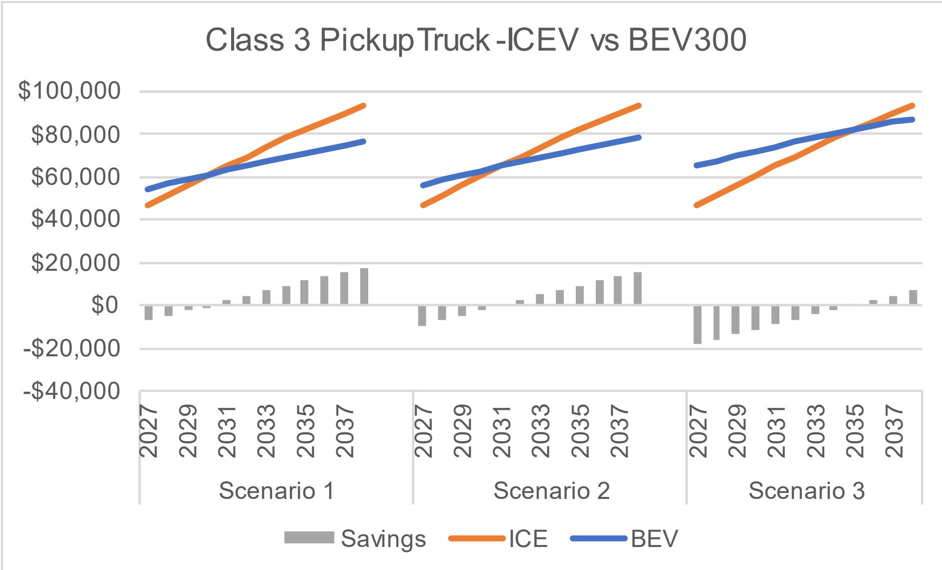


**Figure 137: TCO parity of class 3 pickup truck ICEV vs BEV300 with commercial charging.**

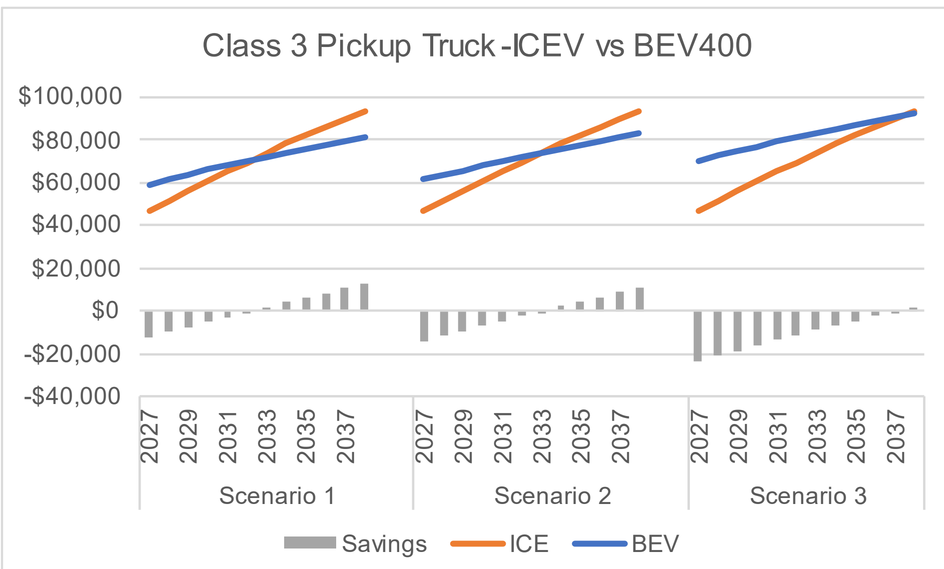


**Figure 138: TCO parity of class 3 pickup truck ICEV vs BEV400 with commercial charging.**

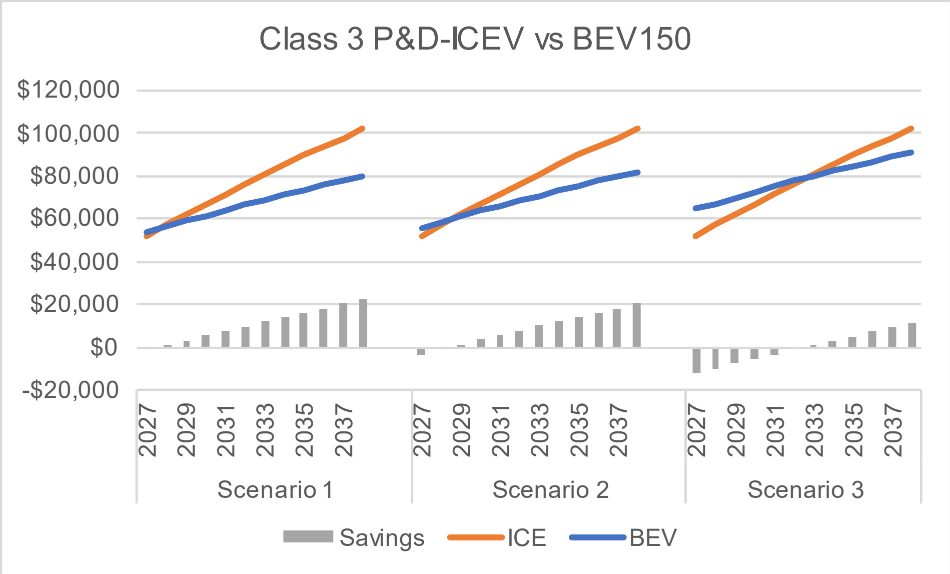


**Figure 139: TCO parity of class 3 package and delivery truck ICEV vs BEV150 with commercial charging.**

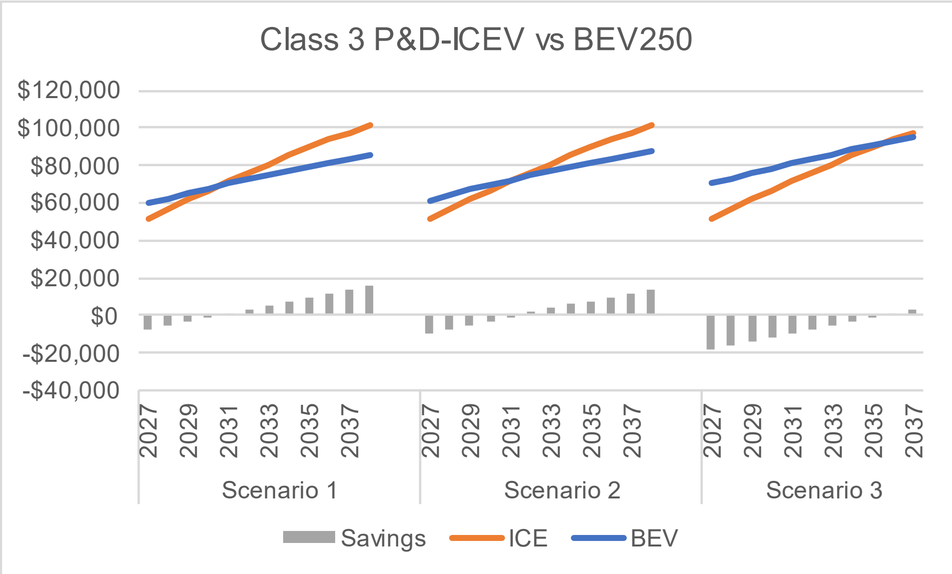


**Figure 140: TCO parity of class 3 package and delivery truck ICEV vs BEV250 with commercial charging.**

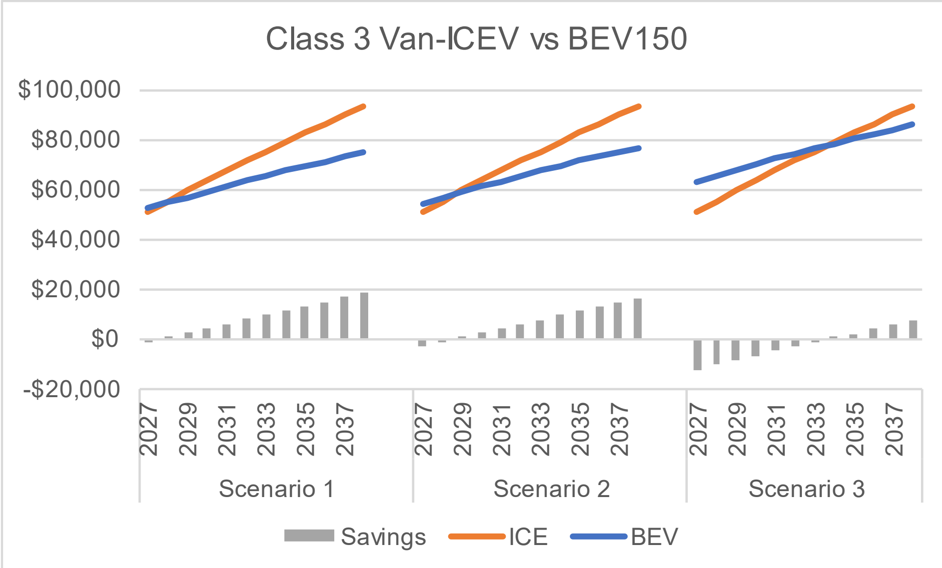


**Figure 141: TCO parity of class 3 van ICEV vs BEV150 with commercial charging.**

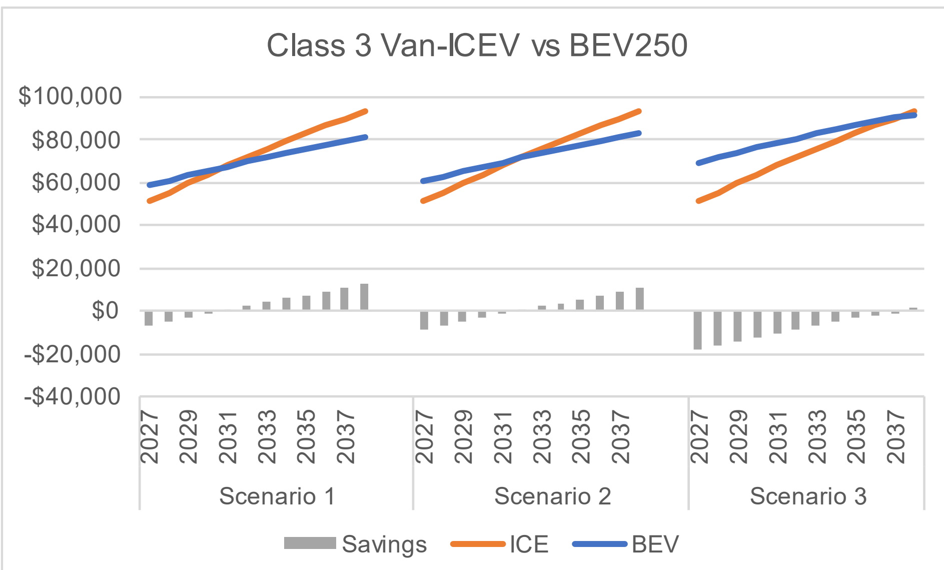


**Figure 142: TCO parity of class 3 van ICEV vs BEV150 with commercial charging.**

## 9.6 Total Cost of Ownership Parity of MY 2030 BEVs in a Commercial Charging Scenario

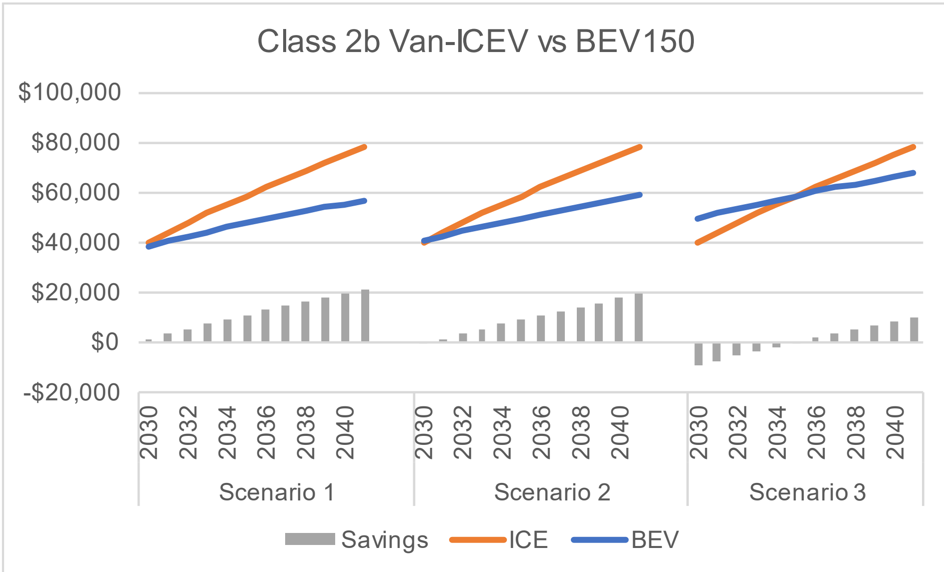


**Figure 143: TCO parity of class 2b van ICEV vs BEV150 with commercial charging.**

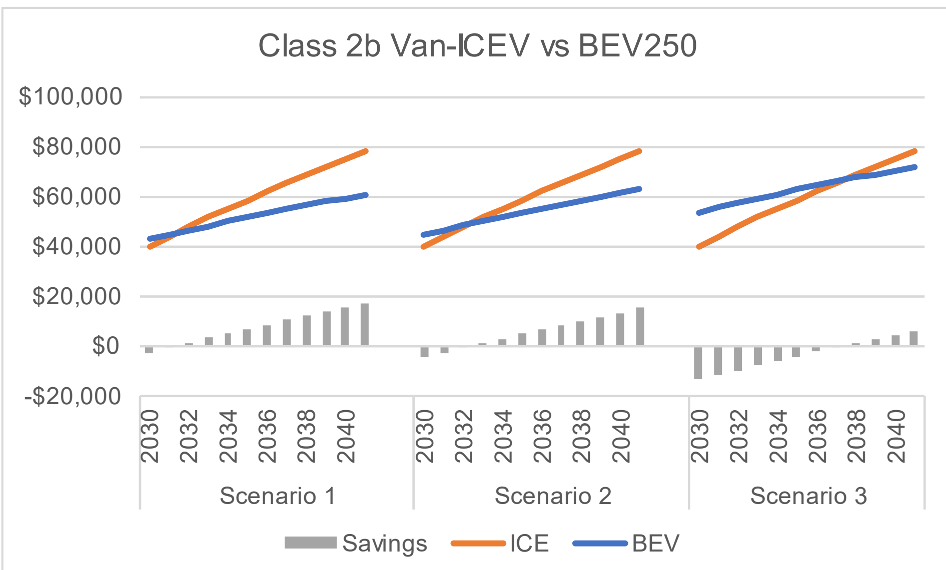


**Figure 144: TCO parity of class 2b van ICEV vs BEV250 with commercial charging.**

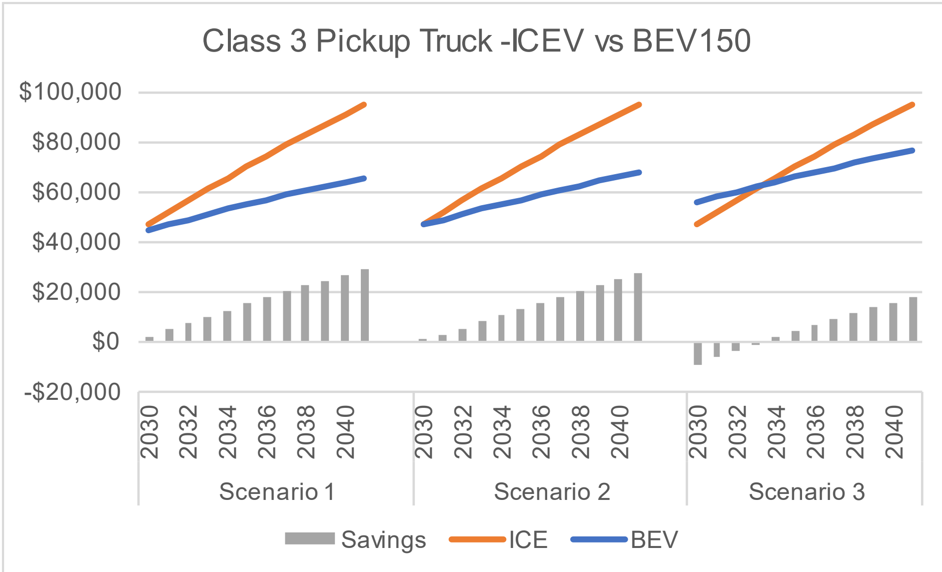


**Figure 145: TCO parity of class 3 pickup truck ICEV vs BEV150 with commercial charging.**

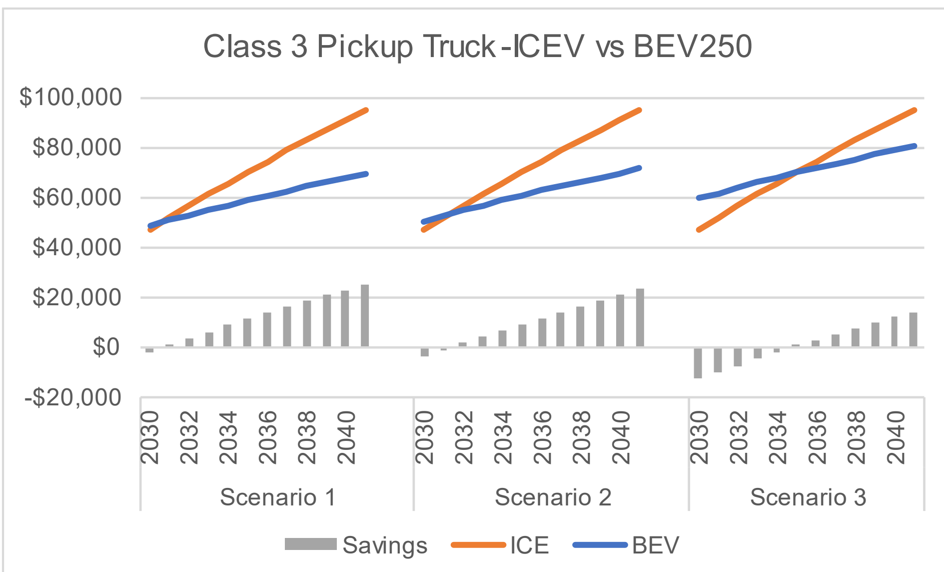


**Figure 146: TCO parity of class 3 pickup truck ICEV vs BEV250 with commercial charging.**

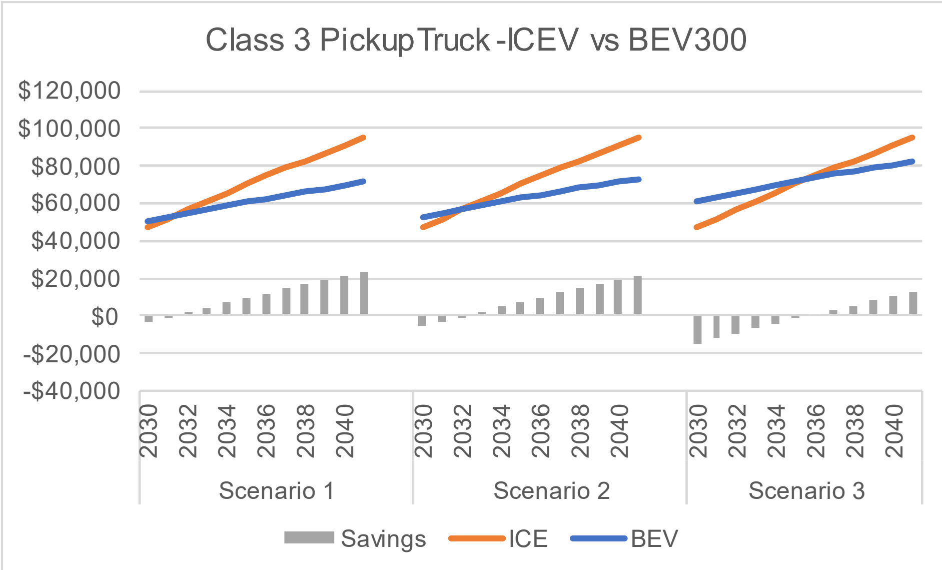


**Figure 147: TCO parity of class 3 pickup truck ICEV vs BEV300 with commercial charging.**

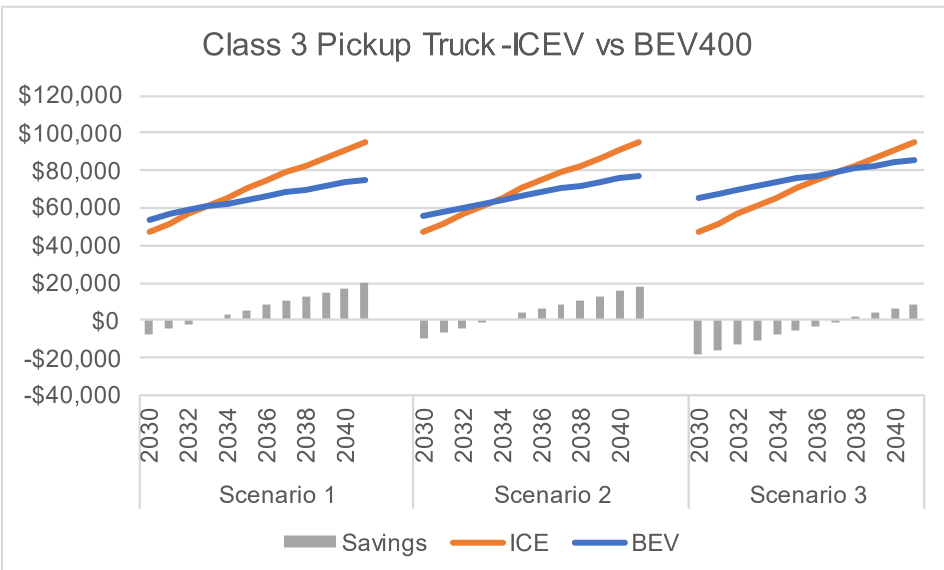


**Figure 148: TCO parity of class 3 pickup truck ICEV vs BEV400 with commercial charging.**

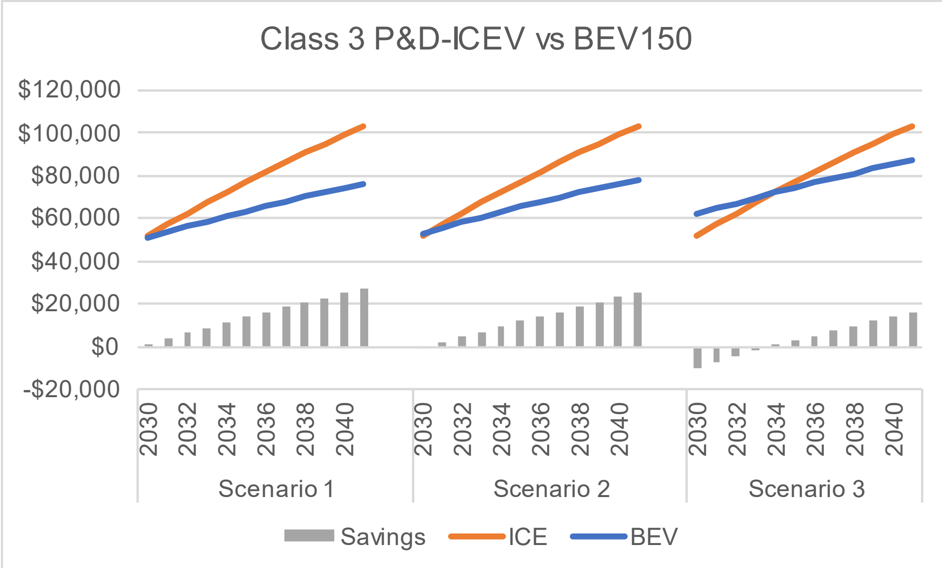


**Figure 149: TCO parity of class 3 package and delivery truck ICEV vs BEV150 with commercial charging.**

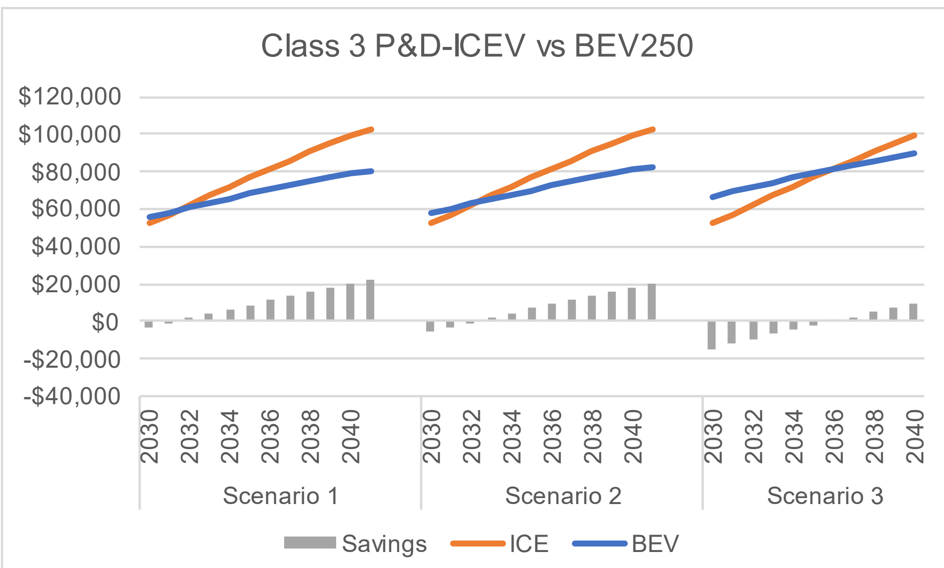


**Figure 150: TCO parity of class 3 package and delivery truck ICEV vs BEV250 with commercial charging.**

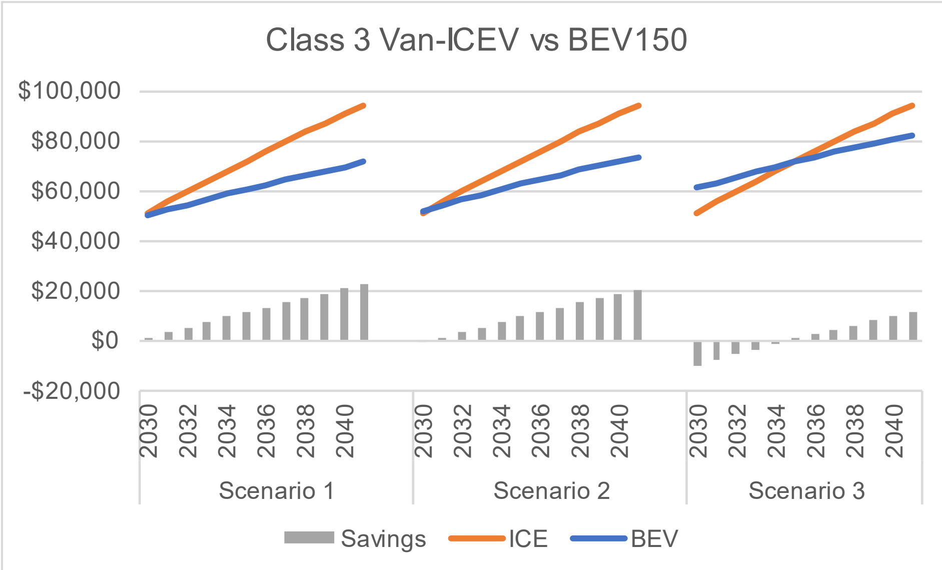


**Figure 151: TCO parity of class 3 van ICEV vs BEV150 with commercial charging.**

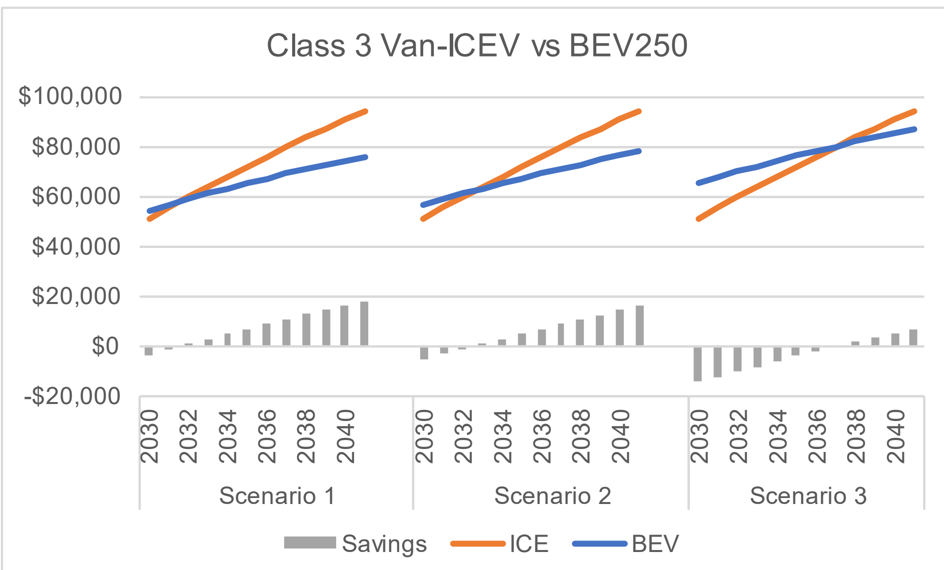


**Figure 152: TCO parity of class 3 van ICEV vs BEV150 with commercial charging.**

## 9.7 List of Critical Minerals Eligible for IRA Credits Under §45X

The term "applicable critical mineral" means any of the following:

a) Aluminum which is—
   i) converted from bauxite to a minimum purity of 99% alumina by mass, or
   ii) purified to a minimum purity of 99.9% aluminum by mass.

b) Antimony which is—
   i) converted to antimony trisulfide concentrate with a minimum purity of 90% antimony trisulfide by mass, or
   ii) purified to a minimum purity of 99.65% antimony by mass.

c) Barite which is barium sulfate purified to a minimum purity of 80% barite by mass.

d) Beryllium which is—
   i) converted to copper-beryllium master alloy, or
   ii) purified to a minimum purity of 99% beryllium by mass.

e) Cerium which is—
   i) converted to cerium oxide which is purified to a minimum purity of 99.9% cerium oxide by mass, or
   ii) purified to a minimum purity of 99% cerium by mass.

f) Cesium which is—
   i) converted to cesium formate or cesium carbonate, or
   ii) purified to a minimum purity of 99% cesium by mass.

g) Chromium which is—
   i) converted to ferrochromium consisting of not less than 60% chromium by mass, or
   ii) (purified to a minimum purity of 99% chromium by mass.

h) Cobalt which is—
   i) converted to cobalt sulfate, or
   ii) purified to a minimum purity of 99.6% cobalt by mass.

i) Dysprosium which is—
   i) converted to not less than 99% pure dysprosium iron alloy by mass, or
   ii) purified to a minimum purity of 99% dysprosium by mass.

j) Europium which is—
   i) converted to europium oxide which is purified to a minimum purity of 99.9% europium oxide by mass, or
   ii) purified to a minimum purity of 99% by mass.

k) Fluorspar which is—
   i) converted to fluorspar which is purified to a minimum purity of 97% calcium fluoride by mass, or
   ii) purified to a minimum purity of 99% fluorspar by mass.

l) Gadolinium which is—
   i) converted to gadolinium oxide which is purified to a minimum purity of 99.9% gadolinium oxide by mass, or

ii) purified to a minimum purity of 99% gadolinium by mass.

m) Germanium which is—
  i) converted to germanium tetrachloride, or
  ii) purified to a minimum purity of 99.99% germanium by mass.

n) Graphite which is purified to a minimum purity of 99.9% graphitic carbon by mass.

o) Indium which is—
  i) converted to—
    a. indium tin oxide, or
    b. indium oxide which is purified to a minimum purity of 99.9% indium oxide by mass, or
  ii) purified to a minimum purity of 99% indium by mass.

p) Lithium which is—
  i) converted to lithium carbonate or lithium hydroxide, or
  ii) purified to a minimum purity of 99.9% lithium by mass.

q) Manganese which is—
  i) converted to manganese sulphate, or
  ii) purified to a minimum purity of 99.7% manganese by mass.

r) Neodymium which is—
  i) converted to neodymium-praseodymium oxide which is purified to a minimum purity of 99% neodymium-praseodymium oxide by mass,
  ii) converted to neodymium oxide which is purified to a minimum purity of 99.5% neodymium oxide by mass
  iii) purified to a minimum purity of 99.9% neodymium by mass.

s) Nickel which is—
  i) converted to nickel sulphate, or
  ii) purified to a minimum purity of 99% nickel by mass.

t) Niobium which is—
  i) converted to ferronibium, or
  ii) purified to a minimum purity of 99% niobium by mass.

u) Tellurium which is—
  i) converted to cadmium telluride, or
  ii) purified to a minimum purity of 99% tellurium by mass.

v) Tin which is purified to low alpha emitting tin which—
  i) has a purity of greater than 99.99% by mass, and
  ii) possesses an alpha emission rate of not greater than 0.01 counts per hour per centimeter square.

w) Tungsten which is converted to ammonium paratungstate or ferrotungsten.

x) Vanadium which is converted to ferrovanadium or vanadium pentoxide.

y) Yttrium which is—

i) converted to yttrium oxide which is purified to a minimum purity of 99.999% yttrium oxide by mass, or
ii) purified to a minimum purity of 99.9% yttrium by mass.

z) Any of the following minerals provided that such mineral is purified to a minimum purity of 99% by mass:
i) Arsenic.
ii) Bismuth.
iii) Erbium.
iv) Gallium.
v) Hafnium.
vi) Holmium.
vii) Iridium.
viii) Lanthanum.
ix) Lutetium.
x) Magnesium.
xi) Palladium.
xii) Platinum.
xiii) Praseodymium.
xiv) Rhodium.
xv) Rubidium.
xvi) Ruthenium.
xvii) Samarium.
xviii) Scandium.
xix) Tantalum.
xx) Terbium.
xxi) Thulium.
xxii) Titanium.
xxiii) Ytterbium.
xxiv) Zinc.
xxv) Zirconium.

## 9.8 Results on Application of Credits from IRA of 2022

### 9.8.1 Impact of Clean Vehicle Credits under §30D

#### 9.8.1.1 MY 2027

**Table 37: MY 2027 ICEV and BEV purchase prices with §30D clean vehicle credits.**

| Vehicle Type | BEV Segment | ICE MSRP (RPE=1.5) | | | BEV MSRP with IRA (RPE=1.2) | | | Savings Price Band | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | $39,916 | $36,290 | $35,426 | $26,802 | $27,097 | $27,891 | $13,115 | $9,193 | $7,535 |
| | BEV250 | $39,916 | $36,290 | $35,426 | $31,902 | $32,393 | $33,717 | $8,015 | $3,897 | $1,709 |
| Class 3 Pickup Truck | BEV150 | $47,117 | $41,887 | $41,023 | $32,416 | $32,695 | $33,446 | $14,701 | $9,192 | $7,577 |
| | BEV250 | $47,117 | $41,887 | $41,023 | $37,238 | $37,702 | $38,954 | $9,879 | $4,184 | $2,069 |
| | BEV300 | $47,117 | $41,887 | $41,023 | $39,649 | $40,206 | $41,709 | $7,468 | $1,680 | -$686 |
| | BEV400 | $47,117 | $41,887 | $41,023 | $44,470 | $45,214 | $47,217 | $2,647 | -$3,328 | -$6,194 |
| Class 3 Package & Delivery Truck | BEV150 | $52,117 | $46,887 | $46,023 | $38,539 | $38,888 | $39,827 | $13,578 | $7,999 | $6,196 |
| | BEV250 | $52,117 | $46,887 | $46,023 | $44,569 | $45,150 | $46,715 | $7,548 | $1,737 | -$692 |
| Class 3 Van | BEV150 | $52,117 | $46,887 | $46,023 | $38,077 | $38,408 | $39,300 | $14,040 | $8,478 | $6,723 |
| | BEV250 | $52,117 | $46,887 | $46,023 | $43,802 | $44,354 | $45,841 | $8,314 | $2,532 | $182 |

Table 38: Years to reach TCO parity for MY 2027 BEVs with §30D clean vehicle credits.

| Vehicle Type | BEV Segment | With IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | <1 | <1 | <1 |
| | BEV250 | <1 | <1 | <1 |
| Class 3 Pickup Truck | BEV150 | <1 | <1 | <1 |
| | BEV250 | <1 | <1 | <1 |
| | BEV300 | <1 | <1 | 2 |
| | BEV400 | <1 | 2 | 7 |
| Class 3 Package & Delivery Truck | BEV150 | <1 | <1 | <1 |
| | BEV250 | <1 | <1 | 3 |
| Class 3 Van | BEV150 | <1 | <1 | <1 |
| | BEV250 | <1 | <1 | 2 |

**Table 39: Comparison of the total cost of ownership (TCO) per mile for MY 2027 BEVs with §30D clean vehicle credits against ICEVs.**

| Vehicle Type | Category | With IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | ICE | 42.8¢ | 37.5¢ | 33.6¢ |
| | BEV150 | 26.2¢ | 26.5¢ | 26.9¢ |
| | BEV250 | 28.7¢ | 29.1¢ | 29.8¢ |
| Class 3 Pickup Truck | ICE | 54.4¢ | 40.3¢ | 35.8¢ |
| | BEV150 | 27.1¢ | 27.4¢ | 27.8¢ |
| | BEV250 | 29.2¢ | 29.6¢ | 30.1¢ |
| | BEV300 | 30.2¢ | 30.7¢ | 31.3¢ |
| | BEV400 | 32.3¢ | 32.8¢ | 33.7¢ |
| Class 3 Package & Delivery Truck | ICE | 53.7¢ | 40.2¢ | 36.0¢ |
| | BEV150 | 30.0¢ | 30.3¢ | 30.7¢ |
| | BEV250 | 32.4¢ | 32.8¢ | 33.5¢ |
| Class 3 Van | ICE | 57.0¢ | 42.2¢ | 38.0¢ |
| | BEV150 | 31.7¢ | 32.1¢ | 32.5¢ |
| | BEV250 | 34.3¢ | 34.8¢ | 35.5¢ |

**Table 40: Cumulative net savings of MY 2027 BEVs with §30D clean vehicle credits over equivalent ICEVs.**

| Vehicle Type | BEV Segment | Cumulative Net Savings with IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | $34,062 | $22,488 | $13,585 |
| | BEV250 | $28,962 | $17,191 | $7,758 |
| Class 3 Pickup Truck | BEV150 | $63,285 | $29,847 | $18,737 |
| | BEV250 | $58,463 | $24,840 | $13,229 |
| | BEV300 | $56,053 | $22,336 | $10,475 |
| | BEV400 | $51,231 | $17,328 | $4,966 |
| Class 3 Package & Delivery Truck | BEV150 | $59,872 | $24,965 | $13,215 |
| | BEV250 | $53,843 | $18,703 | $6,327 |
| Class 3 Van | BEV150 | $55,657 | $22,431 | $12,084 |
| | BEV250 | $49,931 | $16,485 | $5,543 |

### 9.8.1.2 MY 2023

**Table 41: MY 2023 ICEV and BEV purchase prices with §30D clean vehicle credits. BEV400 class 3 pickup is not eligible for clean vehicle credits (highlighted in yellow) as it is above $80,000.**

| Vehicle Type | BEV Segment | ICE MSRP (RPE=1.5) | | | BEV MSRP with IRA (RPE=1.5) | | | Savings Price Band | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | $36,964 | $35,505 | $35,505 | $39,629 | $40,228 | $42,199 | -$2,665 | -$4,723 | -$6,695 |
| | BEV250 | $36,964 | $35,505 | $35,505 | $52,373 | $53,371 | $56,656 | -$15,409 | -$17,866 | -$21,152 |
| Class 3 Pickup Truck | BEV150 | $46,133 | $40,193 | $40,193 | $45,106 | $45,665 | $47,507 | $1,027 | -$5,473 | -$7,314 |
| | BEV250 | $46,133 | $40,193 | $40,193 | $57,009 | $57,941 | $61,010 | -$10,876 | -$17,749 | -$20,818 |
| | BEV300 | $46,133 | $40,193 | $40,193 | $62,961 | $64,079 | $67,762 | -$16,828 | -$23,887 | -$27,569 |
| | BEV400 | $46,133 | $40,193 | $40,193 | $82,364 | $83,855 | $88,765 | -$36,231 | -$43,662 | -$48,573 |
| Class 3 Package & Delivery Truck | BEV150 | $51,133 | $46,289 | $45,193 | $53,805 | $54,516 | $56,859 | -$2,672 | -$8,228 | -$11,667 |
| | BEV250 | $51,133 | $46,289 | $45,193 | $68,951 | $70,137 | $74,042 | -$17,818 | -$23,849 | -$28,850 |
| Class 3 Van | BEV150 | $51,133 | $46,289 | $45,193 | $52,611 | $53,286 | $55,508 | -$1,478 | -$6,997 | -$10,315 |
| | BEV250 | $51,133 | $46,289 | $45,193 | $66,974 | $68,099 | $71,803 | -$15,842 | -$21,811 | -$26,610 |

**Table 42: Years to reach TCO parity for MY 2023 BEVs with §30D clean vehicle credits.**

| Vehicle Type | BEV Segment | With IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | 1 | 4 | End of Life |
| | BEV250 | 8 | End of Life | End of Life |
| Class 3 Pickup Truck | BEV150 | <1 | 3 | 8 |
| | BEV250 | 2 | 10 | End of Life |
| | BEV300 | 4 | End of Life | End of Life |
| | BEV400 | 8 | End of Life | End of Life |
| Class 3 Package & Delivery Truck | BEV150 | <1 | 6 | End of Life |
| | BEV250 | 4 | End of Life | End of Life |
| Class 3 Van | BEV150 | <1 | 6 | End of Life |
| | BEV250 | 4 | End of Life | End of Life |

**Table 43: Comparison of the total cost of ownership (TCO) per mile for MY 2023 BEVs with §30D clean vehicle credits against ICEVs.**

| Vehicle Type | Category | With IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | ICE | 41.4¢ | 37.1¢ | 33.6¢ |
| | BEV150 | 32.5¢ | 32.9¢ | 33.9¢ |
| | BEV250 | 38.7¢ | 39.3¢ | 40.9¢ |
| Class 3 Pickup Truck | ICE | 54.0¢ | 39.5¢ | 35.5¢ |
| | BEV150 | 32.6¢ | 33.0¢ | 33.8¢ |
| | BEV250 | 37.7¢ | 38.3¢ | 39.6¢ |
| | BEV300 | 40.3¢ | 40.9¢ | 42.5¢ |
| | BEV400 | 48.6¢ | 49.5¢ | 51.6¢ |
| Class 3 Package & Delivery Truck | ICE | 53.3¢ | 40.0¢ | 35.6¢ |
| | BEV150 | 36.0¢ | 36.5¢ | 37.5¢ |
| | BEV250 | 42.0¢ | 42.7¢ | 44.3¢ |
| Class 3 Van | ICE | 56.5¢ | 42.0¢ | 37.6¢ |
| | BEV150 | 38.3¢ | 38.8¢ | 39.8¢ |
| | BEV250 | 44.8¢ | 45.5¢ | 47.2¢ |

**Table 44: Cumulative net savings of MY 2023 BEVs with §30D clean vehicle credits over comparable ICEVs. Negative values indicate BEV is costlier than comparable ICEV.**

| Vehicle Type | BEV Segment | Cumulative Net Savings with IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | $18,282 | $8,571 | -$645 |
| | BEV250 | $5,538 | -$4,572 | -$15,103 |
| Class 3 Pickup Truck | BEV150 | $49,611 | $15,183 | $3,846 |
| | BEV250 | $37,708 | $2,907 | -$9,657 |
| | BEV300 | $31,756 | -$3,231 | -$16,409 |
| | BEV400 | $12,353 | -$23,007 | -$37,413 |
| Class 3 Package & Delivery Truck | BEV150 | $43,622 | $8,738 | -$4,647 |
| | BEV250 | $28,476 | -$6,882 | -$21,830 |
| Class 3 Van | BEV150 | $40,139 | $6,955 | -$4,955 |
| | BEV250 | $25,775 | -$7,858 | -$21,250 |

### 9.8.1 Impact of Clean Vehicle Credits under §45W

#### 9.8.1.1 MY 2027

**Table 45: MY 2027 ICEV and BEV purchase prices with §45W qualified commercial clean vehicle credits.**

| Vehicle Type | BEV Segment | ICE MSRP (RPE=1.5) | | | BEV MSRP with IRA (RPE=1.2) | | | Savings Price Band | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | $39,916 | $36,290 | $35,426 | $34,302 | $34,597 | $35,391 | $5,615 | $1,693 | $35 |
| | BEV250 | $39,916 | $36,290 | $35,426 | $39,402 | $36,290 | $35,426 | $515 | $0 | $0 |
| Class 3 Pickup Truck | BEV150 | $47,117 | $41,887 | $41,023 | $39,916 | $40,195 | $40,946 | $7,201 | $1,692 | $77 |
| | BEV250 | $47,117 | $41,887 | $41,023 | $44,738 | $41,887 | $41,023 | $2,379 | $0 | $0 |
| | BEV300 | $47,117 | $41,887 | $41,023 | $47,117 | $41,887 | $41,709 | $0 | $0 | -$686 |
| | BEV400 | $47,117 | $41,887 | $41,023 | $47,117 | $45,214 | $47,217 | $0 | -$3,328 | -$6,194 |
| Class 3 Package & Delivery Truck | BEV150 | $52,117 | $46,887 | $46,023 | $46,039 | $46,388 | $46,023 | $6,078 | $499 | $0 |
| | BEV250 | $52,117 | $46,887 | $46,023 | $52,069 | $46,887 | $46,715 | $48 | $0 | -$692 |
| Class 3 Van | BEV150 | $52,117 | $46,887 | $46,023 | $45,577 | $45,908 | $46,023 | $6,540 | $978 | $0 |
| | BEV250 | $52,117 | $46,887 | $46,023 | $51,302 | $46,887 | $46,023 | $814 | $0 | $0 |

**Table 46: Years to reach TCO parity for MY 2027 BEVs with §45W qualified commercial clean vehicle credits.**

| Vehicle Type | BEV Segment | With IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | <1 | <1 | 2 |
| | BEV250 | <1 | 1 | 2 |
| Class 3 Pickup Truck | BEV150 | <1 | <1 | 1 |
| | BEV250 | <1 | <1 | 1 |
| | BEV300 | <1 | <1 | 2 |
| | BEV400 | <1 | 2 | 7 |
| Class 3 Package & Delivery Truck | BEV150 | <1 | <1 | 2 |
| | BEV250 | <1 | <1 | 3 |
| Class 3 Van | BEV150 | <1 | <1 | 2 |
| | BEV250 | <1 | 1 | 2 |

**Table 47: Comparison of the total cost of ownership (TCO) per mile for MY 2027 BEVs with §45W qualified commercial clean vehicle credits against ICEVs.**

| Vehicle Type | Category | With IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | ICE | 42.8¢ | 37.5¢ | 33.6¢ |
| | BEV150 | 29.9¢ | 30.2¢ | 30.6¢ |
| | BEV250 | 32.3¢ | 31.0¢ | 30.6¢ |
| Class 3 Pickup Truck | ICE | 54.4¢ | 40.3¢ | 35.8¢ |
| | BEV150 | 30.4¢ | 30.6¢ | 31.0¢ |
| | BEV250 | 32.4¢ | 31.4¢ | 31.0¢ |
| | BEV300 | 33.5¢ | 31.4¢ | 31.3¢ |
| | BEV400 | 33.5¢ | 32.8¢ | 33.7¢ |
| Class 3 Package & Delivery Truck | ICE | 53.7¢ | 40.2¢ | 36.0¢ |
| | BEV150 | 33.0¢ | 33.3¢ | 33.2¢ |
| | BEV250 | 35.3¢ | 33.5¢ | 33.5¢ |
| Class 3 Van | ICE | 57.0¢ | 42.2¢ | 38.0¢ |
| | BEV150 | 35.1¢ | 35.5¢ | 35.5¢ |
| | BEV250 | 37.7¢ | 35.9¢ | 35.5¢ |

**Table 48: Cumulative net savings of MY 2027 BEVs with §45W qualified commercial clean vehicle credits over comparable ICEVs.**

| Vehicle Type | BEV Segment | Cumulative Net Savings with IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | $26,562 | $14,988 | $6,085 |
| | BEV250 | $21,462 | $13,294 | $6,049 |
| Class 3 Pickup Truck | BEV150 | $55,785 | $22,347 | $11,237 |
| | BEV250 | $50,963 | $20,655 | $11,160 |
| | BEV300 | $48,584 | $20,655 | $10,475 |
| | BEV400 | $48,584 | $17,328 | $4,966 |
| Class 3 Package & Delivery Truck | BEV150 | $52,372 | $17,465 | $7,019 |
| | BEV250 | $46,343 | $16,966 | $6,327 |
| Class 3 Van | BEV150 | $48,157 | $14,931 | $5,360 |
| | BEV250 | $42,431 | $13,953 | $5,360 |

#### 9.8.1.2 MY 2023

**Table 49: MY 2023 ICEV and BEV purchase prices with §45W qualified commercial clean vehicle credits.**

| Vehicle Type | BEV Segment | ICE MSRP (RPE=1.5) | | | BEV MSRP with IRA (RPE=1.5) | | | Savings Price Band | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | $36,964 | $35,505 | $35,505 | $39,629 | $40,228 | $42,199 | -$2,665 | -$4,723 | -$6,695 |
| | BEV250 | $36,964 | $35,505 | $35,505 | $52,373 | $53,371 | $56,656 | -$15,409 | -$17,866 | -$21,152 |
| Class 3 Pickup Truck | BEV150 | $46,133 | $40,193 | $40,193 | $46,133 | $45,665 | $47,507 | $0 | -$5,473 | -$7,314 |
| | BEV250 | $46,133 | $40,193 | $40,193 | $57,009 | $57,941 | $61,010 | -$10,876 | -$17,749 | -$20,818 |
| | BEV300 | $46,133 | $40,193 | $40,193 | $62,961 | $64,079 | $67,762 | -$16,828 | -$23,887 | -$27,569 |
| | BEV400 | $46,133 | $40,193 | $40,193 | $74,864 | $76,355 | $81,265 | -$28,731 | -$36,162 | -$41,073 |
| Class 3 Package & Delivery Truck | BEV150 | $51,133 | $46,289 | $45,193 | $53,805 | $54,516 | $56,859 | -$2,672 | -$8,228 | -$11,667 |
| | BEV250 | $51,133 | $46,289 | $45,193 | $68,951 | $70,137 | $74,042 | -$17,818 | -$23,849 | -$28,850 |
| Class 3 Van | BEV150 | $51,133 | $46,289 | $45,193 | $52,611 | $53,286 | $55,508 | -$1,478 | -$6,997 | -$10,315 |
| | BEV250 | $51,133 | $46,289 | $45,193 | $66,974 | $68,099 | $71,803 | -$15,842 | -$21,811 | -$26,610 |

**Table 50: Years to reach TCO parity for MY 2023 BEVs with §45W qualified commercial clean vehicle credits.**

| Vehicle Type | BEV Segment | With IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | 1 | 4 | End of Life |
| | BEV250 | 8 | End of Life | End of Life |
| Class 3 Pickup Truck | BEV150 | <1 | 3 | 8 |
| | BEV250 | 2 | 10 | End of Life |
| | BEV300 | 4 | End of Life | End of Life |
| | BEV400 | 6 | End of Life | End of Life |
| Class 3 Package & Delivery Truck | BEV150 | <1 | 6 | End of Life |
| | BEV250 | 4 | End of Life | End of Life |
| Class 3 Van | BEV150 | <1 | 6 | End of Life |
| | BEV250 | 4 | End of Life | End of Life |

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**Table 51: Comparison of the total cost of ownership (TCO) per mile for MY 2023 BEVs with §45W qualified commercial clean vehicle credits against ICEVs.**

| Vehicle Type | Category | With IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | ICE | 41.4¢ | 37.1¢ | 33.6¢ |
| | BEV150 | 32.5¢ | 32.9¢ | 33.9¢ |
| | BEV250 | 38.7¢ | 39.3¢ | 40.9¢ |
| Class 3 Pickup Truck | ICE | 54.0¢ | 39.5¢ | 35.5¢ |
| | BEV150 | 33.0¢ | 33.0¢ | 33.8¢ |
| | BEV250 | 37.7¢ | 38.3¢ | 39.6¢ |
| | BEV300 | 40.3¢ | 40.9¢ | 42.5¢ |
| | BEV400 | 45.4¢ | 46.2¢ | 48.4¢ |
| Class 3 Package & Delivery Truck | ICE | 53.3¢ | 40.0¢ | 35.6¢ |
| | BEV150 | 36.0¢ | 36.5¢ | 37.5¢ |
| | BEV250 | 42.0¢ | 42.7¢ | 44.3¢ |
| Class 3 Van | ICE | 56.5¢ | 42.0¢ | 37.6¢ |
| | BEV150 | 38.3¢ | 38.8¢ | 39.8¢ |
| | BEV250 | 44.8¢ | 45.5¢ | 47.2¢ |

Table 52: Cumulative net savings of MY 2023 BEVs with §45W qualified commercial clean vehicle credits over comparable ICEVs. Negative values indicate BEV is costlier than comparable ICEV.

| Vehicle Type | BEV Segment | Cumulative Net Savings with IRA | | |
|---|---|---|---|---|
| | | Scenario 1 | Scenario 2 | Scenario 3 |
| Class 2b Van | BEV150 | $18,282 | $8,571 | -$645 |
| | BEV250 | $5,538 | -$4,572 | -$15,103 |
| Class 3 Pickup Truck | BEV150 | $48,584 | $15,183 | $3,846 |
| | BEV250 | $37,708 | $2,907 | -$9,657 |
| | BEV300 | $31,756 | -$3,231 | -$16,409 |
| | BEV400 | $19,853 | -$15,507 | -$29,913 |
| Class 3 Package & Delivery Truck | BEV150 | $43,622 | $8,738 | -$4,647 |
| | BEV250 | $28,476 | -$6,882 | -$21,830 |
| Class 3 Van | BEV150 | $40,139 | $6,955 | -$4,955 |
| | BEV250 | $25,775 | -$7,858 | -$21,250 |