Electrification Cost Evaluation of Light-Duty Vehicles for MY 2030

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Abbreviations and Acronyms

AAA	American Automobile Association
ADEAC	Advanced Cylinder Deactivation
AEO	Annual Energy Outlook
ANL	Argonne National Laboratory
ASSB	All-Solid-State Battery
AT	Automatic Transmissions
AT10L2	10-Speed Automatic Transmission, Level 2
AT8L2	8-Speed Automatic Transmission, Level 2
ATK	Atkinson Cycle Engine
AWD	All Wheel Drive
BEA	Bureau Of Economic Analysis
BEV	Battery Electric Vehicle
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)
BloombergNEF	Bloomberg New Energy Finance
BMS	Battery Management System
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CEGR1	Advanced Turbocharged Downsized Technology with 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
DI	Direct Injection
DMC	Direct Manufacturing Costs
DOE	U.S. Department of Energy
DOHC	Dual Overhead Cam
DOT	U.S. Department of Transportation
eCVT	Electronic Continuously Variable Transmission

EGR	Exhaust Gas Recirculation
EIA	U.S. Energy Information Administration
EOL	End-Of-Life
EPA	U.S. Environmental Protection Agency
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FHWA	Federal Highway Administration
FTP	Federal Test Procedure
FWD	Front-Wheel Drive
GCTP	Gravimetric Cell-to-Pack Ratio
GHG	Green House Gas
GM	General Motors
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GWh	Gigawatt-Hour
GVWR	Gross Vehicle Weight Rating
HCs	Hydrocarbons
HCR1	High Compression Ratio, Level 1
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
km	Kilometer
km/h	Kilometers Per Hour
kW	Kilowatt
kWh	Kilowatt-Hour
LAB	Lead Acid Battery
LDV	Light Duty Passenger Vehicle

LFP	Lithium Ferro (Iron) Phosphate
LIB	Lithium-Ion Battery
LMFP	Lithium Manganese Ferro Phosphate
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
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
NPRM	Notice of Proposed Rulemaking
NVH	Noise Vibration Harshness
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
SAE	Society of Automotive Engineers
SAFE	Safer Affordable Fuel-Efficient Vehicles Rule
SESM	Separately Excited Synchronous Motor
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	Turbocharging and Downsizing, Level 1
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
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

8-speed Automatic Transmission (AT8) with level 3 high-efficiency gearbox (HEG) technology (AT8L3) – AT is a multi-speed transmission that automatically selects and shifts between transmission gears during vehicle operation. They have been assigned from small cars to midsize SUVs in the analysis.

10-speed Automatic Transmission (AT10) with level 3 high-efficiency gearbox (HEG) technology (AT10L3) – They have been assigned to large SUVs and pickup trucks in the analysis.

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

Battery-Electric Vehicles (BEV) 200/300/400 – Batteries power the motors to propel the vehicle. The numbers represent the ranges of BEV in miles.

Conventional (CONV) – A vehicle that does not include any level of hybridization [1].

Cooled Exhaust Gas Recirculation (cEGR) – It is 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 which improves airflow thereby increasing power and efficiency.

Deactivation (DEAC) – Method of selective valve deactivation thereby shutting 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.

High Compression Ratio 1 (HCR1) – Enhanced Atkinson engines with variable valve timing (VVT) and stoichiometric gasoline direct-injection (SGDI) technologies. High compression ratio (HCR) engines represent a class of engines that achieve a higher level of fuel efficiency by implementing an alternate combustion cycle [1].

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 only kicking in when the power demands are less than moderate [1].

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, higher compression ratio, and increasing thermodynamic efficiency.

Turbocharging and Downsizing Level 1 (TURBO1) – It 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 of operations.

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Executive summary

Key Findings

The transportation sector is the largest source of greenhouse gas (GHG) emissions in the U.S. [2]. In 2021, light-duty vehicles (LDV), comprising passenger cars and light-duty trucks, contributed 58% of the U.S. transportation GHG emissions. Prioritizing the decarbonization of the LDV fleet is a critical strategy for reducing GHG emissions [2]. The passage of the Inflation Reduction Act, recent state and federal actions, and commitments from ambitious automakers, coupled with growing demand for battery electric vehicles (BEVs) and rapidly declining electrification costs, have dramatically sped up the deployment of clean technology and the transition to zero-emission transportation. Battery cost is the leading indicator determining the economic viability of manufacturing and adoption of BEVs. This study assesses the upfront and lifetime costs of light-duty BEVs relative to traditional internal combustion engine vehicles (ICEVs) in the 2030 timeframe, without considering the impacts of the IRA. This report focuses primarily on BEV costs in model year (MY) 2030; however, our supplemental study "*Impact of the Inflation Reduction Act of 2022 on Light-Duty Vehicle Electrification Costs for MYs 2025 and 2030*" [3] examines cost parity in earlier model years.

High-level conclusions of this report include the following:

a) For all BEVs up to a 300-mile range, purchase price parity with a comparable ICEV is reached by 2030, across all vehicle classes and segments evaluated.
b) By 2030, the total cost of ownership (TCO) for all BEVs up to a 400-mile range will be lower than that of their ICEV counterparts across all classes and segments.
c) BEVs purchased in 2030 result in an average cumulative net savings of about $15,000 over the lifetime of the vehicle compared to an ICEV, across all classes and segments.
d) For consumers who charge their vehicles equally at home and at public fast charging stations, the TCO of a BEV is still lower than an ICEV, despite increases in energy costs.
e) Accounting for current real-world gasoline prices, all BEVs up to the 400-mile range achieve TCO parity immediately or within the first year of ownership at the latest. Purchasing BEVs results in an average cumulative net savings of about $33,000 over an ICEV during the vehicle's lifetime due to the lower operating expenses of BEVs.

These conclusions are based on an analysis that does not reflect the impacts of the recently passed Inflation Reduction Act (IRA). If these were accounted for, we would expect price parity to be achieved even sooner than 2030 and the TCO proposition to be even more compelling.

Background

The transportation sector is the largest source of greenhouse gas (GHG) emissions in the U.S. [2]. In 2021, light-duty vehicles (LDV), comprising passenger cars and light-duty trucks, contributed 58% of the U.S. transportation GHG emissions [2]. Prioritizing the decarbonization of the LDV fleet is a critical strategy for reducing GHG emissions. The Biden Administration has set an ambitious goal of having at least half of all new passenger cars and light trucks sold in 2030 be zero-emission vehicles (ZEVs), including battery electric, plug-in hybrid electric, or fuel cell electric vehicles [4], [5]. Additionally, Congress recently passed the Inflation Reduction Act (IRA) of 2022, which could have game-changing impacts on the pace of electrifying the LDV market and the development of supporting infrastructure. With states such as California and New York committing to selling 100% of new cars and light trucks as ZEVs by 2035, including plug-in hybrid electric vehicles (PHEVs), the automotive industry is undergoing a paradigm shift. Tesla, one of the most successful entrants in this space, has redefined the LDV sector, with legacy automakers such as Ford, General Motors (GM), and Volkswagen (VW) rapidly transitioning to the production of battery electric vehicles (BEVs) and expanding their EV portfolio. Electrifying LDVs represents a significant opportunity to address climate change, air pollution, and dependence on oil imports.

This report focuses primarily on BEV costs in MY 2030; however, our supplemental study "*Impact of the Inflation Reduction Act of 2022 on Light-Duty Vehicle Electrification Costs for MYs 2025 and 2030*" [3] examines the cost parity in earlier model years (along with assessing the impact of the IRA on BEV economics). The present study conducts a bottom-up, component-by-component analysis of the future economics of light-duty vehicle electrification by projecting the incremental costs of vehicle electrification and the total cost of ownership (TCO) of BEVs over their lifecycles relative to their internal combustion engine vehicle (ICEV) counterparts in the 2030 timeframe. The incremental cost is defined as the cost difference between a BEV and an ICEV powertrain. The engine, transmission, aftertreatment, and electrification systems are the primary cost drivers. Other costs, unrelated to the powertrain, are assumed to be comparable between the two powertrain options. We include the cost of a residential charger when we compare the upfront cost of purchasing a BEV compared to an ICEV, as the cost of a residential charger would be borne at the time of vehicle purchase. TCO, expressed in U.S. dollars per mile, includes the upfront cost to purchase the vehicle and the operational and maintenance costs incurred over its lifetime.

The recent passage of the IRA and its clean vehicle provisions are anticipated to dramatically lower the powertrain cost and the TCO of BEVs and accelerate their deployment. As mentioned above, we have conducted a supplemental study to this report that analyzes the economic impact of the IRA credits and grants on the purchase price of a light-duty BEV, charger unit cost, and the TCO of the vehicle [3]. Overall, the IRA significantly reduces the electrification costs of LDVs and increases deployment. Furthermore, it accelerates the time required for BEVs to achieve parity with ICEVs, both in the near and long term.

Key Assumptions and Methodology

Within the 2030 timeframe, BEV volumes are assumed to be in the range of 50% of new vehicle sales, consistent with the President's Executive Order goals for 2030 [4], [5]. This report considers only tangible financial aspects related to vehicle ownership, namely vehicle price, charging infrastructure, fuel, and maintenance costs. Nontangible benefits, such as societal, health, environmental, and enhanced vehicle 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 in 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 and 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 a direct comparison of a BEV against an equivalent ICEV.

ICEV and BEV costs are compared for entry-level (base) and luxury (premium) versions of six vehicle subclasses (see Figure 1). The study compares three ICEV fuel-saving engine technology pathways and two BEV ranges for each vehicle subclass and segment combination. These pathways capture the wide range of technologies expected to be in the marketplace in the 2030 timeframe, based on the current progression of regulations and market technologies.

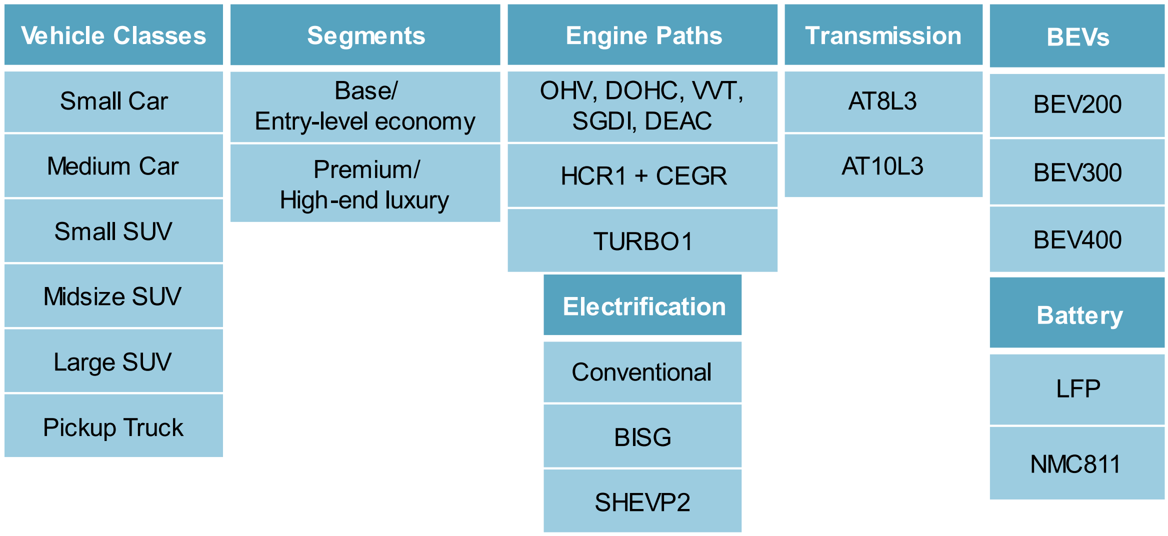

Figure 1: Technology pathways considered for light-duty vehicles

To assess the cost of electrification over fossil fuel-powered vehicles, an incremental cost of powertrain approach is used for the analysis. This approach tries to capture the 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 derived using three different scenarios that reflect increasing levels of cost: Scenario 1, Scenario 2, and Scenario 3. These scenarios compare the powertrain cost of an ICEV to an equivalent 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 of switching to a BEV. It 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 of switching to a BEV. It has the highest incremental cost of electrification, and a BEV takes the longest time to achieve TCO parity against an ICEV.

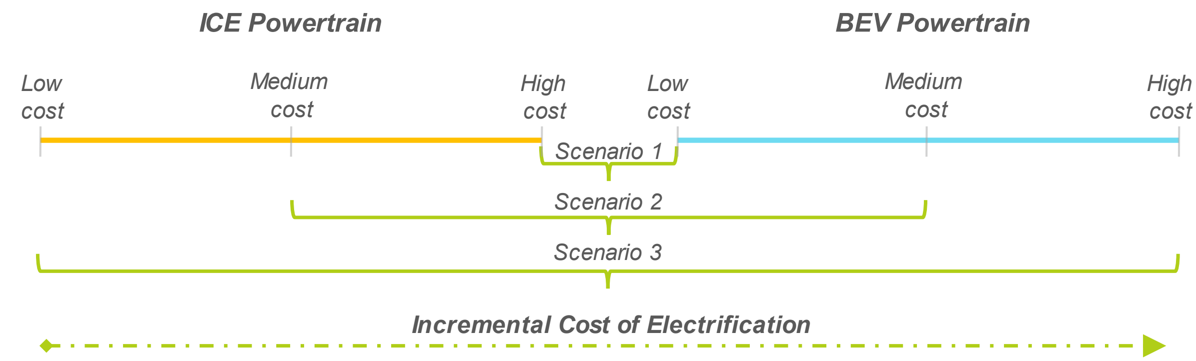

Figure 2: Conceptual illustration of the incremental cost of electrification scenarios

The ICEV technology packages considered in the study are based on various market offerings, future vehicles under development, and general technology trends [1]. The technology content assigned to each vehicle subclass under the three scenarios of the incremental cost of electrification is illustrated in Figure 3. The engine pathways are considered for both the base and premium segments, respectively, while the level of electrification for each powertrain determines the scenario they fall under. The blue and yellow colors represent the base and premium segments, respectively. The light to dark green range represents increasing levels of hybridization, i.e., from a low-cost conventional powertrain to a high-cost P2 hybrid. These three cost cases are used to develop the three electrification scenarios (refer to Figure 2). All segments are assumed to have an 8-speed transmission (AT8L3), except large SUVs and pickup trucks, which are assumed to have a 10-speed transmission (AT10L3). Diesel engines are not considered in the study because of their low market penetration and the high present and future costs of emission compliance.

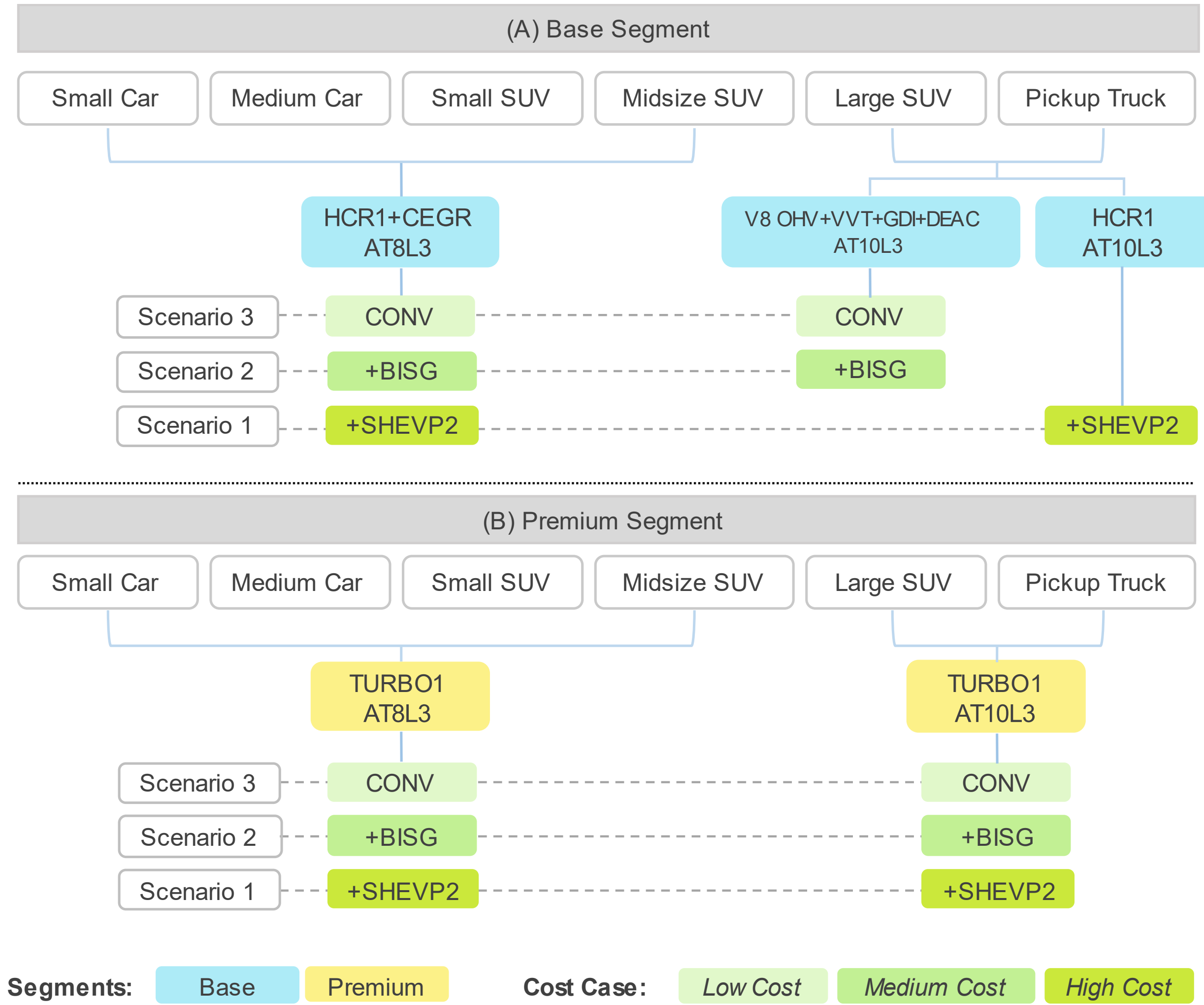

Figure 3: Technology pathways considered for ICEVs, under the three electrification scenarios.

Based on the relevant market offerings (see Figure 4) and various studies [6]–[8], the following describes the choice of powertrains for BEVs:

a) For all but large SUVs and pickups, BEV200s are for base vehicles, BEV300s are for premium vehicles, and
b) For large SUVs and pickups, BEV300s are base vehicles, and BEV400s are premium vehicles.

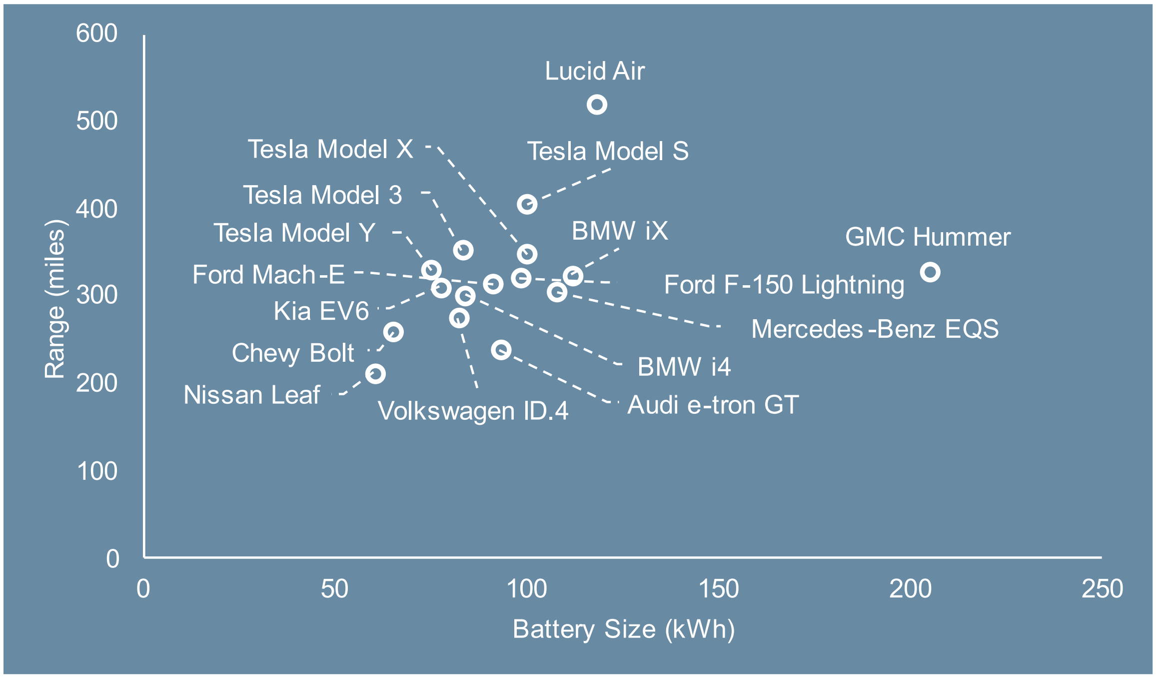

Figure 4: Market offerings of BEVs in the LDV segment.

NMC811 and LFP battery chemistries are used in the cost analysis of BEVs as they are expected to have a significant presence in the EV market by the 2030 timeframe. The OEMs are expected to take a tiered approach, with entry-level vehicles using cobalt-free LFP batteries and higher-end models and trims using NMC batteries. Since the LFP is seen as an alternative to nickel-based chemistries, its selection in Scenario 1 (or a low-cost scenario) is more than a simple cost-saving scenario. LFP, NMC811, and a 10% costlier NMC811 are used to develop the low-, medium-, and high-cost BEV powertrains. Along with the initial purchase of a BEV, the user is assumed to purchase a residential charger to charge their vehicle, which is included in the TCO analysis. The technology content assigned to each vehicle subclass under the three scenarios of the incremental cost of electrification is illustrated in Figure 5. The blue and yellow colors represent the base and premium segments, respectively. The light to dark green range represents a low-cost LFP option to a high-cost NMC811 option that is 10% more expensive. These three cost cases are used to develop the three electrification scenarios (refer to Figure 2).

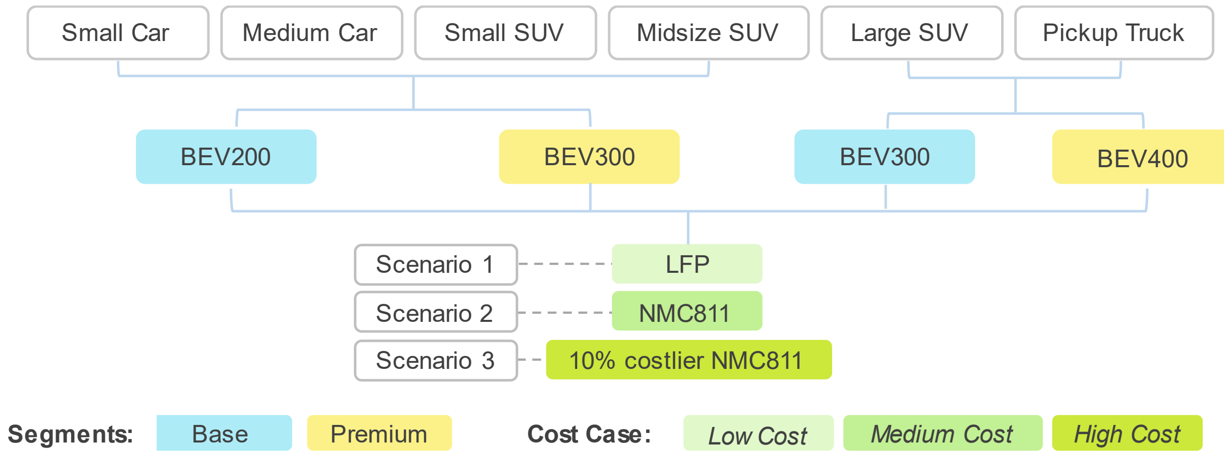

Figure 5: Technology pathways considered for BEVs under the three scenarios of electrification on a cost basis (or battery technology).

Figure 6 depicts the price breakdown of ICEVs and BEVs, which is the sum of the price of the glider (the vehicle without a powertrain) and the price of the powertrain. The powertrain price is calculated by multiplying the powertrain cost by a retail price equivalent (RPE) factor. For each segment with three electrification scenarios, we assigned the same glider price to both ICEVs and BEVs. The vehicle purchase price is then calculated using an RPE factor of 1.5 for ICEVs [11] and 1.2 for BEVs. The RPE factor is lower for BEVs compared to ICEVs due to multiple factors explained in detail in Section 2.5 below. The primary reason for this difference is that BEVs have a much simpler architecture and lower indirect costs than comparable ICEVs. The main driver of indirect costs for BEVs is the production overhead of batteries, which will be substantially absorbed by the battery manufacturers. Additionally, many EV drivetrain components such as motors, inverters, and power electronics will be sourced externally, further reducing the overhead and the RPE factor.

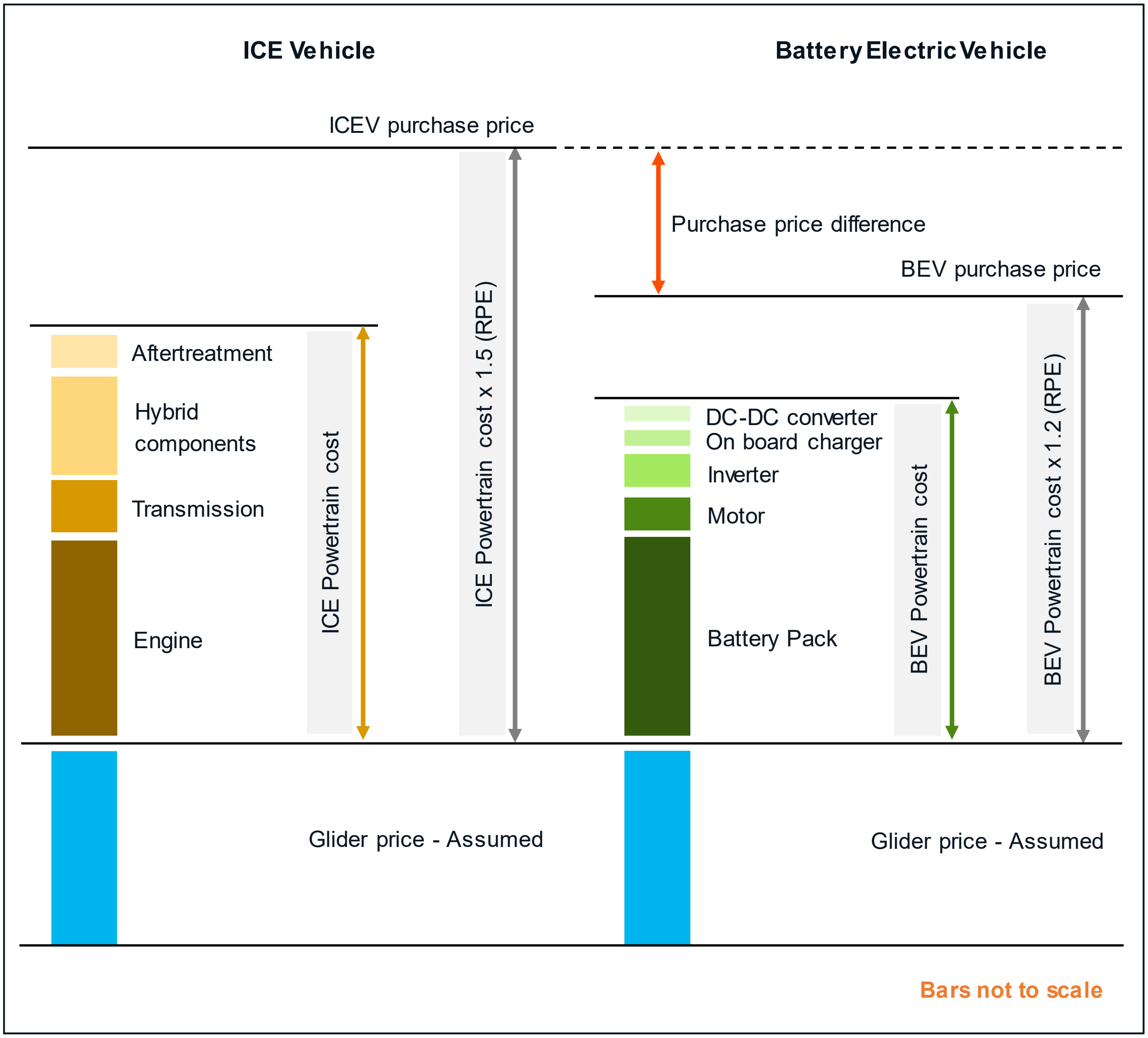

Figure 6: Methodology to estimate the vehicle purchase price.

Primary Analysis and Results

Incremental Cost of BEV over ICEV

The direct manufacturing cost of a BEV powertrain is less than that of an equivalent ICEV in the 2030 timeframe, except for the base large SUV in Scenarios 2 and 3, the base pickup truck in Scenario 3, and premium versions of the large SUVs and pickups across all three scenarios, as shown in Figure 7.

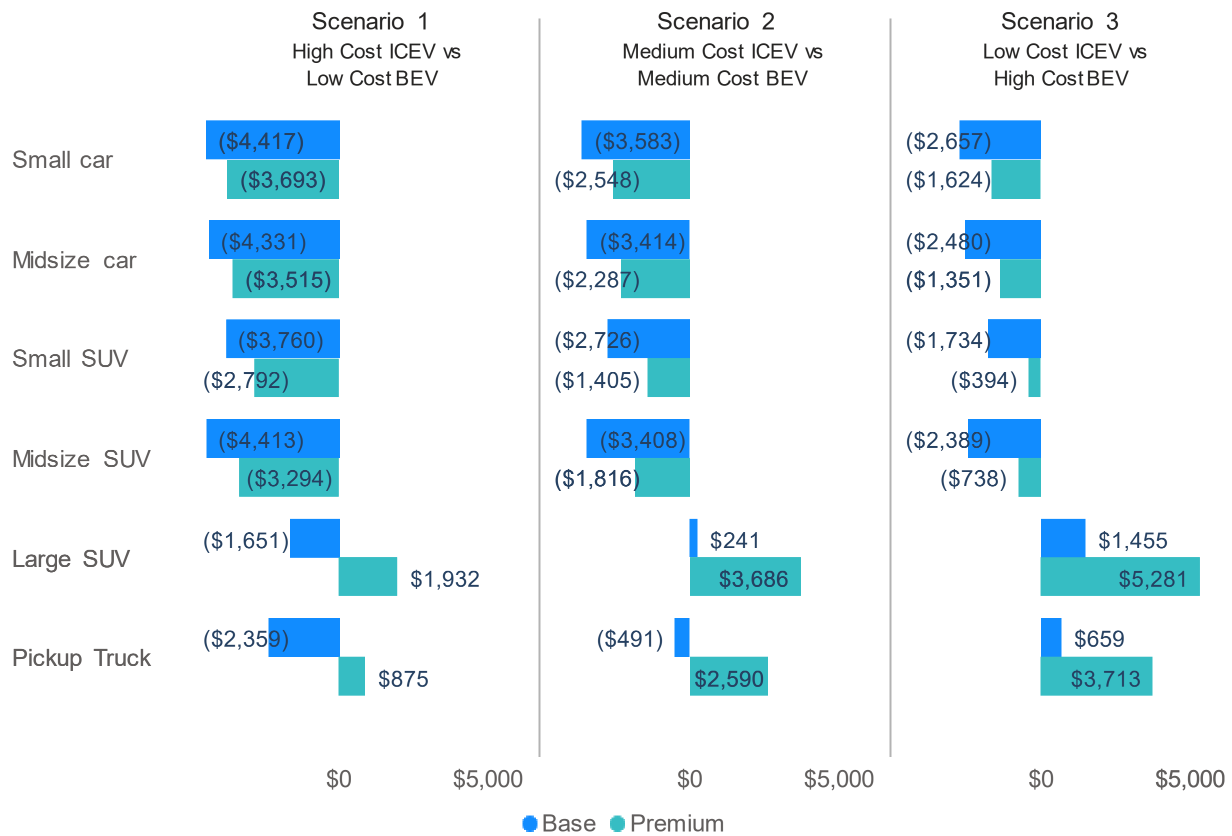

Figure 7: Projected incremental cost of BEV over ICE powertrain in 2030 for LDVs. Negative values in parenthesis indicate that a BEV provides savings over an ICEV

In the case of large SUVs and pickup trucks, the longer range assumption of 300 miles for base versions and 400 miles for premium versions requires a larger and more expensive battery pack, motor, and power electronics for BEVs, resulting in a higher cost for the powertrain. To compensate for this higher cost, automakers can explore cost reductions across the rest of the vehicle. For instance, they can adopt advanced vehicle construction techniques, such as cell-to-chassis, or use advanced materials to *lightweight* battery packs, such as pack enclosures, lowering the glider price relative to ICEVs, thus reducing incremental costs. The clean-sheet design of BEVs also offers an opportunity for standardization and simplification of glider architecture across models, leading to greater efficiency gains and weight reduction for BEVs. Startups and new EV automakers have successfully demonstrated that BEV glider design can be approached differently than an ICEV and could have potential weight and cost savings in the future, which are not addressed in this study.

Furthermore, the price of ICEVs will also impact the incremental costs. As more stringent emissions standards are adopted beyond 2026, ICEV powertrain costs are expected to increase as reflected in Scenario 1 where a transition to a fully hybridized fleet would also increase ICEV costs. Additionally, it is anticipated that the EPA will revise the criteria emission standards, including NOx, particulate matter, and hydrocarbons, to be at least as stringent as those in California's Advanced Clean Cars II regulations, further increasing the cost of ICEVs relative to BEVs. All these factors will eventually reduce the cost difference between BEVs and ICEVs for large SUVs and pickups.

Incremental Purchase Price of BEV over ICEV

The estimation of retail equivalent vehicle prices starts with direct manufacturing costs and adds indirect costs. Because of their simpler design and the facts that battery manufacturers are conducting research into battery improvements and OEMs will generally purchase electric motors from suppliers (versus in-house ICEs), we project that the indirect costs related to BEV powertrains will be lower than those related to ICEV powertrains in percentage terms. As a result, when coupled with the above powertrain costs, we project that BEV prices (including the cost of a home charger) in the base segment will be significantly lower than ICEV prices under all three scenarios, thereby achieving immediate purchase price parity in 2030, except for the large SUV in Scenario 3. In the premium segment, except for the large SUV in all three scenarios and the pickup truck in scenarios 2 and 3, all the vehicle types would again achieve parity immediately upon purchase in 2030. The price of a BEV with a charger relative to an ICEV is shown in Table 1.

Table 1: Incremental Purchase Price of a BEV including charger over an ICEV in 2030

Subclass	Scenario 1		Scenario 2		Scenario 3	
	Base	Premium	Base	Premium	Base	Premium
Small car	-$6,510	-$5,910	-$5,061	-$4,240	-$3,976	-$2,975
Midsize car	-$6,432	-$5,719	-$5,086	-$3,926	-$3,764	-$2,647
Small SUV	-$5,774	-$4,891	-$4,260	-$2,868	-$2,868	-$1,499
Midsize SUV	-$6,823	-$5,832	-$5,357	-$3,681	-$3,932	-$2,231
Large SUV	-$3,822	$399	-$1,064	$2,904	$548	$4,974
Pickup Truck	-$4,671	-$870	-$1,943	$1,589	-$406	$2,979

As with incremental powertrain costs, the four smaller vehicle segments show the potential for considerable consumer savings for both base (BEV200) and premium (BEV300) versions. On the other end of the vehicle spectrum, the incremental purchase prices for the largest two segments (BEV300s and BEV400s) range from a savings of nearly $5,000 for a base pickup in Scenario 1 (low incremental BEV cost) to an additional cost of nearly $5,000 for a premium large SUV in Scenario 3 (high incremental BEV cost). On a TCO basis, as shown in Figure 8, all categories (even the premium large SUVs and pickups) will provide consumers with substantial savings compared to an equivalent ICEV.

Total Cost of Ownership (TCO)

In addition to the upfront purchase price, the consumer also incurs operating costs over a vehicle's lifetime, called the total cost of ownership (TCO). Operating costs include energy costs and maintenance and repair (M&R) costs over an assumed lifespan of 15 years. The energy costs are computed using the annual vehicle miles traveled (VMT) [7], fuel economy [6], and fuel prices [12]. The energy prices used in this study are based on the gasoline price ($ per gallon) and the residential electricity price ($ per kWh) using the EIA Annual Energy Outlook 2022 projections in the 2030–2044 timeframe for ICEV and BEV, respectively [12]. Gasoline prices (excluding taxes) and residential electricity prices are used to compute the energy price across the three different scenarios. Scenario 1 assumes gasoline prices in the range of $4.23/gallon to $4.41/gallon; Scenario 2 is in the range of $2.80/gallon to $3.15/gallon; and Scenario 3 is in the range of $2.07/gallon to $2.27/gallon. As mentioned earlier, a retail price equivalent (RPE) multiplier of 1.5 for ICEVs and 1.2 for BEVs has been used to compute the vehicle purchase price, which has a bearing on the total cost of ownership.

This analysis concludes that the TCO of a BEV is significantly lower than an equivalent ICEV across all classes and segments in 2030, as shown in Figure 8. (The only exception is the premium large SUV under Scenario 3, which shows that BEVs have the same TCO as ICEVs). The average cost of ownership per mile for a BEV is about 26% lower than that of an ICEV in the base segment of all vehicle classes, with the cost being $0.21 per mile for a BEV and $0.284 per mile for an ICEV. Similarly, in the premium segment, the TCO per mile is $0.267 for a BEV and $0.316 for an ICEV, making the cost of owning a BEV about 15% less than that of an equivalent ICEV. Any initial savings only get larger over time because BEVs have significantly lower energy and maintenance costs, making them increasingly economically attractive over their lifetime of ownership. The discounted lifetime costs and savings for each vehicle class and their respective segments are depicted in Appendices 8.3 and 8.4.

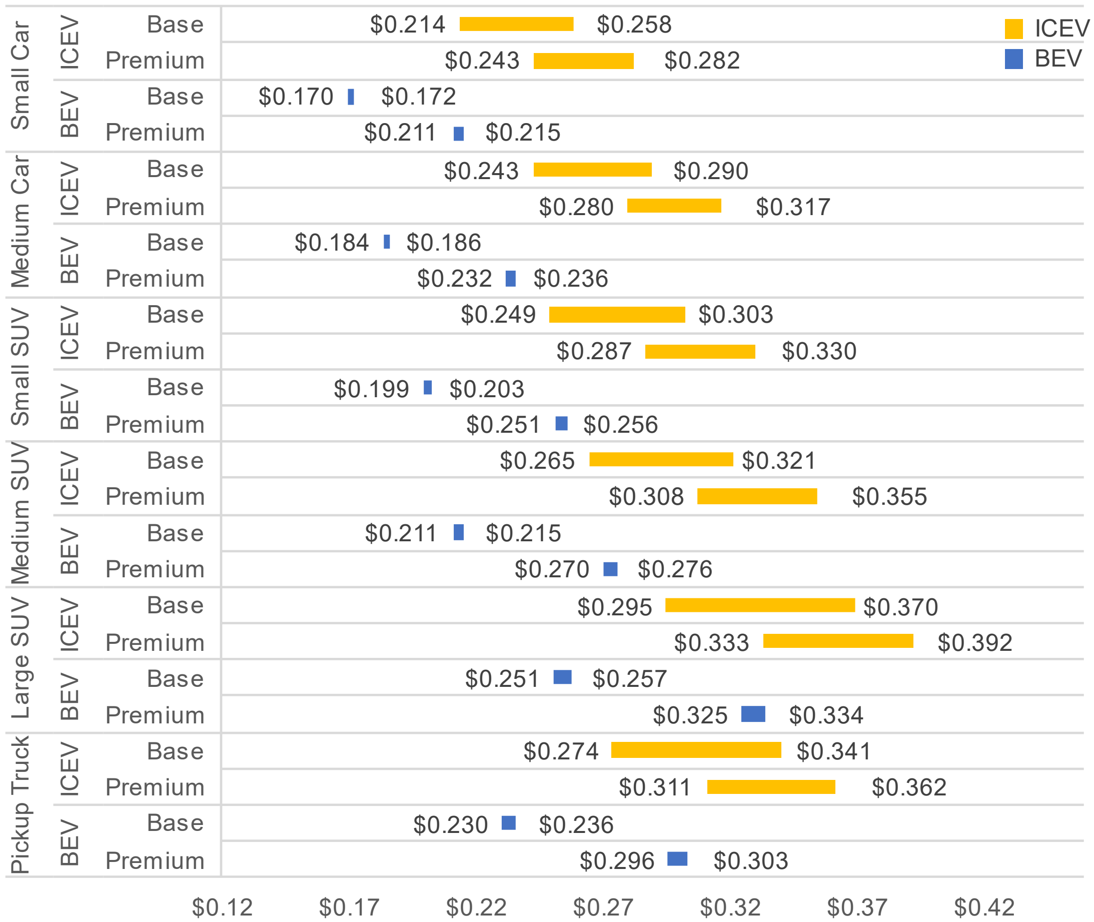

Figure 8: Projected TCO ranges of BEVs and ICEVs across three electrification scenarios in 2030

As illustrated in Figure 9, purchasing a BEV offers significant cumulative lifetime savings of thousands of dollars, averaging around $15,000 over an equivalent ICEV across all scenarios and vehicle segments. The only case where lifetime BEV costs exceed those of an equivalent ICEV is the BEV400 in the premium large SUV segment in Scenario 3, where the net difference is a couple of hundred dollars out of a total cost of $90,000. The purchaser of a BEV pickup truck in 2030 would save $11,000–$31,000 over the life of the vehicle compared to a comparable gasoline pickup truck across the three scenarios. And the purchaser of a BEV midsize car could save roughly $13,000–$25,000 over the life of the vehicle, depending on the cost scenario.

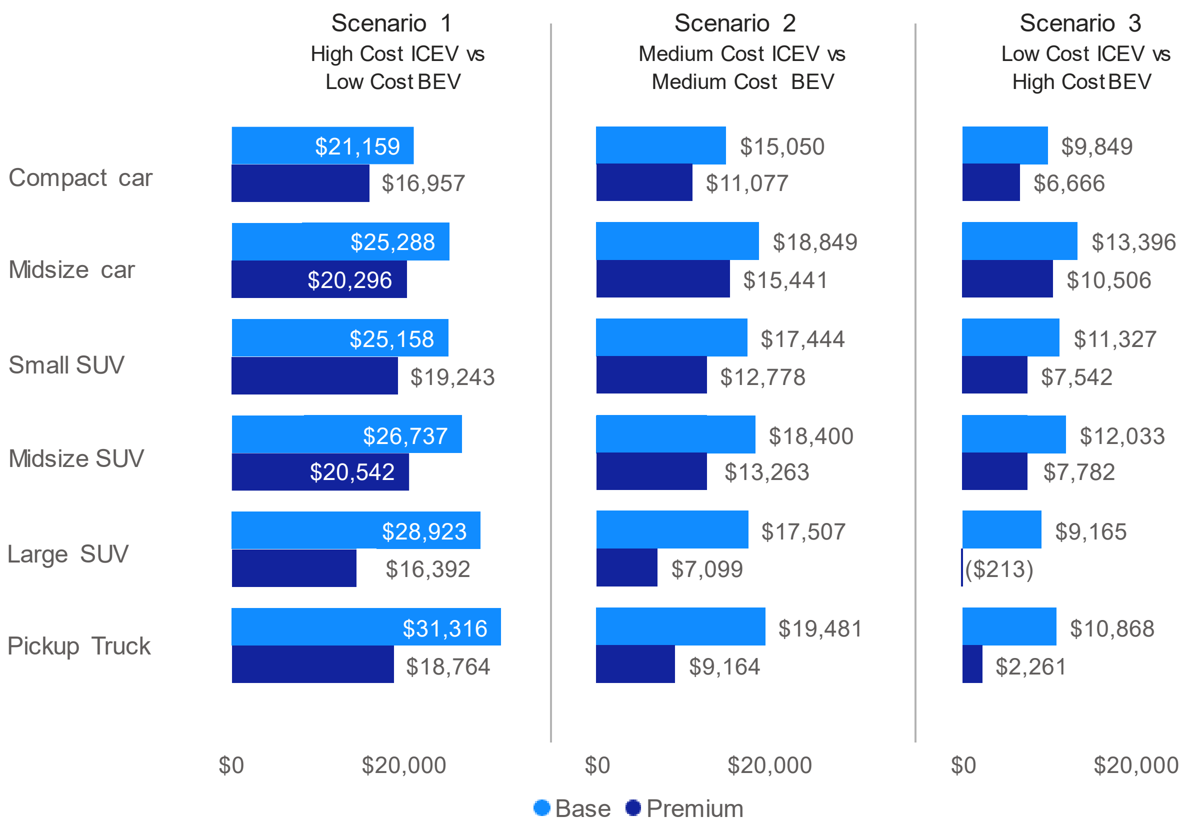

Figure 9: Projected cumulative net savings of a MY 2030 BEV over an equivalent ICEV during its lifetime

BEV analyses often calculate the number of years of reduced operational costs needed to compensate for higher upfront costs. However, as discussed above, BEVs in many segments start with lower upfront costs. Total cost savings only increase as the BEVs are used. Thus, there is no number of years of operation where the cumulative cost of ownership and operation are the same. BEVs save money from the start.

However, there are a few segments where BEVs are still projected to cost more than their ICEV equivalents in MY 2030. In the base large SUV segment, the BEV requires one year of operation to compensate for its higher upfront cost in Scenario 3. In the premium large SUV segment, the BEV requires 4 years of operation to compensate for its higher upfront cost in Scenario 2 and a little longer than its assumed 15-year life in Scenario 3. In the premium pickup segment, the BEV requires 2 years of operation to compensate for its higher upfront cost in Scenario 2 and 8 years in Scenario 3. It is pertinent to note that Scenario 3 has the lowest-cost ICEV powertrain coupled with the lowest gasoline prices in the range of $1.57/gallon to $1.77/gallon (without taxes), which makes it challenging for a premium BEV400 large SUV to achieve parity. It should also be noted that the fuel economy values projected by ANL [6] for the ICEVs are on the optimistic side. If these fuel economies are not achievable, then the BEVs would achieve parity earlier than estimated, and the TCO savings could increase substantially.

Table 2: Time to achieve parity for light-duty BEVs with a 2030 purchase timeframe in the base and premium segments

Subclass	Segment	Scenario 1 (High-Cost ICEV vs Low-Cost BEV)	Scenario 2 (Medium-Cost ICEV vs Medium-Cost BEV)	Scenario 3 (Low-Cost ICEV vs High-Cost BEV)
Compact Car	Base	Immediate	Immediate	Immediate
	Premium	Immediate	Immediate	Immediate
Midsize Car	Base	Immediate	Immediate	Immediate
	Premium	Immediate	Immediate	Immediate
Small SUV	Base	Immediate	Immediate	Immediate
	Premium	Immediate	Immediate	Immediate
Midsize SUV	Base	Immediate	Immediate	Immediate
	Premium	Immediate	Immediate	Immediate
Large SUV	Base	Immediate	Immediate	Immediate
	Premium	Immediate	4	End of Life
Pickup Truck	Base	Immediate	Immediate	Immediate
	Premium	Immediate	2	8

What-if Scenarios

Results for the MY 2030 Projected Fleet

In addition to the primary analysis, we conducted a high-level analysis using fleetwide sales-weighted average costing based on MY 2030 sales projections to evaluate the powertrain cost and TCO of BEVs 200 and 300 against an equivalent ICEV for each subclass. BEV400s were not included in this analysis due to the limited sales projections. Using EPA's MY 2030 sales projections, we found that the sales-weighted average cost of the powertrain, retail price equivalent, and TCO of BEVs are lower than an equivalent ICEV. The sales projections are based on the various combinations of technology pathways that the OEMs might choose to comply with the revised MYs 2023–2026 GHG standards [13]. The key finding is that the powertrain costs of BEV200s and BEV300s are generally lower than ICE powertrain costs. This, coupled with a lower RPE factor, translates into lower BEV purchase prices, as shown in Table 3. Moreover, BEVs are much cheaper to own and operate than an equivalent ICEV, resulting in an overall average savings of about $15,800, as shown in Figure 10. Details of the analysis can be found in section 5.4.1.

Table 3: Incremental price of a BEV powertrain including charger over a sales-weighted ICEV powertrain in 2030.

Subclass	BEV200	BEV300
Small Car	-$4,600	-$2,588
Medium car	-$4,782	-$2,659
Small SUV	-$3,993	-$1,638
Medium SUV	-$5,967	-$3,118
Pickup Truck	-$5,726	-$3,033

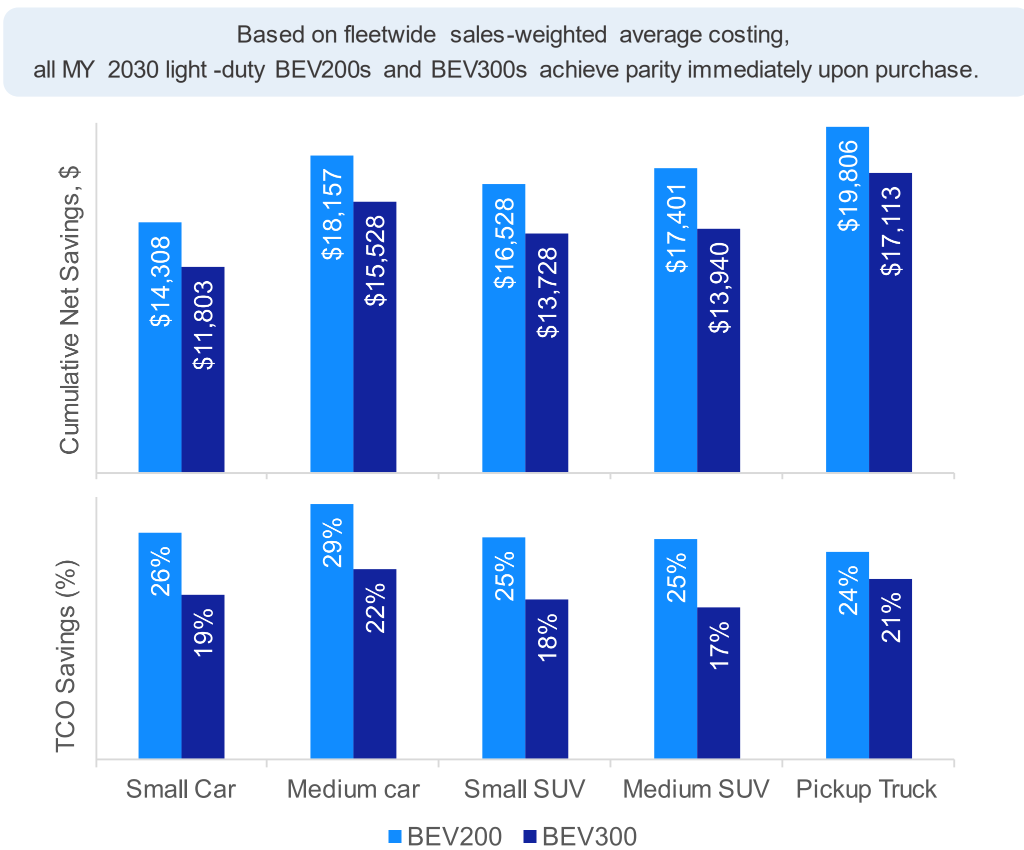

Figure 10: Fleetwide sales-weighted average costing analysis favors BEVs 200 and 300 over equivalent ICEVs.

Results of Additional Sensitivities

It is critical to state 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. With the ongoing geopolitical crises and volatility in the oil and gas sector, per the EIA, the price of retail gasoline had reached an all-time high of $6.294 in California in 2022, 43% higher than the “high” oil price used for Scenario 1, which reflects the upper limit on gasoline prices in our analysis. This has a direct and detrimental impact on the operating expenses that affect the TCO of the ICEV. To reflect the parity timeline with current oil prices, a sensitivity analysis, as explained in Section 5.5, is conducted where even the BEV400 large SUVs and pickup trucks achieve parity within the first year of ownership. Ongoing fuel prices at these levels would result in significant savings of several thousands of dollars across all classes and segments, with an average discounted lifetime savings of about $33,000 over the lifetime of a BEV.

In addition to the primary choice of a residential charging scenario, this analysis also explores a demand-based charging scenario wherein the customer would charge equally at their residence and a public charging station. The findings support the argument that the total operating costs of a BEV in 2030 would be indifferent to the varying charging infrastructure costs and the electricity prices considered. The cost of public charging is expected to decrease in the future with higher BEV penetration and economies of scale.

Technological Advancements and the Way Ahead

Battery cost is the leading indicator that determines the economic viability of manufacturing and the adoption of EVs. Due to the high fluctuation of raw material costs and engineering challenges, the battery constitutes anywhere from 25%–40% of the vehicle’s cost, depending on its chemistry and configuration [14]–[16]. The battery cost projections in this study are based on economies of scale. Disruptions or shortages in the supply chain could have a negative impact on the parity timeline presented in this report. However, the IRA provisions are expected to significantly reduce the powertrain cost and TCO of BEVs, as well as accelerate parity timeframes. Another factor that could lower the cost of battery packs is that the OEMs are shifting their focus to the midstream and potentially upstream (mining and refining) of the battery value chain, as well as vertical integration of cell manufacturing. This would allow them to tightly control and manage the battery value chain and the battery cost. After accounting for all the engineering and technological advancements currently being pursued, there exist clear pathways for cost-competitive, sustainable, reliable, and environmentally friendly BEVs as a replacement option for fossil fuel-powered ICEVs. Advancements in battery technology, as discussed in Section 3 (Electrification Technology Review), are expected to further reduce the battery costs and operating costs of BEVs.

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. By recycling readily available, dense concentrations of battery raw materials and feeding them to the industry, recyclers can create lasting positive social, environmental, and economic impacts. Recycling is a relatively low-carbon pathway compared to virgin metal mining. In the future, with increased penetration of BEVs, the recycling and reprocessing industry is expected to have a significant presence. 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 the sustenance of the BEV industry. In addition to driving down cell costs, recycling will also be key to attaining a net-zero carbon footprint.

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, eliminating the cost and environmental footprint 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 such as 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 provide sustainable and economically viable powertrain solutions for the EV industry.

Finally, to support the transition to BEVs, charging infrastructure must be scaled adequately to meet rising demand and respond to consumer range anxiety concerns. A robust network of charging stations with corridor fast charging, public charging, and workplace charging is required. There are numerous programs already in existence to foster the development of a charging infrastructure [4]. There are no known technical barriers to BEV adoption, as the technology is improving at a rapid pace and the cost savings are attractive to a typical consumer. With the acceleration in BEV deployment and infrastructure build-up, a BEV will be a financially attractive ownership prospect for a typical consumer compared to an ICEV by 2030.

Major commitments by the automakers and manufacturers, in step with government policy initiatives, are driving investments toward electrification of the light-duty vehicle segment. Recently approved Advanced Clean Cars II (ACC II) standards by CARB in August 2022 will accelerate the transition to EVs. Furthermore, 17 other states may also follow suit and implement the ACC II standards. 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 Program and the Inflation Reduction Act drive huge investments into the EV ecosystem, benefiting all stakeholders.

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

1. Introduction

1.1 Background

The transportation sector is the biggest source of greenhouse gas emissions in the U.S., as shown in Figure 11 [2]. Light-duty vehicles (including passenger cars and light-duty trucks) and medium- and heavy-duty vehicles (vehicles with a gross vehicle weight rating (GVWR) > 8,500 pounds) accounted for 82% of the GHG emissions in the transportation sector in 2021 [2]. GHG emissions comprise carbon dioxide, methane, and nitrous oxide emitted through the combustion of fuel [2]; vehicles also emit other air pollutants such as ozone precursors, sulfur oxides, and particulate matter [17]. These emission constituents and other pollutants contribute to climate change and air pollution.

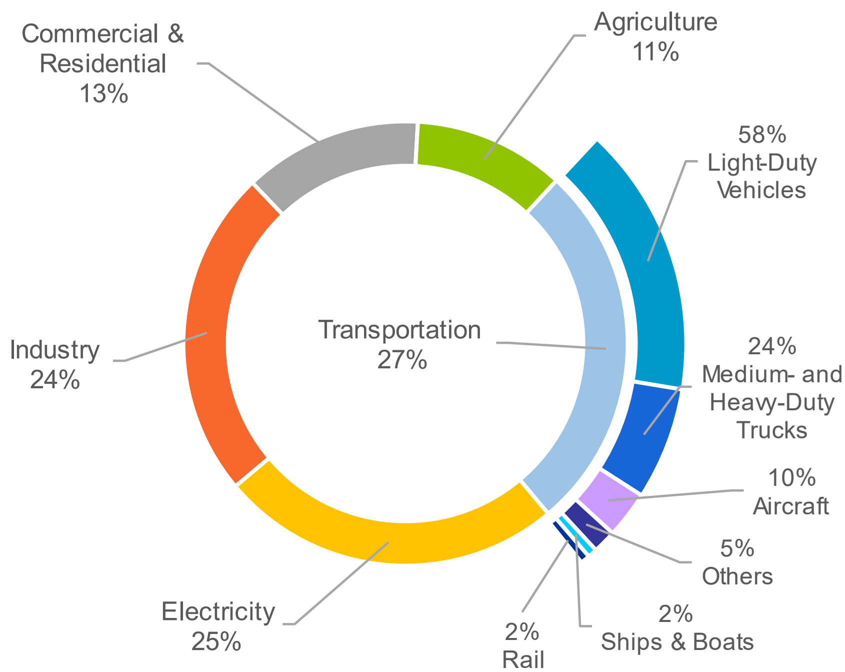

Figure 11: Distribution of U.S. greenhouse gas (GHG) emissions by sector [2].

Decarbonization of the transportation sector is one such concrete step to mitigate GHG emissions by reducing the carbon footprint. A typical fossil fuel-powered passenger vehicle emits nearly 4.6 metric tons of carbon dioxide per year [18]. Electrification of light-duty vehicles (up to 8,500 lbs.) will be instrumental in eliminating fossil fuel-reliant powertrains and significantly reducing GHG emissions while allowing the U.S. to maintain technology leadership and competitiveness. In 2019, 253 million LDVs were registered in the U.S., consuming 131.45 billion gallons of fuel [19], contributing to more than 50% of the GHG emissions [2] and other tailpipe pollutants. These include passenger cars, light trucks, vans, and sport utility vehicles. The volume share of these vehicle types has changed in recent years as the typical consumer has moved away from sedans to SUVs and pickups, as shown in Figure 12 [20].

The U.S. Department of Transportation's (DOT) National Highway Traffic Safety Administration (NHTSA) regulates fuel economy standards using the CAFE program to reduce national energy consumption, while the U.S. Environmental Protection Agency (EPA) regulates GHG emissions [21]. In December 2021, EPA finalized revised national GHG emissions standards for passenger cars and light trucks for MY 2023–2026 that result in avoiding more than 3 billion tons of GHG emissions through 2050. In April 2022, NHTSA released the new CAFE standard, which requires an industry-wide fleet average fuel efficiency of 49 mpg for passenger cars and light trucks in model year (MY) 2026. It increases the fleet-wide average fuel economy of MY 2026 by 10 mpg compared to MY 2021 [11]. CAFE ratings are based on laboratory test drive cycles with a weighted average of 55% city and 45% highway conditions [22]. NHTSA notes both that real-world fuel economy is generally 20%–30% lower than the estimated required CAFE level stated above and that the actual CAFE standards are a function of the vehicle footprints of passenger cars and light trucks that the industry produces for sale in those model years [23]. Furthermore, in April 2022, during the Leaders Summit on Climate, President Biden announced a new target for the U.S. to achieve about a 50% reduction from 2005 levels in economy-wide net greenhouse gas pollution in 2030 [24]. This shift in segment preference has decreased fleet average fuel economy, mitigating the positive impact of improved fuel economy within each segment. Shifting consumer preferences have thwarted the impact of CAFE and GHG regulations. Switching to less-carbon-intensive fuels or electrifying LDVs in conjunction with other mitigation strategies could help in achieving climate targets quickly, which is stabilizing the atmospheric CO_2 concentrations.

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 electric vehicle. The benefits are plentiful and can help a consumer save thousands of dollars over the lifetime of ownership of an EV, primarily due to greater fuel economy and less maintenance. The LDV segment is poised to benefit from these advancements, which should incentivize the customer to make the transition to battery electric vehicles (BEVs).

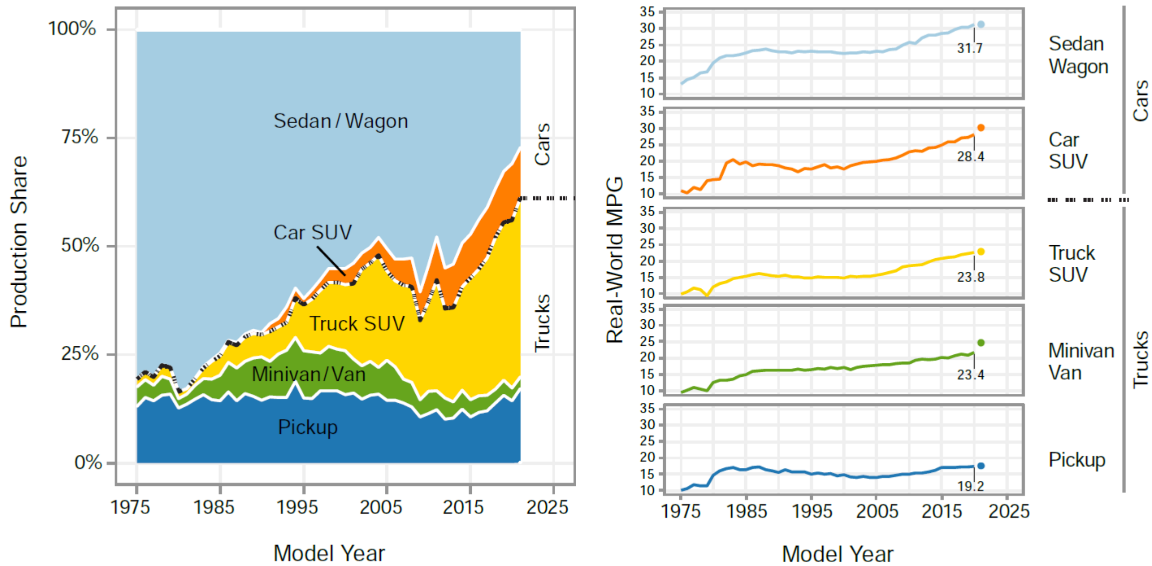

Figure 12: Production share of light-duty vehicles (LDVs) with their record high real-world fuel economy of MY 2020 [20]

1.2 Current State

To enable a clean transportation future, the Biden Administration has set a goal to accelerate and deploy electric vehicles and charging stations to achieve a target of 50% EV sales share in 2030 [4]. The Bipartisan Infrastructure Law (BIL), enacted as the Infrastructure Investment and Jobs Act (IIJA), Public Law 117-58, signed into law on November 15, 2021, provides momentum to the electric vehicle program through the following initiatives:

a) The National Electric Vehicle Infrastructure (NEVI) Formula Program provides up to $7.5 billion to invest in the U.S. Electric Vehicle (EV) charging infrastructure [25]. 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 [26].
b) Establishment of the Joint Office of Energy and Transportation, a modernized and interagency approach to supporting the deployment of zero-emission, convenient, accessible, and equitable transportation infrastructure
c) Apportionment of Highway Infrastructure Program Funds for the National Electric Vehicle Infrastructure Program
d) The program will provide nearly $5 billion over five years to help states create a network of EV charging stations along designated Alternative Fuel Corridors.
e) Provision of resources to jumpstart the EV transformation, such as by providing a toolkit for Planning and Funding Rural Electric Mobility.

Furthermore, 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. The provisions in the act provide incentives, tax credits, and funding for various programs to electrify the transportation sector. Roush has conducted a supplemental study that analyzes the impact of those provisions in the IRA on the LDV segment and attempts to quantify the credits on the purchase price of a BEV, charger unit cost, and the TCO of the vehicle. Additionally, the qualitative impact of IRA provisions on the LDV ecosystem from upstream to downstream is also looked at in detail [3].

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 U.S. [27], [28]. The emissions associated with a BEV are caused by the provision of electric energy for charging the batteries [27], [28]. These emissions are related to power generation, which also includes the emissions associated with the extraction, processing, and distribution of energy sources [27]. However, decarbonization can be mineral intensive [29], [30], and the pace of the energy transition depends on the supply chain and value chain of the raw materials required for producing a lithium-ion battery, as shown in Figure 13. President Biden signed a determination on March 31, 2022, permitting the use of the Defense Production Act (DPA) Title III authorities to encourage the domestic production of minerals for large-capacity batteries [31]. It allows the agencies and industries to increase domestic mining and processing of critical materials required for creating a large-capacity battery supply chain [31]. Section 3 (Electrification Technology Review) describes numerous potential technologies under development that reduce or eliminate the need for various critical raw materials.

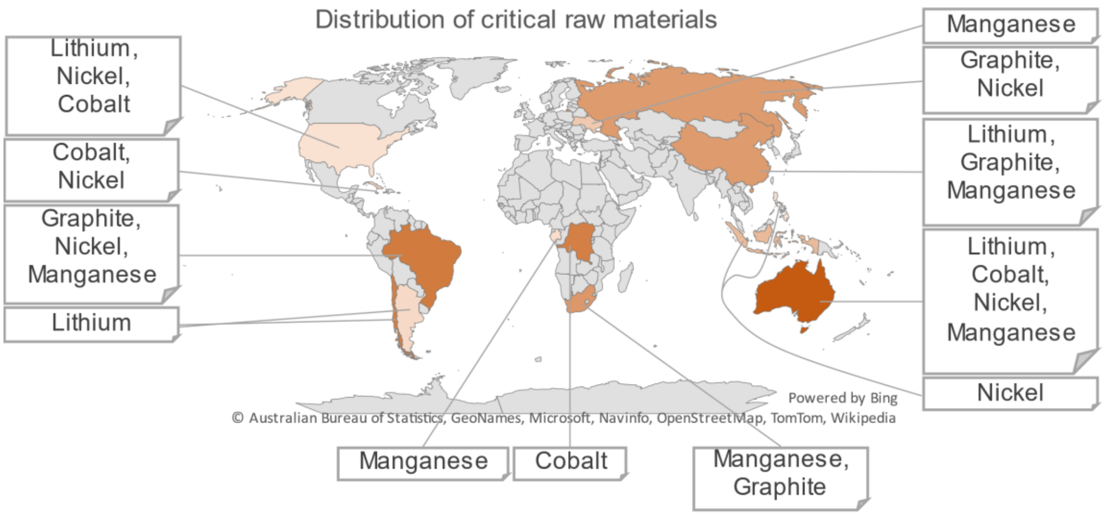

Figure 13: Distribution of battery-critical raw materials based on the data from the USGS Commodity Summary 2022 [32]

1.3 Challenges

The production of a BEV is vastly 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 package. 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 commonality, lowering costs, and strengthening supply chains. But the challenges for traditional OEMs are unique compared to companies like Tesla and other recent EV startups. They would have to retool and/or reconfigure 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 [33]. 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, and the U.S. and Europe are stressing the importance of greater regionalization of battery supply chains [34]. Recently, automakers have begun addressing various choke points to avoid a repeat of the microprocessor supply chain disruption. The cost of cells has a direct impact on the economic viability of mass-producing EVs, and automakers are hoping to improve their margins through economies of scale. Investments in gigafactories and offtake agreements for sourcing battery raw materials are also on the rise and would help automakers make a smooth transition. Furthermore, recycling battery materials has the potential to provide enough feedstock to reduce reliance on virgin materials.

1.4 Study Considerations

The scope of this study is to project the incremental costs of electrification and compare the TCO of light-duty ICEVs with comparable BEVs in the 2030 purchase timeframe. The study assumes 50% penetration in the LDV segment and economies of scale in the costed technology segments. 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. Experience and industry knowledge are used in vetting the information, and the authors of this study make reasonable efforts to represent current and accurate information.

Only tangible, direct-cost inputs are considered in this study. Home infrastructure upgrade costs to install the charger are not considered. Other benefits, such as societal, social, 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 grows simultaneously to meet the 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 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 LDV types comprising passenger cars, SUVs, and pickup trucks. These vehicle types are further categorized by powertrain for selected size classes, i.e., small cars, midsize cars, small SUVs, midsize SUVs, large SUVs, and pickup trucks. Broadly, each class differs in key attributes such as weight, footprint, and power that affect their real-world fuel economy and CO_2 emissions. Going further, each class is divided into base and premium segments. The base segment represents entry-level vehicles, and the premium segment represents top-of-the-line performance-level vehicles. The relative costs of ICEVs and BEVs are presented for each segment.

We have not considered platform-level changes as they are outside the scope of the study. Additionally, an anticipated increase in the tightening of fuel economy and emission standards beyond 2026, which are not considered in this study, would affect the cost of ICE powertrains.

Finally, this study was conducted in the 2021–2022 timeframe before the IRA of 2022 was signed into law. This report focuses primarily on BEV costs in model year (MY) 2030; however, our supplemental study "*Impact of Inflation Reduction Act of 2022 on Light-Duty Vehicle Electrification*" [3] examines the issue of cost parity in earlier model years. Generally, the IRA of 2022 positively impacts the electrification of LDVs and boosts the entire ecosystem. Furthermore, it also accelerates the time needed to achieve parity across all classes, favoring the LDV segment's electrification.

2. Methodology

Three cost scenarios of powertrains are developed for each vehicle subclass to capture the entire spectrum of ICE technology costs, recognizing their adoption in the 2030 timeframe. Conventional, mild hybrid (BISG), and strong hybrid (SHEVP2) electrification pathways are selected with the HCR1 (representing base segment) and TURBO1 (representing premium segment) powertrains. The powertrain and electrification pathway combinations result in three scenarios per segment for developing the incremental cost of electrification. The incremental cost of electrification is defined as the difference between the direct manufacturing costs (DMC) of ICE components and BEV components on an ICE platform. In other words, the incremental cost is defined as the excess cost of a BEV powertrain over an ICE powertrain. DMCs are the component and labor costs of producing and assembling the physical parts and systems, assuming a high volume production [35]. The incremental costs are determined by identifying the major components in an ICEV that would be removed and by identifying components that must be added to a vehicle for electrification to transform it into a BEV. In other words, the incremental cost is the difference between the DMCs of an ICE and BEV powertrains. The resulting three scenarios developed for the ICEVs and BEVs are used to determine the DMCs and TCO, thereby providing a direct comparison between them. The powertrain costs of each vehicle subclass and type under consideration are used to determine the vehicle purchase price.

ICEV powertrain costs are taken from NHTSA rulemaking, as represented in their use of the Volpe model to project compliance costs. This process is described in Section 2.1. Section 2.2 describes the BEV powertrain costing methodology. Section 2.3 details the electrification cost scenarios based on the incremental costs of electrification. Section 2.4 describes the methodology used to estimate the purchase price of an ICEV and a BEV. Section 2.5 explains the rationale behind the selection of the retail price equivalent (RPE) multiplier for ICE and BEV. Section 2.6 details the inputs and approach to calculating the TCO for the various vehicle types under consideration. The technology for the chosen powertrains is influenced by the anticipated emission regulations in 2027 and beyond; however, costs related to meeting the performance requirements such as fuel efficiency and aftertreatment are not considered. 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

We chose a non-performance (base) and performance (premium) engine technology (HCR1 and TURBO1) along with various levels of electrification (non-electrified, BISG, and SHEVP2) to capture the associated technology costs and meet the anticipated emission regulations. Other technologies were also considered, and it was ascertained that HCR1- and TURBO1-based technology pathways in the base and premium segments, respectively, would be widely prevalent in 2030.

The cost of both ICEVs and BEVs depends on the size and type of powertrains present. For BEVs, battery size is the key determinant of the cost, as it accounts for up to one-third of total vehicle costs [16]. The ICE powertrain option assumptions for various segments of the light-duty market in 2030 are summarized in Table 4. The selection of powertrain technologies is based on the current mix of vehicles on sale today, various future vehicles under development, and general technology trends. The following engine and transmission technologies are considered in each segment for developing the powertrain costs:

a) **Base segment**: An NA SI HCR1 with a CEGR engine and AT8L3 transmission for classes spanning from small cars to medium SUVs is considered. An HCR1 engine is defined as an enhanced Atkinson-enabled NA, DOHC, VVT, and SGDI engine. An NA SI V8 DOHC, VVT, SGDI, DEAC engine with an AT10L3 transmission for large SUVs and pickup trucks is considered for low- and medium-cost powertrain scenarios, i.e., Scenarios 3 and 2, respectively. An NA SI HCR1 engine with an AT10L3 transmission for large SUVs and pickup trucks is considered for the high-cost powertrain (or Scenario 1).
b) **Premium segment**: An SI TURBO1 engine with an AT8L3 transmission is considered for small cars to medium SUVs. An SI TURBO1 engine with an AT10L3 transmission is considered for large SUVs and pickup trucks. A TURBO1 engine is a “basic” level of turbocharged downsized technology applied to a DOHC-based engine, assuming the application of SGDI, VVT, and VVL to the engine [11].

To develop the three powertrain costs in both segments, the following hybridization technologies are considered for the respective engine technologies:

a) **Low-cost powertrain**: The vehicle does not include any level of hybridization.
b) **Medium-cost powertrain**: Mild hybrids with fixed battery capacity 48-volt (or 48V) systems with engine-belt-driven motor/generators (BISG). BISG is also referred to as a “mild hybrid system,” provides idle-stop capability, and uses a 48V battery, which allows the use of a smaller, more powerful, and 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 [36]. With stricter vehicle fuel economy and emission standards, the 48V mild-hybrid system provides 5%–10% [1] fuel economy improvement (based on the size of the vehicle, the power output of the system, and other factors) due to improved start-stop, electrification of various accessories, and hybrid power assist. The improved power output of the 48V system enables other fuel efficiency and

emission improvement technologies such as electrically assisted boosting systems, heated catalysts, and more.

c) **High-cost powertrain**: In both the base and premium segments, the high-cost powertrain is assumed to be a P2 parallel strong hybrid system. P2 technology implies the location of the motor, which is between the engine and transmission. 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 [11].

Diesel engines are not considered in the study due to their low market penetration and the high current and future costs of emission compliance. Table 4 summarizes the ICE powertrain options for ICEVs in the 2030 timeframe.

Table 4: ICE powertrain assumptions for different segments in 2030

Vehicle Description			ICE Powertrain						
Vehicle type	**Subclass**	**Base/ Premium**	**Gasoline Naturally aspirated**	**Mild hybrid BISG SI**	**Conventional SI turbo**	**Mild hybrid SI turbo**	**Parallel HEV SI**	**Parallel HEV SI turbo**	**Diesel**
Car	Compact (Small) car	Base	● (green)	● (orange)			● (red)		
		Premium			● (green)	● (orange)		● (red)	
	Midsize (Medium) car	Base	● (green)	● (orange)			● (red)		
		Premium			● (green)	● (orange)		● (red)	
SUV	Small SUV	Base	● (green)	● (orange)			● (red)		
		Premium			● (green)	● (orange)		● (red)	
	Midsize (Medium) SUV	Base	● (green)	● (orange)			● (red)		
		Premium			● (green)	● (orange)		● (red)	
	Large SUV	Base	● (green)	● (orange)			● (red)		● (grey)
		Premium			● (green)	● (orange)		● (red)	● (grey)
Pickup Truck	Pickup Truck	Base	● (green)	● (orange)			● (red)		● (grey)
		Premium			● (green)	● (orange)		● (red)	● (grey)
● (green)	Low-cost powertrain								
● (orange)	Medium-cost powertrain								
● (red)	High-cost powertrain								
● (grey)	Not considered as part of the 2030 mix due to low penetration and high cost of compliance								

The technology options and descriptors are taken from the draft CAFE model of August 2021 [1], and the fuel efficiency is sourced from the 2021 ANL study titled, "*A Detailed Vehicle Modeling & Simulation Study Quantifying Energy Consumption and Cost Reduction of Advanced Vehicle Technologies Through 2050*" [6].

The ANL study [6] simulated various powertrain configurations to evaluate the energy consumption and cost of advanced powertrain technologies using Autonomie, an in-house developed tool in collaboration with General Motors. The study conducted a detailed assessment of future technologies, considering the following choices:

a) There are five LDV subclasses: compact cars, midsize cars, small SUVs, midsize SUVs, and pickup trucks.
b) There are two performance categories: base (non-performance) and premium (performance).
c) Six timeframes: Production year (or model year) is with a 5-year delay from laboratory years 2015 (reference), 2020, 2025, 2030, and 2045.
d) There are five powertrain configurations: conventional, hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV): split HEV, split PHEV, extended-range PHEV, fuel cell electric vehicles (FCEV), and battery electric vehicle (BEV).
e) There are two technology progress uncertainty levels: a low case that is aligned with OEM improvements based on regulations and a high case that is aligned 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. To quantify the benefits without the added costs of lightweighting, an additional high-technology case without lightweighting is also simulated.

Based on an in-depth analysis of current offerings, the study does a ground-up modeling exercise and sizes the powertrains based on the vehicle technical specifications defined by minimum requirements and performance metrics such as maximum speed, 0–60 mph time, and gradeability with a 6% grade at 65 mph. In addition to these, 900 kg payload and up to 4,350 kg towing for pickups were also assumed by the ANL study. To provide a fair comparison, several automated sizing algorithms were used that considered vehicle-specific technical assumptions and attributes [6].

Both the referenced studies [1], [6] lack a separate costing or detailed assessment for large SUVs. However, in this study, we created a large SUV class based on discussions with EDF, to accurately capture all light-duty vehicles on the market. We assumed that the large SUVs (Lincoln Navigator and Chevrolet Tahoe) have the same powertrain components as pickup trucks and, therefore, the same powertrain costs as pickup trucks (Ford F-150 and Chevrolet Silverado).

Table 5 summarizes the assumed technology content of the different powertrain components for various vehicle segments in 2030.

Table 5: Technology pathways considered for ICEV classes and segments

<table>
<tr><th colspan="8">Base Segment</th></tr>
<tr><th>Cost scenarios</th><th>Component</th><th>Small car</th><th>Medium car</th><th>Small SUV</th><th>Midsize SUV</th><th>Large SUV</th><th>Pickup Truck</th></tr>
<tr><td rowspan="3">Low-cost powertrain</td><td>Engine</td><td colspan="4">HCR1 + CEGR</td><td colspan="2">V8 OHV + VVT + GDI + DEAC</td></tr>
<tr><td>Transmission</td><td colspan="4">AT8L3</td><td colspan="2">AT10L3</td></tr>
<tr><td>Hybrid system</td><td colspan="4">-</td><td colspan="2">-</td></tr>
<tr><td rowspan="3">Medium-cost powertrain</td><td>Engine</td><td colspan="4">HCR1 + CEGR</td><td colspan="2">V8 OHV + VVT + GDI + DEAC</td></tr>
<tr><td>Transmission</td><td colspan="4">AT8L3</td><td colspan="2">AT10L3</td></tr>
<tr><td>Hybrid system</td><td colspan="4">BISG</td><td colspan="2">BISG</td></tr>
<tr><td rowspan="3">High-cost Powertrain</td><td>Engine</td><td colspan="4">HCR1 + CEGR</td><td colspan="2">HCR1</td></tr>
<tr><td>Transmission</td><td colspan="4">AT8L3</td><td colspan="2">AT10L3</td></tr>
<tr><td>Hybrid system</td><td colspan="4">SHEVP2</td><td colspan="2">SHEVP2</td></tr>
<tr><th colspan="8">Premium Segment</th></tr>
<tr><td rowspan="3">Low-cost powertrain</td><td>Engine</td><td colspan="4">TURBO1</td><td colspan="2">TURBO1</td></tr>
<tr><td>Transmission</td><td colspan="4">AT8L3</td><td colspan="2">AT10L3</td></tr>
<tr><td>Hybrid system</td><td colspan="4">-</td><td colspan="2">-</td></tr>
<tr><td rowspan="3">Medium-cost powertrain</td><td>Engine</td><td colspan="4">TURBO1</td><td colspan="2">TURBO1</td></tr>
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<tr><td>Transmission</td><td colspan="4">AT8L3</td><td colspan="2">AT10L3</td></tr>
<tr><td>Hybrid system</td><td colspan="4">SHEVP2</td><td colspan="2">SHEVP2</td></tr>
</table>

Table 6 lists the component-level costs of the ICE powertrain from the CAFE model used in this analysis.

Table 6: ICE powertrain costs from the CAFE model [11] without RPE. Large SUVs are assumed to have the same powertrain costs as Pickups trucks.

Vehicle Subclass	Segment	Description	Component	2022	2030	2035
Engine Costs						
Small Car/Medium Car/Small SUV	Base	Engine	HCR1+CEGR (I4)	$3,959	$3,964	$3,964
Small Car/Medium Car/Small SUV	Premium	Engine	TURBO1 (I4)	$4,698	$4,660	$4,657
Midsize SUV	Base	Engine	HCR1+CEGR (V6)	$4,785	$4,791	$4,791
Midsize SUV	Premium	Engine	TURBO1 (I4)	$5,555	$5,497	$5,491
Large SUV/Pickup truck	Base	Engine	HCR1 (V8)	$5,296	$5,277	$5,276
Large SUV/Pickup truck	Base	Engine	OHV + VVT + GDI + DEAC (V8)	$4,984	$4,944	$4,938
Large SUV/Pickup truck	Premium	Engine	TURBO1 (V6)	$5,555	$5,497	$5,491
Mild Hybrid Costs						
Small Car/Medium Car/Small SUV/Midsize SUV	Base & Premium	Battery for mild hybrid	Batteries for BISG	$342	$216	$171
Small Car/Medium Car/Small SUV/Midsize SUV/ Large SUV/Pickup truck	Base & Premium	Mild hybrid	BISG excluding battery	$389	$304	$295
Strong Hybrid Costs						
Small Car	Base	Battery for strong hybrid	Batteries for SHEVP2	$1,167	$736	$585
Small Car	Base	Strong hybrid	SHEVP2 excluding batteries	$2,518	$2,345	$2,313
Small Car	Premium	Battery for strong hybrid	Batteries for SHEVP2	$1,167	$736	$585
Small Car	Premium	Strong hybrid	SHEVP2 excluding batteries	$2,542	$2,365	$2,333
Medium Car	Base	Battery for strong hybrid	Batteries for SHEVP2	$1,201	$758	$602
Medium Car	Base	Strong hybrid	SHEVP2 excluding batteries	$2,589	$2,404	$2,371
Medium Car	Premium	Battery for strong hybrid	Batteries for SHEVP2	$1,205	$760	$604
Medium Car	Premium	Strong hybrid	SHEVP2 excluding batteries	$2,607	$2,419	$2,386
Small SUV	Base	Battery for strong hybrid	Batteries for SHEVP2	$1,363	$860	$683
Small SUV	Base	Strong hybrid	SHEVP2 excluding batteries	$2,578	$2,395	$2,362
Small SUV	Premium	Battery for strong hybrid	Batteries for SHEVP2	$1,405	$886	$704
Small SUV	Premium	Strong hybrid	SHEVP2 excluding batteries	$2,612	$2,423	$2,390
Midsize SUV	Base	Battery for strong hybrid	Batteries for SHEVP2	$1,386	$874	$695

Vehicle Subclass	Segment	Description	Component	2022	2030	2035
Midsize SUV	Base	Strong hybrid	SHEVP2 excluding batteries	$2,606	$2,418	$2,385
Midsize SUV	Premium	Battery for strong hybrid	Batteries for SHEVP2	$1,431	$903	$717
Midsize SUV	Premium	Strong hybrid	SHEVP2 excluding batteries	$2,670	$2,471	$2,436
Large SUV/Pickup truck	Base	Battery for strong hybrid	Batteries for SHEVP2	$1,401	$884	$702
Large SUV/Pickup truck	Base & Premium	Strong hybrid	SHEVP2 excluding batteries	$2,728	$2,519	$2,484
Large SUV/Pickup truck	Premium	Battery for strong hybrid	Batteries for SHEVP2	$1,473	$930	$739
Transmission						
Small Car/Medium Car/Small SUV/Midsize SUV	Base & Premium	Transmission	AT8L3	$1,745	$1,713	$1,711
Large SUV/Pickup truck	Base & Premium	Transmission	AT10L3	$1,811	$1,772	$1,770
Aftertreatment						
Small Car/Medium Car/Small SUV	Base	-	-	$284	$284	$284
Small Car/Medium Car/Small SUV	Premium	-	-	$381	$381	$381
Midsize SUV	Base	-	-	$381	$381	$381
Midsize SUV	Premium	-	-	$610	$610	$610
Large SUV/Pickup truck	Base & Premium	-	-	$610	$610	$610

Table 7 gives the after-treatment system costs without the RPE factor assumed in this report for a stoichiometric gasoline engine. The costs are based on the breakdown costs of three-way catalyst (TWC) estimated in the 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 potential global supply chain disruptions and price volatility of platinum group metals on after-treatment system costs between 2022 and 2035 is also not considered. The aftertreatment system was assigned to each vehicle segment.

Table 7: Gasoline three-way catalyst (TWC) after-treatment system cost (expressed in €$_{2021}$). (In 2022, €1 = $1.02). *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 (assumed)	**Volume (liter)**	**Total Cost**
4-cylinder	2.3	$284
6-cylinder	3.5	$381
8-cylinder	6.3	$610

2.2 BEV powertrain

Based on the availability of 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 and their ranges [6]. Charger efficiency was also considered in the study to compute the efficiency and costs of future electric traction drive systems. Table 8 lists the powertrain sizing for the considered LDVs for the laboratory and production years analyzed by ANL (the ANL study [6] assumed a 5-year delay between laboratory years and production model years). The highlighted cells in green were used for our primary MY 2030 LDVs analysis, though we show BEV powertrain costs in Appendix 8.1 for all three model years listed in Table 8.

ANL does not have a separate category or segment for large SUVs. We assumed that the large SUV would have a 10% bigger battery and motor than the pickup truck. Since the ANL study [6] did not specify the size of power electronics, we assumed that the inverter would be the same size as the motor, a 2 kW DC/DC converter, and an onboard charger of 11.5 kW across all classes and segments.

Table 8: BEV powertrain component sizing from the 2021 ANL study [6], except wherever indicated otherwise. Highlighted values have been considered for MY 2030. The production year is 5 years from the laboratory year.

BEV Ranges/Laboratory Years	Base						Premium					
	Battery (kWh)			Motor (kW)			Battery (kWh)			Motor (kW)		
	2020	2025	2030	2020	2025	2030	2020	2025	2030	2020	2025	2030
Production Year (Model Year)	2025	2030	2035	2025	2030	2035	2025	2030	2035	2025	2030	2035
Compact Car												
BEV200	40	40	37	86	82	82	43	42	39	113	108	107
BEV300	61	61	61	90	86	86	65	63	64	119	113	113
Midsize Car												
BEV200	42	41	38	104	99	98	44	43	40	139	133	132
BEV300	64	61	63	109	103	103	67	65	66	147	138	139
Small SUV												
BEV200	51	50	46	123	117	112	52	51	47	163	155	149
BEV300	78	77	75	130	122	118	80	77	77	174	162	157
Midsize SUV												
BEV200	55	54	49	116	111	106	58	57	52	158	151	144
BEV300	83	83	81	122	116	112	88	87	85	167	158	152
Large SUV (*assumed 10% more than pickup truck*)												
BEV300	113	108	108	210	196	190	117	113	113	229	215	209
BEV400	165	157	146	228	207	200	174	167	154	250	227	219
Pickup Truck												
BEV300	103	98	98	191	178	173	106	103	103	208	195	190
BEV400	150	143	133	207	188	182	158	152	140	227	206	199
Common to all considered subclasses and ranges (*assumed values*)												
Component	**2020**		**2025**		**2030**		**2020**		**2025**		**2030**	
Inverter (kW)	*Same size as the motor*											
DC-DC converter (kW)	2 *(assumption based on production BEVs and projected demands of the 12V system)*											
Onboard charger (kW)	11.5 *(assumption based on production BEVs)*											

In this study, a small sample of the currently used BEVs on the market is considered for each of the vehicle subclasses to determine their ranges. Some examples of passenger cars include the Chevrolet Bolt, Nissan Leaf, Tesla Model 3, and BMW i4. Nissan Aria, VW ID 4, Kia EV6, Tesla Model Y, Ford Mach E, Audi E-Tron, Tesla Model X, Rivian R1S, and BMW iX are considered for the class of SUVs. GMC Hummer, Ford F-150 Lightning, and Rivian R1T are considered in the pickup truck category. The selection of BEV ranges is also based on typical consumer requirements and the sales projections made in the CAFE model run for final rulemaking [36]. Based on the relevant market offerings and numerous studies, the small cars, medium cars, small SUVs, and medium SUVs in the base segment are assumed to have a range of 200 miles and a range of 300 miles in the premium segment. It is believed that improvements in battery technology (ability to fast charge 10%–80% in 10–15 minutes or less) and improvements in the DC fast charging infrastructure (350 kW+ charge rate with onsite grid-tied storage) will make 200- and 300-mile BEVs attractive for an appreciable portion of the LDV market in 2030. Large SUVs and pickup trucks in the base segment are assumed to have a range of 300 miles, while vehicles in the premium segment (and those used for towing) have a range of 400 miles. Users of large SUVs and pickup trucks would require longer-range vehicles to occasionally commute long distances or haul additional payload. The battery sizing is done based on the available Autonomie modeling data from the ANL study [6], except for large SUVs. Table 9 details the power (kW), battery size (kWh), and range (miles) of the different BEVs used for incremental cost and TCO comparison with ICE vehicles.

Table 9: MY 2030 BEV specifications considered in this study based on the ANL study [6]**.**

Vehicle type	Subclass	Segment	Max power (kW)	Battery size (kWh)	Range (Miles)
Car	Compact (Small) car	Base	82	40	200
		Premium	113	63	300
	Midsize (Medium) car	Base	99	41	200
		Premium	138	65	300
SUV	Small SUV	Base	117	50	200
		Premium	162	77	300
	Midsize SUV	Base	111	54	200
		Premium	158	87	300
	Large SUV *(assumed 10% more than pickup truck)*	Base	196	108	300
		Premium/Towing	227	168	400
Pickup	Pickup Truck	Base	178	98	300
		Premium/Towing	206	152	400

The design philosophy of traditional OEMs and BEV makers is to create and produce a dedicated platform with a modular electric architecture, enabling optimization and commonization of parts. This enables various classes of BEVs to combine multiple smaller light-duty motors with the appropriate gear ratio to produce the required power and torque at the wheels. The costs for power electronics drop significantly, 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.

Table 10 summarizes the component costs used for calculating the BEV powertrain costs for 2022, 2030, and 2035. Sections 2.2.1, 2.2.2, and 2.2.3.3 describe in detail the assumptions and methodology behind the BEV powertrain costs.

Table 10: BEV powertrain costs

Cost Scenario	Component	Unit	2022	2030	2035
Low cost	Battery (LFP)	$/kWh	108.3	61.7	55.5
	Motor	$/kW	4	3.3	3.3
	Inverter	$/kW	3.5	2.4	2.4
	DC-DC converter	$/kW	50	2.4	2.4
	Onboard charger	$/kW	50	2.4	2.4
Medium cost	Battery (NMC811)	$/kWh	111.7	64.2	57.7
	Motor	$/kW	4	3.3	3.3
	Inverter	$/kW	3.5	2.4	2.4
	DC-DC converter	$/kW	50	2.4	2.4
	Onboard charger	$/kW	50	2.4	2.4
High cost	Battery (10 % costlier NMC811)	$/kWh	122.8	70.6	63.5
	Motor	$/kW	4	3.3	3.3
	Inverter	$/kW	3.5	2.4	2.4
	DC-DC converter	$/kW	50	2.4	2.4
	Onboard charger	$/kW	50	2.4	2.4

2.2.1 Motor Cost

Figure 14 summarizes the results of the motor teardown studies done by Munro & Associates, Inc. on mass-produced light-duty BEV motors [39]. 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 $2.5 per kW. Several vehicles (such as Tesla, VW, etc.) that offer AWD BEVs use a combination of PMSM in the rear and IM in the front. The IM is common in situations with high wheel torque demand or limited traction. The front axle IM is freewheeling under normal driving conditions. This enables the rear PMSM to operate at higher average loads and efficiencies. Unlike the PMSM, the IM has no parasitic losses when freewheeling due to the absence of cogging torque. This combination of PMSM on the rear axle and IM on the front axle reduces the average cost ($/kW) of the total traction motor output and increases the efficiency (miles per kWh) of the BEV. Hence, a conservative value of $4/kW for motor costs in 2022 is considered.

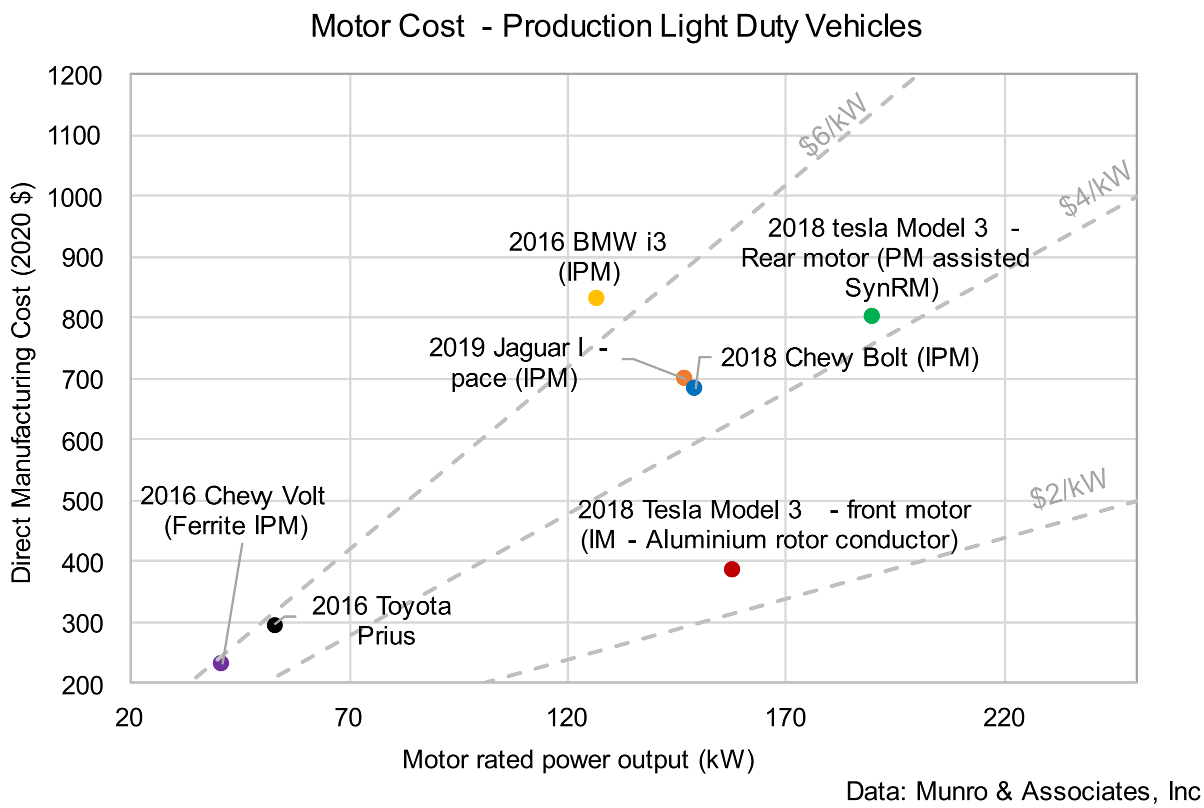

Figure 14: Production light-duty BEV motor cost [9]

As of 2022, there are several production vehicles 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 and reduce costs. Compressed and die-cast aluminum stator windings can replace the more expensive copper stator windings while matching the performance and efficiency of copper windings. All the above technologies are discussed in detail in Section 3, which provides pathways to bring down motor costs even with increasing commodity prices of materials like neodymium and copper. Based on these future technologies and increased economies of scale, a reduced motor cost of $3.3/kW in 2030 is assumed. The motor costs are assumed to be constant from 2030 to 2035. The relevant power level, combined with the $/kW cost, is the maximum power output of the motor.

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% [40].

Figure 15 shows the cost of various light-duty inverters based on teardown studies by Munro & Associates, Inc. [41]. 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.

For this study, an inverter cost of $3.5/kW for 2022 is used, as shown in Figure 15, which is significantly higher than Tesla’s inverter costs in 2020, dropping to $2.4/kW in 2030 (comparable to Tesla’s cost in 2020), and remaining constant from 2030 to 2035.

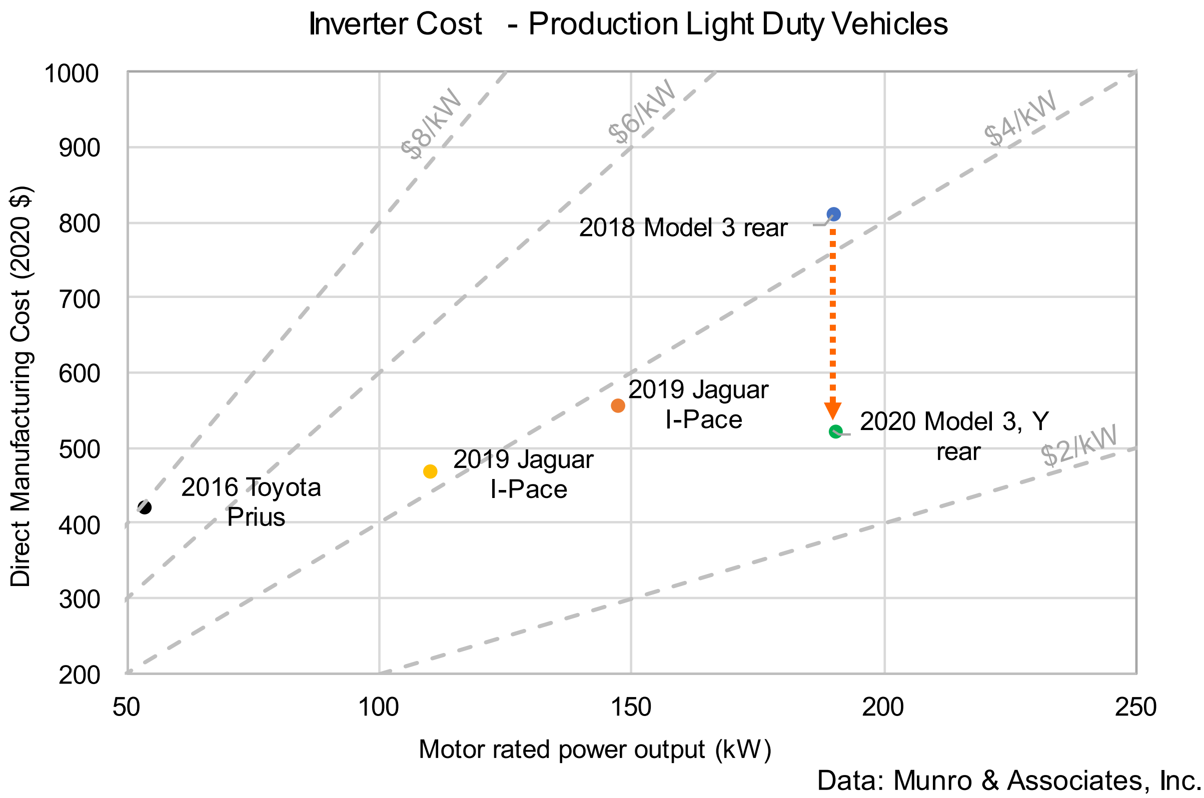

Figure 15: Production BEV inverter cost based on teardown studies. The cost includes Housing, PCBA, IGBT module and cooling structure, DC-link Capacitor, Motor phase lead, connectors, self-contained structural and connected components

The DC-DC converter steps down the high voltage of the BEV traction motor to supply all 12V loads and maintain the 12V battery charge. This report assumes a 2 kW DC-DC converter size for all vehicle types. 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 10–12 kW onboard charger, while a few, like the Lucid Air, are equipped with a 19.2 kW onboard charger. An onboard charger size of 11.5 kW is assumed for all vehicle subclasses and segments in this study.

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. In 2030, it is assumed that inverters, DC-DC converters, and onboard chargers will each have the same $ per kW cost of $2.4/kW.

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 unique performance characteristics and tradeoffs, resulting in a disparate class of chemistries being produced globally by top industry players for numerous EV producers. 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.

The average battery capacity for BEVs in 2021 was 55 kWh, with a volume-weighted average battery pack price of $118/kWh [42], [43]. The demand is projected to climb from 340 GWh in 2021 to nearly 4 TWh by 2030 [42]. 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 [44]. However, since 2021, Tesla has pivoted to LFP in their standard-range vehicles since it reduces their 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 cheap, entry-level, high-volume EVs. It is expected that with 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 [42].

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 key factor that determines the economic viability of manufacturing and the 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 cost depending on its chemistry and configuration [14]–[16]. For BEVs to be cost-competitive with the ICEVs, BloombergNEF has estimated that the battery pack prices need to drop below $100/kWh, while the Vehicle Technologies Office of the U.S. Department of Energy has set the federal target of reducing the cost of EV batteries to $80/kWh by 2025 [15], [43], [45].

Various scientific literature articles and market reports published since 2017 on battery costs were reviewed and evaluated. 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"* and "*BatPaC V5.0"* for calculating battery cost projections in 2030 were selected as described in more detail below [46], [47]. 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, will be conjecture.

Broadly, the battery costs can be estimated using the following methods [46]:

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 the pack prices will drop below $100/kWh in 2024 and will reach $58/kWh in 2030 [15].
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 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, a hybrid approach to arriving at battery costs in 2030 is adopted that uses a combination of literature articles and BatPaC.

2.2.3.3 Roush Approach

The selected publications from the review article 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 profits and warranties (referred to as "Cost to Consumer") or do not (referred to as "Cost to Build"). For forecasting the pack cost in 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 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 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 [47], 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 only influenced 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 ' ower' 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 [17], [47]. 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 12 details the battery cost inputs used in the analysis.

For the 2030 timeframe, the plant size is assumed to be 120 GWh considering the scaling of production volumes of these cells to meet the projected market demand of nearly 4 TWh. In addition to volume scaling, a cost factor of 0.66 is applied to the BatPaC-derived costs. 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 11, from the 2021 review article, "*Battery cost forecasting: a review of methods and results with an outlook to 2050"* [46]. The review article analyzes 53 relevant peer-reviewed publications with original battery cost or price forecasts from 2361 publications. The publication presents the findings in a comprehensive, systematic, and transparent manner and provides supplementary information citing relevant article sources and methodologies. Roush used the detailed time-based forecasted values from the supplementary information provided by the 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 inaccurate forecasts. The primary reason behind this is the exponential fall in battery prices since 2010 [43].
b) Identification of articles with estimated/forecasted values in the years 2020 and 2030. This resulted in the selection of 7 articles of the 24 articles with time-based forecasted values tabulated by the authors [46].
c) Compute the ratio of the forecasted item using the formula, (2030 value ÷ 2020 value)
d) Calculate the average cost factor from the computed ratios.

Table 11: Publications selected for determining cost factor

Authors & year	Publication Title
Few et al. (2018)	Prospective improvements in cost and cycle life of off-grid lithium-ion battery packs: an analysis informed by expert elicitations
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

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 12: Battery costs considered for this study

Year	Plant Size GWh	Cost to Build $/kWh		Supplier Margin	Cell cost to OEM $/kWh		Cell-to-Pack multip-lier	OEM cost to build pack $/kWh	
		NMC811	LFP		NMC811	LFP		NMC811	LFP
2022	20	$78	$75	15%	$89	$87	1.25	$112	$108
2030	120	$50	$48	10%	$55	$52	1.18	$64	$62
2035	*10% recycling and learning rate applied on 2030 costs*							$58	$55

For the 2030 projections with a plant size of 120 GWh, the average cost factor of 0.66 is then applied to the current battery costs of $75/kWh and $72/kWh for NMC811-G (Energy) and LFP-G (Energy) cells respectively derived from BatPaC 5.0. The resulting cost to build a cell of NMC811-G (Energy) and LFP-G (Energy) in 2030 is $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 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 [15], [43], and going forward to 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 [15], [43]. Historical data suggests that the cell-to-pack split would further improve as the learning efficiency and resource utilization improves (despite lower cell costs). Furthermore, as the cell-to-pack (CTP) and cell-to-chassis (CTC) or cell-to-vehicle technology improves, the cell-to-pack split may further reduce. 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 2030 is $64/kWh and $62/kWh, respectively.

For the battery cost estimation in the 2035 timeframe, a factor of 10% savings is applied to the 2030 pack costs. Recycling is expected to play a crucial role in bringing the costs further down by 2035 and will have a far-reaching and significant contribution towards achieving a circular sustainable economy. The battery pack costs projected in 2035 for NMC811-G (Energy) and LFP-G (Energy) cells are $58/kWh and $55/kWh, respectively.

The projected pack costs are believed to be conservative and may be reduced 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 ICE and BEVs, there are three different incremental cost scenarios for electrification. This approach captures the entire spectrum of various combinations of technology pathways within the base and premium segments. It does not project the use of these specific technologies in 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 of the powertrains of an ICE and a BEV, respectively. Figure 16 depicts the three scenarios developed to compare the ICEV and BEV powertrain costs, vehicle purchase price, and TCO for LDVs. A sample plot representing the incremental cost of electrifying a small car is also shown in the figure. The detailed results of all the other segments are shown in Section 4 (Results).

a) **Incremental Cost of Electrification Scenario 1**: Migrating from a high-cost ICE powertrain (SHEVP2) 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 (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 2.
c) **Incremental Cost of Electrification Scenario 3**: Migrating from a low-cost ICE powertrain (non-hybrid, conventional HCR1 + CEGR or TURBO1) to a high-cost BEV

powertrain (high-cost NMC811 batteries that are 10% more costly than under the Scenario 2). This represents a migration from the lowest-cost ICE powertrain to the most expensive BEV powertrain, i.e., the least favorable scenario 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 shortest amount of time after purchase.

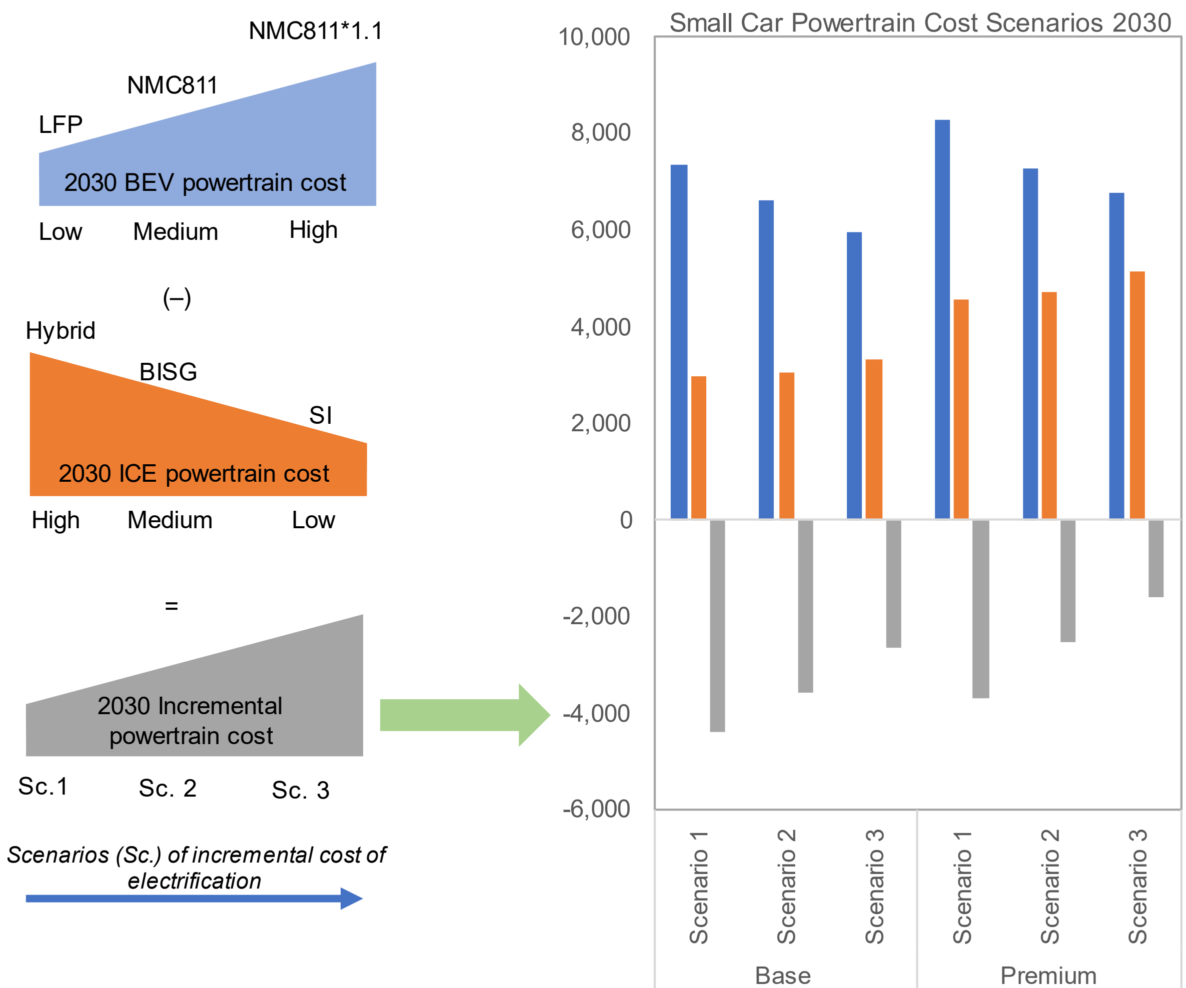

Figure 16: Scenarios 1, 2, and 3 incremental costs of electrification with a sample plot of a small car.

2.4 Purchase Price Estimation

Figure 17 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 [48]. With the advent of dedicated BEV platforms, the potential for light weighting would benefit the glider price when compared to an equivalent 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 [11]. An RPE of 1.2 is assumed for the battery-electric powertrain components, as discussed in more detail below.

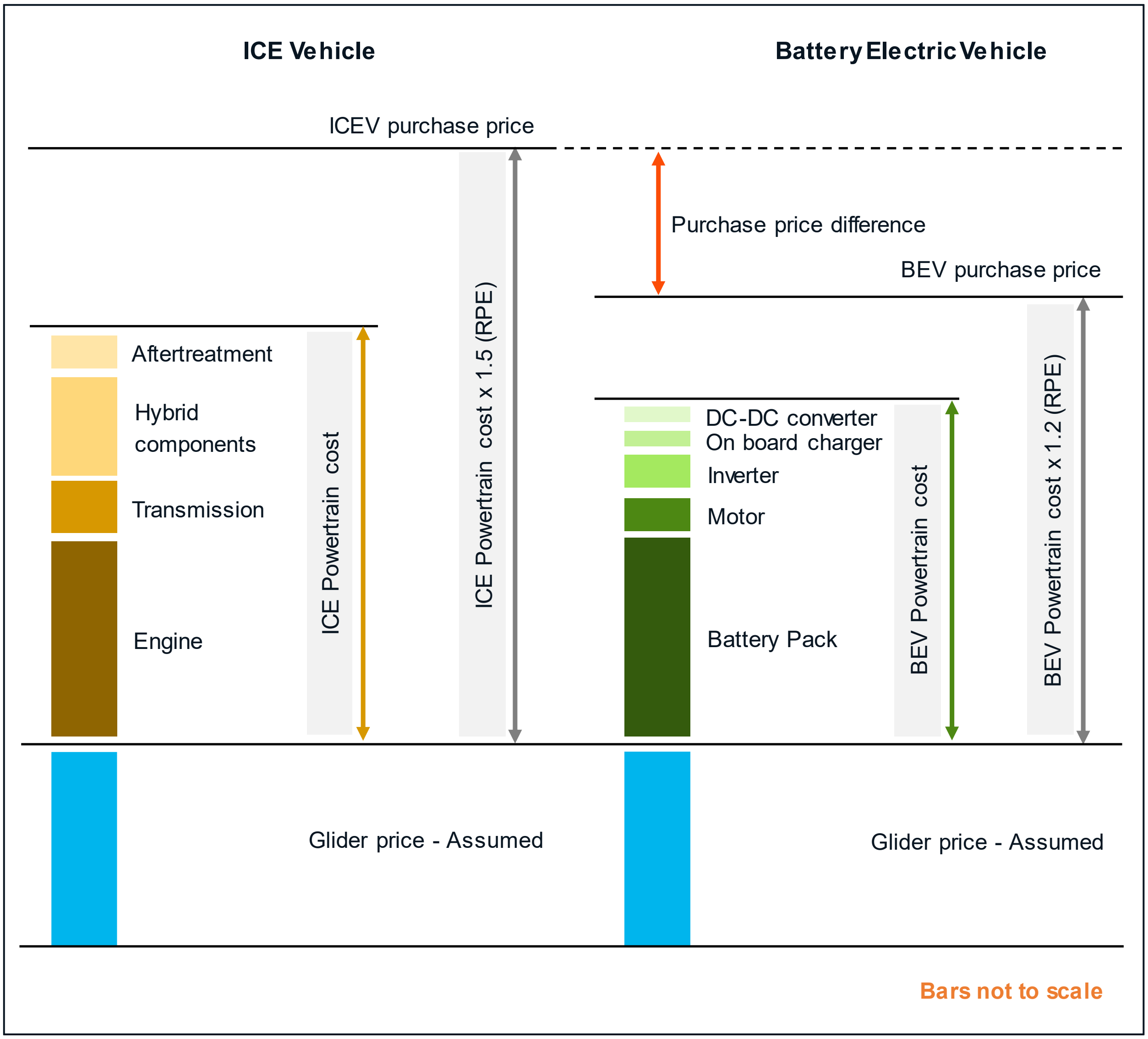

Figure 17: Methodology for calculating the purchase prices of ICEVs and BEVs

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. The agencies account for these indirect costs using a scalar markup of DMCs known as the retail price equivalent, or RPE [49]. RPE is the ratio of vehicle retail price to manufacturing cost [7], a scalar markup factor used by OEMs for them to earn a competitive rate of return on their production investment [50]. 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 13 [49]. 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 13: Retail Price Components as considered by DOT [49]

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 [49]. Figure 18 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 to estimate the cost 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 [49]. An RPE of 1.5 for ICEVs is used in this study.

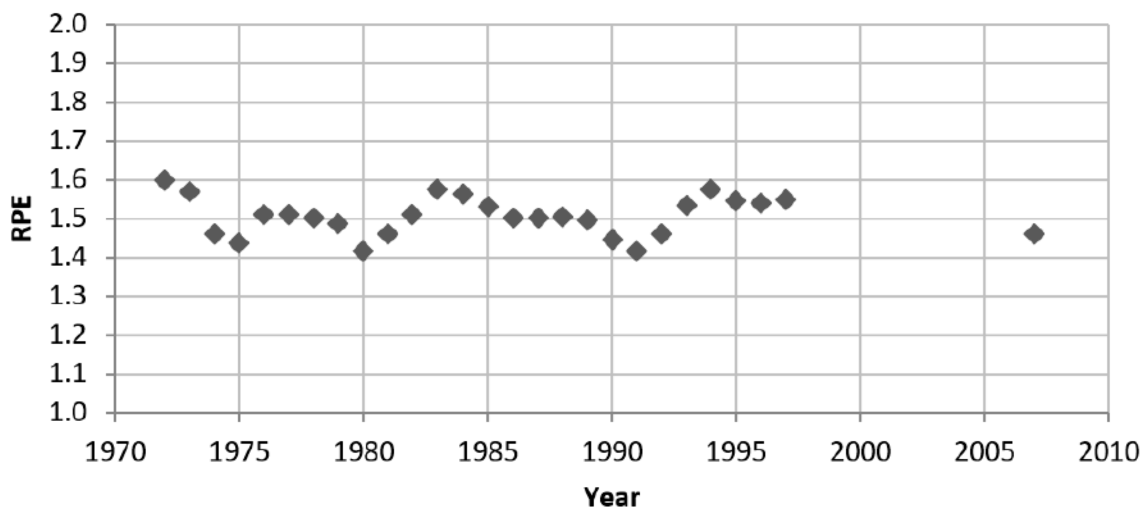

Figure 18: Historical data for Retail Price Equivalent (RPE). Source: NHTSA [49]**.**

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. Subsequently, 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 therefrom 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 [7], [50]. 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 [50]. 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 [7].

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 14 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, energy generation and storage segment, and other services [51]. 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. It should be noted that the R&D expenses are not just limited to the automotive arm.

Table 14: Research and development expense as a percentage of revenues from Tesla's 10-K filing of 2021 [51]

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

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

a) The literature sources, as listed in Table 11, used to determine inputs to battery costing had both price and cost data points. Of the seven selected articles, four projected price points while the balance three projected cost points. In general, prices do not equal costs, and factors like strategic pricing, long-term contracts, and subsidies influence battery pricing significantly [46]. 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 ICE 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 mark up cell costs when selling to automakers. This indicates that the battery cost is partially factoring into the retail element of pricing. It would be unfair to penalize BEV makers by considering a higher RPE.
c) With tightening fuel economy and emission standards, the cost of regulating an ICEV 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 the burden of meeting the emission norms. We believe that the RPE of BEVs will be lower than that of ICEVs in the 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 2030 timeframe. This is, however, outside of 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 [52]. 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 of incremental BEV cost. A set of scenarios is presented for both the base and premium segments. Only tangible financial aspects of ownership related to the vehicle are considered for the TCO analysis as shown in Table 15. They include:

a) **Vehicle Glider Price (VGP):** It 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 ICEV and BEV in a class. 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) Gasoline price for ICE
d) Electricity price for BEV
e) Maintenance and repair (M&R) costs
f) Only BEV charging costs

Costs associated with staffing and labor, scrap or resale, insurance, taxes, grants, subsidies, or intangible benefits such as healthcare costs or environmental costs related to emission reductions or fuel 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 2030 purchase year are the common inputs to both ICE and BEV categories, as mentioned in Table 15. An annual VMT of 15,922 miles for cars, 16,234 miles for SUVs, and 18,964 miles for pickup trucks have been considered for analysis [7]. 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 [7]. Based on the ANL study about TCO, a lifespan of 15 years is considered for all vehicle subclasses, and an annual discount rate of 3% is considered for both categories [7].

Table 15: 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 base price	VGP + (1.5 × ICE p/t)	VGP + (1.2 × BEV p/t)
Maintenance and Repair (M&R) ($/mile)	Depending on class	7.7¢ (Same for all BEVs)
Fuel efficiency (Mpg or kWh/mile)	Depending on class	Depending on class
Annual VMT (miles/annum)	Same for both depending on vehicle subclass	
Charger cost including installation for BEVs	-	$1,000
Lifespan	15 years	
Annual discount rate	3%	
Purchase year	2030	

2.6.1 ICEV

Annual VMT is from the 2021 ANL study, and an RPE of 1.5 is considered for TCO analysis [7]. Fuel economy is sourced from the real-world mpg based on adjusted fuel consumption from the ANL study [6], except for the large SUV, as the study does not have a separate category for it. Based on the current offerings and market analysis, large SUVs have lower fuel economy than pickup trucks. We have assumed that pickup trucks are 10% more efficient than the large SUV, and, hence, a multiplier of 0.9 is used to compute the fuel economies of large SUVs across both segments. Table 16 lists the fuel economy results from the ANL study [6] under the *high without lightweighting case*, except for large SUVs as discussed above. *High without lightweighting* presents an optimistic scenario where advanced technologies are adopted to increase fuel economy, or, in other words, a best-case scenario. The actual fuel economy is expected to be lower; however, the estimates are aligned with the conservative approach of this study concerning the incremental costs of electrification.

Table 16: Fuel economy from the 2021 ANL study [6], except for large SUVs. Highlighted values have been considered in the study for MY 2030. The production year is five years from the laboratory year.

Adjusted Fuel Economy, Combined 43/57 - real world (mpg)						
	Base			Premium		
Subclass/Laboratory Years	**2020**	**2025**	**2030**	**2020**	**2025**	**2030**
Production Year (Model Year)	**2025**	**2030**	**2035**	**2025**	**2030**	**2035**
Compact car						
Conventional SI	39	34	39	34	31	36
Mild Hybrid BISG SI	40	36	41	36	32	37
Conventional SI Turbo	44	46	51	40	42	46
Mild Hybrid BISG SI Turbo	47	48	54	42	44	49
Par HEV SI	47	41	43	42	37	40
Par HEV SI Turbo	51	53	57	48	49	53
Midsize car						
Conventional SI	35	32	36	30	28	33
Mild Hybrid BISG SI	37	33	38	31	29	34
Conventional SI Turbo	41	42	47	36	36	41
Mild Hybrid BISG SI Turbo	43	45	50	37	38	44
Par HEV SI	44	38	41	38	34	37
Par HEV SI Turbo	49	50	54	45	46	49
Small SUV						
Conventional SI	32	29	33	28	26	30
Mild Hybrid BISG SI	34	30	35	29	27	32
Conventional SI Turbo	37	38	43	33	34	39
Mild Hybrid BISG SI Turbo	39	40	45	34	36	41
Par HEV SI	39	34	37	35	31	34
Par HEV SI Turbo	43	45	49	41	43	46
Midsize SUV						
Conventional SI	32	28	32	28	25	29
Mild Hybrid BISG SI	33	29	33	29	26	30
Conventional SI Turbo	36	37	41	32	33	37
Mild Hybrid BISG SI Turbo	37	38	44	34	35	39
Par HEV SI	38	32	35	34	30	33
Par HEV SI Turbo	41	42	46	39	40	44
Large SUV *(assumed)*						
Conventional SI	23	20	23	21	19	22
Mild Hybrid BISG SI	24	21	24	22	20	23
Conventional SI Turbo	26	27	30	25	26	28
Mild Hybrid BISG SI Turbo	27	28	31	26	27	30

Adjusted Fuel Economy, Combined 43/57 - real world (mpg)						
	Base			**Premium**		
Subclass/Laboratory Years	**2020**	**2025**	**2030**	**2020**	**2025**	**2030**
Production Year (Model Year)	**2025**	**2030**	**2035**	**2025**	**2030**	**2035**
Par HEV SI	28	24	26	26	23	25
Par HEV SI Turbo	31	32	35	30	31	34
Pickup Truck						
Conventional SI	25	23	26	24	22	24
Mild Hybrid BISG SI	26	24	27	25	22	26
Conventional SI Turbo	29	30	33	27	29	32
Mild Hybrid BISG SI Turbo	30	31	35	29	30	33
Par HEV SI	31	27	29	29	26	28
Par HEV SI Turbo	34	36	39	33	34	37

In the plotted representation of the fuel economy listed in Table 16 for the base and premium segments in Figure 19 and Figure 20, respectively, the NA engines have an inconsistent trend while the turbocharged engines have a consistently increasing trend in fuel economy across laboratory years 2020 to 2030. We recognize that this could be based on certain model assumptions made regarding the technical requirements of base and premium vehicles; however, we are not completely sure of the reasons behind the results and would avoid speculating on them. The laboratory year 2025 (equivalent to MY 2030) fuel economy numbers have been used in this study for the computation of TCO for ICEVs.

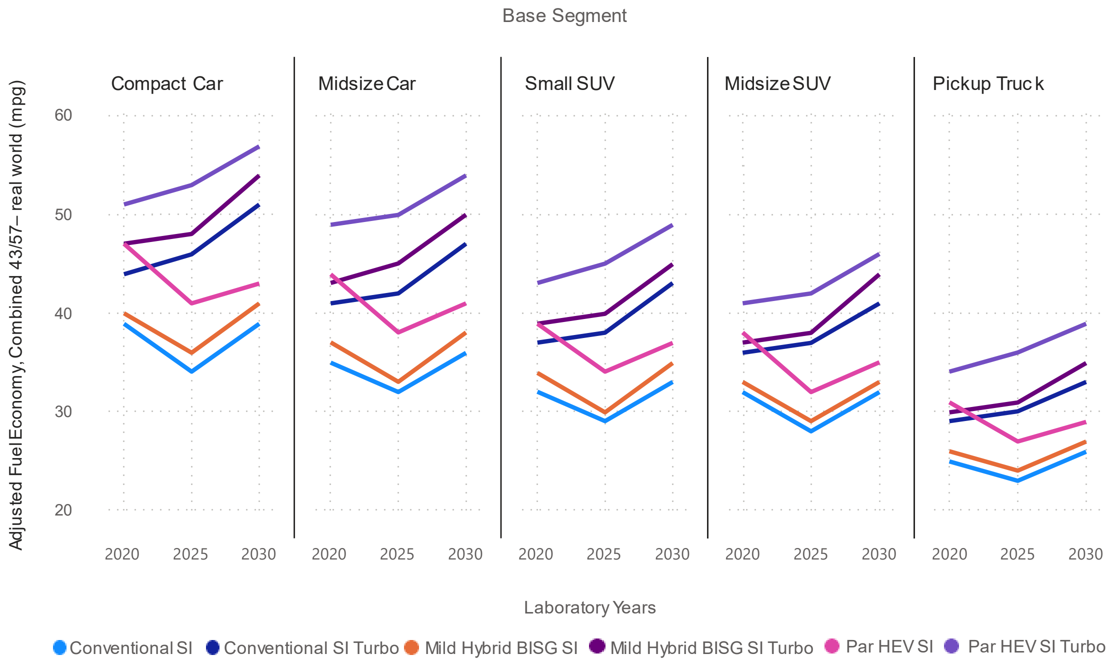

Figure 19: Fuel economies of LDVs in the base segment from the ANL study [6]**.**

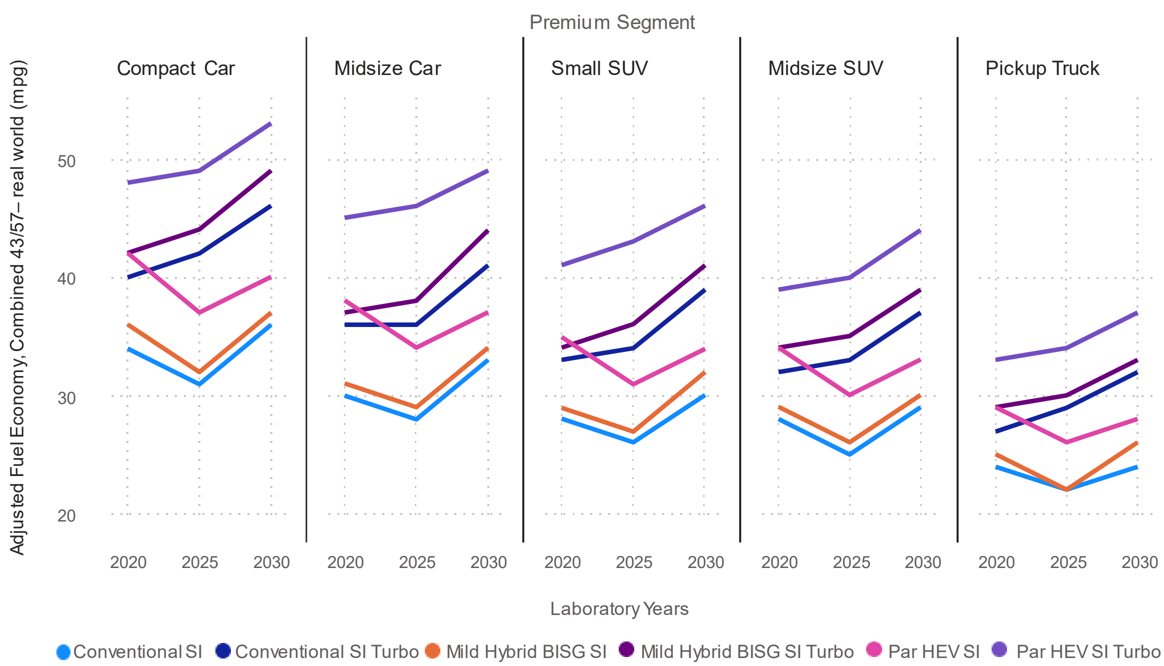

Figure 20: Fuel economies of LDVs in the premium segment from the ANL study [6]**.**

The vehicle's initial purchase price, estimated from the glider price and powertrain cost, represents the upfront price. For the computation of operating costs, fuel economy, VMT, M&R, and fuel prices are used as inputs. The resultant costs are discounted by 3%

annually to arrive at the cumulative annual 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 17 summarizes the TCO inputs such as glider price, fuel economy, and maintenance cost used in the analysis for ICEV.

Table 17: Total Cost of Ownership (TCO) inputs for ICEV

Vehicle type	Subclass ANL	Segment	Vehicle Glider Price	ICE efficiency (mpg)			Maintenance cost per mile [53]
				Scenario 1	Scenario 2	Scenario 3	
Car	Compact car	Base	$15,000	41	36	34	$0.088
		Premium	$22,500	49	44	42	
	Midsize car	Base	$18,000	38	33	32	$0.104
		Premium	$27,000	46	38	36	
SUV	Small SUV	Base	$20,000	34	30	29	$0.099
		Premium	$30,000	43	36	34	
	Midsize SUV	Base	$22,000	32	29	28	
		Premium	$33,000	40	35	33	
	Large SUV	Base	$24,000	24	21	20	$0.100
		Premium	$36,000	31	27	26	
Pickup Truck	Pickup Truck	Base	$26,000	27	24	23	$0.099
		Premium	$39,000	34	30	29	

Figure 21 shows retail gasoline prices from the EIA AEO 2022 [12]. The application of gasoline 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 $4.23/gallon-$4.41/gallon, Scenario 2 in the range of $2.80/gallon-$3.15/gallon, and Scenario 3 in the range of $2.07/gallon-$2.27/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) [12]. 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 component amounting to 49.4¢ is removed from the retail price of gasoline. The M&R cost of ICEVs ranges from 9.2¢ to 9.9¢ per mile [53]. To provide a perspective of TCO and TCO parity timelines with real-world gasoline prices, a fuel price sensitivity analysis is conducted and can be found in Section 5.4.1.

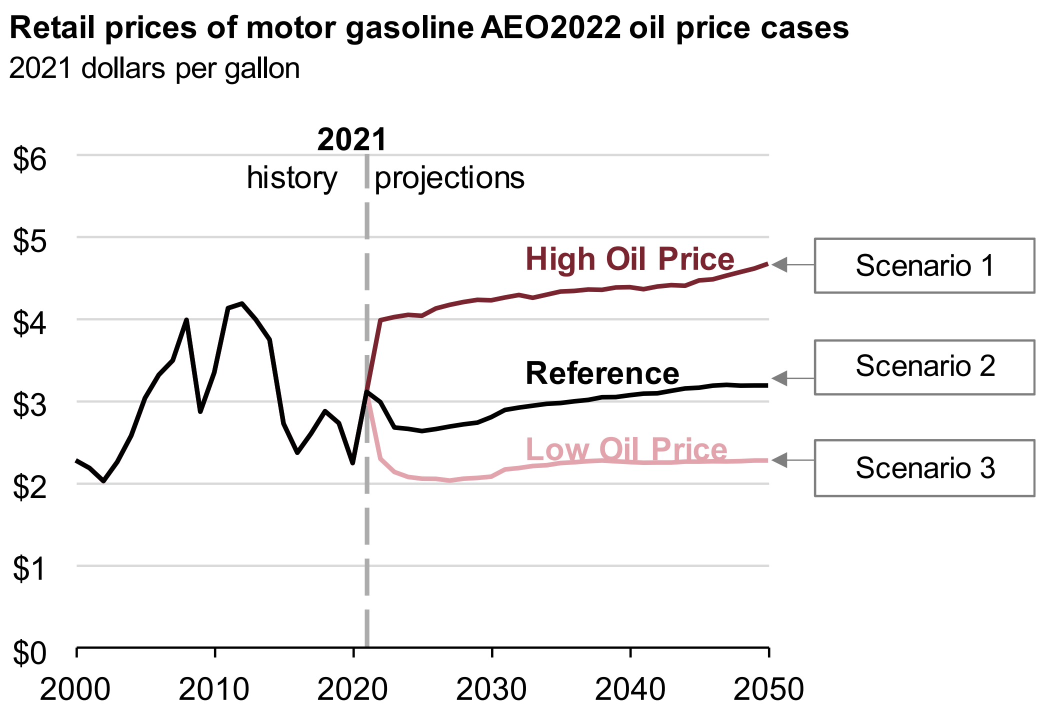

Figure 21: AEO2022 projected retail prices of motor gasoline in 2021 dollars per gallon [12]

2.6.2 BEV

The energy consumption of BEVs has been sourced from the 2021 ANL study [6], as highlighted in Table 18. Real-world adjusted energy consumption values with a combined driving cycle of 43/57 with a charger from the laboratory year 2025 have been considered for this analysis. To compare with their ICE counterparts, the values of large SUVs have been scaled by 10% to the pickup truck, with the assumption that large SUVs consume more energy than pickups.

Table 18: Energy consumption from the 2021 ANL study [29]. Highlighted values have been considered in the study for MY 2030. The production year is another five years over the laboratory year.

Adjusted Electricity Consumption, Combined 43/57 - real world (Wh/mi) with Charger						
	Base			Premium		
Subclass/ Laboratory Year	**2020**	**2025**	**2030**	**2020**	**2025**	**2030**
Production Year (Model Year)	**2025**	**2030**	**2035**	**2025**	**2030**	**2035**
Compact Car						
BEV200	201	194	187	211	203	197
BEV300	208	199	201	218	209	212
Midsize Car						
BEV200	207	199	192	217	209	202
BEV300	214	204	208	225	215	219
Small SUV						
BEV200	255	245	233	262	252	240
BEV300	263	252	248	272	259	256
Midsize SUV						
BEV200	277	267	252	289	278	264
BEV300	286	275	269	299	286	282
Large SUV *(assumed)*						
BEV300	384	365	359	399	381	376
BEV400	415	391	366	435	409	385
Pickup Truck						
BEV300	349	332	326	363	346	342
BEV400	377	355	333	395	372	350

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. A maintenance cost of 7.7¢ is considered for all types of BEVs in the TCO analysis [53], as listed in Table 19. Residential electricity price projections are shown in Figure 22 from the EIA AEO 2022, and the charging rates are considered as EV energy inputs [12]. It is pertinent to note that most of the TCO studies [7]–[9], [52], [54], [55] 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]. In this analysis, a constant maintenance cost of 7.7¢ per mile in the BEV category results in a 14% to 35% difference across all the vehicle types in the ICE category.

Table 19: Total Cost of Ownership (TCO) inputs for BEV

Vehicle type	Subclass	Segment	Vehicle Glider Price	BEV Range (Miles)	BEV efficiency (kWh/mile)	Maintenance cost per mile
Car	Compact car	Base	$15,000	200	0.194	$0.077
		Premium	$22,500	300	0.209	
	Midsize car	Base	$18,000	200	0.199	
		Premium	$27,000	300	0.215	
SUV	Small SUV	Base	$20,000	200	0.245	
		Premium	$30,000	300	0.259	
	Midsize SUV	Base	$22,000	200	0.267	
		Premium	$33,000	300	0.286	
	Large SUV	Base	$24,000	300	0.365	
		Premium	$36,000	400	0.409	
Pickup	Pickup Truck	Base	$26,000	300	0.332	
		Premium	$39,000	400	0.372	

To factor in the costs related to charging, a 90:10 mix of residential and public charging is assumed for all three scenarios of electrification. It is assumed that a typical user's vehicle is going to spend most of its time at home or a reserved parking location (carport, designated parking spot) and will have access to charging at end-use residential electricity rates. The assumption of a balance of 10% applies to the use of DCFC network charging, with electricity rates at the highest per kWh price prevalent today. These rates have the potential to be lower in the future. A $1,000 upfront cost for a non-networked level 2 AC charger with a capacity of 11.5 kW is considered an additional BEV cost input [9], [10]. Public charging at an Electrify America DCFC station is assumed to be $0.43/kWh based on the pricing plans available on their website [56].

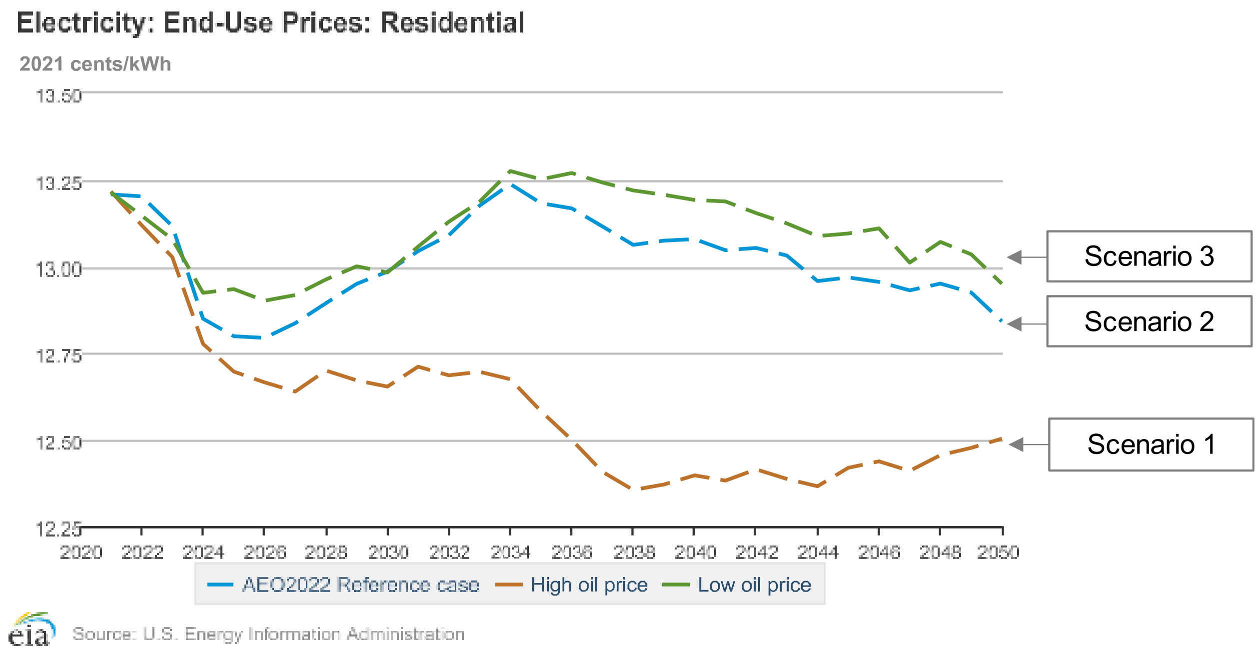

Figure 22: AEO2022 projected electricity prices in 2021¢ per kWh [12]

A what-if scenario analysis is also built in addition to the residential charging scenario, namely demand charging for consumers in an urban scenario where the charging is demand-based, i.e., an assumed equal mix of residential charging and public charging. This scenario is covered in detail in Section 5.3 as a "what-if" scenario. Additionally, to provide a perspective on TCO and a parity timeline with real-world electricity prices, an energy price sensitivity analysis is conducted and can be found in Section 5.6.

2.6.3 Calculations

The vehicle purchase price is computed by summing the glider price with the RPE marked-up powertrain price for ICE and BEV, respectively. In the case of BEV, the consumer also needs to purchase and install a level 2 charger. In addition to the upfront purchase price, the operating costs represent additional costs incurred by the consumer after vehicle purchase to operate a given vehicle. It includes the energy and maintenance and repair costs over the lifetime of the vehicle that have been assumed to occur each year. The equations used to arrive at the energy costs on an annual basis are,

a) $\text{ICEV energy cost} = \text{Annual VMT(mile)} \div \text{Fuel economy(mpg)} \times \text{Gasoline cost(\$/gallon)}$

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

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. The technology review is guided by the following:

a) Technologies that can significantly reduce the DMC and TCO of light-duty vehicles from 2022 through 2030 and beyond.
b) Technologies that can mitigate increases in commodity prices or supply constraints due to geopolitical or other factors (such as rare earth metals, critical raw materials, etc.) that might negatively affect 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 its significance in achieving a sustainable 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. Though these technologies have not been considered in the costing exercise, they demonstrate that the analysis in the 2030 timeframe is conservative, and a BEV would have an edge over an equivalent ICEV from a cost and technology perspective.

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 the BEVs. They 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 [57]. 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). Critical elements like lithium, cobalt, nickel, graphite, and manganese are combined in various stoichiometric ratios to form a LIB. Currently, cathodes of NCM, NCA, and LFP dominate the EV market.

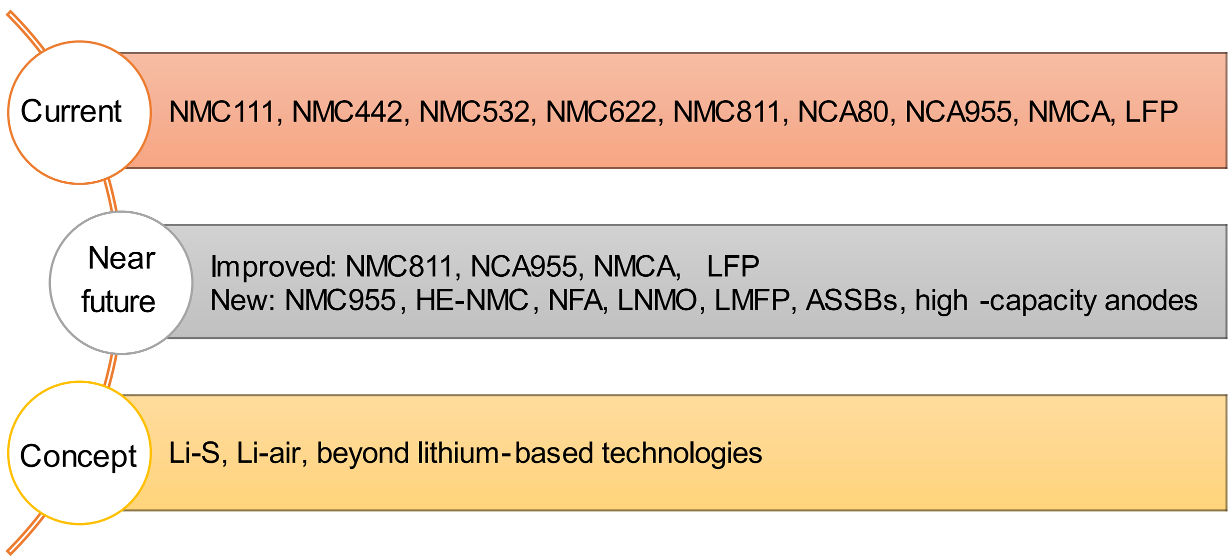

Figure 23: Snapshot of current and expected EV battery chemistries. Numbers represent the ratios of nickel-manganese-cobalt or nickel-cobalt-aluminum in the cathode.

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 [58]. Additionally, LFP was one of the fastest-growing chemistries in 2021 and is expected to continue the trend in the coming years [58]. 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 [59]. This could be partly because of its likely wide-scale deployment in the stationary energy storage market.

A battery supply chain consists of five main value-chain steps: 1) raw material production; 2) material refinement and processing; 3) battery material manufacturing and cell fabrication; 4) battery pack and end-use product manufacturing; and 5) battery end-of-life recycling [18]. The U.S. 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 [30]. Recent reports estimate a critical shortage of lithium due to a dearth of investments, which can be the bottleneck in achieving the electrification targets [60]–[62]. Automakers are exploring scenarios for entering the upstream and midstream segments of the supply 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 [63]. The CEOs of Tesla, Rivian, and Stellantis have already flagged their concerns regarding a severe shortfall of lithium and other critical materials that may hamper their growth. According to a leading industry expert, Joe Lowry, also referred to as "Mr. Lithium," the sheer volume of lithium demand may outstrip supply, which can put pressure on battery prices [64]. The current administration's initiative is expected to boost domestic upstream extraction projects in both the short and long term.

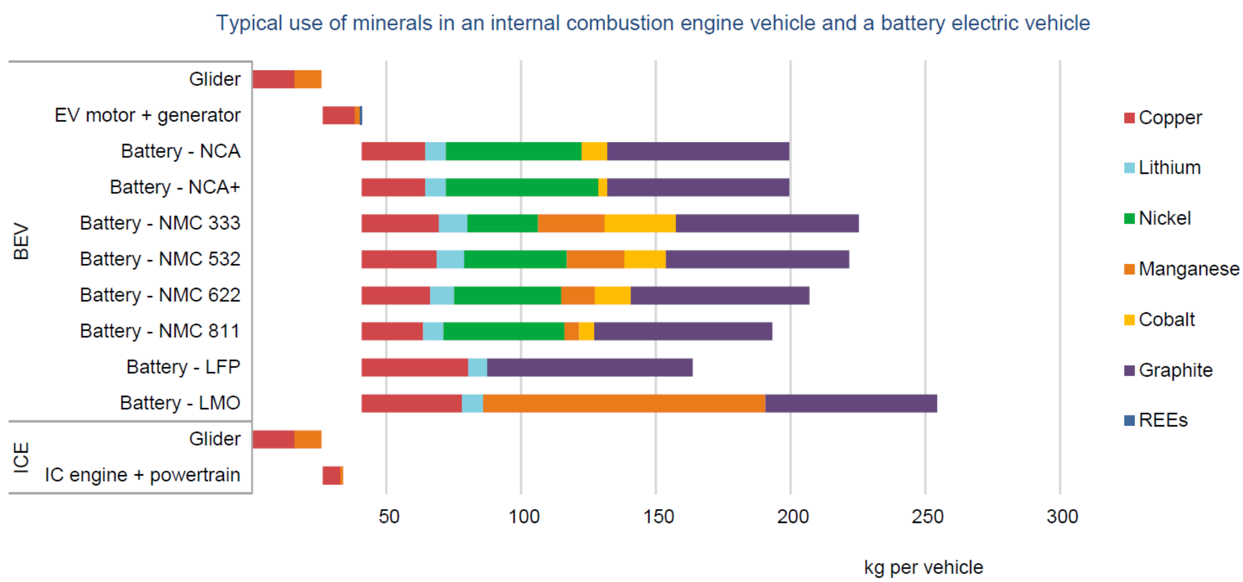

Figure 24: IEA estimates a typical BEV requires around six times more minerals than a conventional ICEV. 75 kWh battery with graphite anodes and PMSM shown here [30]**.**

Table 20: Requirements of critical raw materials [29]

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)

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. The bill of materials of a battery is dictated by the cathode chemistry and stringent purity requirements set forth by the cell manufacturer [29]. 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 other rare earth elements will be in huge 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 [65]. With the projected growth of EVs, the automotive demand for lithium, nickel, and cobalt will keep surging, as shown in Figure 25, and could outpace the production capacities [66]. Xu, C., *et al.* have attempted to quantify the future demand for battery-critical raw materials [66]. 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 [67]. By 2030, demand is expected to be nearly 4 TWh [42]. 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 huge role in the long-term financial viability of mass production and penetration of EVs.

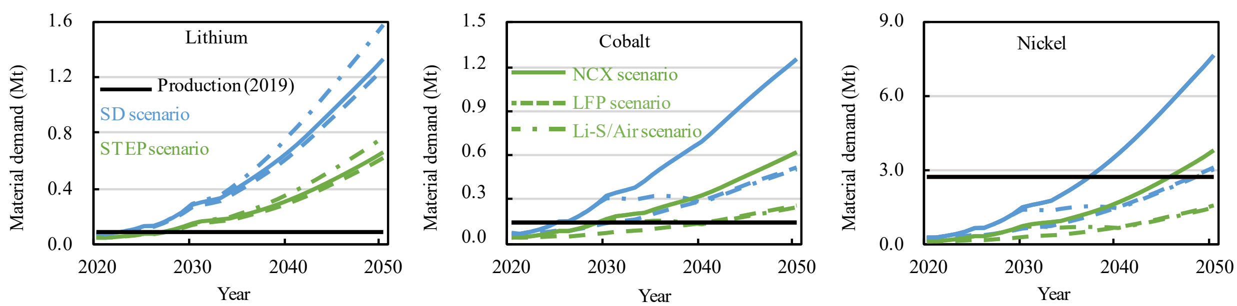

Figure 25: Projected global demand for lithium, cobalt, and nickel for EV batteries in million tons in the NCX, LFP, and Li-S/Air battery scenarios based on two scenarios of the International Energy Agency (IEA), the Stated Policies (STEP) and Sustainable Development (SD) scenario [66]**.**

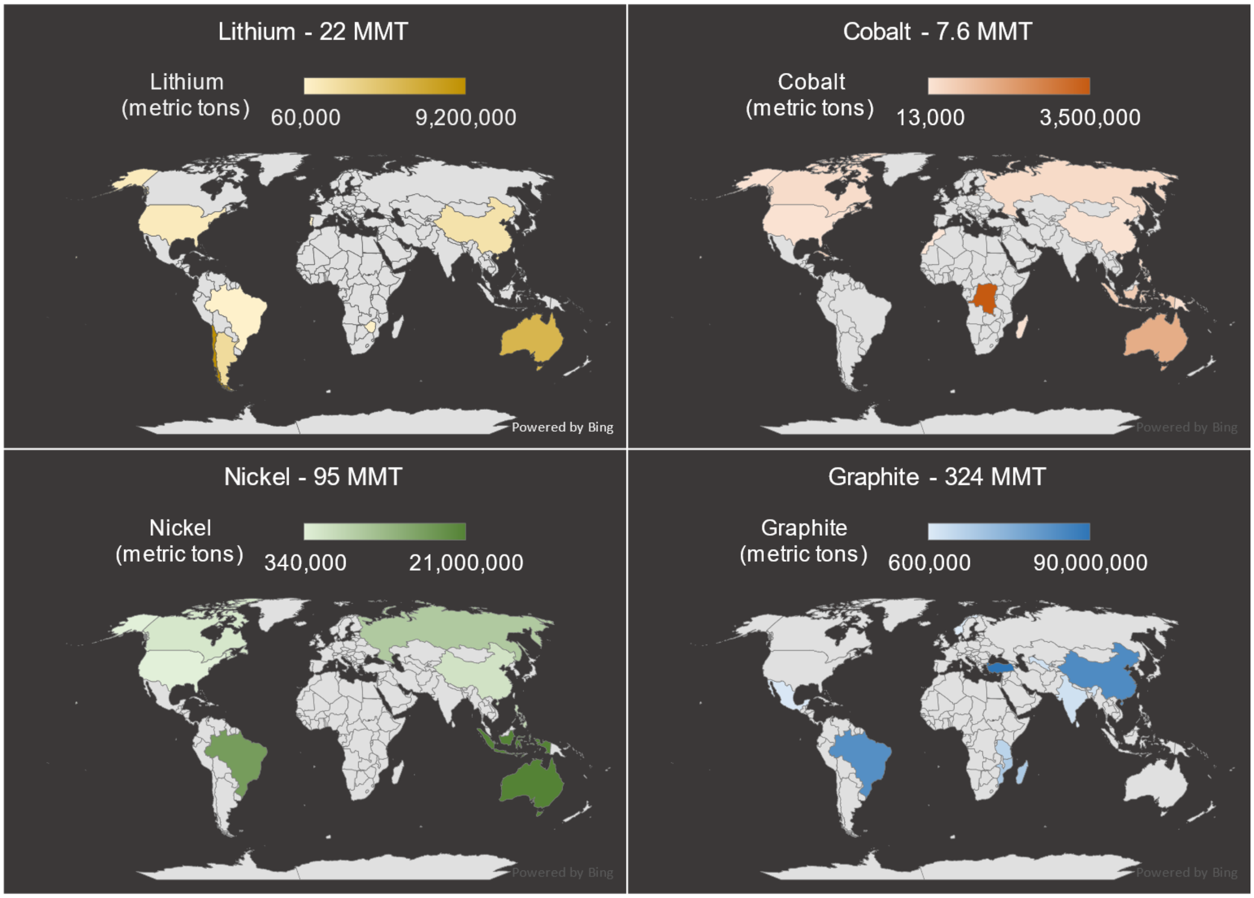

Figure 26: Estimated reserves of battery critical raw materials in million metric tons (MMT) based on Mineral Commodity Summaries 2022 by U.S. Geological Survey [32]

3.1.2.1 Lithium

Lithium is found naturally in the form of pegmatites, brines, and sediments [29], [32], [68]–[70]. Australia, Argentina, Chile, and China accounted for the majority of the lithium production in 2021 [32]. 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 [69], [71]. Sedimentary lithium-clay sources are in various stages of development in Mexico and the United States [32]. Thacker Pass in northern Nevada, 100% owned by Lithium Americas (LAC), has clay mineral reserves of 3.1 million metric tons of lithium carbonate equivalent (LCE) with an estimated mine life of 46 years. LAC plans to produce 60,000 tonnes of battery-grade lithium carbonate per year for

$2,570 per tonne [72]. Compared to the large physical footprint of brine salars, as shown in Figure 27, 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 [69], [73]. General Motors 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 [74], [75].

Figure 27: Cauchari-Olaroz project jointly operated by Lithium Americas (LAC) and Ganfeng Lithium in Argentina. Source: Lithium Americas [72]

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 [32]. It is a preferred material as it provides structural stability and boosts energy density and battery life [76]. China was the world's leading producer and consumer of refined cobalt, with most of it being used by their rechargeable battery industry [32]. 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 [29], [77]. Large-scale mining (LSM) and artisanal and small-scale mining (ASM) have a share of 87% and 13%, respectively [78]. Additionally, cobalt ores in various forms can be found in Zambia, Australia, and nearby island countries, Cuba, Canada, Russia, and the United States [32]. Furthermore, the seabed of the Atlantic, Indian, and Pacific Oceans hosts abundant regions of cobalt crusts, estimated to be more than 120 million tons [32], some as big as Europe in the western Pacific [79]. However, given the technical and environmental challenges, economic methods of deep-sea mining are still being explored and are in the early stages [80].

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 [81]. High-purity Class 1 nickel (> 99%) found in sulfide deposits is used in its sulfate form in cell manufacturing [82]. 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 [17]. 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 [17]. As with cobalt, nickel resources are also found on the ocean floor [32]. 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 [32]. In November 2021, nickel was added to the U.S. critical minerals list [32].

3.1.2.4 Graphite

LIBs use graphite-based anodes, as their layered structure allows for intercalation and deintercalation [17]. 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 [29]. 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 [32]. 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 [17]. The fast charging of EVs is limited due to lithium-ion diffusion within the graphite anode due to the risk of lithium plating [83]. 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 [17], [84]. Self-healing or auto-repair mechanisms in batteries are being explored to address this issue [84].

3.1.2.5 Manganese

In 2021, South Africa, Gabon, and Australia led the production of manganese ores [32]. 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 [85]. 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 [86].

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% [87]. It is estimated that 296.8 GWh worth of batteries were deployed across EVs [87]. As shown in Figure 28, 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 [87].

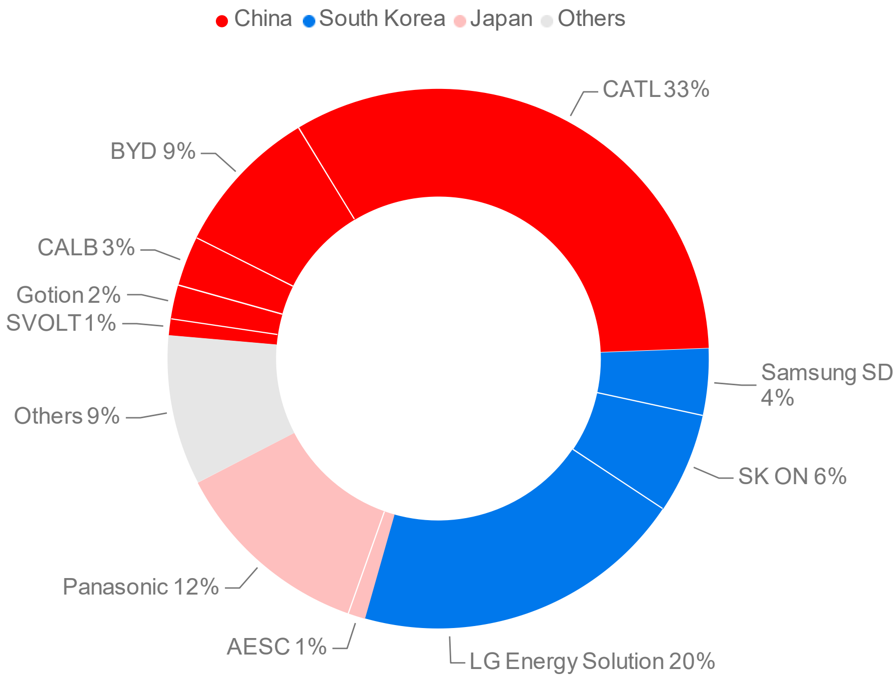

Figure 28: Top 10 EV battery manufacturers in 2021 based on data from SNE Research [87]

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 [81]. Per the Department of Energy (DOE) report, thirteen new gigafactories were announced and are expected to be operational within the next five years [88].

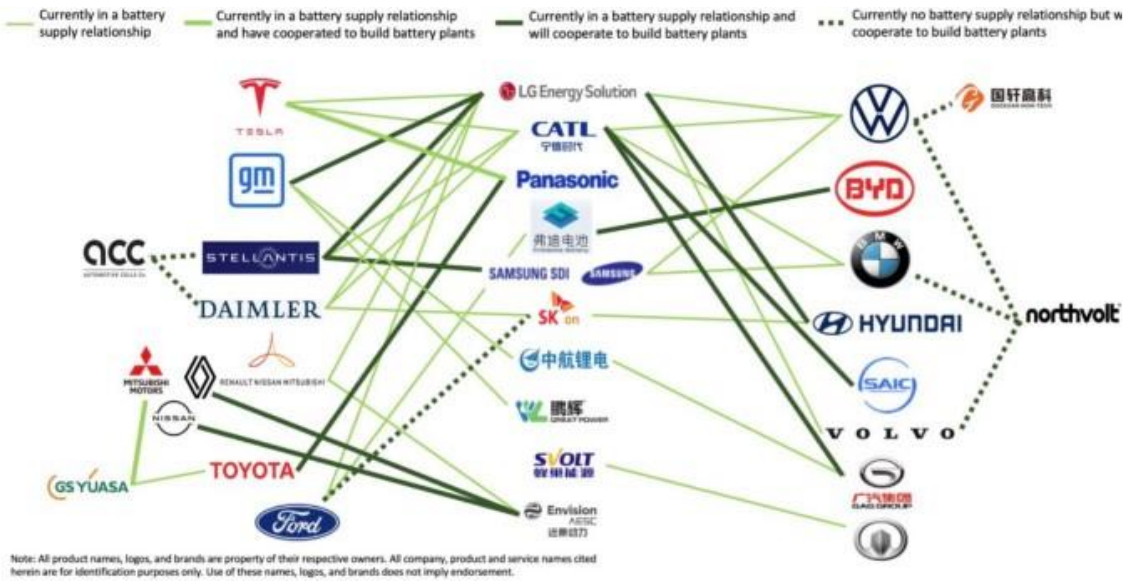

Figure 29: Joint Ventures and Partnerships. Image Source: Researcher & Researcher [89]

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 29 and Figure 30, 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 [90]. A large number of startups are also working on the next generation of batteries, promising to revolutionize the sector [90], [91].

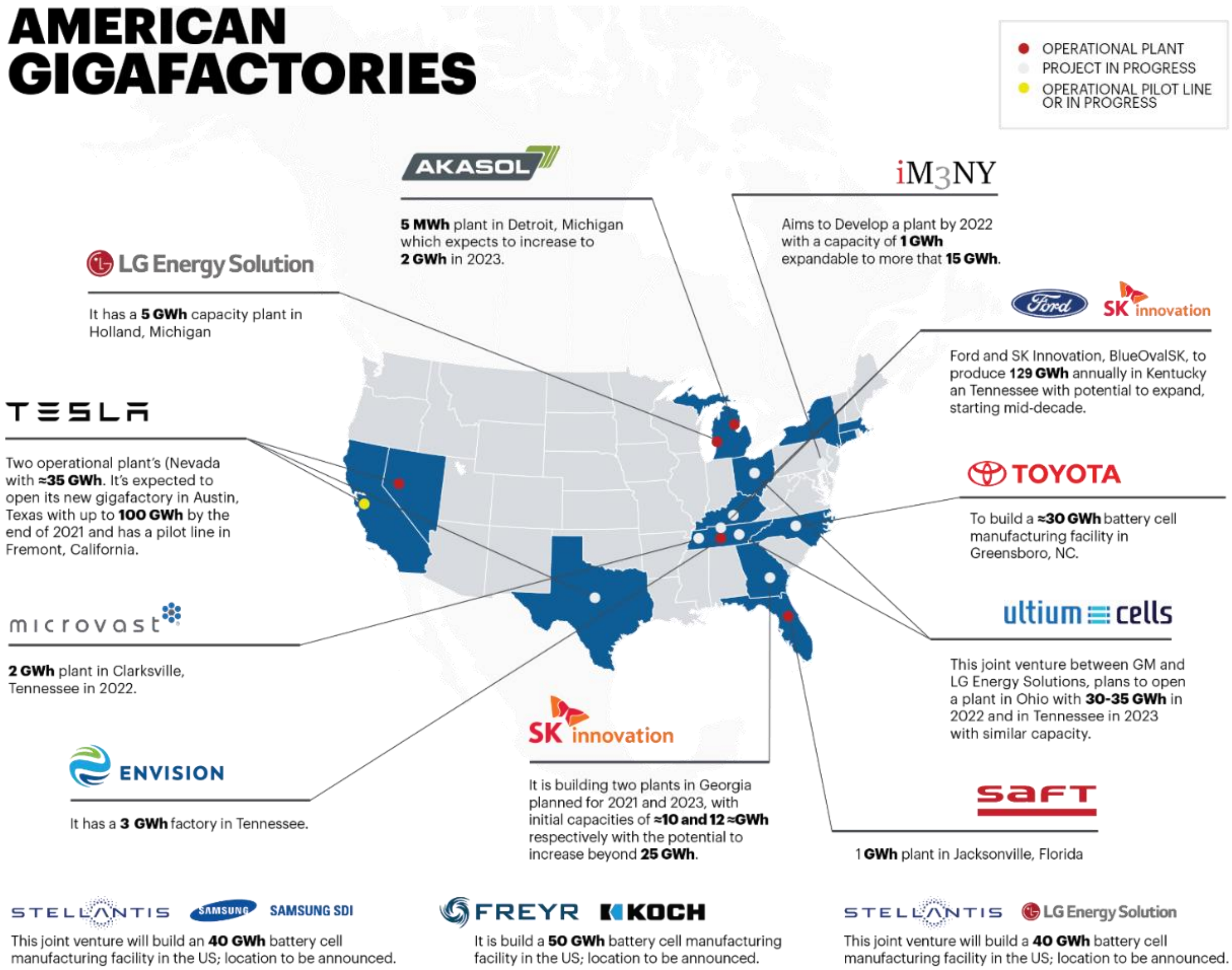

Figure 30: Major announcements made in the U.S. Source: PIEDMONT Lithium [92]

3.1.4 Recycling

Unlike the fossil fuel in 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. 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 [93]. 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 [93], [94]. 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 potentially going to waste unless they are reused, repurposed, or recycled. Creating a circular supply chain economy, as shown in Figure 31, is the way forward to reduce dependence on critical raw materials and mitigate the associated environmental impact [81], [84], [95].

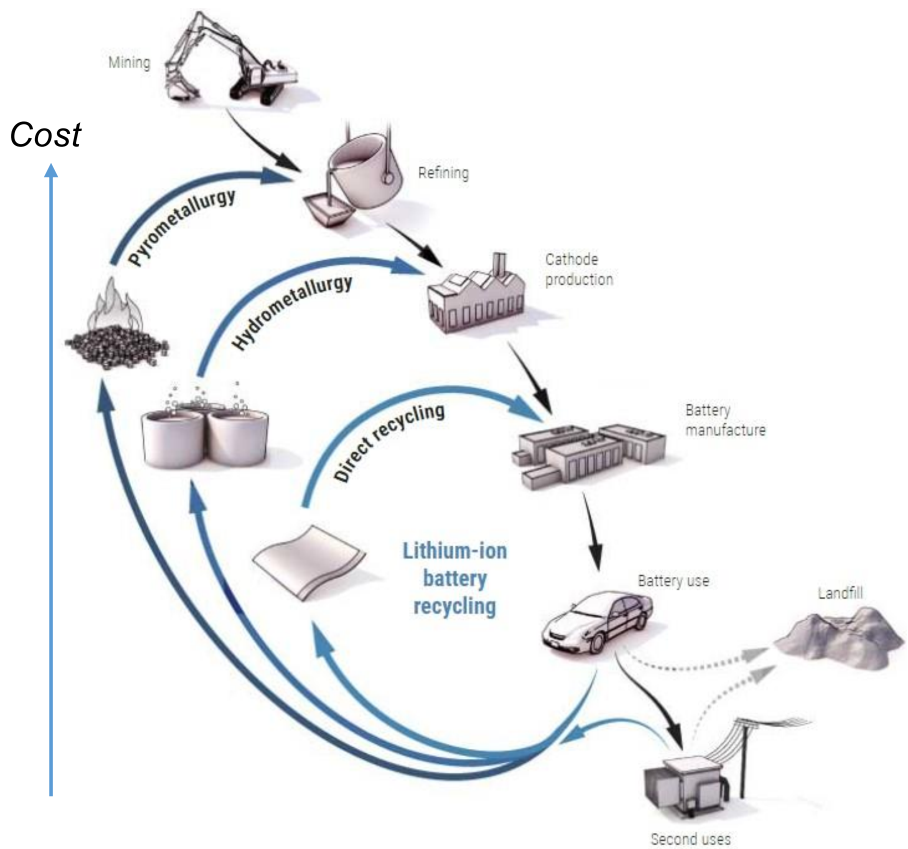

Figure 31: Potential LIB recycling practices from a cost and efficiency perspective to create a circular supply chain. Image Source: Science [96]

Repurposing of second-life batteries (SLB) for other applications, such as less demanding stationary energy storage applications, is underway, but technical challenges remain [94],

[97]. 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 [65]. 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 32. Creating and scaling the EV supply value chain presents challenges due to a gap in raw materials and know-how. In the future, the recycling and reprocessing industry is expected to be bigger than the mining industry with increased penetration of EVs. They are poised to play a decisive role in sustaining the EV industry.

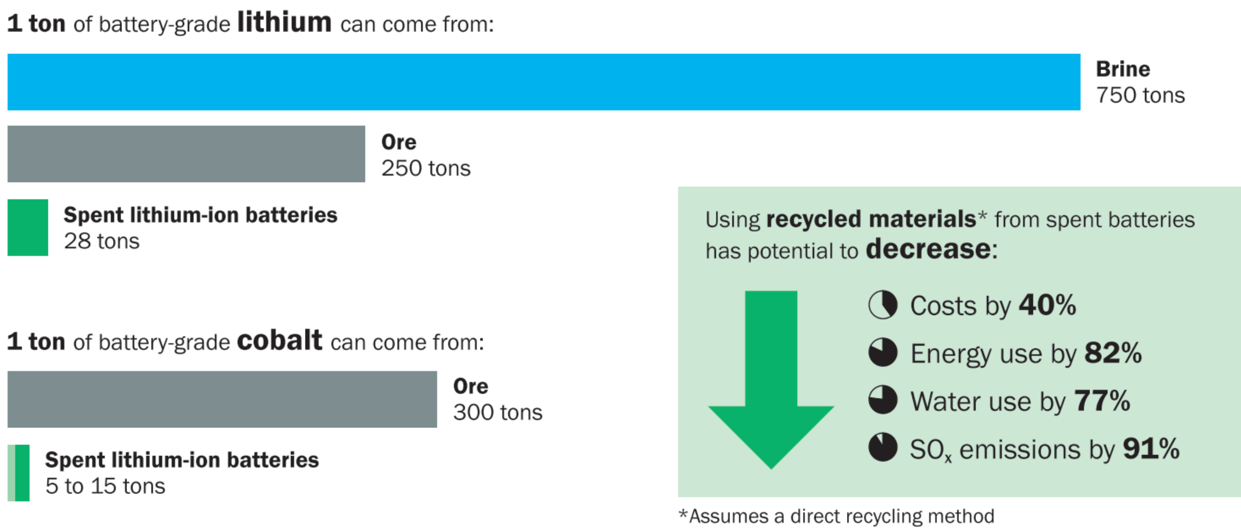

Figure 32: Batteries have a high elemental concentration of critical materials compared to naturally available resources making recycling them an attractive prospect [81], [95]

The cost of recycling, the variety of cathode chemistries used, and the cell design in use, as shown in Figure 33, are a few of the 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 [98].

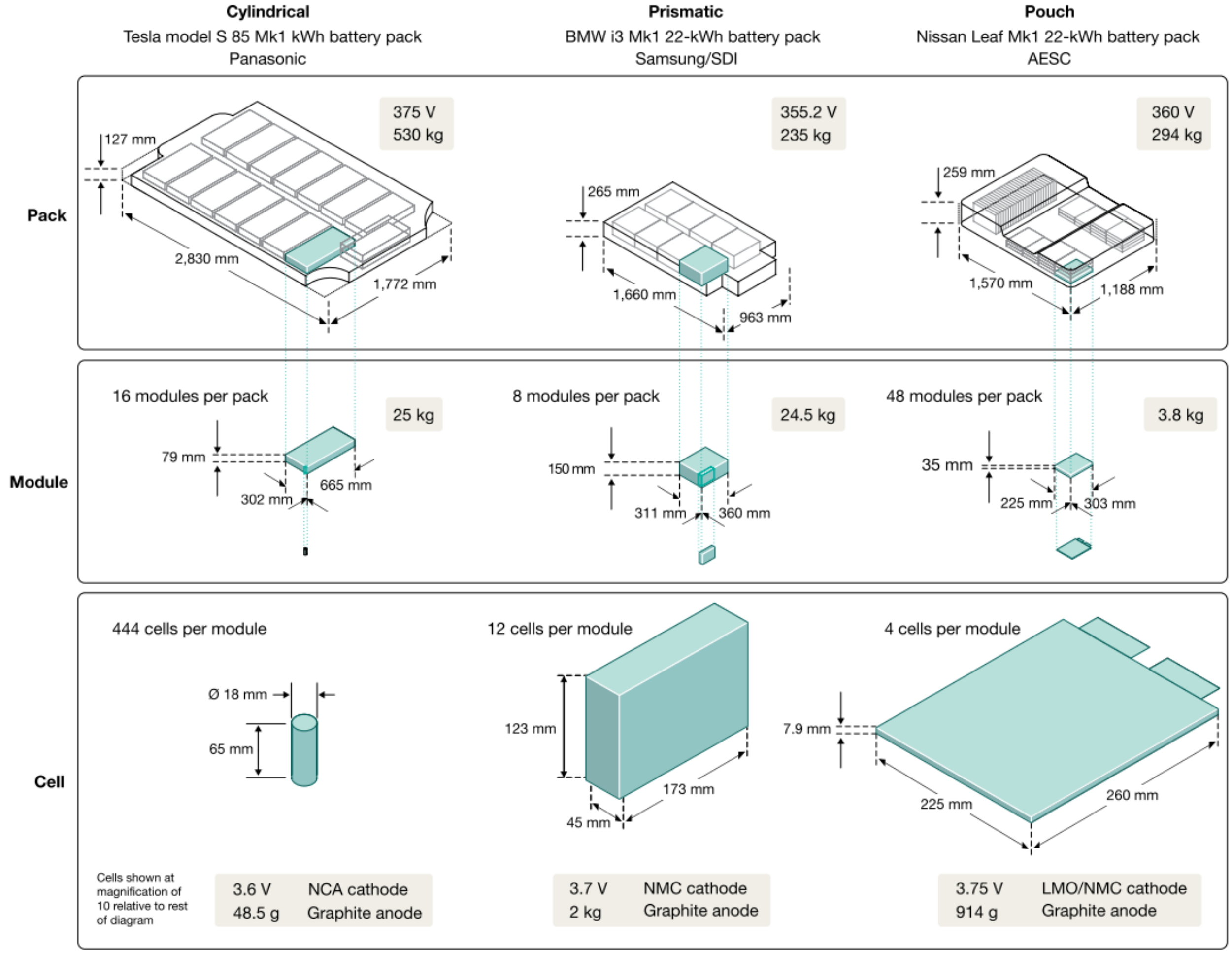

Figure 33: Different battery pack configurations pose a challenge to recyclers [99]

In addition to bringing costs down, their efforts are focused on minimizing the consumption of limited resources, strengthening national security, and creating a robust battery supply chain [100]. ANL also developed EverBatt, a closed-loop battery recycling cost and environmental impacts model, to help evaluate recycling technologies and their challenges [101]. 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 that will feed the industries. 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 [102].

Currently, there are three primary methods of recycling: pyrometallurgical recycling, hydrometallurgical recycling, and direct cathode recycling, or direct recycling [101], as shown in Figure 34. 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 a challenge, as can be seen in Figure 33 and Table 21. Since recycling is in its infancy stage, a standard and cost-effective recycling system is not in place.

Comparison of different LiB recycling methods Best ••••• •••• ••• •• • Worst

	Technology readiness	Complexity	Quality of recovered material	Quantity of recovered material	Waste generation	Energy usage	Capital cost	Production cost
Pyrometallurgy	•••••	•••••	•	•••	••	•	•	•••••
Hydrometallurgy	••••	•••	•••	••••	•••	•••	•••	•••
Direct recycling	••	•	••	•••••	••••	•••	•••	•

	Presorting of batteries required	Cathode morphology preserved	Material suitable for direct re-use	Cobalt recovered	Nickel recovered	Copper recovered	Manganese recovered	Aluminium recovered	Lithium recovered
Pyrometallurgy	•••••	No	No	•••••	•••••	•••••	••	No	•
Hydrometallurgy	••••	No	No	•••••	•••••	••••	•••	•••••	•••
Direct recycling	•	•••••	••••	•••••	•••••	•••••	•••••	•••••	•••••

Figure 34: Comparison of recycling methods [99]

3.1.4.1 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 [96], [99], [101]. 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 [99], [101]. Lithium, manganese, and aluminum typically end up in the slag, which can also be potentially recovered using hydrometallurgical processes [99], [103]. 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 [99], [101], [103].

3.1.4.2 Hydrometallurgical Recycling

After separating the batteries based on their physical properties, they are pretreated and shredded, followed by low-temperature calcination [101], [103]. These steps are followed by acid leaching or biological leaching and reduction [103]. 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 [101]. 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 [96], [99]. 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 [104]**.**

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

3.1.4.3 Direct Recycling

Direct recycling is one of the most promising methods as it can keep the cathode crystal structure intact [95]. 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 [101]. 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 [95]. 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 [95]. 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. However, significant work is to be done in this field to meet the desired electrochemical performance.

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 [105]. 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 [106]. 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. In Q1 2022, 50% of all Tesla 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 [47]. 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 [105], [107].

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). The energy density of production LFP cells has increased from 120-150 Wh/kg in 2015 to 210 Wh/kg in 2021 (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 [108] 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 [109]
[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 35, 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.

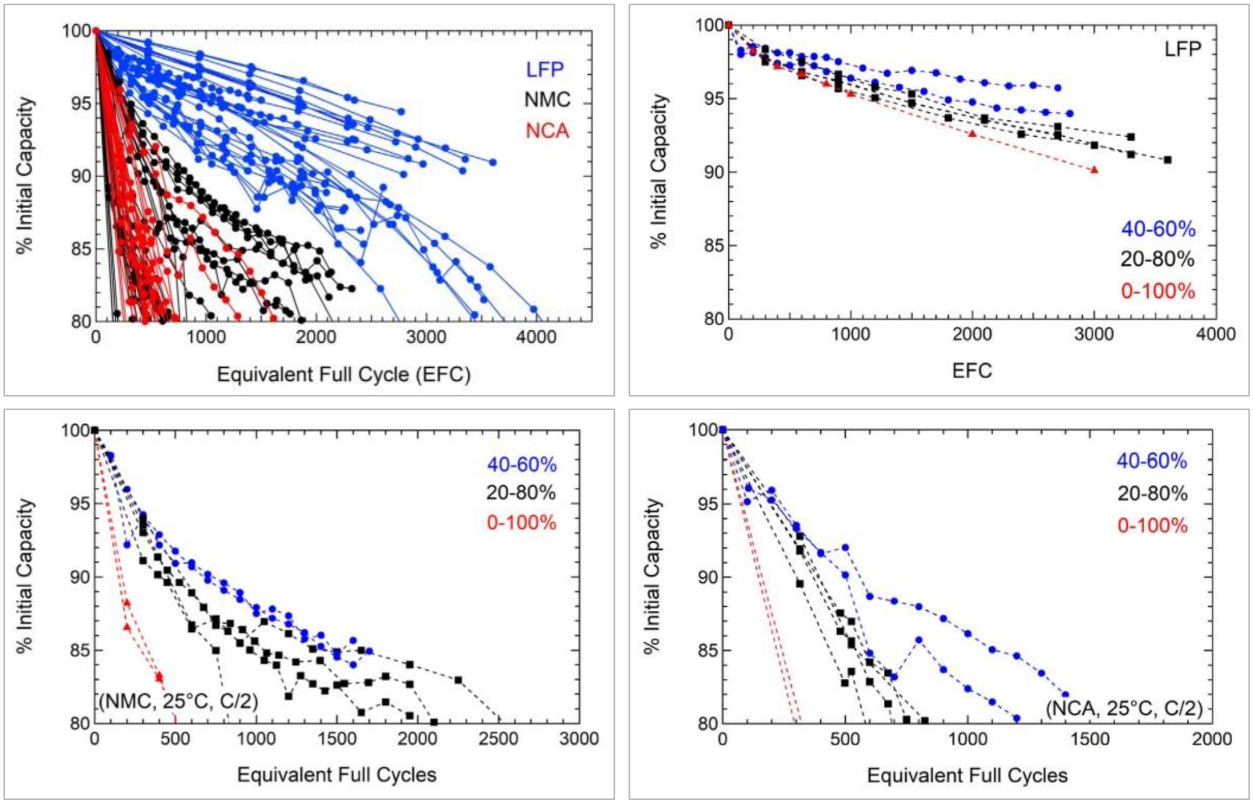

Figure 35: Capacity retention of various commercially available lithium-ion cells used in light-duty applications (20°C 100% DOD). Effect of depth of discharge on the cycle life of LFP, NMC, and NCA cells. Cycle life = 80% of initial capacity [110]

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 [111][112]. NCA chemistry has a shorter cycle life (1000-1500 cycles) when compared to NMC and NCMA cathodes (Figure 36) [110]. 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 [113], as shown in Figure 36. LG cells will initially be used in GM (Ultium™ batteries) EVs.

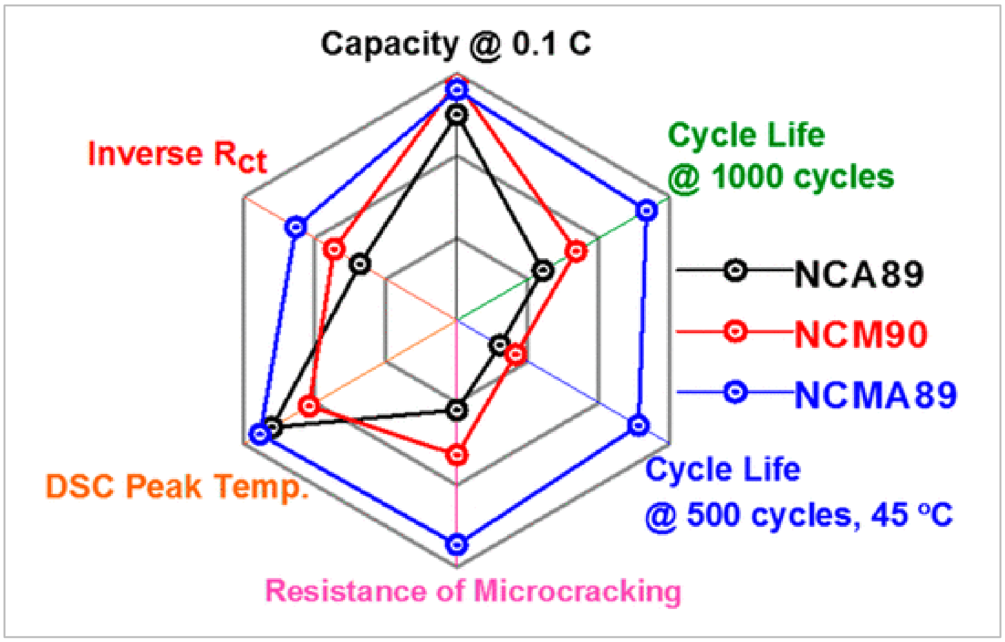

Figure 36: Comparison of NCMA89 chemistry with NCA89 and NCM90 [113]

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 [114]. 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 37, 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.

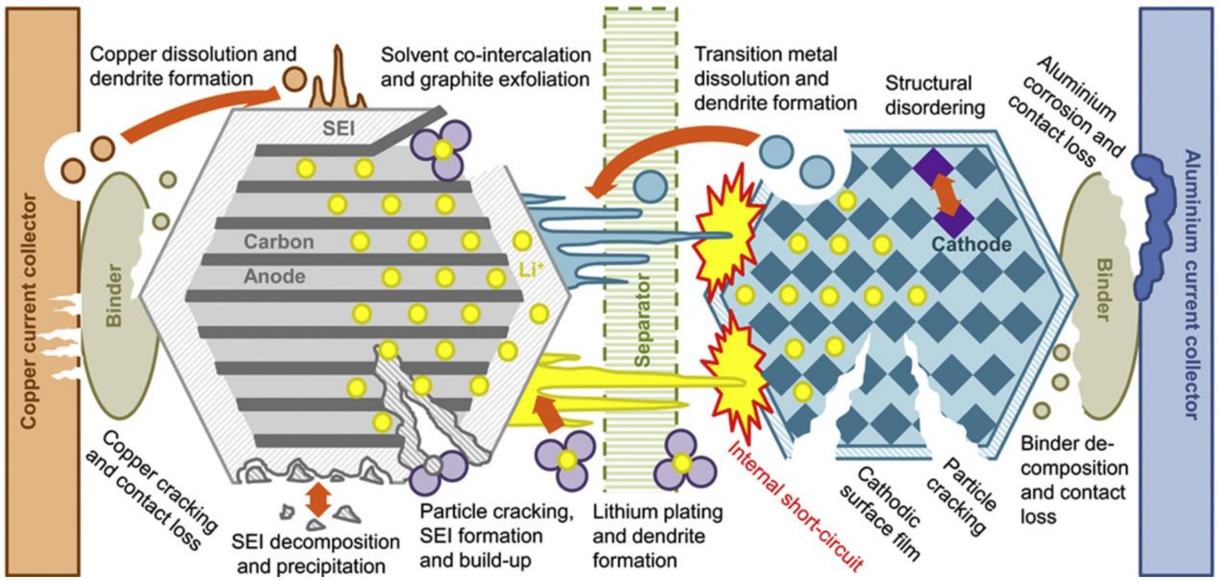

Figure 37: Modes of degradation in lithium-ion cells [114]

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 bring forth 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 [115]. Theoretically, lithium can store 10 times more energy than graphite and would be an ideal anode [17]. 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 [17], [115].

3.1.5.2.2 Silicon Anodes

As with a lithium metal anode, silicon has a capacity 10 times greater than graphite [17] but suffers from volumetric expansion and calendar life issues [18]. 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 [116]. Silicon is usually included in small amounts (<8%) in the graphite anode to boost the energy density without affecting the cycle life [17].

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 [117], 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 [118]. As shown in Figure 38, 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 [17], [119].

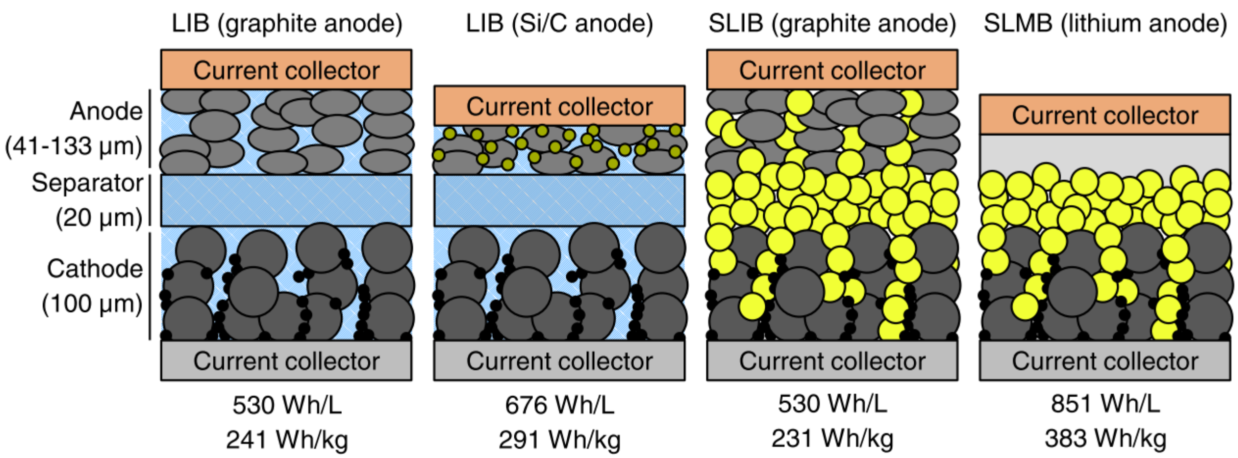

Figure 38: Cell design for different types of LIBs and ASSBs [119]

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 [17], [119], [120]. 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 [17], [119].

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 39. 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.

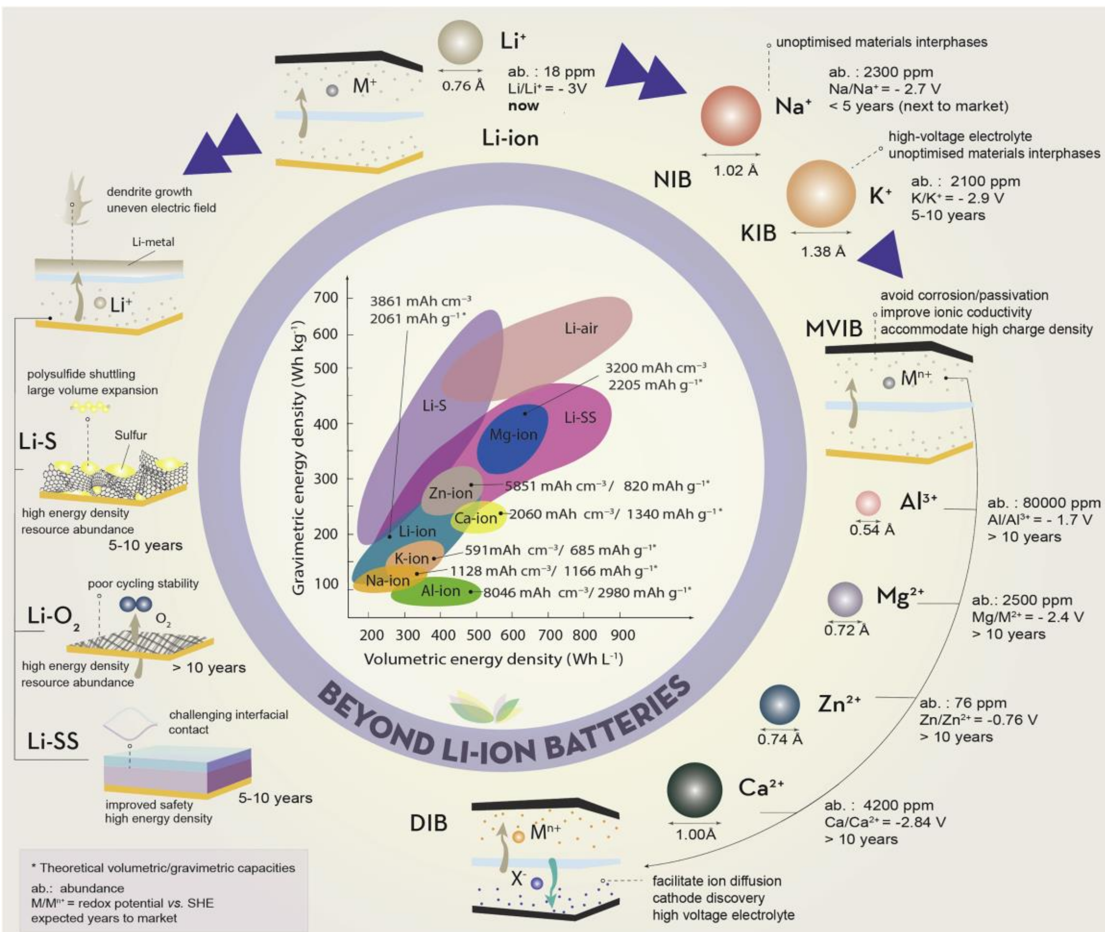

Figure 39: Snapshot of beyond lithium-ion batteries with their status and challenges [120]

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 [121]. In 2021, Faradion UK unveiled a prototype cell based on $Na.Ni_{(1-x-y-z).}Mn_{x.}Mg_y.T_ziO_2$ cathode [122] with an energy density of 140 Wh/kg. However, in the long run, sodium-ion batteries that use NMC cathodes will 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 [108]. 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 40 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.

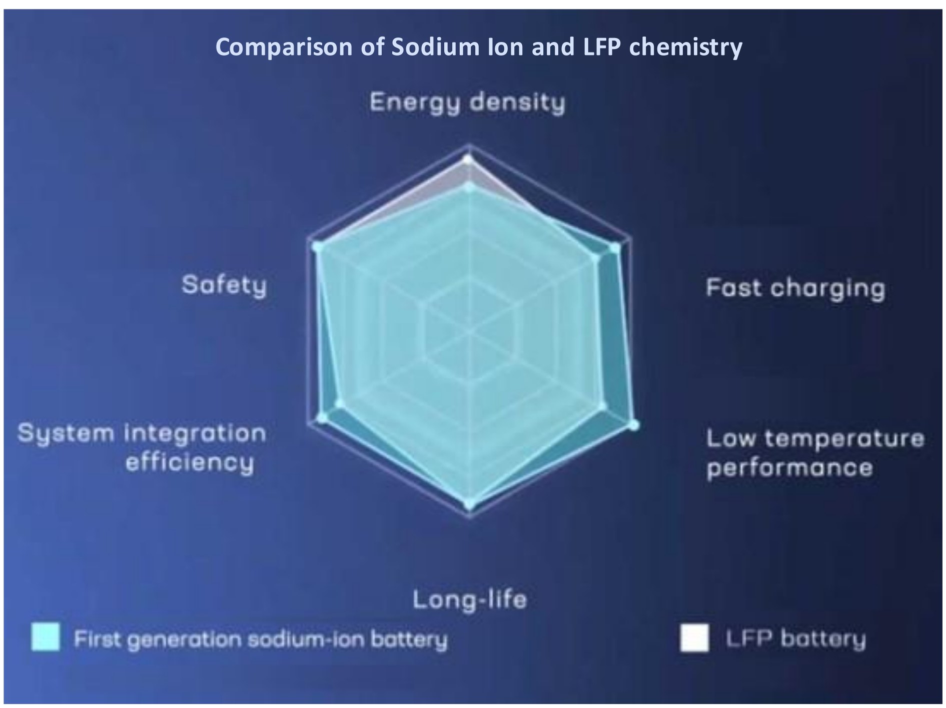

Figure 40: First-generation sodium-ion compared to LFP. CATL 2021 [108]

As shown in Figure 39, 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 [115], [120]. 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 LDVs, given the annual VMT and a 15-year life cycle.

State-of-the-art LFP cells have a cycle life of 5000-7000 cycles, as shown in Figure 35 [110], which is enough to comfortably exceed the longest lifetime mileage requirements. For LDVs with a 200-400 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 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 [123], [124] [125]. 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 [126], [127].

3.1.6.2 Single Crystal Cathode Materials

Single-crystal cathode materials in place of the polycrystalline material used in battery cells today can significantly increase the cycle life of lithium-ion batteries. Under testing, cells with single crystal cathode materials have demonstrated more than 9500 cycles (room temperature, 100% DOD, 1C rate) with capacity retention of over 90% [128]. 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 [129]. Single-crystal cathode materials are compatible with commercial battery chemistries, with no change required to the cell manufacturing process or equipment.

Figure 41 (right) [130] 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.

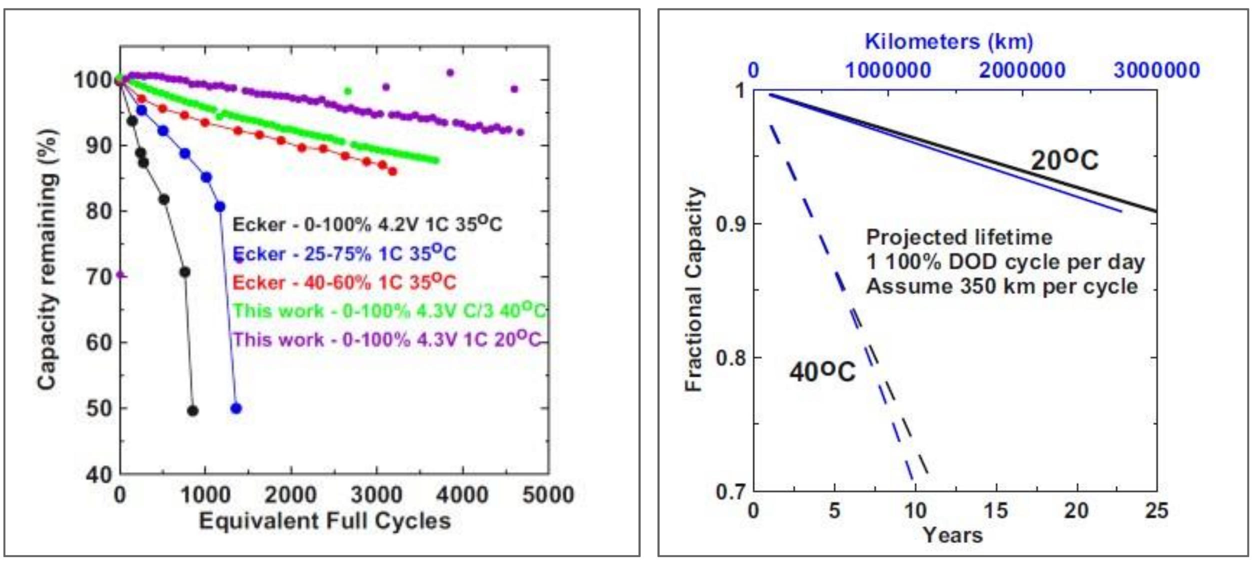

Figure 41: Left: Long-term cycling data plotted as percent initial capacity (left), Right: Worst-case scenario lifetime and total driving range projections for the NMC532/graphite cells 6-hour 100% DOD cycle per day and 350 km initial driving range per cycle [130]

3.1.7 Advances in Battery Cell and Pack Manufacturing

3.1.7.1 Dry Battery Electrode (DBE) Process

Figure 42 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 [131]. 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 [132].

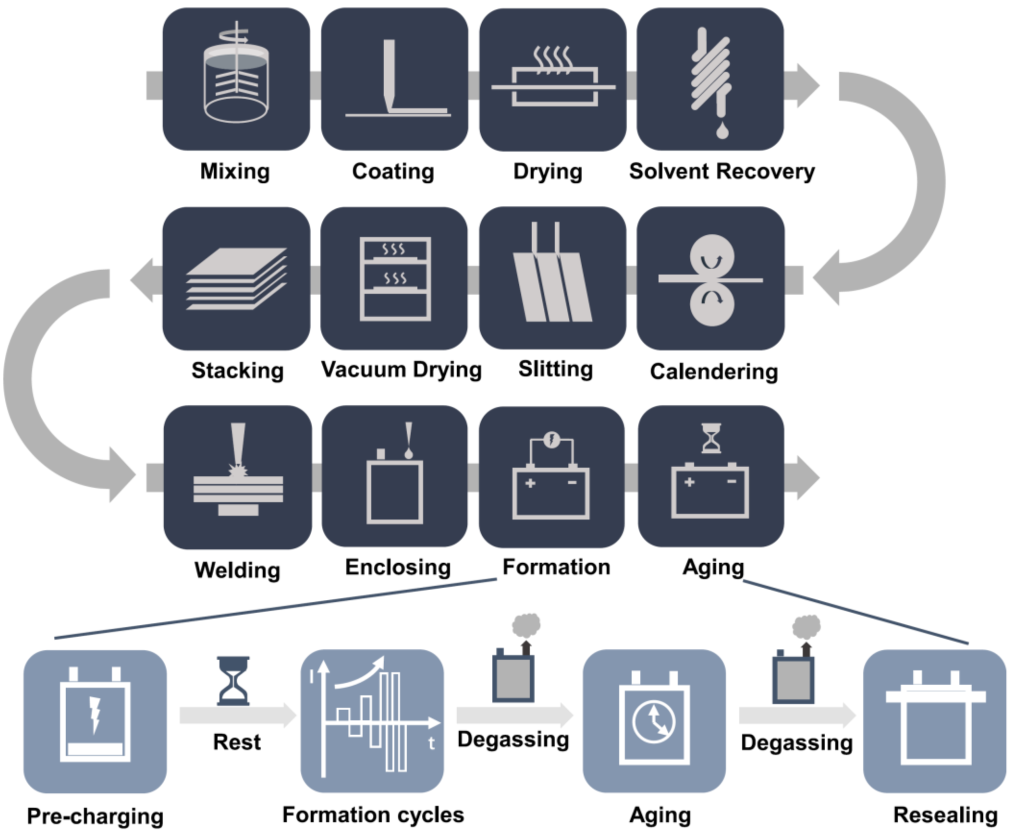

Figure 42: Schematic of lithium-ion battery manufacturing processes [132]

The DBE process eliminates these steps, significantly reducing the cost and GHG emissions from the battery manufacturing process, as shown in Figure 43. Based on their 10 GWh pilot plant, Tesla estimates the DBE process will result in an 18% cost saving [133]. 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.

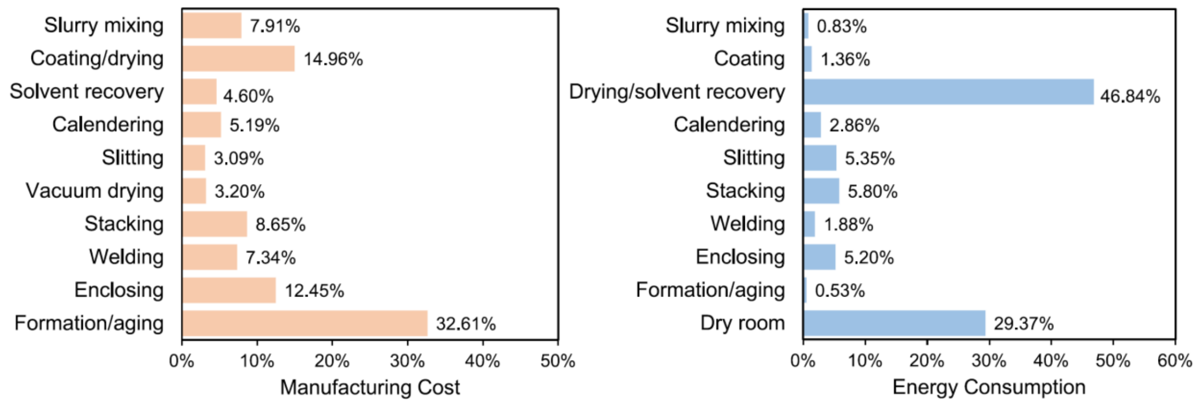

Figure 43: Dry battery electrode (DBE) processing process (left) and the cost and energy consumption breakdown for the conventional wet slurry cell manufacturing process (right) [132]

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 44, left—GM Ultium battery pack).

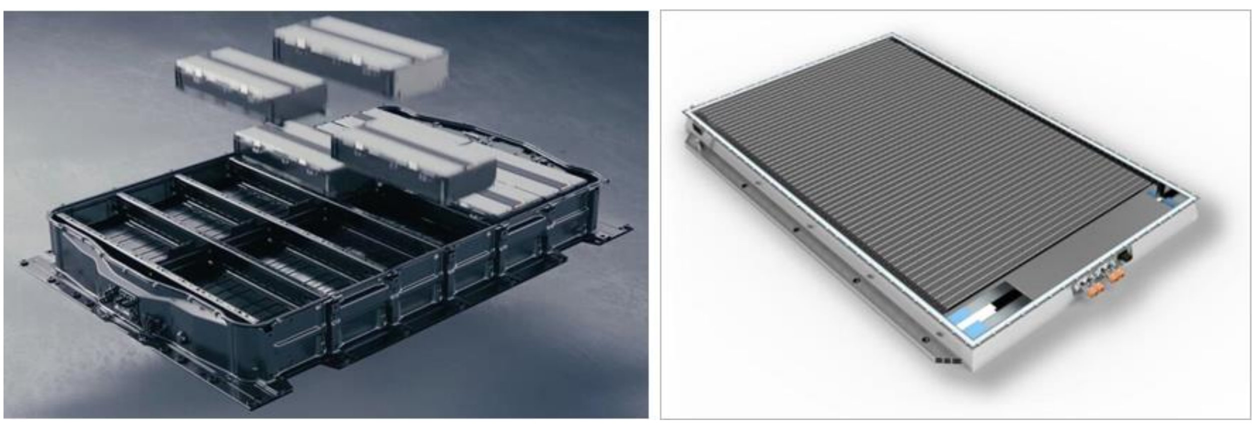

Figure 44: GM Ultium battery pack [134]**. BYD Tang "cell to pack" battery pack** [135]

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 44) that does away with individual modules, reducing the associated cost and complexity, and increasing the GCTP and VCTP.

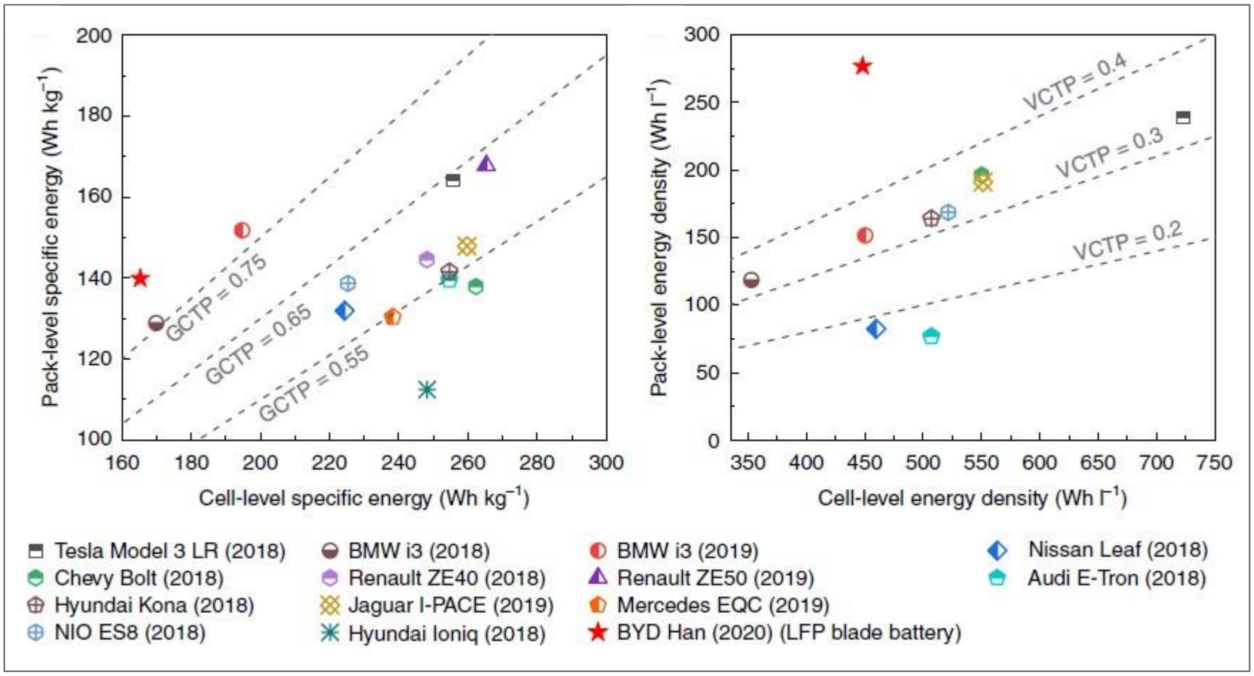

Figure 45: Gravimetric energy density and volumetric energy density of the battery packs in production EVs [108]

Figure 45 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 [108].

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 [133].

3.2 Traction Motors

Figure 46 shows the different types of motors used in production BEVs and OEMs or production applications.

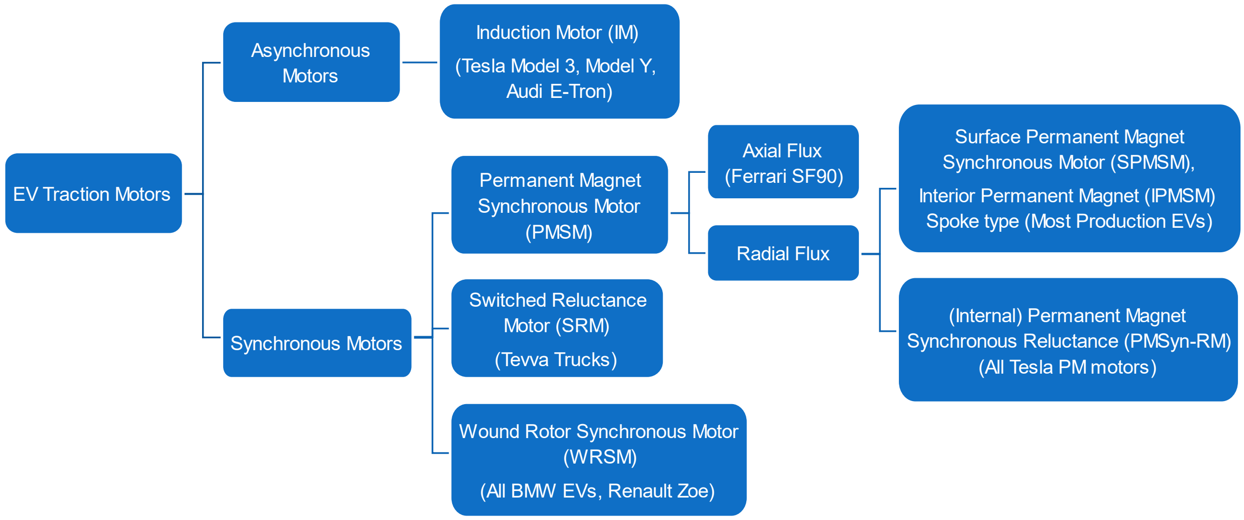

Figure 46: Different types of traction motors in production battery electric vehicles

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 [136]			

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 47), VW, and Rivian are some of the other manufacturers that use induction motors. Induction motors with high power densities will need liquid cooling of the rotors, which adds cost and complexity but is still cheaper than an equivalent PMSM.

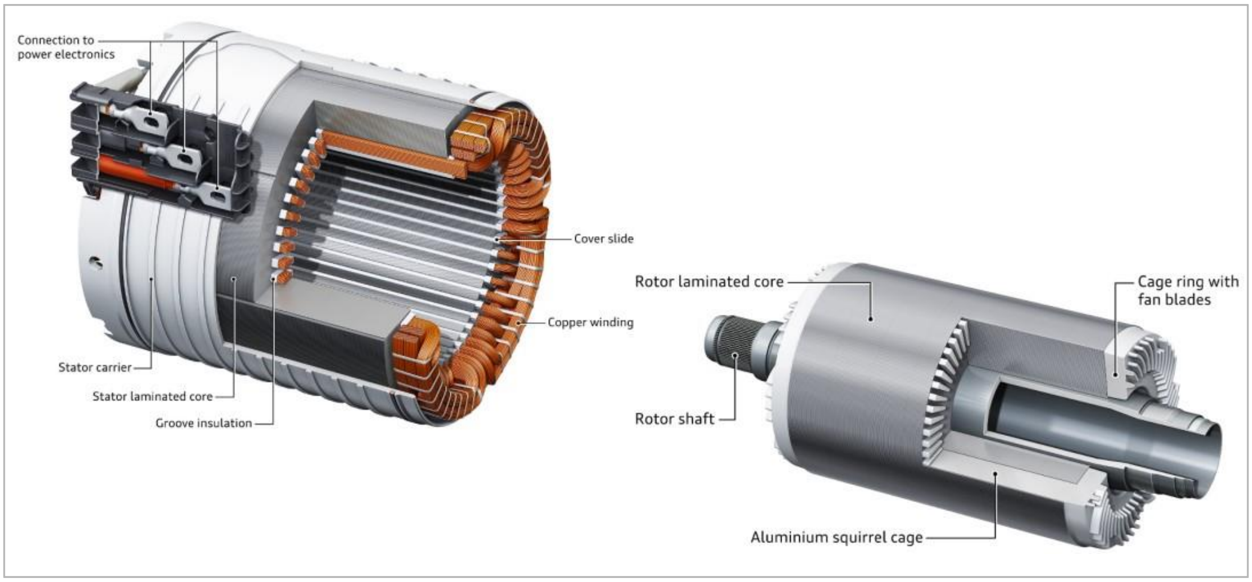

Figure 47: Audi APA250 induction motor with cast aluminum rotor conductors (125kW). [137]

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 48 shows the 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.

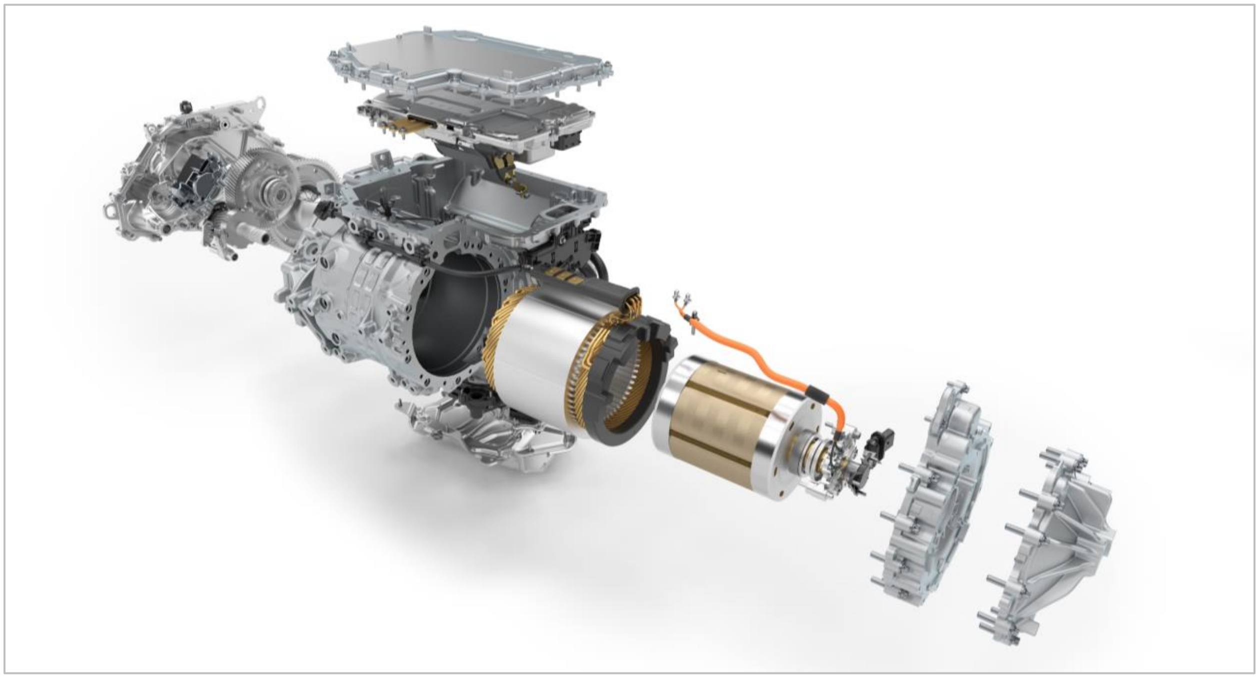

Figure 48: BMW "5th Gen E-drive Technology" employing a wound rotor synchronous rotor. The new BMW iX3 – Drivetrain [138]

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 49 shows the results of the motor teardown studies done by Munro & Associates on mass-produced light-duty BEV motors [39]. 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.

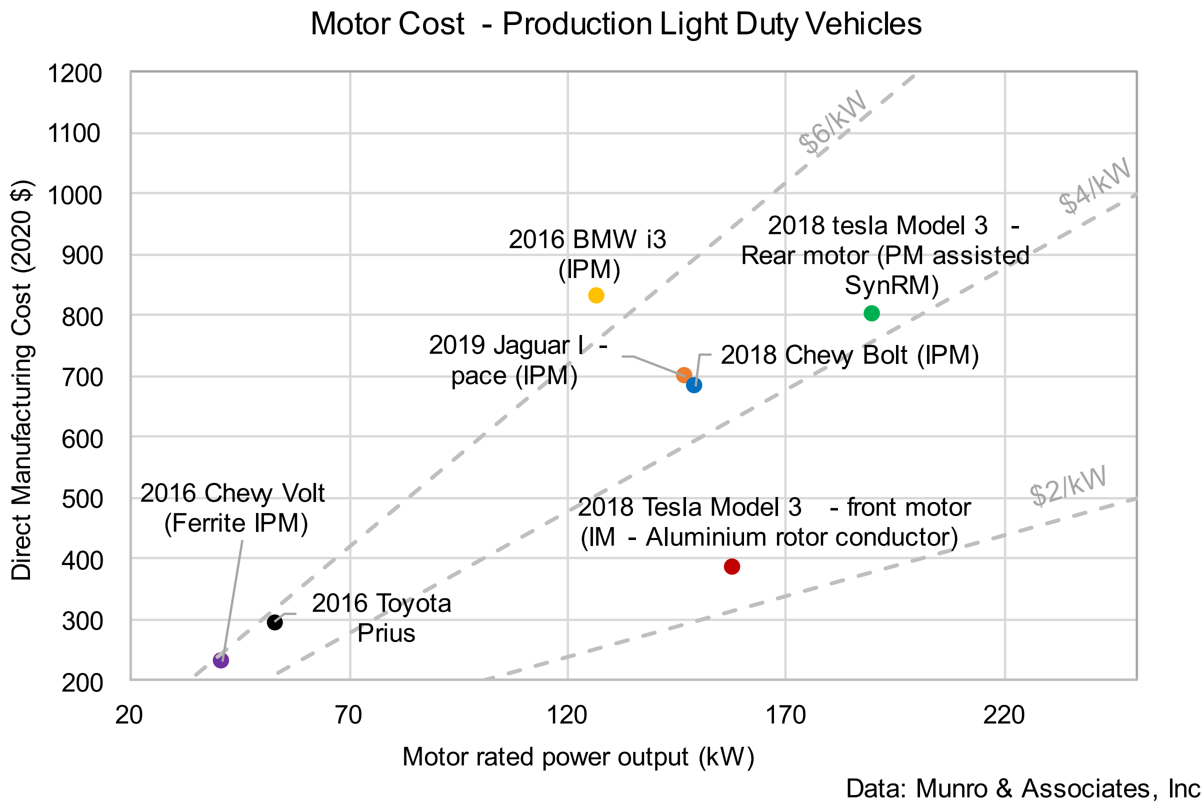

Figure 49: Production light-duty BEV motor cost [9]

Figure 50 shows the materials (commodity prices of raw materials, $/kg in 2020 and 2022) used in the construction of the various parts of 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 50). 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 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 (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 (Wh/mile) of the BEV.

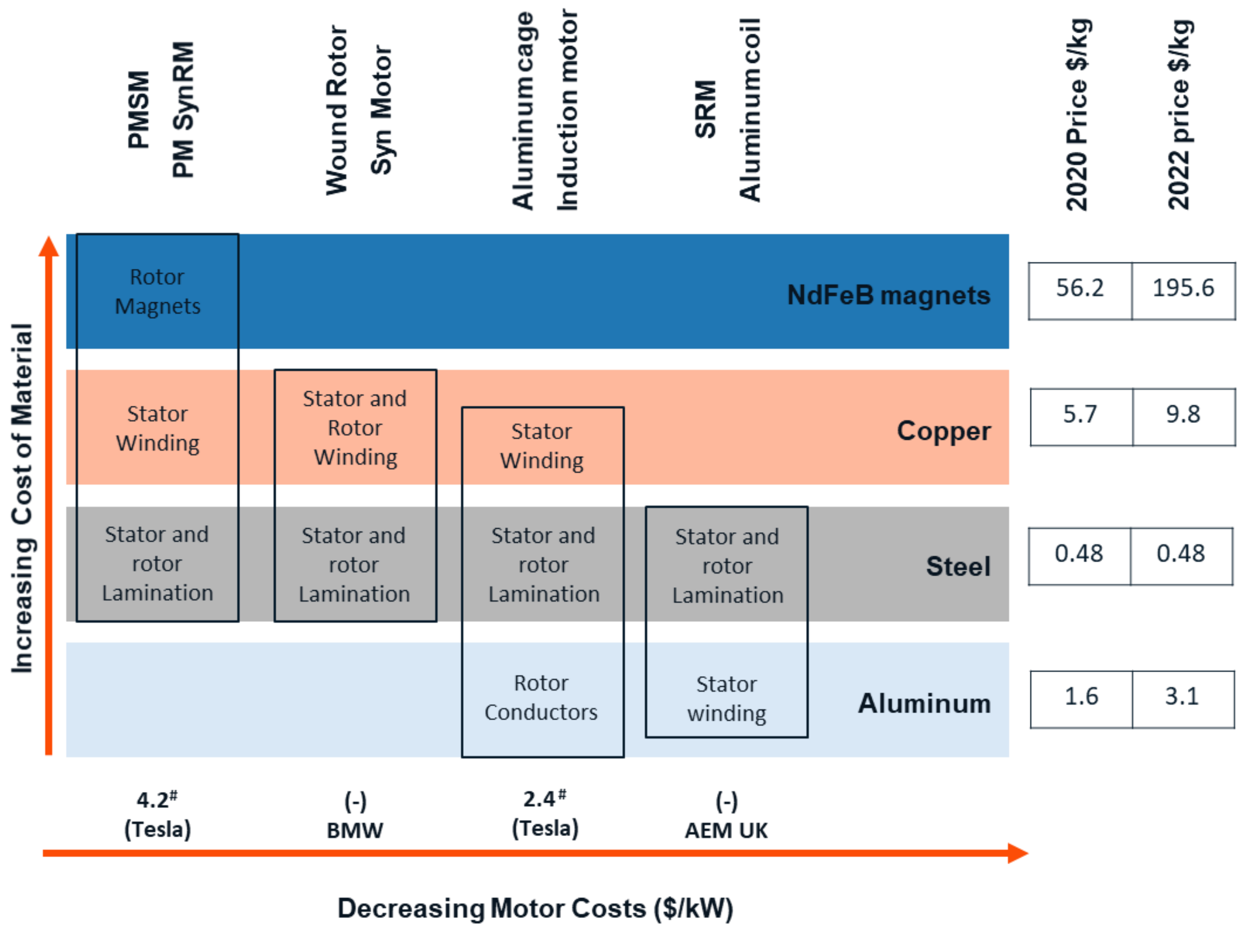

Figure 50: Different types of electric motors and materials used in different parts of their construction. #costs from Munro and Associates Motor teardown report [39]

The increasing cost of NdFeB magnets has pushed some automotive manufacturers to use other types of traction motors in their BEVs. BMW uses WRSMs in all their vehicles, while Rivian uses induction motors. Hence, 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 (α''-$Fe_{16}N_2$) 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.

3.2.6.2 Replacing Copper Stator Coils with Aluminum

Table 23 shows that there is about 6.8 kg of copper in the Tesla and VW ID3 motors. The price of copper has increased from $1.85 per kg in 2000 to $9.3 per kg in 2021 and is projected to rise above $15 per kg in 2025. Between 2021 and 2030, the global demand for copper is projected to increase by 900%, which could result in a significantly higher price for the metal.

Pre-compressed wound aluminum coils, as shown in Figure 51 (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 [139]. 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 51 (C and D).

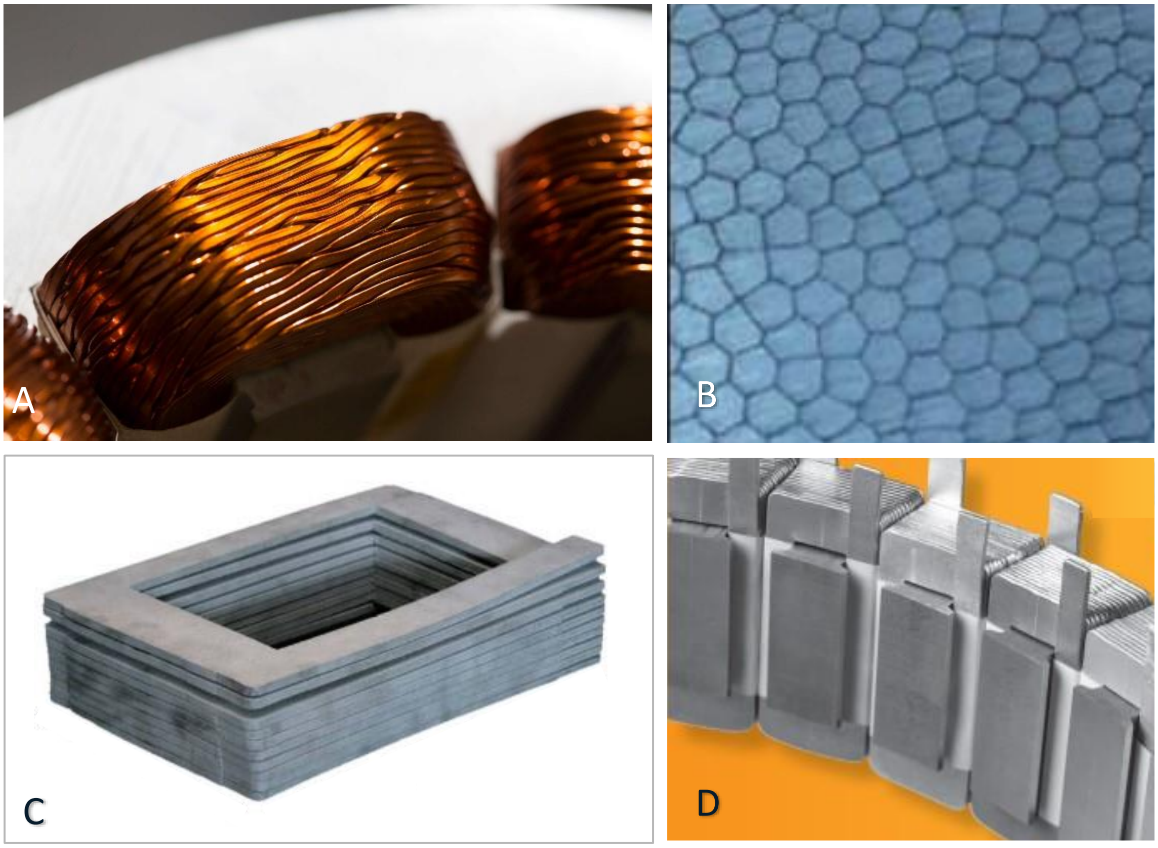

Figure 51: A: Compressed aluminum stator coil (AEM UK), and B), B: cross-section of the compressed aluminum coil, Cand D: die-cast aluminum coils C and D

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 52), 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.

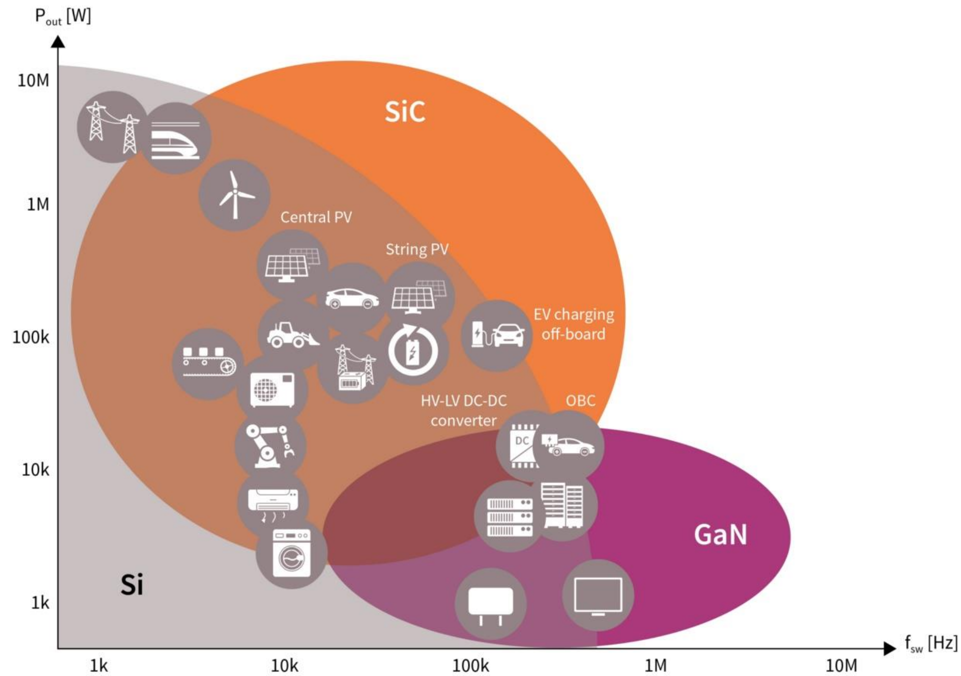

Figure 52: Wide-bandgap semiconductor applications. Source: Infineon [163]

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 53 provides an overview of trends in OBC design and the solutions they offer.

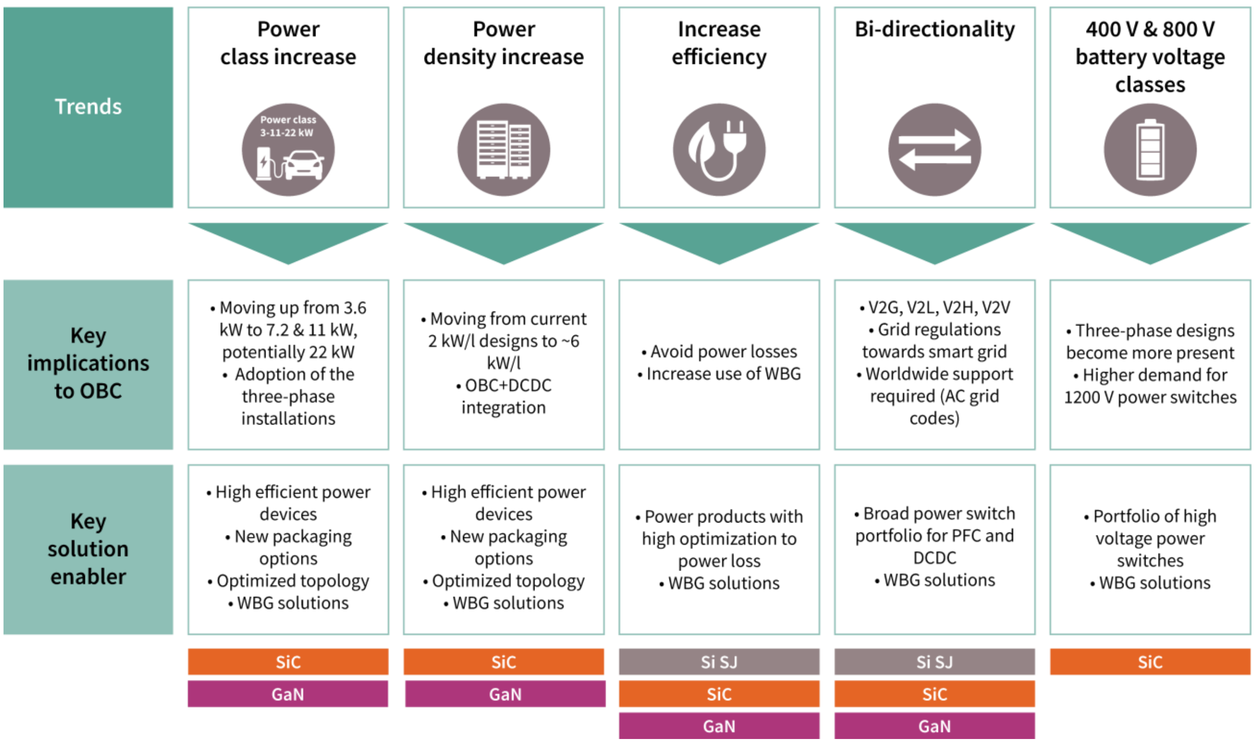

Figure 53: Developments in on-board charger (OBC) design. Source: Power Electronics News [165]

4. Results

This section presents the overall results of the incremental and TCO cost analysis for a BEV against an ICE for the considered LDVs in the 2030 timeframe. The incremental costs of each powertrain type are calculated to determine if purchasing a BEV over an ICE vehicle in 2030 is an attractive option for an individual. The incremental costs presented are conservative estimates, in which the lowest-cost ICE option is compared to the highest-cost BEV option. The powertrain cost inputs for light-duty ICE and BEV powertrains for a small car, medium car, small SUV, medium SUV, large SUV, and pickup truck are appended in Appendix 8.1.

4.1 Incremental Cost of BEV over ICEV

Figure 54 depicts the projected incremental costs of a BEV powertrain over an equivalent ICE powertrain under each of the electrification scenarios. A negative value implies that the cost of the BEV powertrain is cheaper than a comparable ICE powertrain. Converting from a SHEVP2 ICE powertrain to an LFP-based BEV powertrain results in the lowest incremental cost of electrification. Similarly, the highest incremental cost of electrification is derived from going from an HCR1/TURBO1 ICE powertrain to a high-cost NMC811 BEV powertrain. This study indicates that most BEVs with a range between 200 and 300 miles will be cheaper than an equivalent ICEV. The only exceptions are large SUVs and pickup trucks with 300 to 400 miles of range due to their poor energy efficiency (miles per kWh), which results in requiring a larger battery pack. Long-range BEV400s in the premium category are costlier than their ICE counterparts, whereas it is more favorable to migrate to BEV300s and BEV200s.

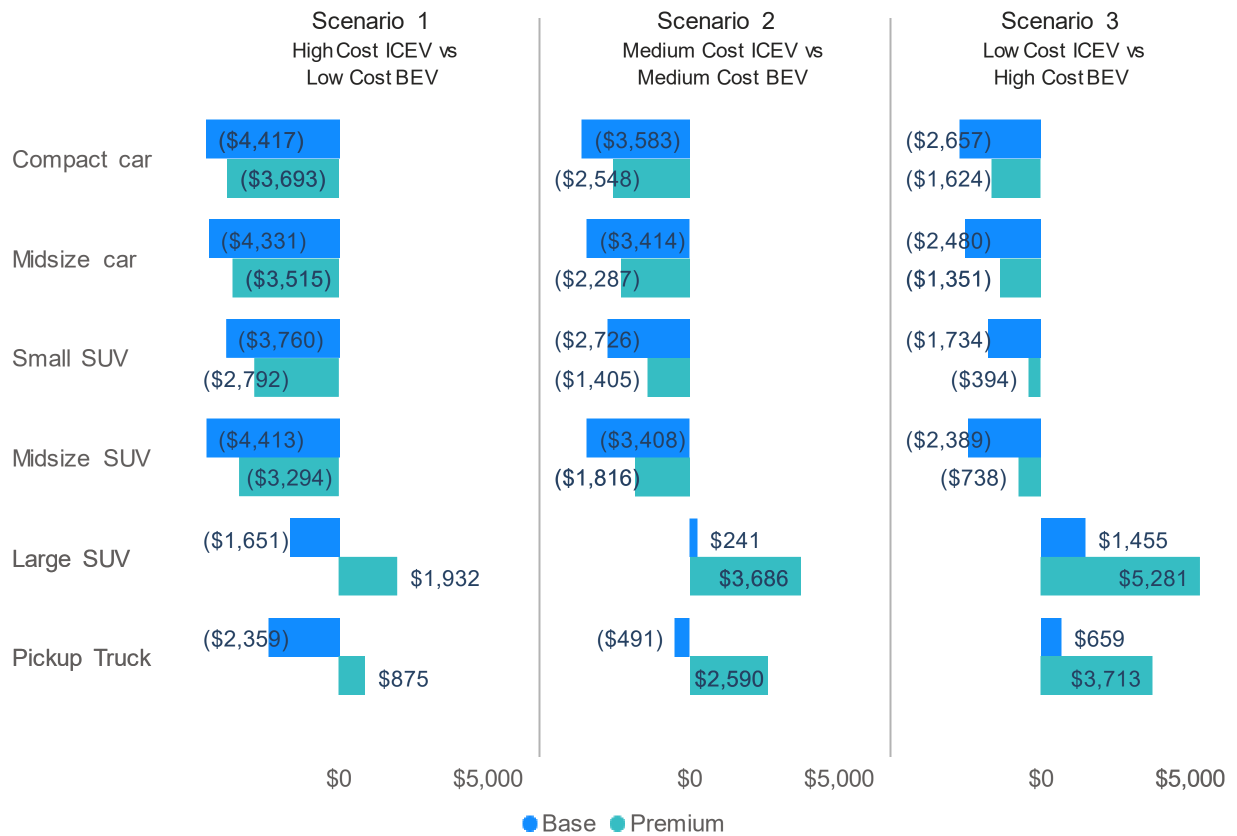

Figure 54: Summary of the projected range of incremental costs of BEV over ICE powertrain in 2030.

BEVs and ICEVs not only vary in their powertrain architecture but also in their upfront purchase price and operating costs that are incurred throughout the lifetime of ownership of these vehicles. The TCO starts with an upfront purchase price and factors in charging, including charger costs, fuel costs, and M&R costs in the 2030–2044 timeframe. As mentioned earlier, a retail price equivalent (RPE) multiplier of 1.5 for ICEVs and 1.2 for BEVs has been assumed to compute the vehicle purchase price, which has a direct bearing on the cost of ownership.

To account for the sensitivity towards charging, two scenarios have been developed, namely, residential charging and demand charging. We have considered residential-type and commercial charging scenarios that encompass the broad spectrum of users who would avail themselves of public charging as much as charging in a residential-type setting. The latter scenario is covered separately as a “what-if” scenario in Section 5.3 (Demand Charging). The analysis considers a 90:10 and 50:50 residential-to-public charging scenario to calculate the time to achieve parity with a 2030 purchase timeframe. A summary of cost inputs considered for ICE and BEV is shown in Table 24 (refer to

Appendix 8.2 for more details). An upfront cost of $1,000 for procurement and installation of a non-networked, level-2 charger of 11.5 kW is considered for both charging scenarios.

Table 24: Total Cost of Ownership (TCO) inputs

Vehicle type	Subclass	Segment	Vehicle Glider Price	ICE efficiency (mpg)			BEV Range (Miles)	BEV efficiency (kWh/mile)	Annual VMT* (miles)
				Scenario 1	Scenario 2	Scenario 3			
Car	Compact car	Base	$15,000	41	36	34	200	0.194	15,922
		Premium	$22,500	49	44	42	300	0.209	
	Midsize car	Base	$18,000	38	33	32	200	0.199	
		Premium	$27,000	46	38	36	300	0.215	
SUV	Small SUV	Base	$20,000	34	30	29	200	0.245	16,234
		Premium	$30,000	43	36	34	300	0.259	
	Midsize SUV	Base	$22,000	32	29	28	200	0.267	
		Premium	$33,000	40	35	33	300	0.286	
	Large SUV	Base	$24,000	24	21	20	300	0.365	18,964
		Premium	$36,000	31	27	26	400	0.409	
Pickup	Pickup Truck	Base	$26,000	27	24	23	300	0.332	
		Premium	$39,000	34	30	29	400	0.372	

4.2 Incremental Purchase Price of BEV over ICEV

Starting with the upfront purchase price to the consumer, Table 25 shows the purchase price of a BEV, including the cost of a home charger, relative to that of an equivalent ICEV. We project that BEV prices (including the cost of a home charger) in the base segment will be significantly lower than ICEV prices, thereby achieving immediate purchase price parity in 2030. In the premium segment, except for the large SUV in all three scenarios and the pickup truck in Scenarios 2 and 3, all the vehicle types would achieve parity immediately upon purchase.

Table 25: Incremental Purchase Price of a BEV including charger over an ICEV in 2030

Subclass	Scenario 1		Scenario 2		Scenario 3	
	Base	Premium	Base	Premium	Base	Premium
Small car	-$6,510	-$5,910	-$5,061	-$4,240	-$3,976	-$2,975
Midsize car	-$6,432	-$5,719	-$5,086	-$3,926	-$3,764	-$2,647
Small SUV	-$5,774	-$4,891	-$4,260	-$2,868	-$2,868	-$1,499
Midsize SUV	-$6,823	-$5,832	-$5,357	-$3,681	-$3,932	-$2,231
Large SUV	-$3,822	$399	-$1,064	$2,904	$548	$4,974
Pickup Truck	-$4,671	-$870	-$1,943	$1,589	-$406	$2,979

As with incremental powertrain costs, the four smaller vehicle segments show the potential for considerable consumer savings for both base (BEV200) and premium (BEV300) versions. The incremental purchase price for the largest two segments ranges from a savings of nearly $5,000 for a base pickup in Scenario 1 (low incremental BEV cost) to an additional cost of nearly $5,000 for a premium large SUV in Scenario 3 (high incremental BEV cost).

4.3 Total Cost of Ownership

Moving to the TCO analysis, the results indicate that all the LDVs in the base segment within the three scenarios of the incremental cost of electrification will reach parity in 2030 upon purchase. In the premium segment, except for the large SUV and pickup truck in Scenarios 2 and 3, all the vehicle subclasses would achieve parity immediately upon purchase. The premium versions of the large SUV and pickup truck could take around 4 years and 2 years, respectively, to achieve parity in Scenario 2; and the pickup could take around 8 years in Scenario 3 of electrification. BEV400 large SUV does not achieve parity in its lifetime in Scenario 3 of electrification.

Table 26 lists the time to achieve parity for a BEV with a comparable ICEV in the base and premium segments, respectively. In the base segment, all the vehicle subclasses are expected to achieve parity immediately upon purchase in 2030. In the premium segment, except for the large SUV and pickup truck, all classes of BEV are projected to achieve parity immediately with their equivalent ICEV. Projected TCO parity timeline plots across all three scenarios of the incremental cost of electrification are included in Appendix 8.3.

Table 26: Time to achieve parity for light-duty BEVs with a 2030 purchase timeframe in the base and premium segments

Vehicle type	Subclass	Segment	Scenario 1	Scenario 2	Scenario 3
Car	Compact (Small) car	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Midsize (Medium) car	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
SUV	Small SUV	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Midsize SUV	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Large SUV	Base	Immediate	Immediate	Immediate
		Premium	Immediate	4	End of Life
Pickup	Pickup Truck	Base	Immediate	Immediate	Immediate
		Premium	Immediate	2	8

Figure 55 depicts the cumulative net savings of BEVs over ICE during their lifetime of 15 years. Scenario 1 has the highest savings when migrating from a high-cost ICEV to a low-cost BEV, and vice versa in Scenario 3. Except for the BEV400 in Scenario 3, all subclasses and segments across the three scenarios demonstrate considerable savings, averaging $15,000, with BEV ownership compared to an ICEV.

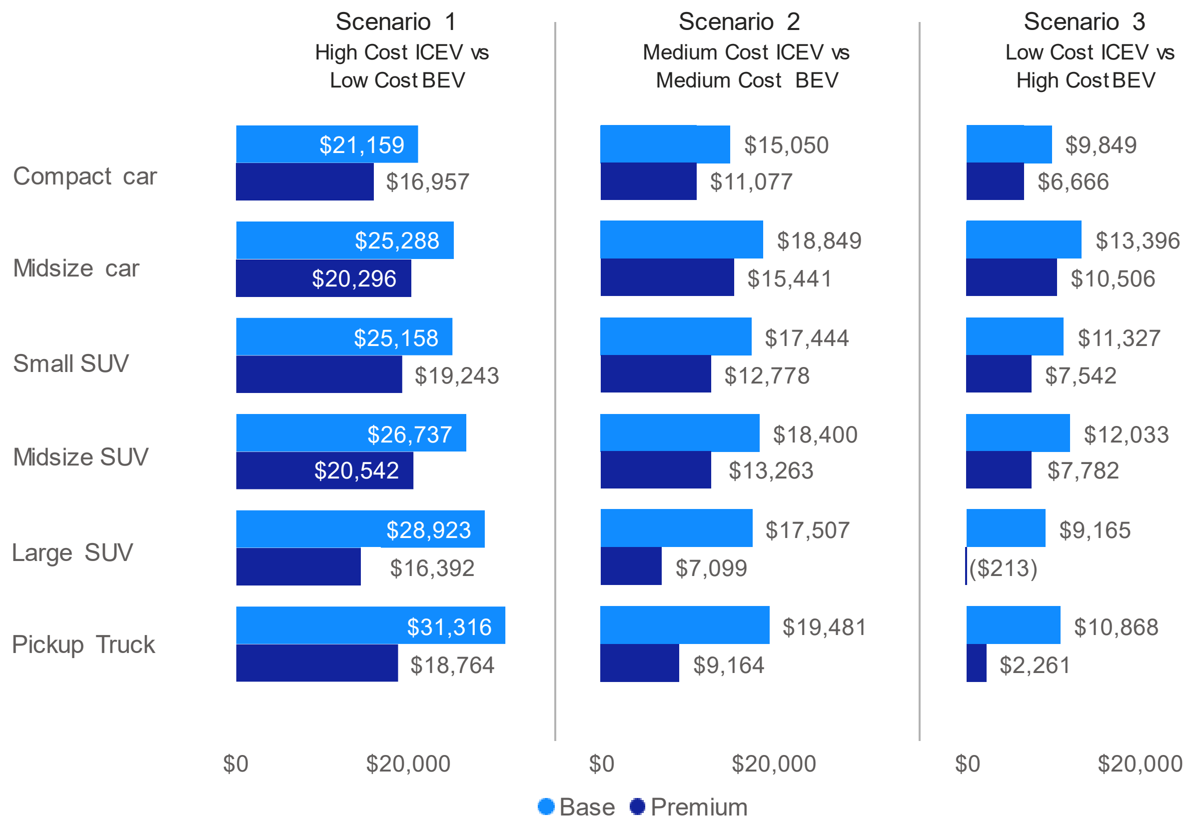

Figure 55: Projected cumulative net savings of a BEV over ICEV during its lifetime.

Figure 56 shows the projected range of TCO per mile in 2030 for the light-duty ICEVs and BEVs in the base and premium segments, respectively, with the residential charging scenario. The total sum of the vehicle purchase price and operating costs is discounted by 3% on an annual basis for the 15-year lifetime of the ICEVs and BEVs to arrive at a discounted cumulative TCO. TCO per mile is calculated by dividing the cumulative TCO by the lifetime miles traveled (annual VMT × 15 years). Except for the negligible difference in the premium large SUV BEV400 in Scenario 3, all the BEVs across all classes, segments, and scenarios have a lower TCO per mile compared to an equivalent ICEV.

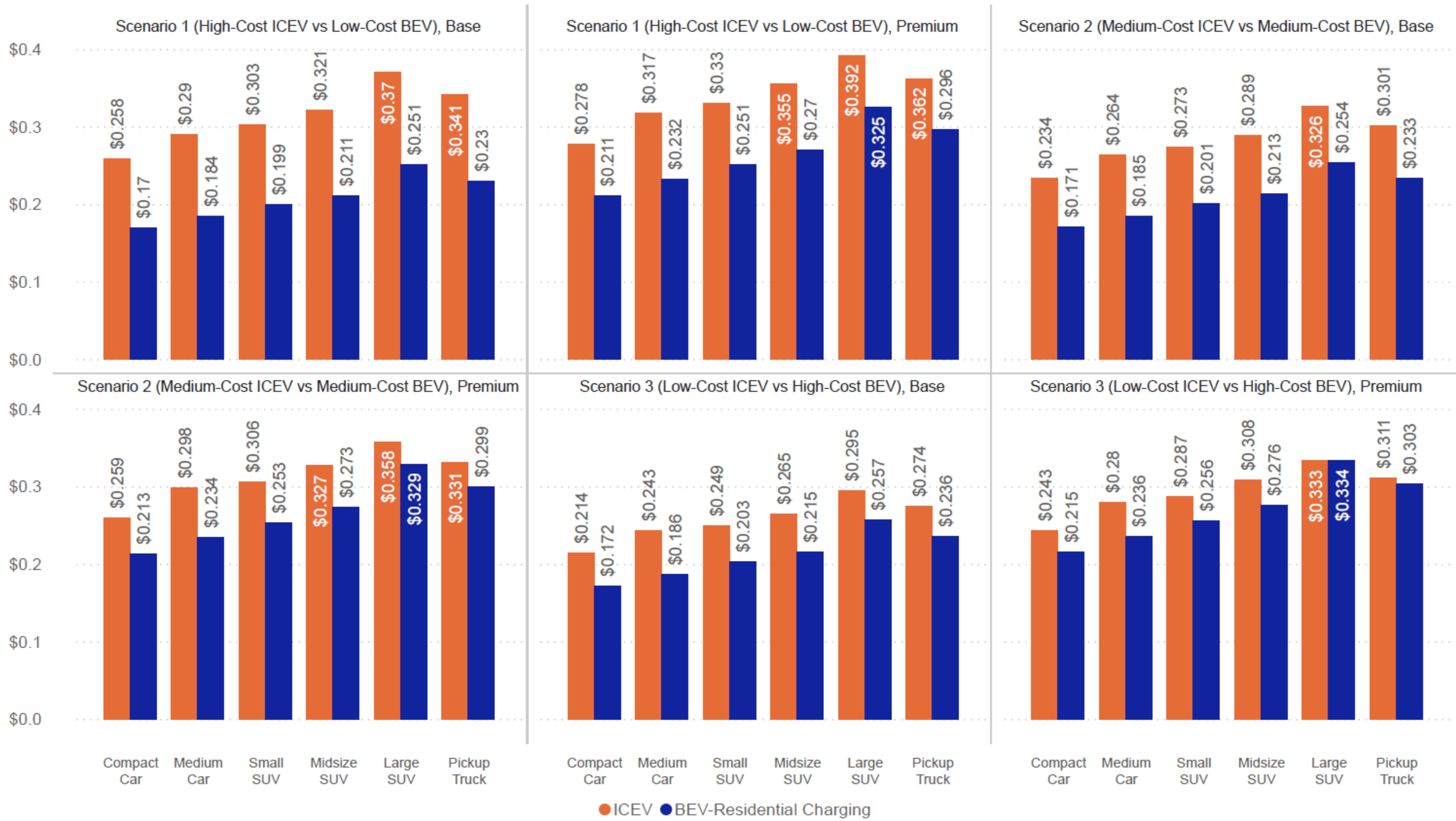

Figure 56: Projected range of Total Cost of Ownership (TCO) per mile in 2030 in a residential charging scenario.

4.3.1 Small car

The incremental cost of electrification across the electrification scenarios can vary from -$4,417 to -$2,657 and -$3,693 to -$1,624 in the base and premium segments, respectively. As shown in Figure 57, the TCO for an ICE-powered small car is 21.4¢ to 25.8¢ while for a comparable BEV, it is 17¢ to 17.2¢ in the base segment. However, in the premium segment, it is 24.3¢ to 28.2¢ for an ICEV, and 21.1¢ to 21.5¢ for a comparable BEV, as shown in Figure 58. The small car class is expected to achieve parity immediately in the 2030 purchase timeframe in the base and premium segments across all three scenarios with a varying incremental cost of electrification.

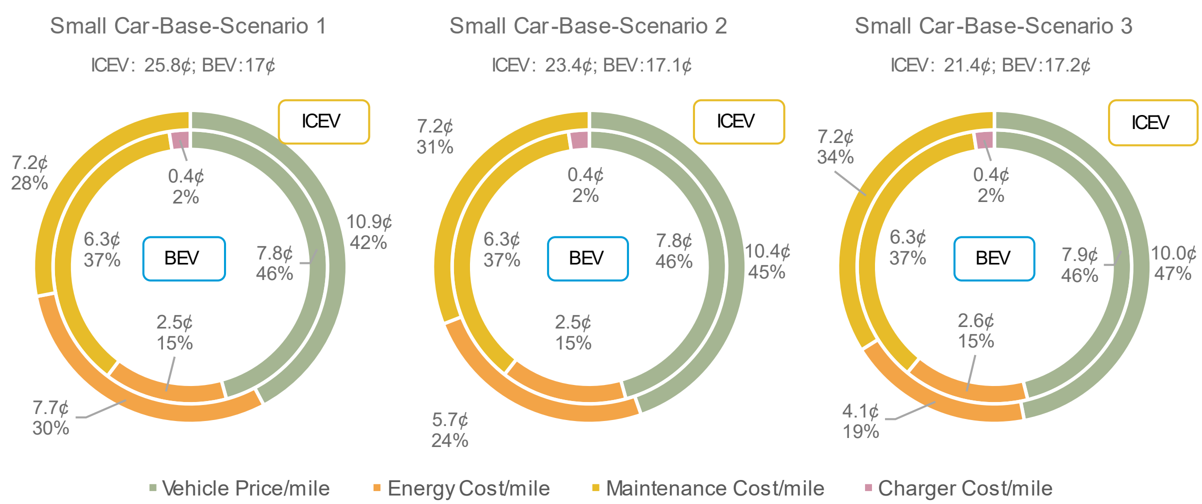

Figure 57: Small car base segment contributions to TCO scenarios.

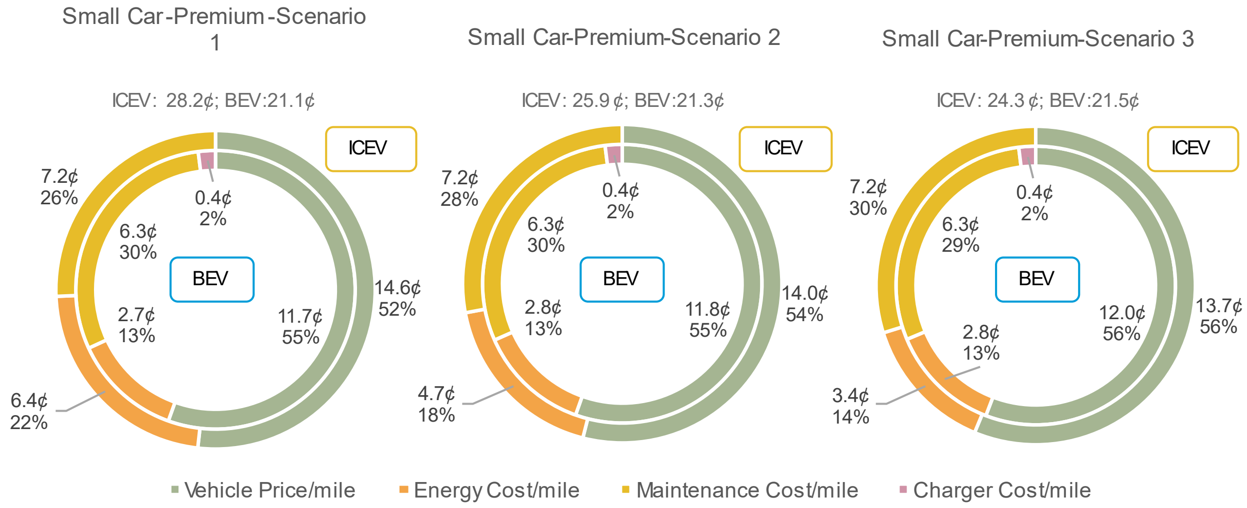

Figure 58: Small car premium segment contributions to TCO scenarios.

4.3.2 Medium car

The incremental cost of electrification across the three scenarios can vary from -\$4,331 to -\$2,480 and -\$3,515 to -\$1,351 in the base and premium segments, respectively. As shown in Figure 59, the TCO for an ICE-powered medium car is 24.3¢ to 29¢ while for a comparable BEV, it is 18.4¢ to 18.6¢ in the base segment. However, in the premium segment, it is 28¢ to 31.7¢ for an ICEV and 23.2¢ to 23.6¢ for a comparable BEV, as shown in Figure 60. The medium car class is expected to achieve parity immediately in the 2030 purchase timeframe in the base and premium segments across all three scenarios with a varying incremental cost of electrification.

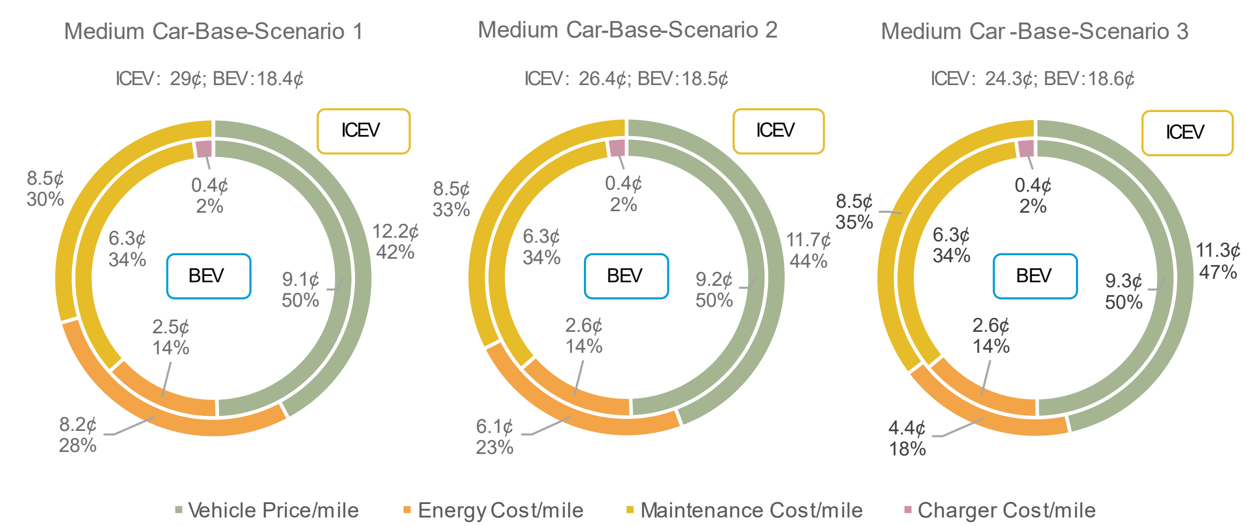

Figure 59: Medium car base segment contributions to TCO scenarios.

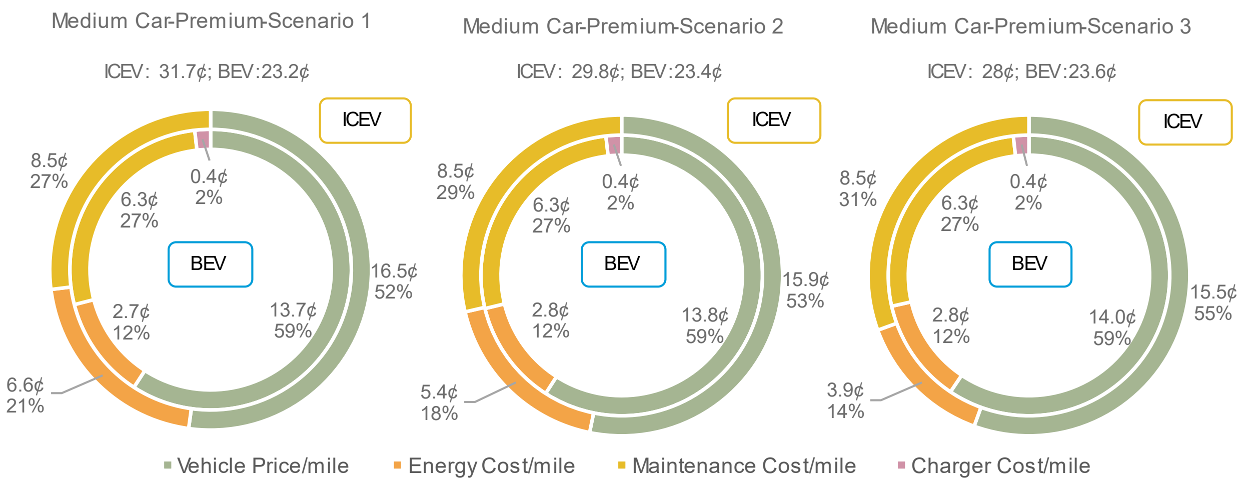

Figure 60: Medium car premium segment contributions to TCO scenarios.

4.3.3 Small SUV

The incremental cost of electrification across the three scenarios ranges from -$3,760 to -$1,734 and -$2,792 to -$394 in the base and premium segments, respectively. As shown in Figure 61, the TCO for an ICE-powered small SUV is 24.9¢ to 30.3¢ while for a comparable BEV, it is 19.9¢ to 20.3¢ in the base segment. However, in the premium segment, it is 28.7¢ to 33¢ for an ICEV and 25.1¢ to 25.6¢ for a comparable BEV, as shown in Figure 62. The small SUV is expected to achieve parity immediately in the 2030 purchase timeframe in the base and premium segments across all three scenarios with varying incremental costs of electrification.

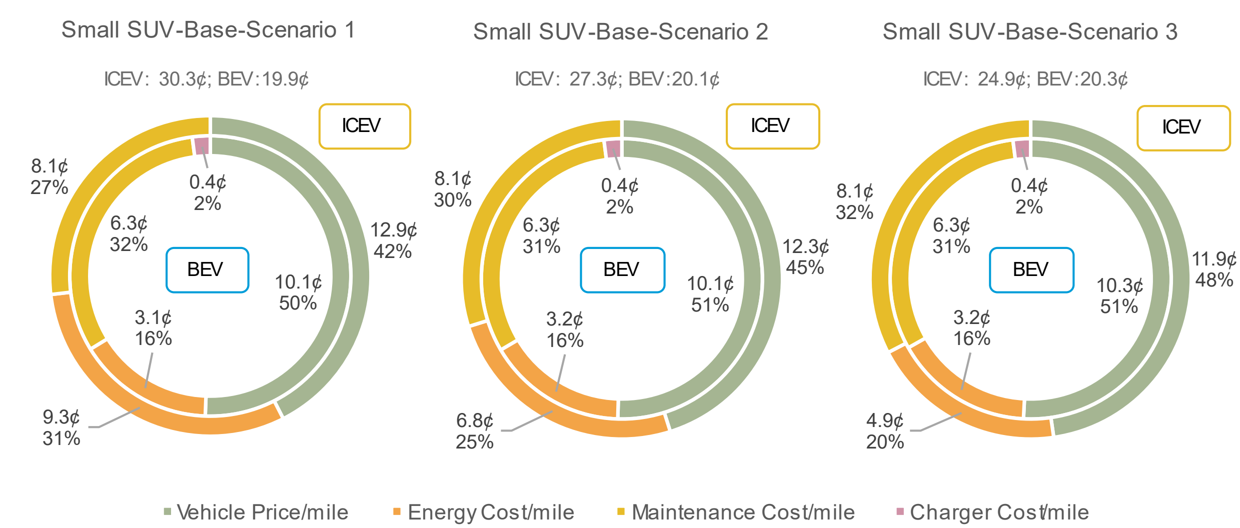

Figure 61: Small SUV base segment contributions to TCO scenarios.

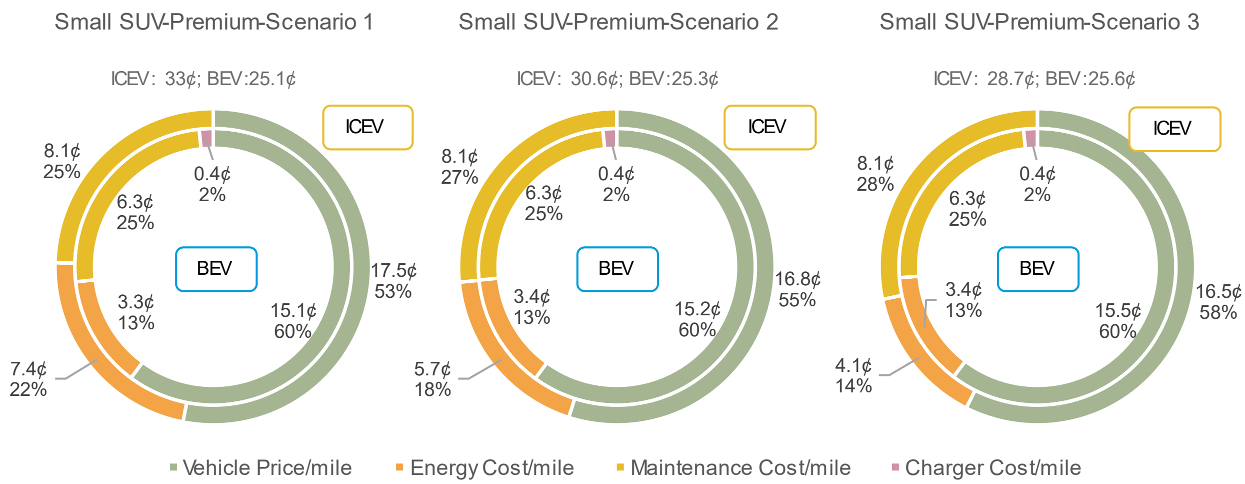

Figure 62: Small SUV premium segment contributions to TCO scenarios.

4.3.4 Midsize SUV

The incremental cost of electrification across the three scenarios ranges from -$4,413 to -$2,389 and -$3,294 to -$738 in the base and premium segments, respectively. As shown in Figure 63, the TCO for an ICE-powered midsize SUV is 26.5¢ to 32.1¢ while for a comparable BEV, it is 21.1¢ to 21.5¢ in the base segment. However, in the premium segment, it is 30.8¢ to 35.5¢ for an ICEV and 27¢ to 27.6¢ for a comparable BEV, as shown in Figure 64. The midsize SUV is expected to achieve parity immediately in the 2030 purchase timeframe in the base and premium segments across all three scenarios with varying incremental costs of electrification.

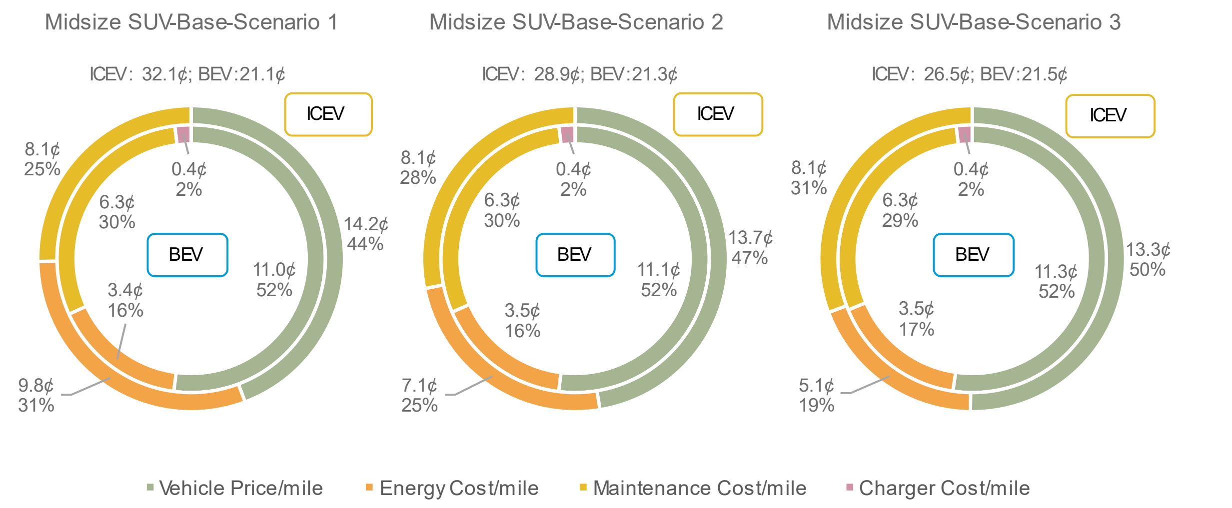

Figure 63: Midsize SUV base segment contributions to TCO scenarios.

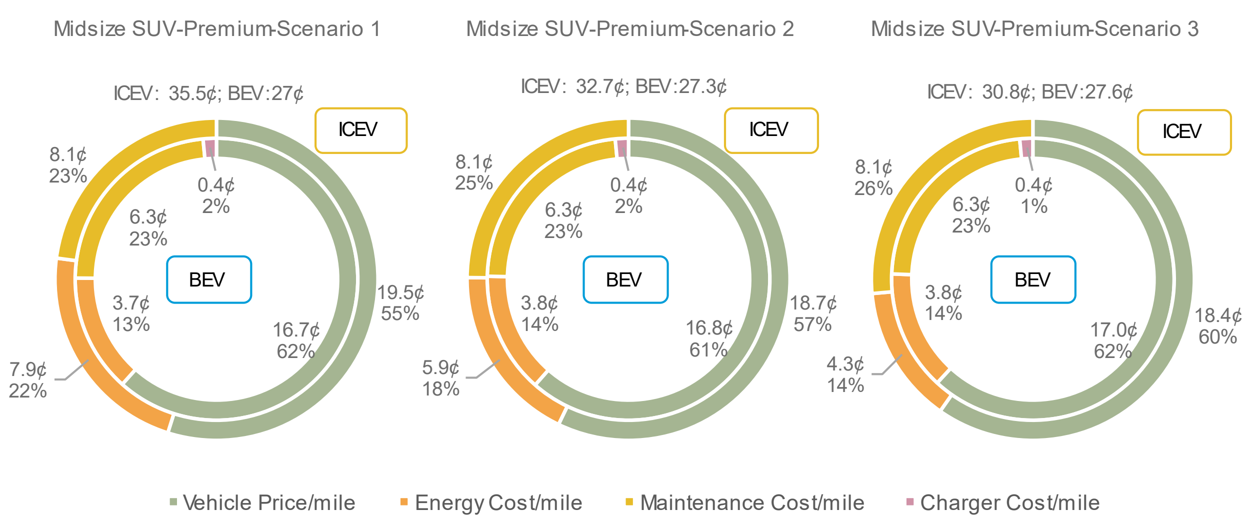

Figure 64: Midsize SUV premium segment contributions to TCO scenarios.

4.3.5 Large SUV

The incremental cost of electrification across the low, medium, and high scenarios can vary from -$1,651 to $1,455 and $1,932 to $5,281 in the base and premium segments, respectively. As shown in Figure 65, the TCO for an ICE-powered large SUV is 29.5¢ to 37¢ while for a comparable BEV, it is 25.1¢ to 25.7¢ in the base segment. However, in the premium segment, it is 33.3¢ to 39.2¢ for an ICEV and 32.5¢ to 33.4¢ for a comparable BEV, as shown in Figure 66. The large SUV BEV300 is expected to achieve parity immediately in the 2030 purchase timeframe in the base segment across all three scenarios with varying incremental costs of electrification. However, in the premium segment, although it achieves parity immediately in Scenario 1, it could take 4 years in the medium-cost Scenario 2. However, a premium large SUV BEV400 would not achieve parity within its lifetime in Scenario 3.

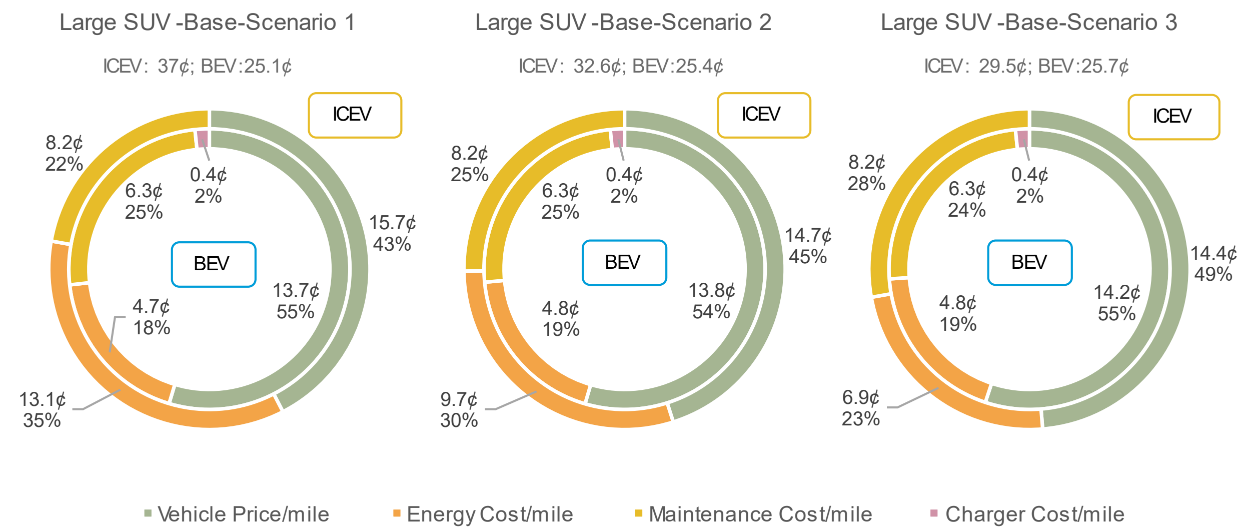

Figure 65: Large SUV base segment contributions to TCO scenarios.

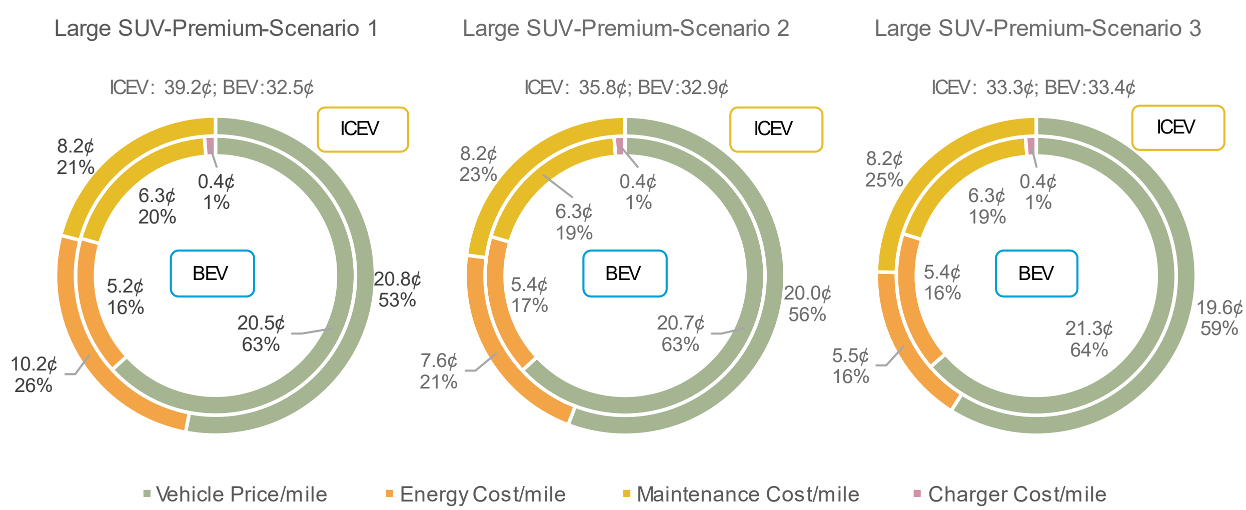

Figure 66: Large SUV premium segment contributions to TCO scenarios.

4.3.6 Pickup Truck

The incremental cost of electrification across the low, medium, and high scenarios can vary from -$2,359 to $659 and $875 to $3,713 in the base and premium segments, respectively. As shown in Figure 67, the TCO for an ICE-powered pickup truck is 27.4¢

to 34.1¢ while for a comparable BEV, it is 23¢ to 23.6¢ in the base segment. However, in the premium segment, it is 31.1¢ to 36.2¢ for an ICEV and 29.6¢ to 30.3¢ for a comparable BEV, as shown in Figure 68. The pickup truck is expected to achieve parity immediately in the 2030 purchase timeframe in the base segment across all three scenarios with varying incremental costs of electrification. However, in the premium segment, although BEV400 achieves parity immediately in Scenario 1, it could take around 2 and 8 years in Scenario 2 and 3, respectively.

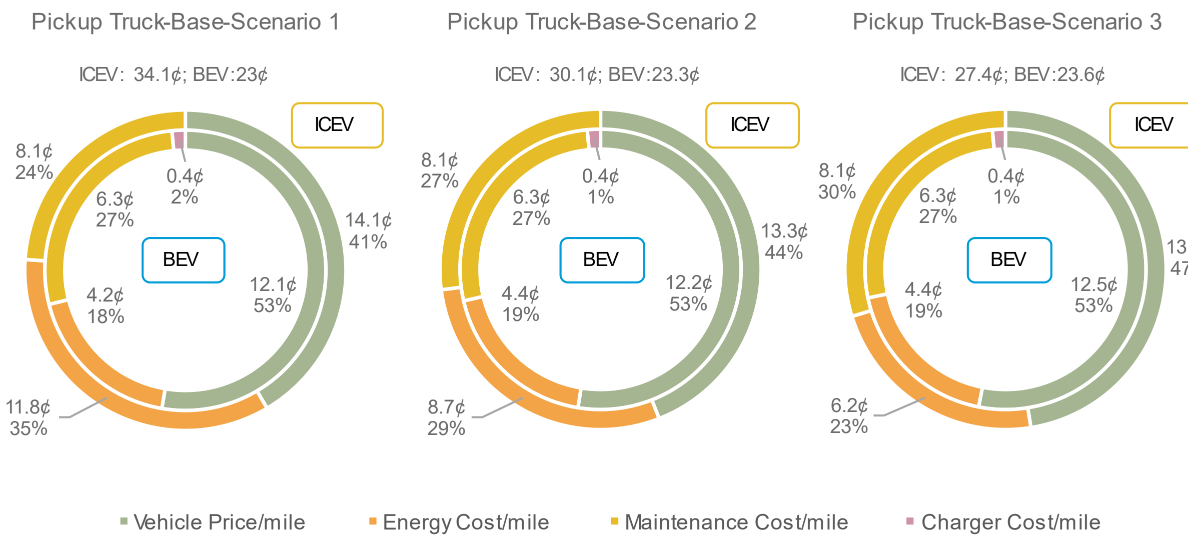

Figure 67: Pickup Truck base segment contributions to TCO scenarios.

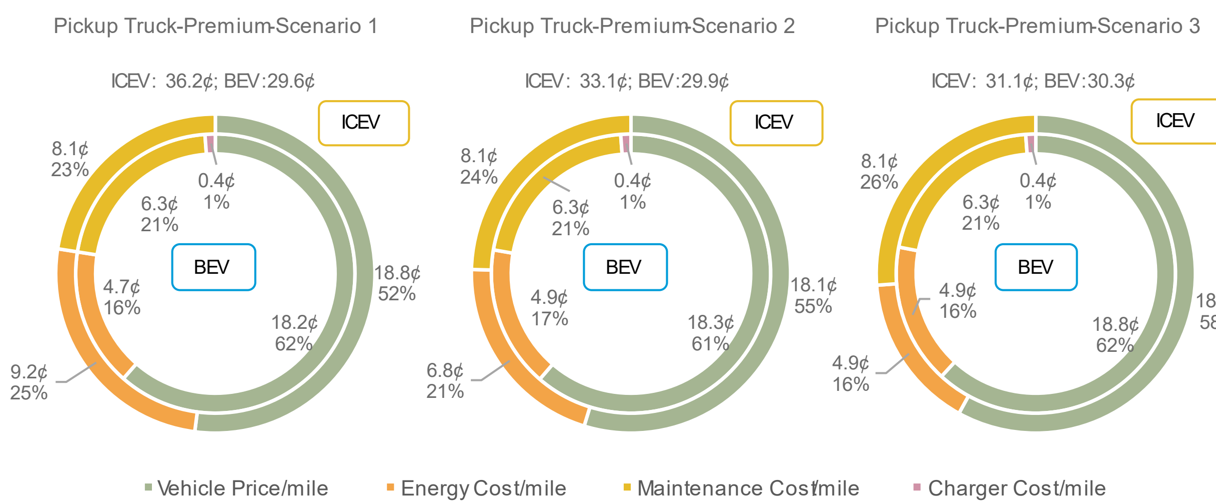

Figure 68: Pickup Truck premium segment contributions to TCO scenarios.

5. What-if Scenarios

5.1 Lightweighting

Table 27 compares the Tesla Model 3, a dedicated BEV, with the BMW i4 and BMW 430i that share a platform with the representative 2030 BEV300 medium car simulated by ANL (high efficiency without light-weighting). It is observed that a dedicated BEV is significantly lighter than the BEV that shares its platform with an ICE vehicle. Also, the Tesla Model 3 has a higher energy efficiency than the 2030 ANL vehicle even when being 600 lbs. heavier.

Table 27: Comparison of a medium car dedicated BEV vs BEV that shares a BEV platform Vs a dedicated BEV Vs ANL simulated medium car 2030 BEV300 (high efficiency without light-weighting)

Vehicle	BMW 430i Grand Coupe	BMW I4 i4e Drive 40 Gran Coupe	Tesla Model 3 standard range plus	ANL study-medium car 2030 BEV300
Wheelbase (in)	112.4	112.4	113.2	
Track (in)	62.9	62.9	62.2	
Footprint (sq. ft.)	49.09	49.09	48.89	
Platform	ICE - BEV shared	ICE - BEV shared	Dedicated BEV	
Battery capacity (kWh)	-	84	50	56
Power (kW)	190	250	192	124
0-60 (s)	5.8	5.5	5.8	6
EV range (miles)	-	279	273	300
Curb weight (lbs.)	3792	4680	3648	3044
Pack energy density (Wh/kg)		149	126	344
Battery Chemistry	-	NMC	LFP	-

Tesla has a battery pack energy density of 126 Wh/kg while the latest cell-to-pack LFP and NCM battery packs have an energy density of 160 Wh/kg and 250 Wh/kg, respectively [126]. Energy density increase from 126 Wh/kg to 250 Wh/kg will result in a 200 lb. weight saving of the Tesla battery pack. Weight saving in an IC engine vehicle comes at a price premium (usually cost with a $/kg of weight saving), while new battery pack construction results in a simpler and cheaper battery pack.

A structural battery pack that becomes a load-carrying fully stressed part of the final vehicle body decreases the stiffness requirements and weight of the vehicle unibody. This again leads to lower material costs and reduced vehicle weight. In the next few years, without any breakthrough technology, this will result in a Tesla Model 3 equivalent vehicle that is significantly lighter and requires less than a 50 kW battery pack to travel 273 miles. This reduction in required battery capacity will significantly reduce the battery cost of future EVs. Lightweighting is not factored as a cost reduction for this study but is believed to be a significant pathway to reduce the cost of manufacturing in the future and help with the optimization of the current battery packs for higher efficiency,

5.2 Towing

The vehicle range decrease due to towing a trailer is dependent not only on the weight of the trailer but also on the aerodynamics of the trailer. At highway speeds, a heavy trailer with a low frontal area will lead to a less reduction in range compared to a lighter trailer with a high frontal area (empty horse carriage). A quantification of range reduction when towing is beyond the scope of this study.

With the rollout of DCFC infrastructure, and the ability to be able to charge 20%-80% in less than 20 minutes, occasional towing is a use case that can be supported with present battery technology. For example, the range of Rivian R1T comes down by 50% or lesser when towing [140]. We have sized a 400-mile range for large SUVs and pickup trucks in this study. With improvements in battery technology, higher ranges with towing are possible in the 2030 timeframe.

5.3 Demand Charging

Demand charging is defined as non-residential charging in public or on highways. To factor in an urban scenario where the charging is more demand-based, an equal mix of residential charging and public charging is assumed. When compared to the residential charging scenario, the equal split in charging results in an average increase of 75% in the charging costs from 16 ¢/kWh to 28 ¢/kWh. However, the end effect on the TCO per mile on an average across all classes and segments goes up to 27¢ from 24¢, nearly a 12.5% change. The time to achieve parity is still immediate in most scenarios across all vehicle subclasses and segments. However, in scenarios 2 and 3 of the premium segments of the large SUV and the pickup truck, BEV400s never achieve parity. Increased degree of public charging results in high charging costs per annum for the BEV400 models of large SUVs and pickup trucks which makes the discounted cost of ownership costlier than an equivalent ICEV. Table 28 summarizes the time to achieve TCO parity in the demand-based charging scenario across all vehicle types and segments with a 2030 purchase timeframe.

Table 28: Time to achieve parity for light-duty BEVs with a 2030 purchase timeframe in the base and premium segments

Vehicle type	Subclass ANL	Segment	Scenario 1	Scenario 2	Scenario 3
Car	Compact car	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Midsize (Medium) car	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
SUV	Small SUV	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Midsize SUV	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Large SUV	Base	Immediate	Immediate	9
		Premium	Immediate	End of Life	End of Life
Pickup	Pickup Truck	Base	Immediate	Immediate	Immediate
		Premium	Immediate	End of Life	End of Life

Figure 69 shows the comparison of TCO per mile in 2030 with both charging settings for Scenario 2 in the base and premium segments, respectively. A split of 90:10 and 50:50 has been considered for residential and demand-based charging scenarios, respectively. Except in Scenarios 2 and 3 in the premium segment of the large SUV class and Scenario 3 of a premium pickup truck, all the TCOs per mile for light-duty BEVs are less than those for ICEVs.

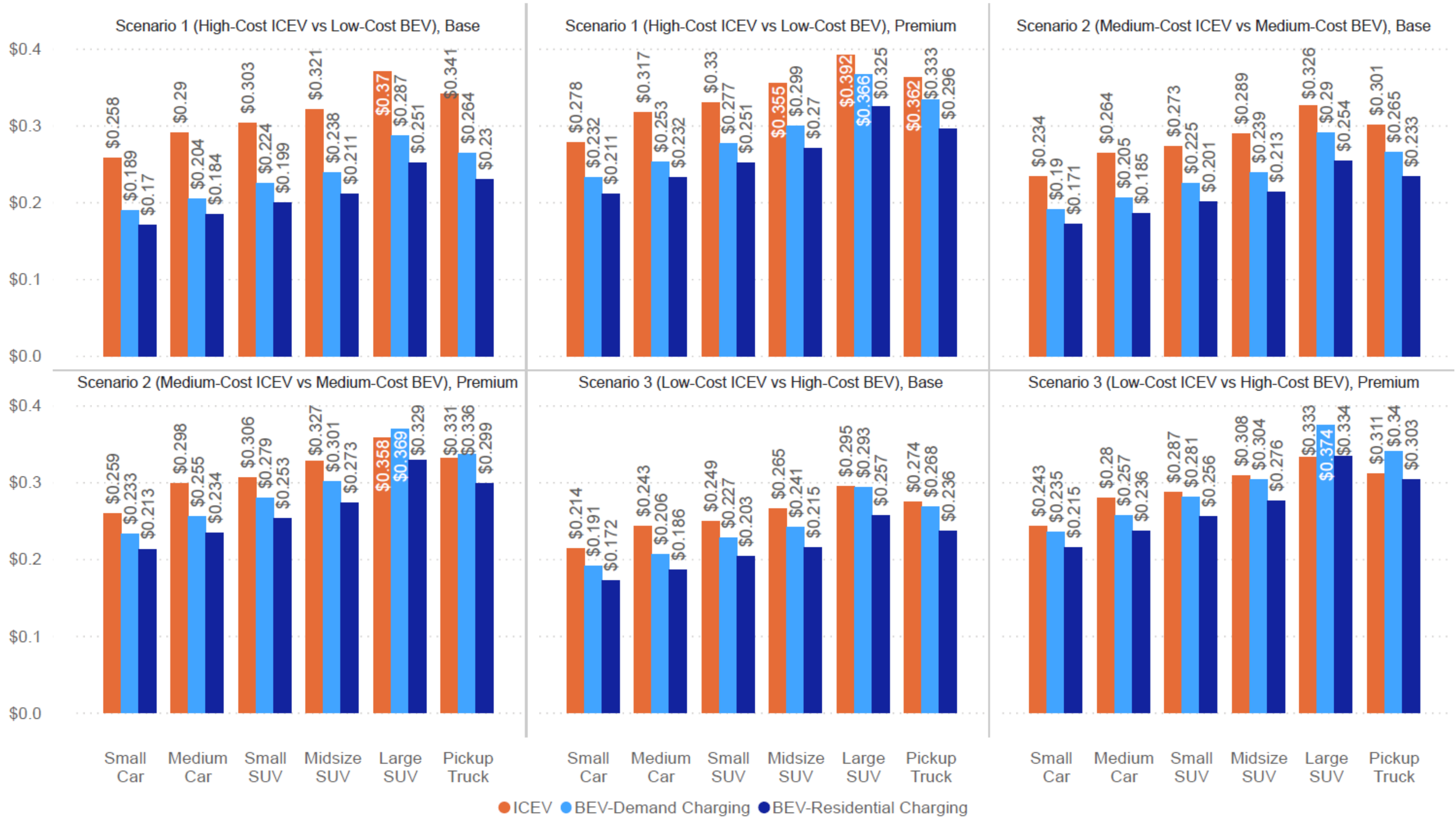

Figure 69: Projected range of Total Cost of Ownership (TCO) in $/mile in 2030 with the demand based (50/50) and residential (90/10) charging scenario

BEV ownership is found to be economical compared to an ICEV, despite considering an extreme demand-based charging scenario where 50% of the user's charges would be at a DCFC public charging station. This is due to the cumulative savings that a consumer would gain with BEV ownership due to low operating and maintenance costs compared to an ICEV. In the base segment, all the vehicle subclasses are expected to achieve parity immediately upon purchase in 2030. In the premium segment, except for the large SUV and pickup truck, all classes of BEV are projected to achieve parity with their comparable ICEV.

On average, across all vehicle subclasses and segments, the TCO per mile is 30.6¢ for an ICEV, and 26.3¢ for a BEV, which means that the TCO per mile of a BEV is ≈14% lesser than an ICEV. It brings forth the fact that the savings are greater with BEV ownership when compared to ICEV ownership, irrespective of the charging preference. Projected TCO per mile across all three scenarios of the incremental cost of electrification along with the parity plots are included in Appendix 8.4.

5.4 Fleetwide Sales-Weighted Average Cost

From the perspective of compliance to meet the stringent GHG and fuel economy standards, regulatory cost components due to technology application also weigh against the ICEV when compared to BEV. NHTSA in collaboration with EPA has established CAFE standards for model years (MYs) 2024–2026 passenger cars (PC) and light trucks (LT) [11]. The agency analyzed a range of action alternatives with fuel economy stringencies that increase annually for the automakers to conform with. The estimates define fleetwide fuel economy based on production volumes of the estimated future fleets of new passenger cars and light trucks across all manufacturers. As the GHG and fuel economy standards are expected to be increasing in stringency beyond 2026, an effort is made here to project the fleetwide sales-weighted average powertrain cost of an ICEV to compare it with a BEV using three different scenarios in the 2030 timeframe. This direct comparison demonstrates the cost savings resulting from the adoption of BEV for a typical consumer.

To estimate the fleetwide sales-weighted average powertrain cost of an ICEV, the market penetration projections for the base (HCR) and premium (TURBO) engine technologies with electrification pathways (conventional, mild hybrid, strong hybrid) from the *EPA CCEMS Post Processing Tool Project - Technology Utilization* sheet are used. The powertrain cost estimates used in the primary analysis (refer to section 2.1) from the CAFE model [1] for HCR1 and TURBO1 technologies are used as cost inputs. The electrification pathways considered are conventional (CONV), start-stop 12-Volt (SS12V), BISG, and strong hybrid (SHEV). We did not calculate an ICEV cost for a vehicle with start-stop technology. However, NHTSA/EPA projected that a significant percentage of the fleet would have this technology in the *Vehicles Report FRM* sheet. Since the cost of SS12 is roughly halfway between that of a non-electrified vehicle and one with BISG, we assigned half of the SS12V vehicles to non-electrified and half to BISG. We assigned the cost of our vehicles with HCR engine technology to those NHTSA/EPA vehicles with SOHC, DOHC, EFR, VVT, VVL, SGDI, and DEAC; advanced engine technology pathways such as HCR0, HCR1, and HCR2. We assigned the cost of our vehicles with TURBO engine technology to those NHTSA/EPA vehicles with TURBO1, TURBO2, TURBOAD, and TURBOD pathways. This allows for capturing 75% of the market share for analysis accounting for the majority of the projected ICE technologies with another 20% shared with BEVs. Cost estimates taken from the Volpe sheets for the analysis are used here without the RPE to compare the fleetwide sales-weighted average direct costs of ICE powertrains against a BEV. The technology utilization sheet projects market penetration up to MY2029. Hence, for this analysis, we have considered MY2029 sales numbers. Per the technology utilization sheet, the market share of MY 2029 PC and LT is assumed to be 48% and 52%, respectively. Of the six vehicle subclasses considered in this study, based on the CAFE and GHG regulatory definitions, the small car, medium car, small SUV, and medium SUV are considered passenger cars as they have a GVWR below 6000 lbs., while the large SUV and pickup truck are considered as light trucks as they are above 6000 lbs. [20], [36]. The three scenarios explored to develop the sales-weighted average costs are:

a) Scenario A: No action alternative assumes that MY 2024–2026 CAFE standards continue to apply for MY 2027 and beyond. It provides an analytical baseline for comparison.
b) Scenario B: Migration of all CONV to BISG; SHEV remains the same.
c) Scenario C: Migration of all CONV to BISG and SHEV with a 60:40 split, respectively.

The technology utilization report projects the share of BEV200 and BEV300 based on vehicle-level electrification paths. BEV300 has a higher penetration rate (18%) compared to a BEV200 (2%) in the 2030 timeframe, hence, only the BEV300 powertrain is considered for comparison. Forecasting the market share of BEV400 is outside the scope of this analysis, as neither EPA nor NHTSA considered BEVs of this range. Both EPA and NHTSA imposed stringent limits on the conversion of ICEVs to BEV200 technology, which encouraged conversion to BEV300 technology. Table 29 summarizes the projected fleetwide sales-weighted average costs of PC and LT for MY 2029. There would be some ICEVs that will neither have HCR nor TURBO and would utilize a completely different technology pathway. However, they have not been considered in this analysis as these two powertrain technologies are projected to be prevalent in MY 2029. Steps to compute the fleetwide sales-weighted average cost along with the relevant breakdown of sales are included in Appendix 8.5.

Table 29: Projected fleetwide sales-weighted average powertrain costs for MY 2029 passenger cars (PC) and light trucks (LT)

Powertrain	Scenario A (No action)		Scenario B (Migration to mild hybrids)		Scenario C (Migration to mild and strong hybrids)	
	PC	LT	PC	LT	PC	LT
ICE MY 2029	$6,829	$8,471	$7,271	$8,626	$7,562	$8,841
BEV300	$5,621	$7,855	$5,621	$7,855	$5,621	$7,855

As can be seen in Table 29, the cost of ICE continues to increase for meeting the anticipated higher stringency requirements beyond 2026. The associated technology cost of ICE increases, assuming the projected sales, with the migration to mild and strong hybrids. Furthermore, the fleetwide sales-weighted average cost of BEV300 is lower compared to an ICEV across both the PC and LT segments.

5.4.1 Fleetwide Sales-Weighted Average Cost of each Subclass

For the proposed and final rulemaking, EPA chose the CAFE Compliance and Effects Modeling System (CCEMS) for modeling light-duty GHG compliance and costs for the revised MYs 2023–2026 GHG standards to estimate the associated technology pathways and their costs that manufacturers might choose. The CCEMS-generated output *Vehicles Report* data has been split into separate framework-OEM (FWO) and non-framework-OEM (NFWO) fleets to account for the impacts of the California Framework Agreement. In the No-Action case, FWOs have to meet the more stringent Framework emission targets while having access to the additional advanced technology incentive multipliers of the Framework. NFWOs are assumed to meet the less stringent Safer Affordable Fuel-Efficient (SAFE) standards while having access to no advanced technology multipliers [13]. All manufacturers have to meet the same standards in all of EPA's "action" scenarios.

The MY 2030 sales numbers, as listed in Table 30, are from the *EPA CCEMS Post Processing Tool Project – CAFE Model Runs – Output – Vehicles* Report of *20_FWO_Final* and *20_NFWO_Final,* respectively, where "final" indicates the promulgated EPA standards. HCR and TURBO engine technology pathways with an individual combination of electrification pathways of CONV, SS12V, BISG, and SHEVP2 have been considered. As stated earlier, half of the SS12V vehicles have been assigned to non-electrified (CONV) and half to BISG. The technology class/vehicle subclass in the *Vehicles Report* has been grouped to get the aggregate sales number for each vehicle subclass. For instance, SmallCar and SmallCarPerf have been clubbed together to get the sales numbers within each technology pathway. Engine technology options such as diesel engines, advanced cylinder deactivation (ADEAC), variable compression ratio (VCR), variable turbo geometry engine (VTG), VTG with eBooster (VTGE), SHEVPS, P2HCR1, PHEVs, and BEVs have not been considered for analysis as these are separate engine-level paths. It can be observed that this analysis includes 10.94 million vehicles by sales of the overall 12.79 million ICEVs by sales of MY 2030.

Table 30: Projected sales for MY 2030 for LD classes within each technology pathway.

MY 2030 Subclass	HCR CONV	HCR BISG	HCR SHEVP2	TURBO CONV	TURBO BISG	TURBO SHEVP2	Sum of Sales	Total Overall Sales	Sales % covered by the analysis
Small Car	1,594,192	135,632	0	300,213	110,524	0	2,140,560	2,178,172	98%
Medium Car	957,605	42,398	4,650	590,045	233,027	24,646	1,852,370	2,024,882	91%
Small SUV	1,717,497	613,655	38,750	453,008	681,800	0	3,504,709	4,261,876	82%
Midsize SUV	475,523	155,621	703,260	227,678	630,121	28,766	2,220,968	2,457,388	90%
Pickup Truck	395,276	161,029	240,315	3,542	77,396	352,370	1,229,926	1,872,177	66%

The sales-weighted average cost for each class has been computed using the formula, [Σ (Powertrain Costs × Sales) ÷ (Sum of Sales)]. ICEV cost per base and premium vehicle by technology are taken from Table 6 above (or refer to Appendix 8.1). Table 31 lists the powertrain costs considered in the study for the respective combination of technology pathways representing base and premium segments with the sales-weighted average cost.

Table 31: ICE powertrain costs and the sales-weighted average cost in 2030.

Subclass	HCR1 SHEVP2	HCR1 BISG	HCR1 CONV	TURBO1 SHEVP2	TURBO1 BISG	TURBO1 CONV	Sales Weighted Average Cost
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3	
Small Car	$7,366	$6,631	$5,960	$8,261	$7,273	$6,754	$6,181
Medium car	$7,447	$6,631	$5,960	$8,339	$7,273	$6,754	$6,429
Small SUV	$7,540	$6,631	$5,960	$8,469	$7,273	$6,754	$6,453
Medium SUV	$8,425	$7,556	$6,885	$9,599	$8,338	$7,819	$7,963
Pickup Truck	$9,468	$7,845	$7,326	$9,733	$8,398	$8,254	$8,572

Table 32 lists the powertrain costs for BEVs 200/300 within each scenario. Scenario 2 i.e., BEVs 200/300 with NMC811 battery has been used to compare against the sales-weighted average cost of ICEV and to estimate the parity timeline and TCO. To standardize the comparison of fleetwide sales averaged ICE with BEVs 200 and 300, the BEV 200 pickup truck is also included in the analysis.

Table 32: MY 2030 BEV powertrain costs. Scenario 2 (highlighted) values used for comparison.

Subclass	BEV200 LFP	BEV200 NMC811	BEV200 NMC811 10% costlier	BEV300 LFP	BEV300 NMC811	BEV300 NMC811 10% costlier
	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
Small Car	$2,949	$3,048	$3,303	$4,568	$4,725	$5,130
Medium car	$3,115	$3,217	$3,479	$4,824	$4,986	$5,403
Small SUV	$3,780	$3,905	$4,226	$5,677	$5,868	$6,360
Medium SUV	$4,012	$4,148	$4,496	$6,305	$6,522	$7,081
Pickup Truck	$4,950	$5,110	$5,521	$7,109	$7,354	$7,985

Retail vehicle price equivalents were projected by applying the RPE factors described above to both BEV and ICEV powertrains. The results, including a $1000 cost for a home charger, are shown in Table 33. As can be seen, both BEV200s and BEV300s have lower upfront costs than their sales-weighted ICEV counterpart.

Table 33: Incremental price of a BEV powertrain including charger over a sales-weighted ICEV powertrain in 2030.

Subclass	BEV200	BEV300
Small Car	-$4,600	-$2,588
Medium car	-$4,782	-$2,659
Small SUV	-$3,993	-$1,638
Medium SUV	-$5,967	-$3,118
Pickup Truck	-$5,726	-$3,033

Based on the distribution of sales across each class, a fleetwide sales-weighted fuel economy is computed to use as input for TCO analysis, as shown in Table 34. Other inputs and associated costs such as energy and maintenance costs remain unchanged from the original analysis.

Table 34: Fleetwide Sales-Weighted Fuel Economy for MY 2030 LD classes.

Subclass	HCR CONV (mpg)	HCR BISG (mpg)	HCR SHEVP2 (mpg)	TURBO CONV (mpg)	TURBO BISG (mpg)	TURBO SHEVP2 (mpg)	Sales Weighted (mpg)
Small Car	34	36	41	42	44	53	36
Medium Car	32	33	38	36	38	46	34
Small SUV	29	30	34	34	36	43	31
Midsize SUV	28	29	32	33	35	40	32
Pickup Truck	23	24	27	29	30	34	27

In terms of parity timeline, all the BEVs 200 and 300 achieve parity immediately upon purchase in 2030 across all the subclasses, as listed in Table 35.

Table 35: Time to achieve parity based on the fleetwide sales-weighted average approach for MY 2030.

Subclass	BEV200	BEV300
Small Car	Immediate	Immediate
Medium car	Immediate	Immediate
Small SUV	Immediate	Immediate
Medium SUV	Immediate	Immediate
Pickup Truck	Immediate	Immediate

All BEVs 200 and 300 have a lower TCO per mile compared to their ICE counterparts, as listed in Table 36. On average, BEV is cheaper to own by 23% compared to the ICE based on fleetwide sales-weighted average costs. It is important to note that the difference in the purchase price per mile of ICEVs is due to the difference in the glider costs between them even though the sales-weighted average powertrain cost is the same for ICE when compared to BEVs 200 and 300. To ensure an equal point of reference for comparison, the glider costs for ICEVs are kept the same as the BEVs.

Table 36: Breakdown of TCO per mile for sales-weighted ICEVs vs BEVs 200/300.

Vehicle Class	ICE				BEV					
	Purchase Price/mi	Energy/mi	Maint-enance/mi	TCO/mi	Purchase Price/mi	Energy/mi	Maint-enance/mi	Charger cost/mi	TCO/mi	Category (Range in miles)
Small Car	$0.102	$0.057	$0.072	$0.231	$0.078	$0.025	$0.063	$0.004	$0.171	200
	$0.133			$0.262	$0.118	$0.028			$0.213	300
Medium car	$0.116	$0.060	$0.085	$0.261	$0.092	$0.026			$0.185	200
	$0.153			$0.299	$0.138	$0.028			$0.234	300
Small SUV	$0.122	$0.066	$0.081	$0.269	$0.101	$0.032			$0.201	200
	$0.163			$0.310	$0.152	$0.034			$0.253	300
Midsize SUV	$0.139	$0.064	$0.081	$0.285	$0.111	$0.035			$0.213	200
	$0.185			$0.330	$0.168	$0.038			$0.273	300
Pickup Truck	$0.137	$0.075	$0.081	$0.293	$0.113	$0.043			$0.222	200
	$0.137			$0.293	$0.122	$0.044			$0.233	300

Table 37 lists the net savings of BEVs 200 and 300 over the sales-weighted MY 2030 ICE during its lifetime. The average cumulative savings of BEV200 and BEV300 across all classes are about $17,000 and $14,000, respectively.

Table 37: Cumulative net savings of BEV over ICEV.

Subclass	BEV200	BEV300
Small Car	$14,308	$11,803
Medium car	$18,157	$15,528
Small SUV	$16,528	$13,728
Medium SUV	$17,401	$13,940
Pickup Truck	$20,115	$17,113

Considering the MY 2030 projections of each of the classes with various technology combinations and pathways, the key takeaway of this analysis is that the powertrain costs of BEVs 200 and 300 are lower than the ICE powertrain costs which translate to lower purchase prices of BEVs. Moreover, with lower energy and maintenance costs, BEVs are much cheaper to own and operate than an equivalent ICEV resulting in an overall average savings of about $15,000.

5.5 Fuel Price Sensitivity

Due to the rapidly escalating geopolitical risks due to the ongoing war, COVID-19, and ensuing supply chain constraints, the oil price reached historical all-time highs in 2022, as shown in Figure 70. It is impossible to forecast the oil prices and 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 retail price is used as a sensitivity input for ICEVs in all three scenarios of electrification to determine its effect on TCO and parity timeline.

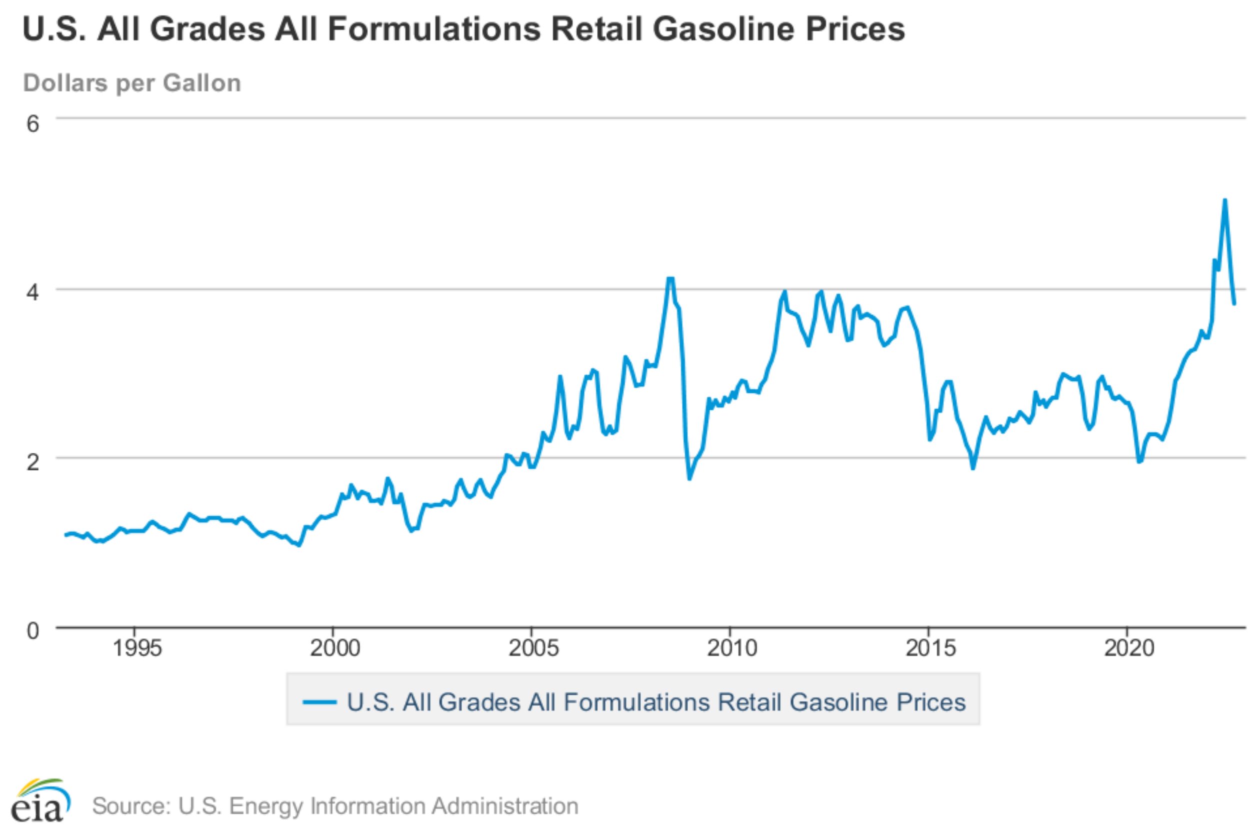

Figure 70: U.S. all grades all formulations retail gasoline prices in $/gallon seen peaking in June 2022. Image Source: EIA.

Gasoline retail prices across various states were looked at to determine the peak retail price. Per EIA's historical data, California had the highest price in comparison to other states like Colorado, Florida, Massachusetts, Minnesota, New York, Ohio, Texas, and Washington. The highest retail gasoline price in California was in June 2022 at $6.294, as shown in Figure 71. The federal and California state tax component amounting to 83.5¢ is removed from the retail price of gasoline, with the pre-tax price being $5.46 per gallon to determine the ICE energy cost.

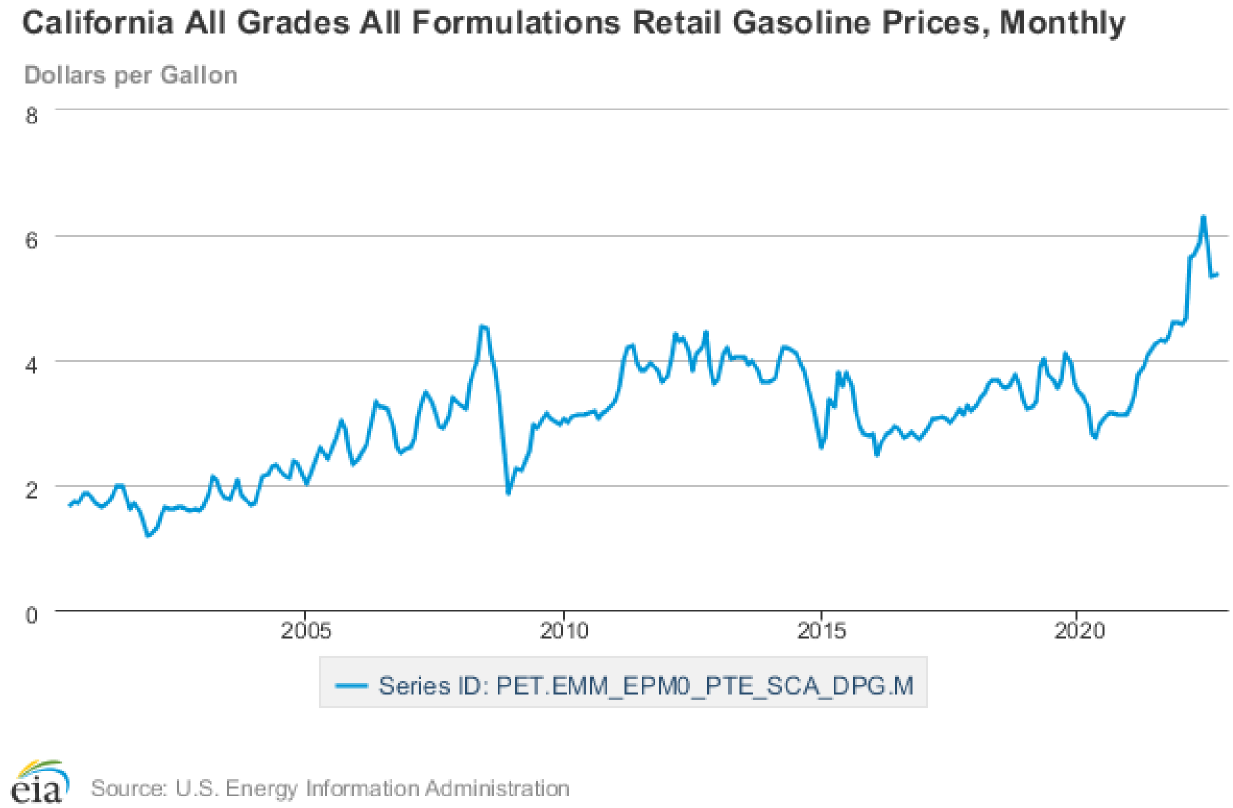

Figure 71: Highest retail price of gasoline was recorded in California in June 2022 at $6.294. Image Source: EIA.

As shown in Figure 72, in a high gasoline retail price scenario, on average the TCO per mile costs of an ICEV are 43% and 31% higher than an equivalent BEV, respectively. The cost of fuel is a major factor that impacts the cumulative savings of BEV ownership over ICEV and the time to achieve parity. In comparison with Table 26, in the premium segment with Scenarios 2 and 3, BEV400s large SUVs and pickup trucks achieve parity within the first year of ownership, as listed in Table 38. It provides a compelling glimpse of the sensitivity to real-world oil prices on the cost of ownership of an ICEV in comparison to an equivalent BEV.

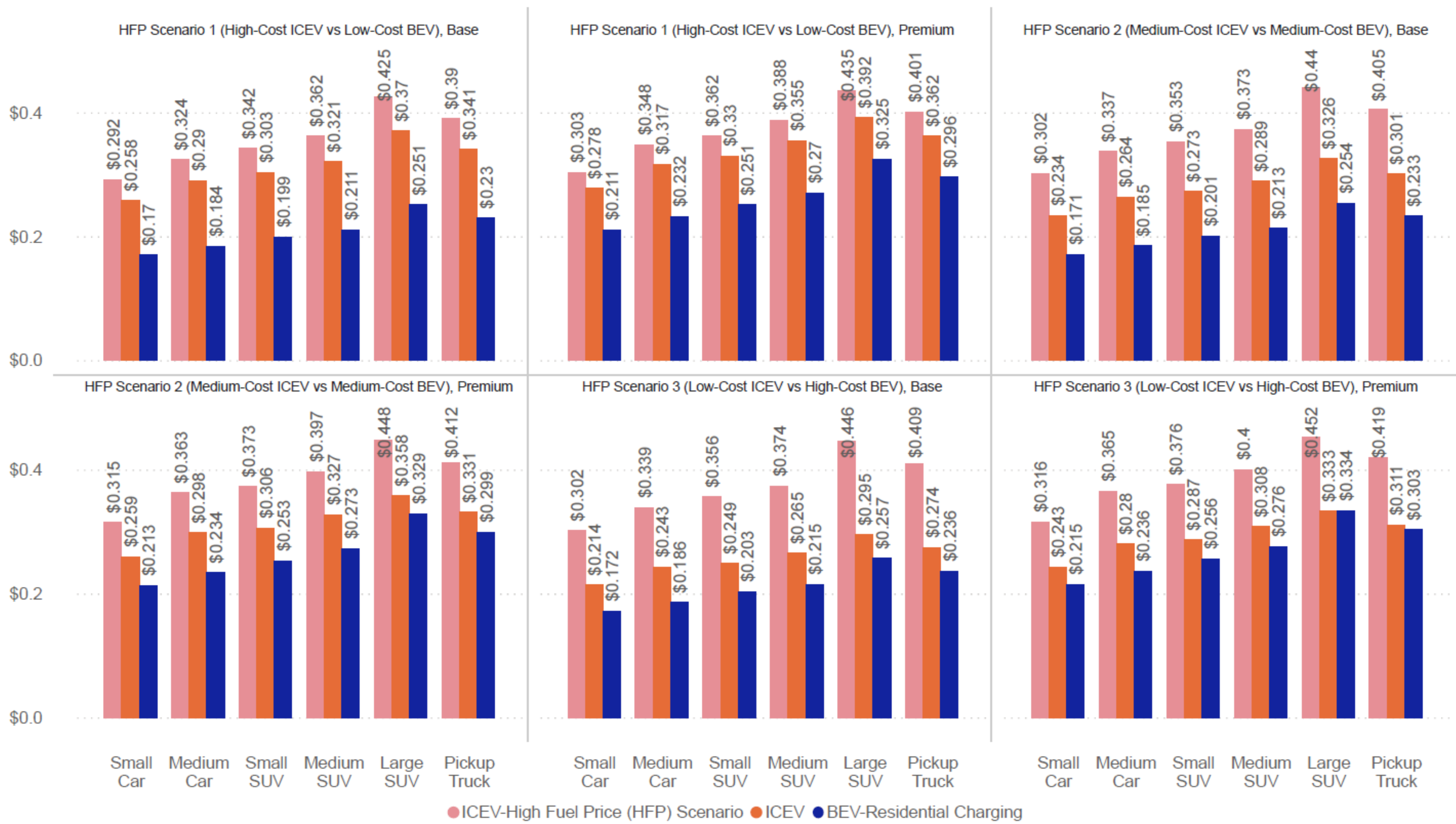

Figure 72: Projected range of Total Cost of Ownership (TCO) per mile with high fuel prices in every scenario.

Table 38: Time to achieve parity for light-duty BEVs with a 2030 purchase timeframe in the base and premium segments in a high gasoline price scenario

Vehicle type	Subclass	Segment	Scenario 1	Scenario 2	Scenario 3
Car	Compact (Small) car	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Midsize (Medium) car	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
SUV	Small SUV	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Midsize (Medium) SUV	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Large SUV	Base	Immediate	Immediate	Immediate
		Premium	Immediate	1	1
Pickup	Pickup truck	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	1

As can be seen in Figure 73, the BEVs offer significant savings of several thousand dollars across all classes and segments with an average savings of about $33,000. Projected TCO parity timeline plots across all three scenarios of the incremental cost of electrification are included in Appendix 8.6.

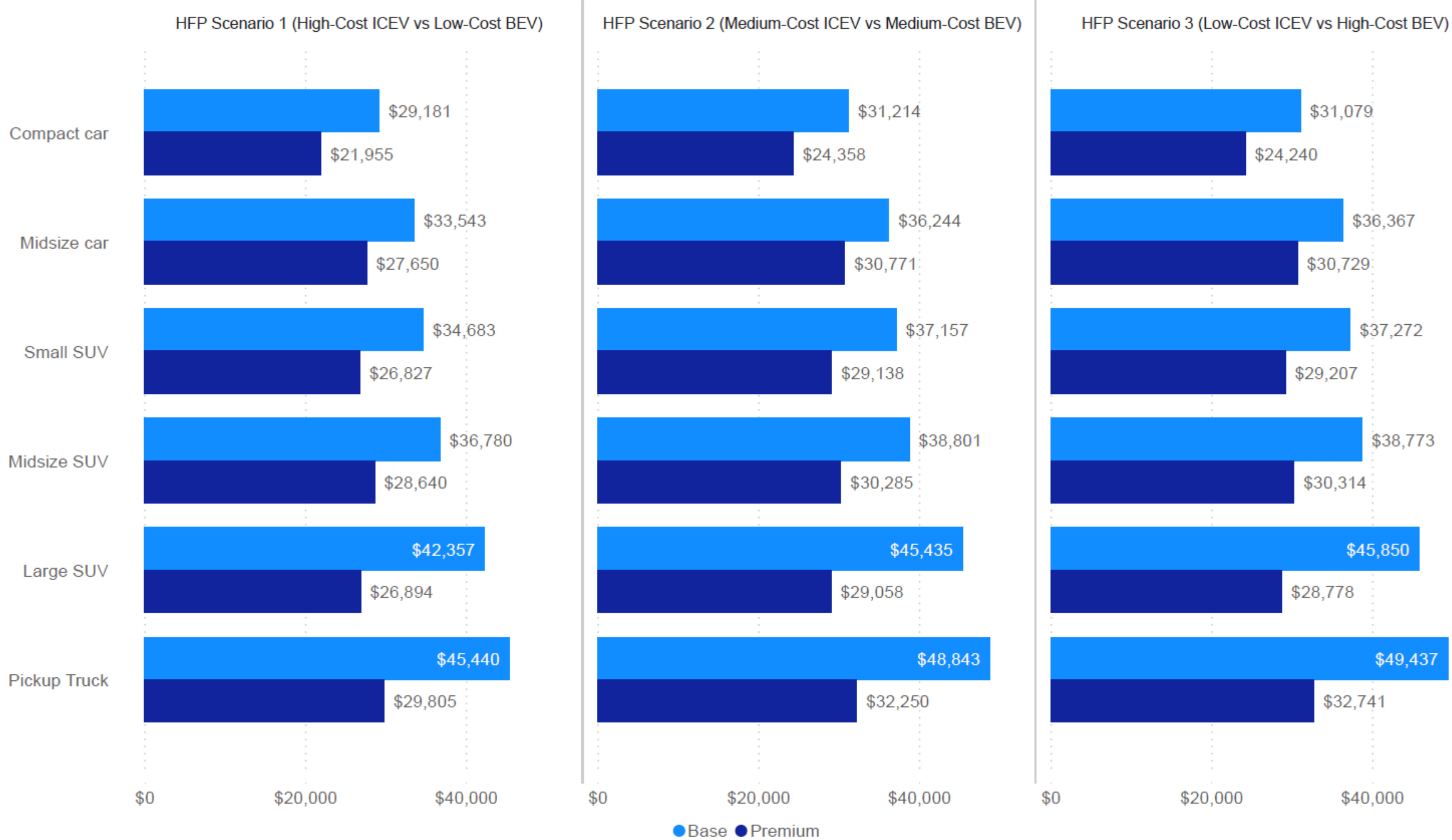

Figure 73: Projected cumulative net savings of BEV over ICEV in a high gasoline price scenario.

5.6 Electricity Price Sensitivity

As an exploratory exercise, real-world state-specific electricity prices, which show a wider variation than average national prices over time, are used to estimate their impact on the three incremental costs of electrification scenarios. The average state-specific price of residential electricity from Jan 2022 to July 2022, as shown in Figure 74, 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 with the rates being 26.26¢, 21.38¢, and 17.63¢, respectively[1]. These are 3 distinct takes on "high" residential electricity rates - remarkably high, high, and somewhat high. These three states capture the spread of the 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.

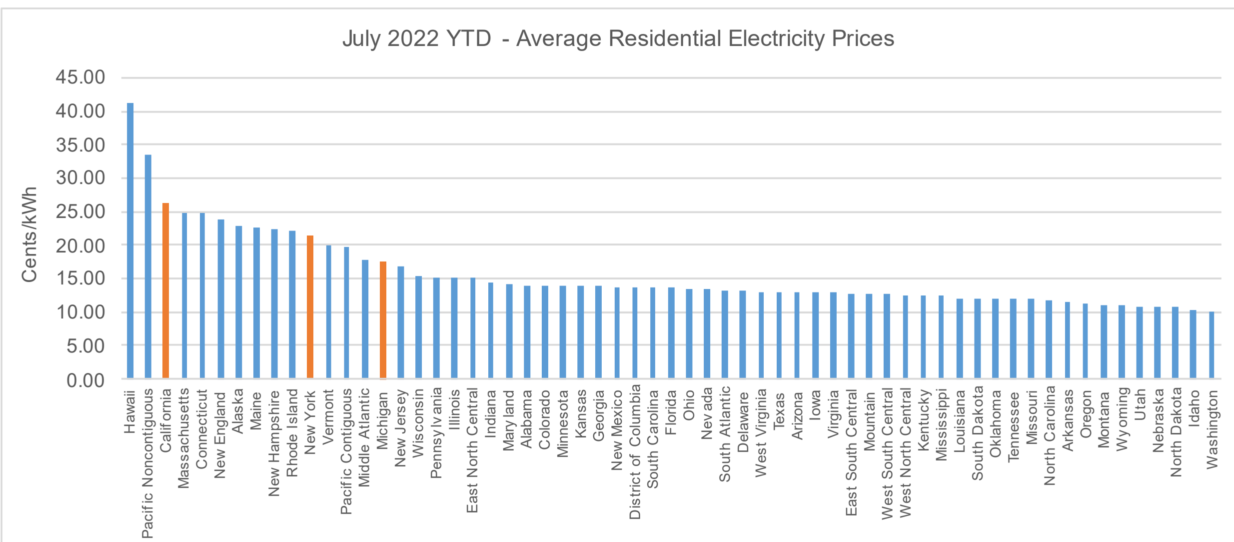

Figure 74: Average Price of Residential Electricity, by State, from January 2022 to July 2022 (¢/kWh). The orange columns are sensitivity inputs. Source: EIA

As shown in Figure 75, the average TCO per mile of an ICEV is 20% and 10% higher than an equivalent BEV, respectively. 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 own and operate than an equivalent ICEV. Exceptions are the BEV400s in the large SUV and pickup truck class in Scenario 3 (California cost of electricity), which would incur an additional 3-4¢/mile. Here, electricity prices are more than double the national

[1] These "Scenarios 1, 2, and 3" only apply within this sensitivity analysis and should not be confused or conflated with the Scenarios 1, 2 and 3 which describe uncertainties in the primary analysis described in this report.

average prices. Please note that we did not adjust gasoline prices for regional variations in this sensitivity analysis.

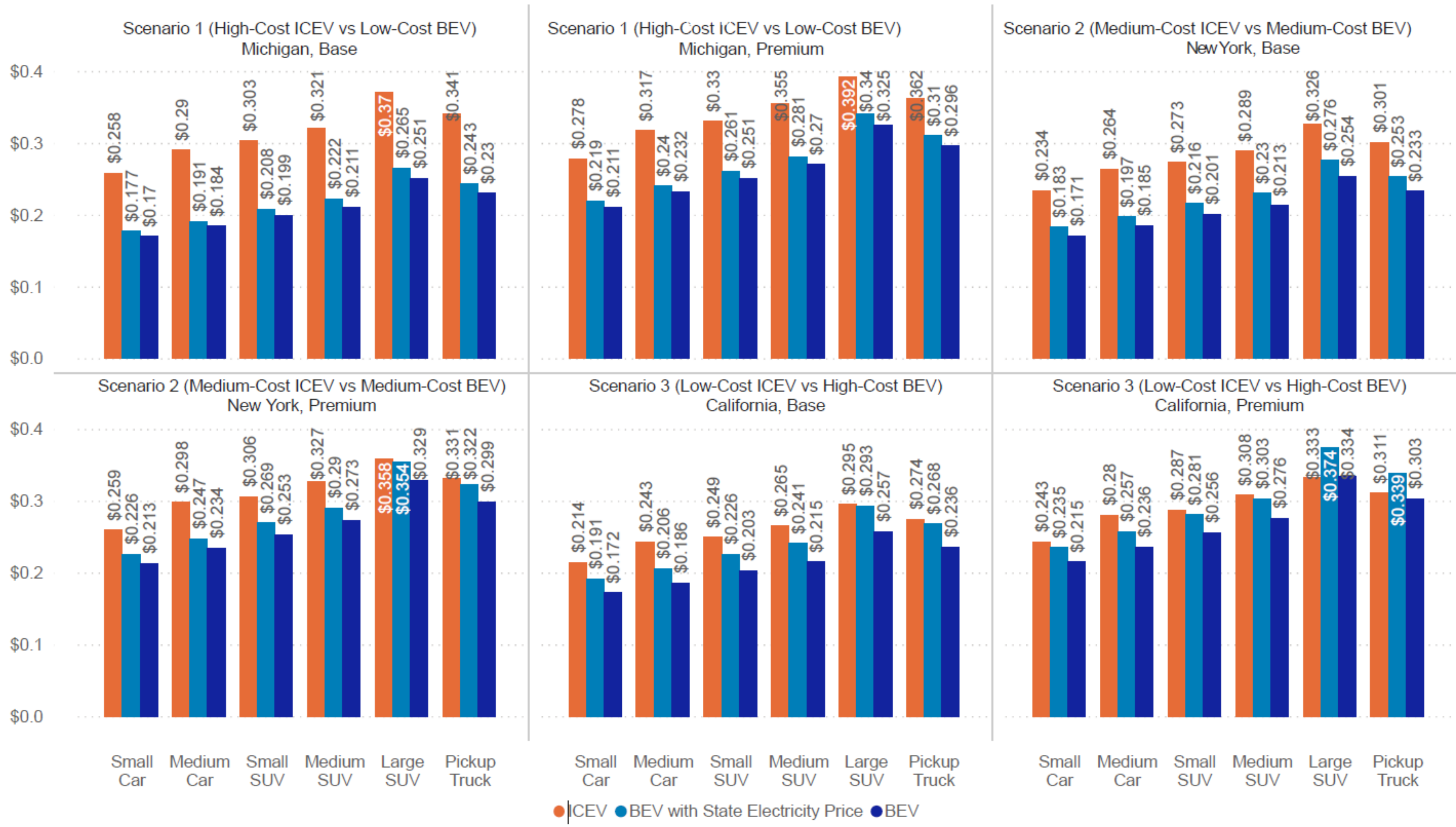

Figure 75: Projected range of Total Cost of Ownership (TCO) in the base segment with electricity price sensitivity.

As shown in Table 39, BEV200s and BEV300s in the compact car to midsize SUV segments achieve immediate parity. The BEV 300 in the Large SUV segment achieves immediate parity under Scenarios 1 and 2 with higher electricity prices and after 8 years in Scenario 3; BEV400s in the large SUV and pickup truck segments achieve immediate parity in Scenario 1. BEV400 large SUVs achieve parity after 11 years in Scenario 2 but do not reach parity in terms of cost of ownership through 15 years in Scenario 3. BEV400s in the pickup class achieve parity after 5 years in Scenario 2 with higher regional electricity prices, but again do not reach parity in terms of cost of ownership through 15 years in Scenario 3.

Table 39: Time to achieve parity for light-duty BEVs with a 2030 purchase timeframe in the base and premium segments with electricity price sensitivity

Vehicle type	Subclass	Segment	Scenario 1	Scenario 2	Scenario 3
Car	Compact (Small) car	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Midsize (Medium) car	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
SUV	Small SUV	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Midsize (Medium) SUV	Base	Immediate	Immediate	Immediate
		Premium	Immediate	Immediate	Immediate
	Large SUV	Base	Immediate	Immediate	8
		Premium	Immediate	11	End of Life
Pickup	Pickup Truck	Base	Immediate	Immediate	Immediate
		Premium	Immediate	5	End of Life

Projected TCO parity timeline plots across all three scenarios of the incremental cost of electrification are included in Appendix 8.7.

6. Conclusions

BEVs are expected to play an important role in the decarbonization of the transportation sector. The results of this study indicate that light-duty ICEVs are generally well-positioned for the transition to BEVs and that consumers would benefit by switching to them, both through very competitive upfront costs and lower costs of operation. This conclusion does not depend on whether residential or public charging was the primary means of powering BEVs, nor on whether the power was purchased in a state with lower or higher than average electricity costs. We also identify several promising battery chemistries and technologies that could reduce battery costs further.

There are many external benefits to BEV adoption, including environmental benefits through the reduction of PM and NOx emissions as well as the reduction in noise in congested environments. While these benefits are not included in this analysis, they would improve the benefits of BEV adoption.

6.1 Upfront Vehicle Cost

We estimate both ICEV and BEV retail price equivalent costs in MY 2030. We evaluate these vehicle costs for a wide variety of vehicle segments, from small cars to full-sized pickups, NA to turbocharged engines, non-hybrid to strong hybrid powertrains, and BEVs with a range of 200 miles to 400 miles. The upfront costs of both BEV200 and BEV300 in the cases of both base and premium small cars, medium cars, small SUVs, and midsize SUVs are lower than upfront ICEV costs across all three scenarios. In the case of the large SUV and pickup truck, the base-segment BEV300s across Scenarios 1 and 2 show lower upfront costs, as does the BEV300 pickup in Scenario 3. The cost of the larger batteries, necessary to enable a 400-mile range, causes the upfront cost of BEV400 large SUVs and pickup trucks to be higher than their premium ICEV equivalents in all but one scenario.

6.2 Total Cost of Ownership

The key finding of this analysis is that over the life of ownership of any class of vehicle in the base or premium segments, a BEV is cheaper to own and operate compared to a comparable ICEV. This total cost of ownership analysis does not consider any subsidies, tax cuts, or other incentives. To realize these cost benefits, it is important to provide the necessary impetus for the development of an interoperable charging infrastructure that provides a seamless charging experience to consumers.

As shown in Figure 76, the projected TCO per mile of an ICEV is wide-ranging compared to a BEV across both segments. It is primarily because of the larger variance in the projected fuel prices compared to more stable electricity rates [12]. The projected gasoline prices for the 2030–2044 timeframe vary from $2.07/gallon to $4.41/gallon while the electricity rates vary between 12.4¢/kWh to 13.3¢/kWh. The average maintenance cost per mile is 9.8¢ for an ICEV and 7.7¢ for a BEV [53].

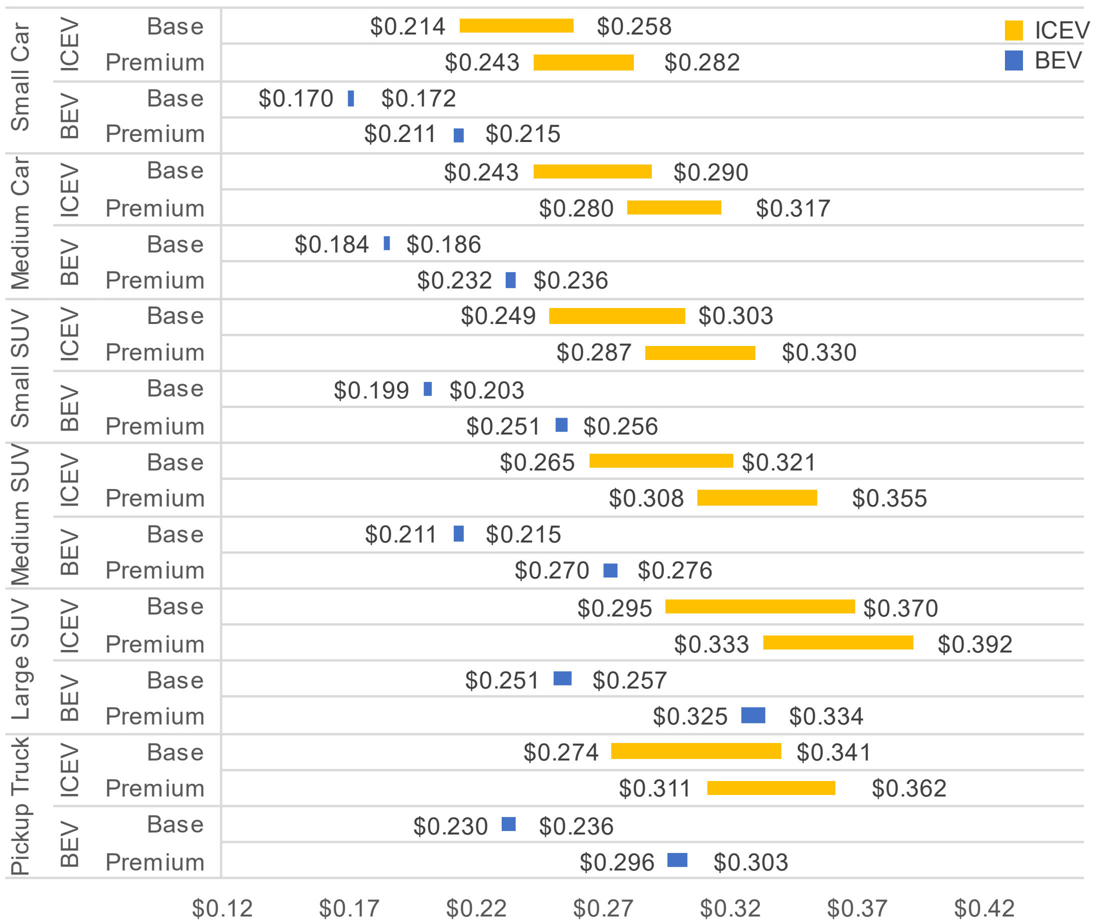

Figure 76: Summary of projected TCO per mile in 2030 for ICEVs and BEVs.

On average, in the base segment across all vehicle subclasses, the TCO per mile is $0.284 for an ICEV and $0.21 for a BEV; therefore, the TCO per mile of a BEV is about 26% less than an equivalent ICEV. On average, in the premium segment across all vehicle subclasses, the TCO per mile is $0.316 for an ICEV and $0.267 for a BEV; therefore, the TCO per mile of a BEV is about 15% less than that of an equivalent ICEV. BEVs have significantly lower energy and M&R costs due to lower electricity rates and fewer moving parts. The analysis demonstrates that over the lifecycle of ownership of the vehicle, owning a BEV could result in significant savings for a typical consumer in addition to environmental benefits by making the switch away from fossil fuel-powered vehicles.

TCO inputs and projected TCO per mile across all three scenarios of the incremental cost of electrification, along with the parity plots, are included in Appendices 8.2 and 8.3.

In most cases, the cost of owning and operating a BEV starts lower than that of an ICEV, and savings only increase over time. However, there are a few segments where BEVs are still projected to cost more than their ICEV equivalents in MY 2030. In the base large SUV segment, the BEV requires one year of operation to compensate for its higher upfront cost in Scenario 3. In the premium large SUV segment, the BEV requires 4 years of operation to compensate for its higher upfront cost in Scenario 2 and a little longer than its assumed 15-year life in Scenario 3. In the premium pickup segment, the BEV requires 2 years of operation to compensate for its higher upfront cost in Scenario 2 and 8 years in Scenario 3.

6.3 Sensitivity Analysis

We carried out sensitivity analyses under various settings that could affect the adoption of BEVs in the future. The analysis revealed that under various projected scenarios, BEVs would remain favorable despite the external factors considered here.

6.3.1 Demand Charging

Charging costs would increase by approximately 75% for a customer who prefers charging equally at home and at public DCFC stations. However, the TCO per mile of a BEV is roughly 11% cheaper than an equivalent ICEV. Overall, the savings may shrink in comparison with a residential-charging scenario, but it would remain economical to own and operate a BEV. The time to achieve parity is immediate in most scenarios across all vehicle subclasses and segments; however, in Scenarios 2 and 3 of the premium segments of the large SUV and the pickup truck, BEV400s never achieve parity.

6.3.2 Fleetwide Sales-Weighted Average Cost

The projected fleetwide sales-weighted average cost of MY 2029 ICE against a BEV300, assuming the projected sales per CAFE model, continues to increase across both the scenarios of migration to mild hybrids only and mild and strong hybrids, respectively, in the passenger car and light truck segments. We believe that the associated technology cost of implementation of ICE will increase to meet the anticipated higher stringency requirement beyond 2026.

At a top level, an analysis using fleetwide sales-weighted average costing based on MY 2030 sales projections is also conducted to analyze the powertrain cost and TCO of BEVs 200 and 300 against an equivalent ICEV for each subclass. The key finding is that the powertrain costs of BEVs 200 and 300 are lower than the ICE powertrain costs, which translates to the purchase price of a vehicle. Moreover, BEVs are much cheaper to own and operate than an equivalent ICEV, resulting in an overall average savings of about $15,000.

6.3.3 Fuel Price Sensitivity

The ongoing geopolitical turmoil and volatile oil prices have severely penalized ICEV owners. Operating costs have significantly risen in recent months as a result of fuel price volatility, and this is expected to continue as global tensions contribute to fuel price volatility. This analysis was based on the highest all-time gasoline retail price recorded in California in June 2022, which was $5.46 without taxes ($6.294 with federal and state taxes). The real-world fuel price used as sensitivity is approximately 43% higher than the projected AEO 2022 fuel prices used in this study. The results of the sensitivity analysis indicate that all vehicle types would achieve parity immediately upon purchase in 2030, except the BEV400s of the large SUVs and pickup truck types, which achieve parity after 1 year of ownership. In a high gasoline retail price scenario, on average, the TCO per mile costs of an ICEV are 43% and 31% higher than an equivalent BEV. Given the sensitivity of ICEV ownership to oil prices, this analysis makes a compelling case for switching to BEVs.

6.3.4 Electricity Price Sensitivity

With rising inflation and an increase in energy rates, we analyzed the effect of real-world energy rates on electrification scenarios. Residential electricity rates in California, New York, and Michigan were used as inputs to the analysis, as these states capture coast-to-coast rates and had higher prices compared to the AEO2022 projected rates used in the study. On average, the real-world state prices were roughly 69% higher than the AEO2022 projected rates used in the study. Compact car to midsize SUV achieves immediate parity, while the BEV 300 achieves parity after 8 years in Scenario 3; the BEV400 large SUV and pickup truck in Scenario 2 achieve parity after 11 and 5 years of ownership, respectively; in Scenario 3, the BEV400s in the large SUV and pickup truck classes do not achieve parity in their lifetimes.

In terms of TCO per mile, BEVs are still cheaper to operate than equivalent ICEVs, with the exception of the BEV400s in the large SUV and pickup truck classes in Scenario 3 of electrification, which would cost an extra $4 per mile and $3 per mile to operate than an equivalent ICEV. The EIA AEO 2022 projected fuel prices used in this study do not reflect the current geopolitical crises that have resulted in a volatile oil and gas market, resulting in a peak in retail gasoline prices. A typical consumer’s savings would increase significantly by switching to BEVs, as the fuel expenses of ICEVs are remarkably high.

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8. Appendix

8.1 Incremental Powertrain Cost without RPE

The green highlight represents the low-cost powertrain option, the red text represents the medium-cost powertrain, and the pink highlight shows represent the high-cost powertrain in each segment (Methodology, Section 2). The detailed comparison of the DMCs of various ICE and BEV powertrains and the incremental cost of electrification (detailed in Figure 16 of the Methodology, Section 2) for 2022, 2030, and 2035 are shown in the following tables and figures.

8.1.1 Small Car

Table 40: ICE and BEV powertrain costs for a small car

Powertrain Cost for Small Car							
Powertrain description	**Technology Description**	**Base**			**Premium**		
		2022	**2030**	**2035**	**2022**	**2030**	**2035**
Conventional SI	HCR1+ CGER+ AT8L3	5,987	5,960	5,958			
Mild Hybrid BISG SI	HCR1+ CGER+ AT8L3+ BISG	6,718	6,479	6,425			
Conventional SI Turbo	Turbo1+ AT8L3	6,165	6,098	6,093	6,825	6,754	6,749
Mild Hybrid BISG SI Turbo	Turbo1+ AT8L3+ BISG	6,896	6,617	6,559	7,555	7,273	7,215
Par HEV SI	HCR1+ AT8L3+ SHEVP2	7,995	7,366	7,182	8,878	8,239	8,053
Par HEV SI Turbo	Turbo1+ AT8L3+ SHEVP2	8,217	7,573	7,389	8,918	8,261	8,073
BEV200 - Low		5,690	2,949	2,533	6,127	3,227	2,809
BEV200 - Medium		5,827	3,048	2,615	6,271	3,331	2,896
BEV200 - High		6,278	3,303	2,827	6,746	3,600	3,122
BEV300 - Low		7,993	4,284	3,903	8,643	4,568	4,238
BEV300 - Medium		8,201	4,436	4,039	8,864	4,725	4,382
BEV300 - High		8,885	4,827	4,391	9,593	5,130	4,753
Low-cost powertrain	(Green highlight)						
Medium-cost powertrain	(Red text)						
High-cost powertrain	(Pink highlight)						

Figure 77: ICE and BEV powertrain costs for a small car.

8.1.2 Medium Car

Table 41: ICE and BEV powertrain costs for a medium car

Powertrain Cost for Medium Car							
Powertrain description	**Technology Description**	**Base**			**Premium**		
		2022	**2030**	**2035**	**2022**	**2030**	**2035**
Conventional SI	HCR1+ CGER+ AT8L3	5,987	5,960	5,958			
Mild Hybrid BISG SI	HCR1+ CGER+ AT8L3+ BISG	6,912	6,631	6,573			
Conventional SI Turbo	Turbo1+ AT8L3	6,165	6,098	6,093	6,825	6,754	6,749
Mild Hybrid BISG SI Turbo	Turbo1+ AT8L3+ BISG	6,896	6,617	6,559	7,555	7,273	7,215
Par HEV SI	HCR1+ AT8L3+ SHEVP2	8,100	7,447	7,257	8,994	8,325	8,131
Par HEV SI Turbo	Turbo1+ AT8L3+ SHEVP2	8,331	7,659	7,468	9,022	8,339	8,145
BEV200 - Low		5,957	3,115	2,673	6,448	3,433	2,986
BEV200 - Medium		6,098	3,217	2,757	6,596	3,539	3,075
BEV200 - High		6,563	3,479	2,974	7,084	3,815	3,304
BEV300 - Low		8,379	4,392	4,125	9,074	4,824	4,499
BEV300 - Medium		8,595	4,544	4,267	9,302	4,986	4,648
BEV300 - High		9,305	4,937	4,632	10,055	5,403	5,030
Low-cost powertrain	(Green highlight)						
Medium-cost powertrain	(Red text)						
High-cost powertrain	(Pink highlight)						

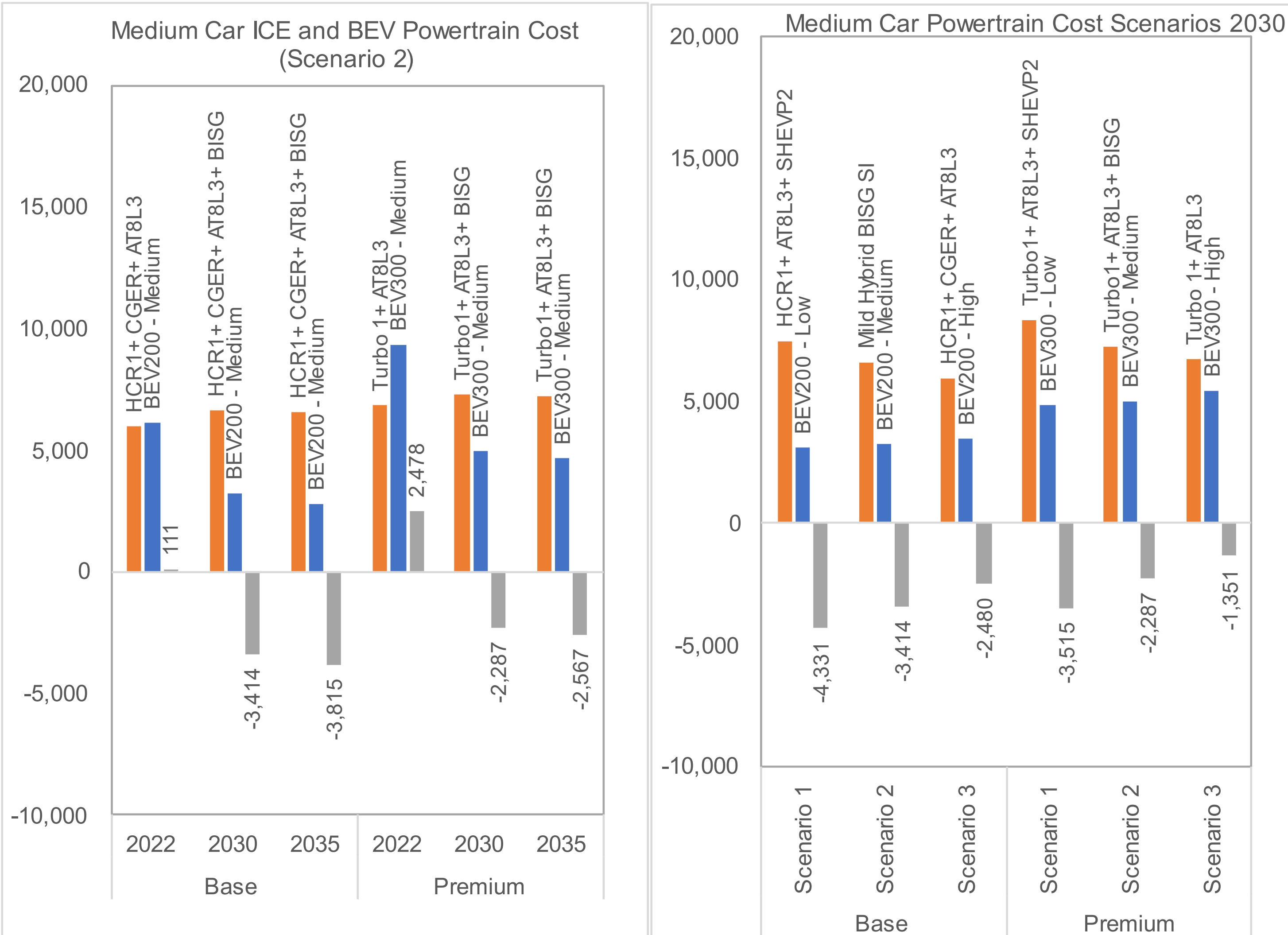

Figure 78: ICE and BEV powertrain costs for a medium car.

8.1.3 Small SUV

Table 42: ICE and BEV powertrain costs for a small SUV

Powertrain Cost for Small SUV								
Powertrain description	Technology Description	Base			Premium		
		2022	2030	2035	2022	2030	2035
Conventional SI	HCR1+ CGER+ AT8L3	5,987	5,960	5,958			
Mild Hybrid BISG SI	HCR1+ CGER+ AT8L3+ BISG	6,912	6,631	6,573			
Conventional SI Turbo	Turbo 1+ AT8L3	6,165	6,098	6,093	6,825	6,754	6,749
Mild Hybrid BISG SI Turbo	Turbo1+ AT8L3+ BISG	6,896	6,617	6,559	7,555	7,273	7,215
Par HEV SI	HCR1+ AT8L3+ SHEVP2	8,252	7,540	7,329	9,159	8,430	8,215
Par HEV SI Turbo	Turbo1+ AT8L3+ SHEVP2	8,491	7,758	7,545	9,227	8,469	8,249
BEV200 - Low		7,124	3,780	3,219	7,553	4,070	3,506
BEV200 - Medium		7,297	3,905	3,322	7,730	4,197	3,612
BEV200 - High		7,867	4,226	3,587	8,313	4,525	3,885
BEV300 - Low		10,071	5,461	4,862	10,638	5,677	5,180
BEV300 - Medium		10,335	5,652	5,030	10,909	5,868	5,352
BEV300 - High		11,203	6,145	5,463	11,801	6,360	5,795
Low-cost powertrain	(Green highlight)						
Medium-cost powertrain	(Red text)						
High-cost powertrain	(Pink highlight)						

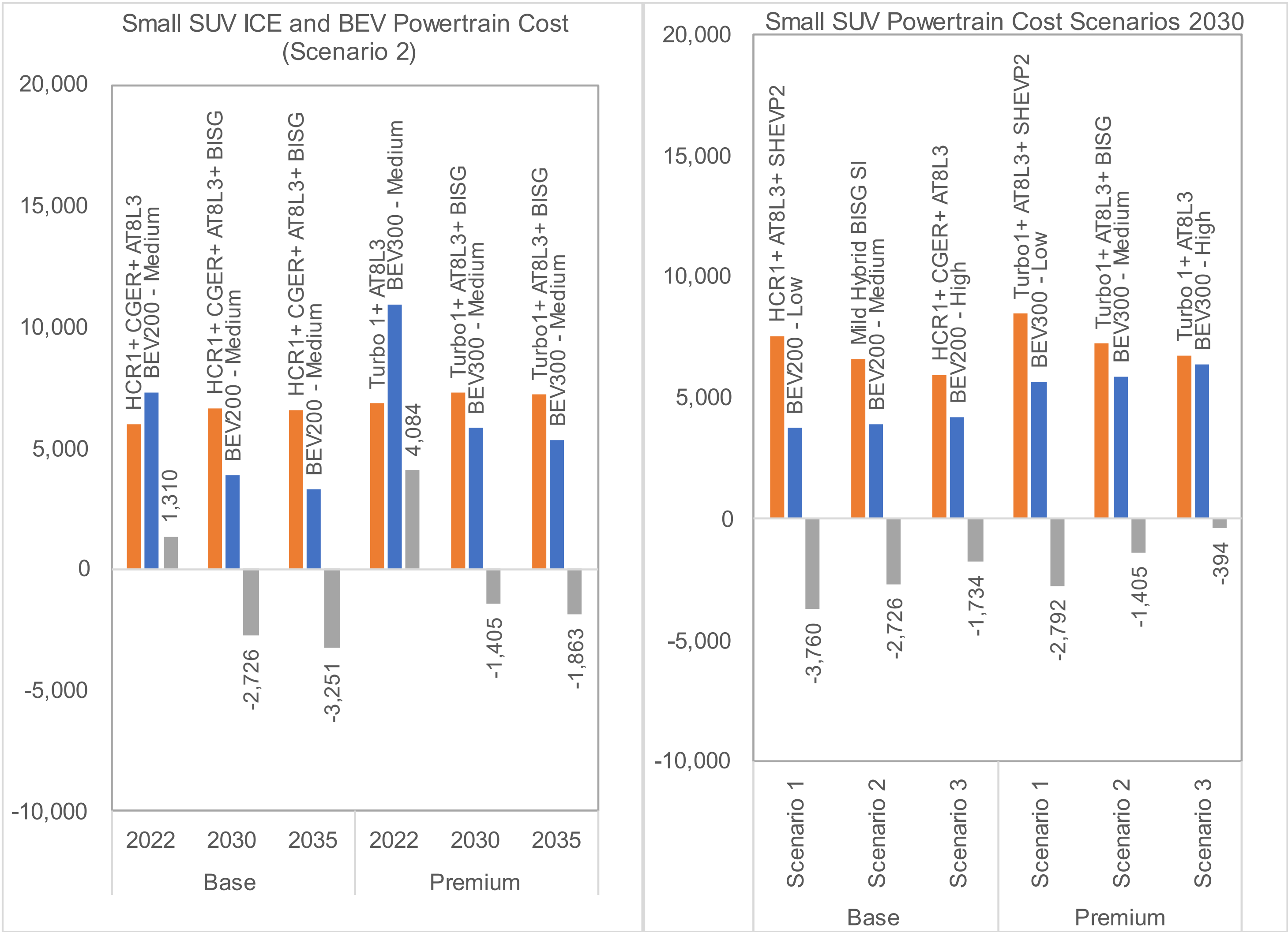

Figure 79: ICE and BEV powertrain costs for a small SUV.

8.1.4 Midsize SUV

Table 43: ICE and BEV powertrain costs for a midsize SUV

Powertrain Cost for Medium SUV								
Powertrain description	**Technology Description**	**Base**			**Premium**			
		2022	**2030**	**2035**	**2022**	**2030**	**2035**
Conventional SI	HCR1+ CGER+ AT8L3	6,912	6,885	6,883	0	0	0
Mild Hybrid BISG SI	HCR1+ CGER+ AT8L3+ BISG	7,837	7,556	7,498	0	0	0
Conventional SI Turbo	Turbo1+ AT8L3	6,825	6,754	6,749	7,910	7,819	7,812
Mild Hybrid BISG SI Turbo	Turbo1+ AT8L3+ BISG	7,555	7,273	7,215	8,641	8,338	8,279
Par HEV SI	HCR1+ AT8L3+ SHEVP2	9,153	8,425	8,210	10,122	9,369	9,149
Par HEV SI Turbo	Turbo1+ AT8L3+ SHEVP2	9,202	8,452	8,235	10,396	9,599	9,373
BEV200 - Low		7,524	4,012	3,351	8,109	4,395	3,745
BEV200 - Medium		7,711	4,148	3,461	8,305	4,537	3,862
BEV200 - High		8,328	4,496	3,743	8,950	4,901	4,163
BEV300 - Low		10,605	5,842	5,158	11,452	6,305	5,612
BEV300 - Medium		10,887	6,050	5,339	11,750	6,522	5,803
BEV300 - High		11,816	6,586	5,806	12,732	7,081	6,293
Low-cost powertrain	(Green highlight)						
Medium-cost powertrain	(Red text)						
High-cost powertrain	(Pink highlight)						

Figure 80: ICE and BEV powertrain costs for a midsize SUV.

8.1.5 Large SUV

Table 44: ICE and BEV powertrain costs for a Large SUV

Powertrain description	Description	Base			Premium		
		2022	2030	2035	2022	2030	2035
Conventional SI	V8 OHV + VVT + GDI + DEAC + AT10L3	7,404	7,326	7,317	7,404	7,326	7,317
Mild Hybrid BISG SI	V8 OHV + VVT + GDI + DEAC + AT10L3 + BISG	8,135	7,845	7,784	8,135	7,845	7,784
Conventional SI Turbo	Turbo1 + AT10L3	7,976	7,879	7,871	7,976	7,879	7,871
Mild Hybrid BISG SI Turbo	Turbo1 + AT10L3 + BISG	8,707	8,398	8,338	8,707	8,398	8,338
Par HEV SI	HCR1 + AT10L3 + SHEVP2	10,230	9,468	9,248	10,261	9,487	9,263
Par HEV SI Turbo	Turbo1 + AT10L3 + SHEVP2	10,520	9,707	9,479	10,562	9,733	9,500
Conventional CI		10,335	10,104	10,081	10,335	10,104	10,081
BEV200 - Low		9,956	5,442	4,591	10,486	5,748	4,965
BEV200 - Medium		10,201	5,618	4,734	10,743	5,933	5,119
BEV200 - High		11,005	6,070	5,102	11,587	6,407	5,515
BEV300 - Low		14,538	7,817	7,077	15,029	8,246	7,502
BEV300 - Medium		14,923	8,086	7,319	15,425	8,529	7,757
BEV300 - High		16,190	8,780	7,939	16,728	9,257	8,410
BEV400 - Low		20,265	10,939	9,288	21,406	11,666	9,831
BEV400 - Medium		20,825	11,332	9,616	21,996	12,084	10,177
BEV400 - High		22,669	12,344	10,461	23,941	13,160	11,067
Low-cost powertrain	(Green highlight)						
Medium-cost powertrain	(Red text)						
High-cost powertrain	(Pink highlight)						

Figure 81: ICE and BEV powertrain costs for a large SUV.

8.1.6 Pickup Truck

Table 45: ICE and BEV powertrain costs for a Pickup Truck

Powertrain description	Description	Base			Premium		
		2022	2030	2035	2022	2030	2035
Conventional SI	V8 OHV + VVT + GDI + DEAC + AT10L3	7,404	7,326	7,317	7,404	7,326	7,317
Mild Hybrid BISG SI	V8 OHV + VVT + GDI + DEAC + AT10L3 + BISG	8,135	7,845	7,784	8,135	7,845	7,784
Conventional SI Turbo	Turbo1 + AT10L3	8,351	8,254	8,246	8,351	8,254	8,246
Mild Hybrid BISG SI Turbo	Turbo1 + AT10L3 + BISG	8,707	8,398	8,338	8,707	8,398	8,338
Par HEV SI	HCR1 + AT10L3 + SHEVP2	10,230	9,468	9,248	10,261	9,487	9,263
Par HEV SI Turbo	Turbo1 + AT10L3 + SHEVP2	10,520	9,707	9,479	10,562	9,733	9,500
Conventional CI		10,335	10,104	10,081	10,335	10,104	10,081
BEV200 - Low		9,113	4,950	4,176	9,594	5,229	4,517
BEV200 - Medium		9,335	5,110	4,307	9,827	5,396	4,657
BEV200 - High		10,066	5,521	4,642	10,595	5,827	5,017
BEV300 - Low		13,278	7,109	6,437	13,724	7,500	6,823
BEV300 - Medium		13,627	7,354	6,656	14,084	7,757	7,054
BEV300 - High		14,779	7,985	7,220	15,269	8,418	7,649
BEV400 - Low		18,484	9,947	8,446	19,521	10,608	8,941
BEV400 - Medium		18,993	10,305	8,745	20,058	10,989	9,255
BEV400 - High		20,669	11,225	9,513	21,826	11,967	10,064
Low-cost powertrain	(Green highlight)						
Medium-cost powertrain	(Red text)						
High-cost powertrain	(Pink highlight)						

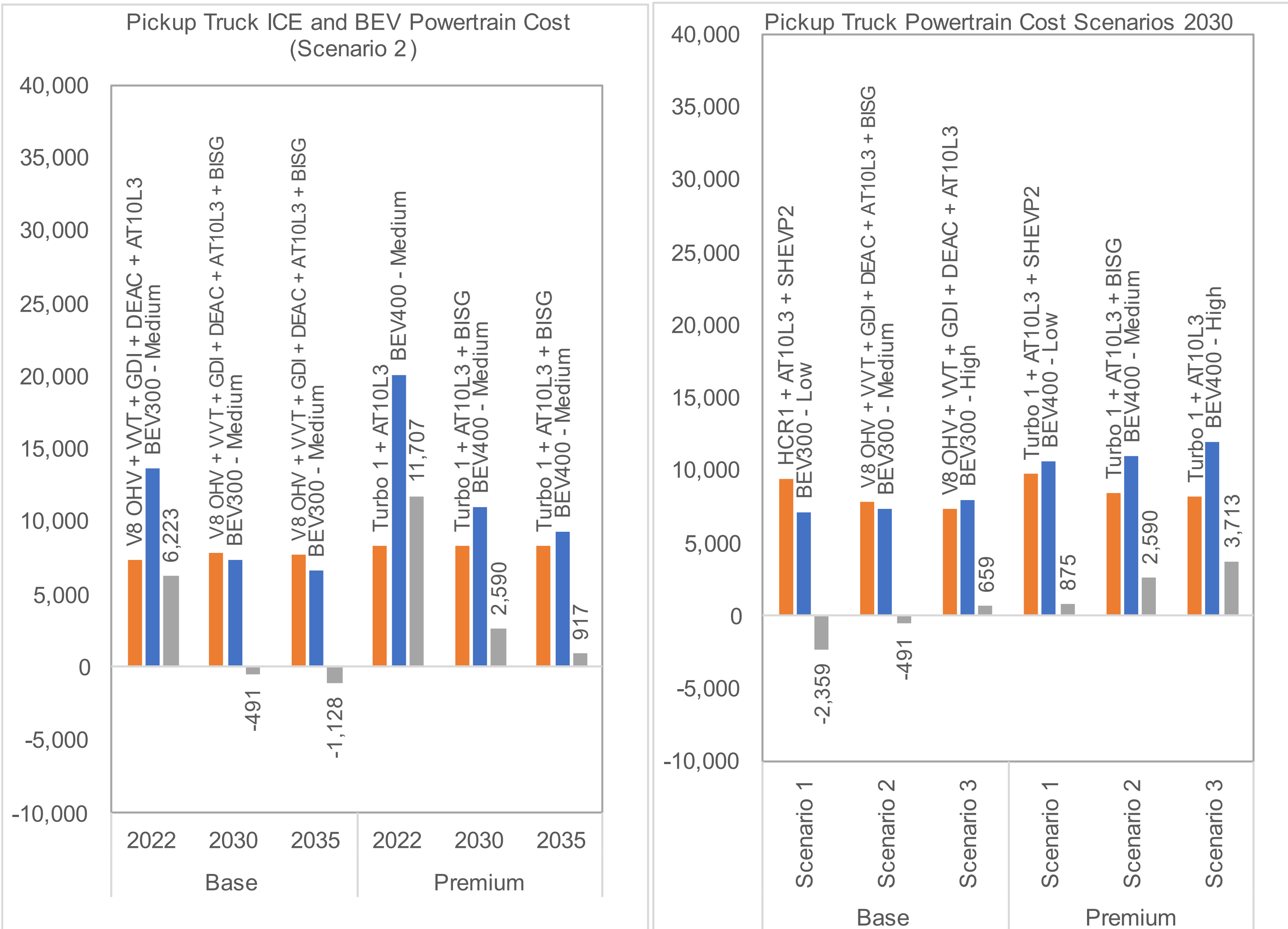

Figure 82: ICE and BEV powertrain costs for a pickup truck.

8.2 Total Cost of Ownership Inputs

The data is sourced from U.S. Energy Information Administration Annual Energy Outlook (AEO) 2022 for the 2030-2044 timeframe [12]. The prices have been used as inputs in the respective incremental cost scenarios included in the column headers.

Table 46: AEO 2022: Real Petroleum Prices Refined Petroleum Product Prices Motor Gasoline (2021 $/gal) and End-Use Prices of Residential Electricity (2021 $/KWh)

Year	Gasoline High oil price $/gal (Scenario 1)	Gasoline Reference case $/gal (Scenario 2)	Gasoline Low oil price $/gal (Scenario 3)	Electricity Residential High oil price $/kWh (Scenario 1)	Electricity Residential Reference case $/kWh (Scenario 2)	Electricity Residential Low oil price $/kWh (Scenario 3)
2030	4.23	2.80	2.07	0.127	0.130	0.130
2031	4.26	2.89	2.16	0.127	0.130	0.131
2032	4.29	2.91	2.17	0.127	0.131	0.131
2033	4.26	2.94	2.20	0.127	0.132	0.132
2034	4.30	2.96	2.21	0.127	0.132	0.133
2035	4.34	2.97	2.24	0.126	0.132	0.133
2036	4.34	2.99	2.25	0.125	0.132	0.133
2037	4.36	3.01	2.26	0.124	0.131	0.132
2038	4.36	3.04	2.27	0.124	0.131	0.132
2039	4.39	3.04	2.26	0.124	0.131	0.132
2040	4.39	3.07	2.25	0.124	0.131	0.132
2041	4.37	3.09	2.24	0.124	0.130	0.132
2042	4.40	3.09	2.24	0.124	0.131	0.132
2043	4.41	3.12	2.24	0.124	0.130	0.131
2044	4.41	3.15	2.25	0.124	0.130	0.131

Table 47: Maintenance Costs from AAA 2021 [53]

Category	Vehicle Subclass	Maintenance cost per mile
ICE	Small Sedan	$0.088
	Medium Sedan	$0.104
	Subcompact SUV	$0.099
	Medium SUV (4WD)	$0.100
	Midsize Pickup	$0.099
BEV	Electric Vehicle (all classes)	$0.077

Table 48: Annual Vehicle Miles Traveled (VMT) from ANL study [7]

Class	Annual VMT (miles)
Cars	15,922
SUVs	16,234
Pickup trucks	18,964

8.3 Total Cost of Ownership Parity with Residential Charging Scenario

8.3.1 Small Car

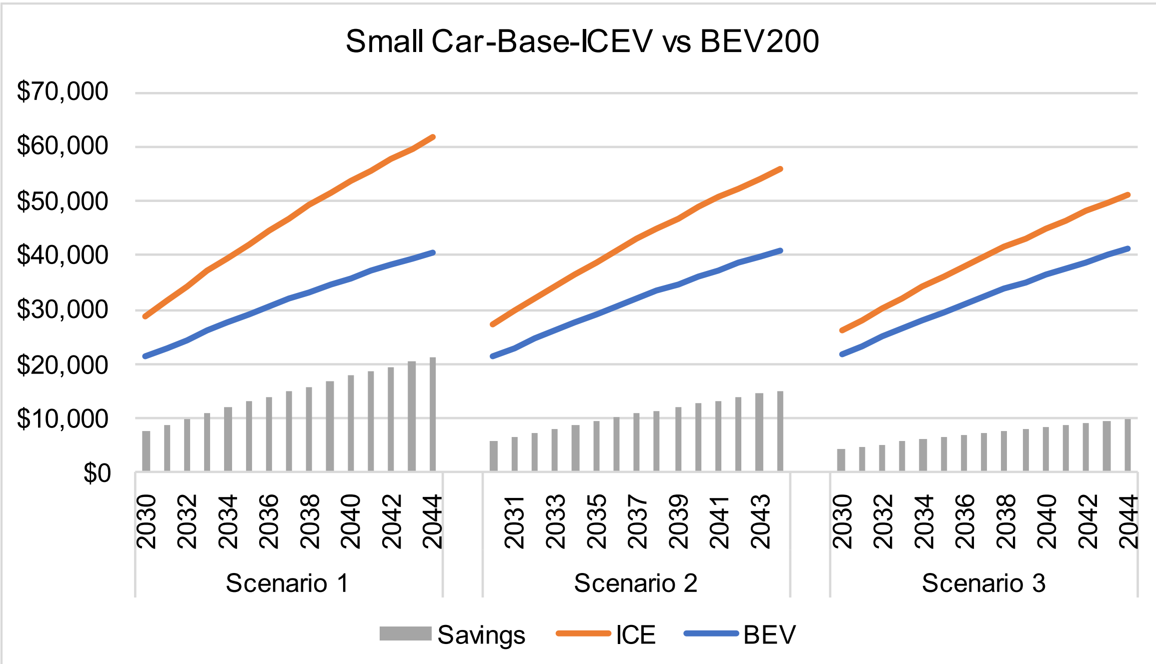

Figure 83: TCO parity of small cars in the base segment with residential charging

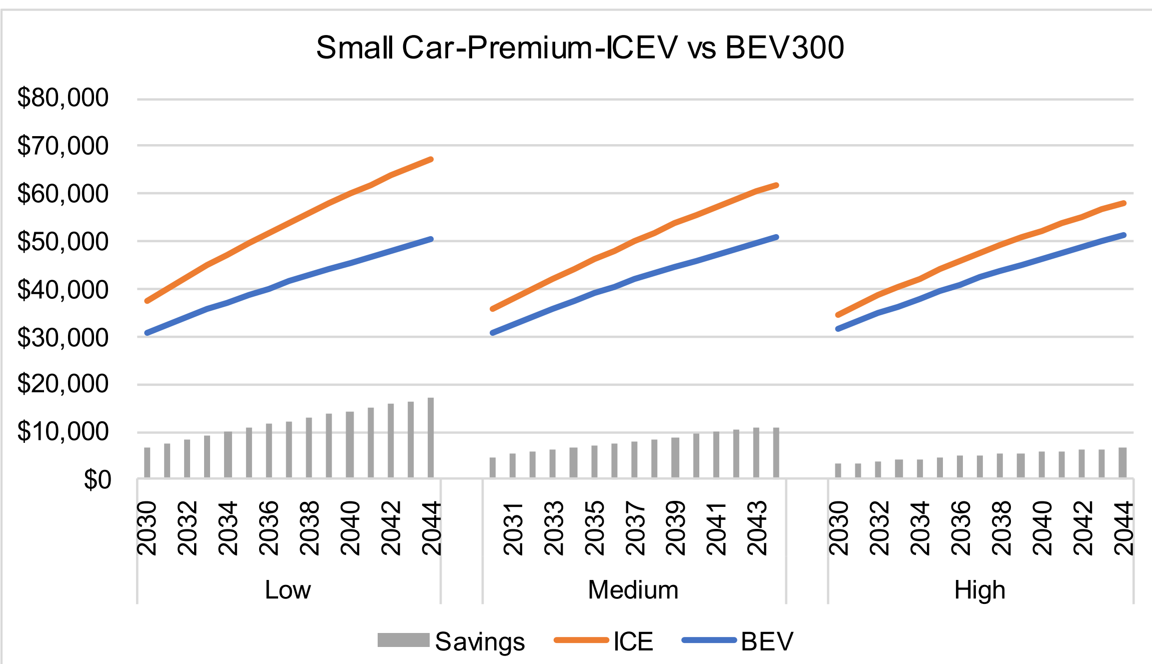

Figure 84: TCO parity of small cars in the premium segment with residential charging

8.3.2 Medium Car

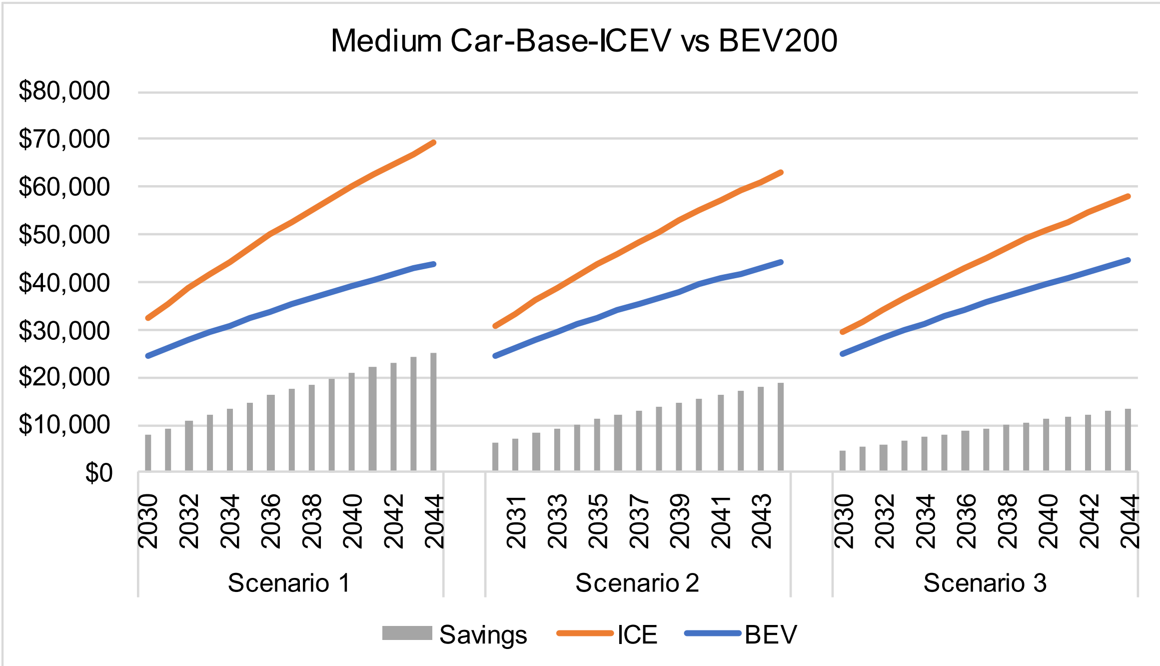

Figure 85: TCO parity of medium car in the base segment with residential charging

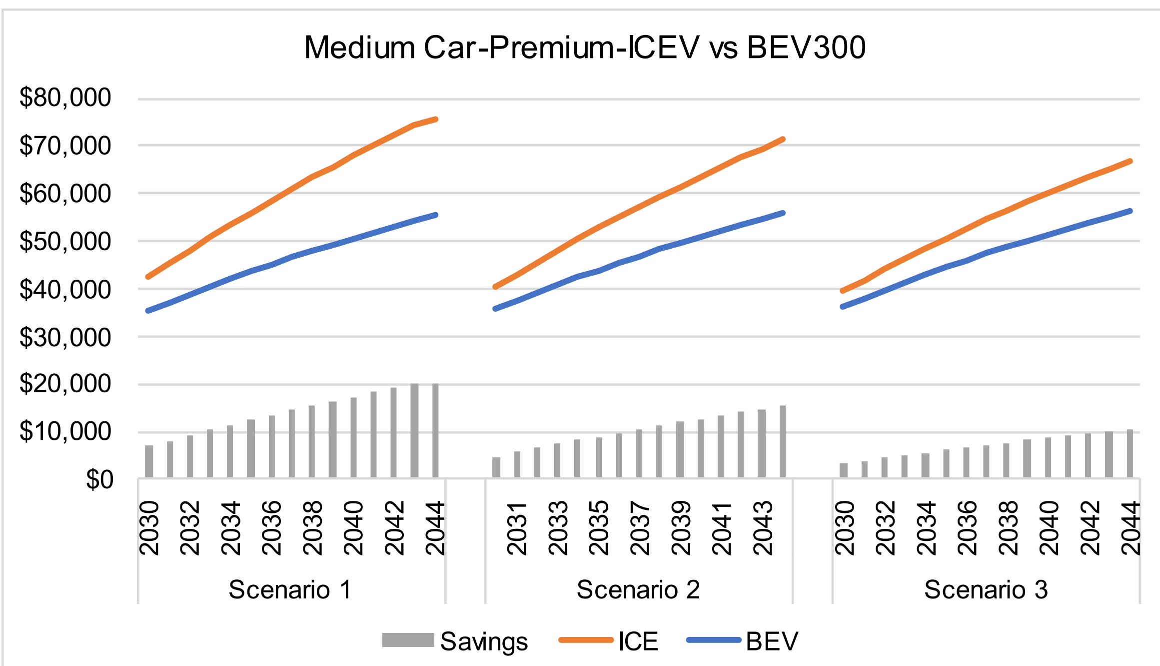

Figure 86: TCO parity of medium car in the premium segment with residential charging

8.3.3 Small SUV

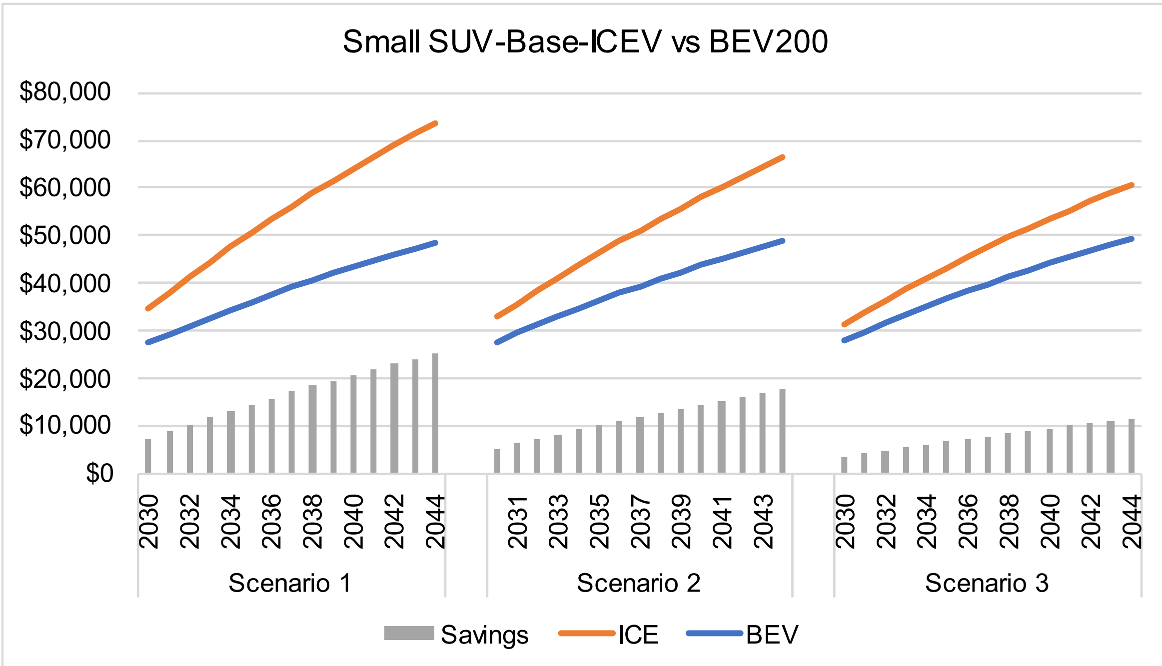

Figure 87: TCO parity of small SUVs in the base segment with residential charging

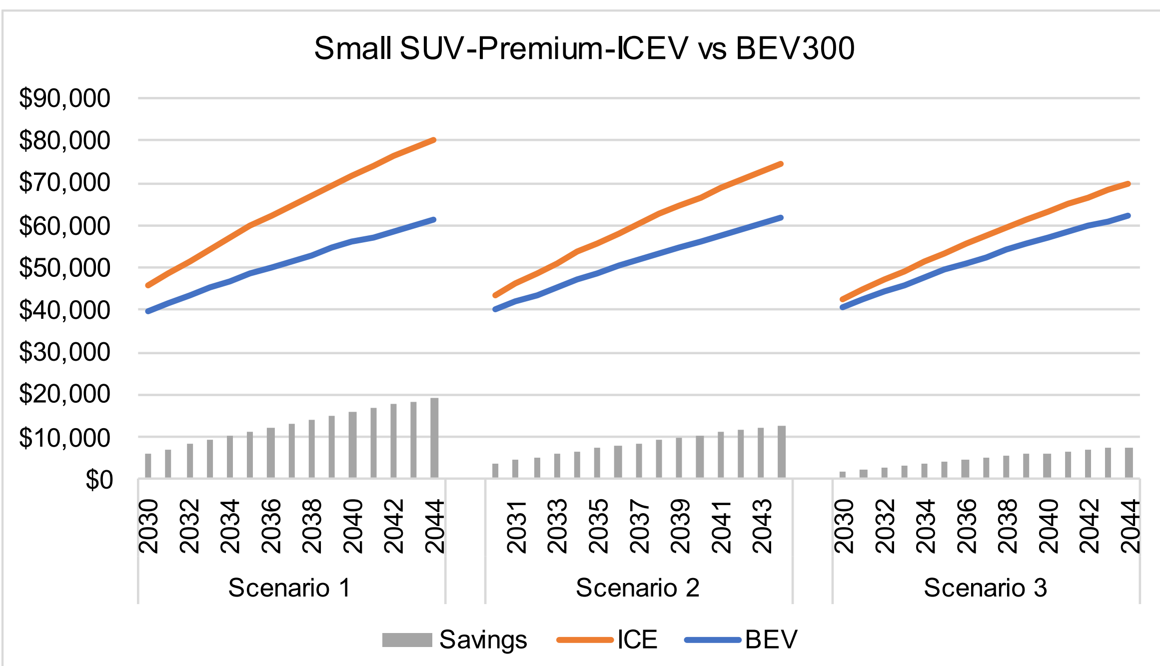

Figure 88: TCO parity of small SUVs in the premium segment with residential charging

8.3.4 Midsize SUV

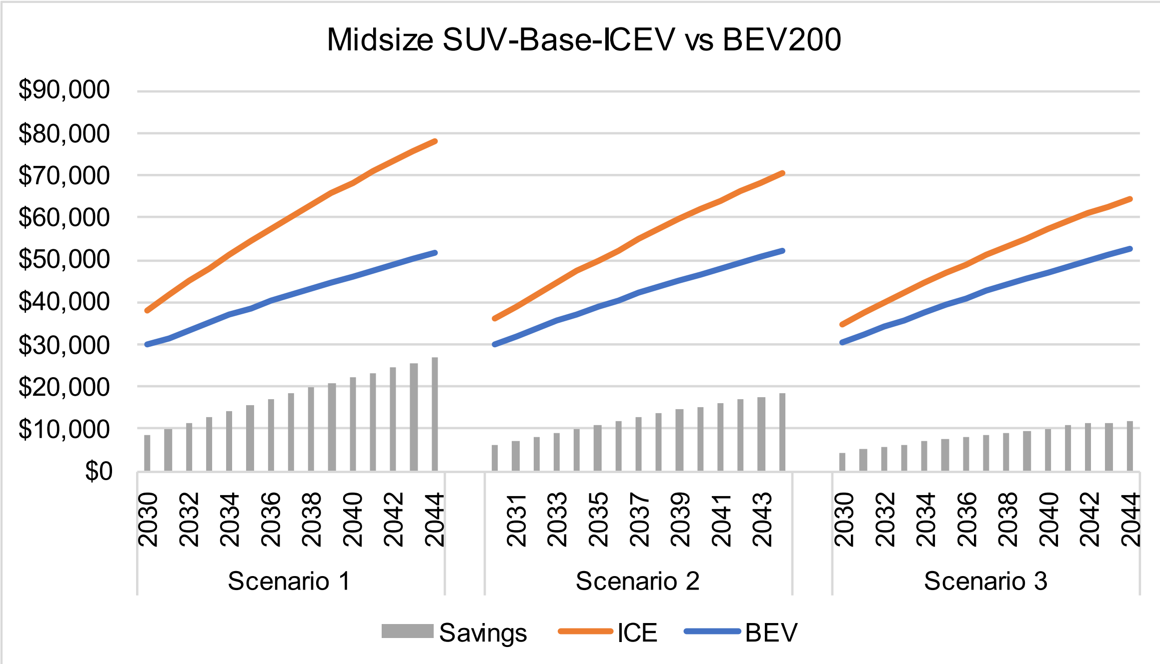

Figure 89: TCO parity of midsize SUV in the base segment with residential charging

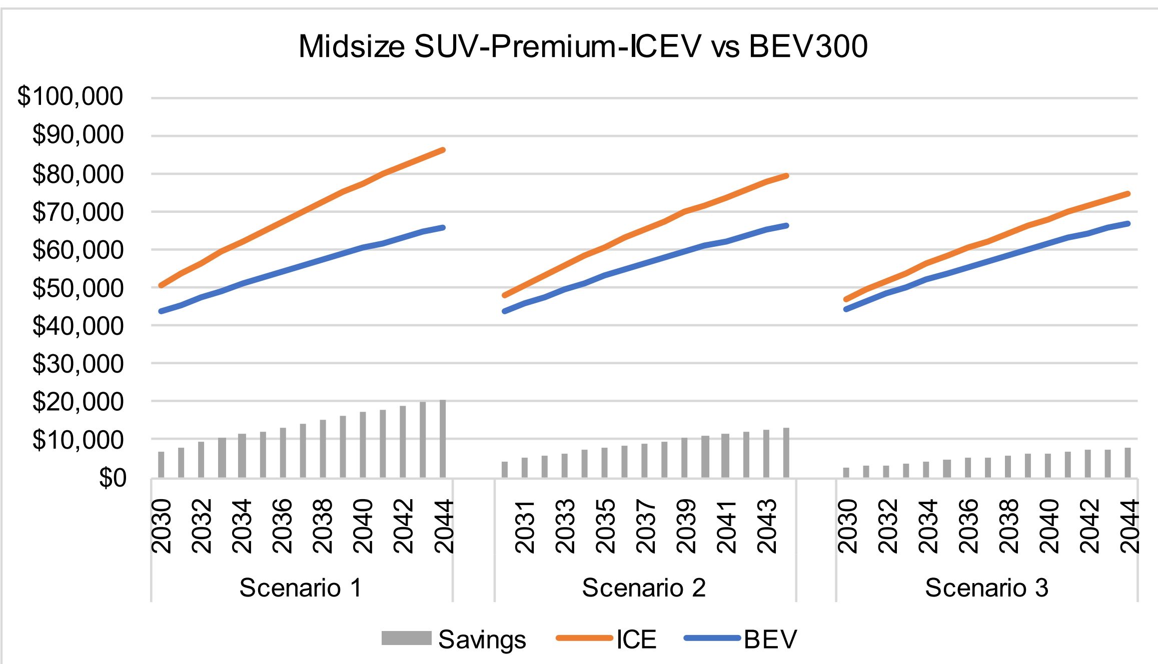

Figure 90: TCO parity of midsize SUV in the premium segment with residential charging

8.3.5 Large SUV

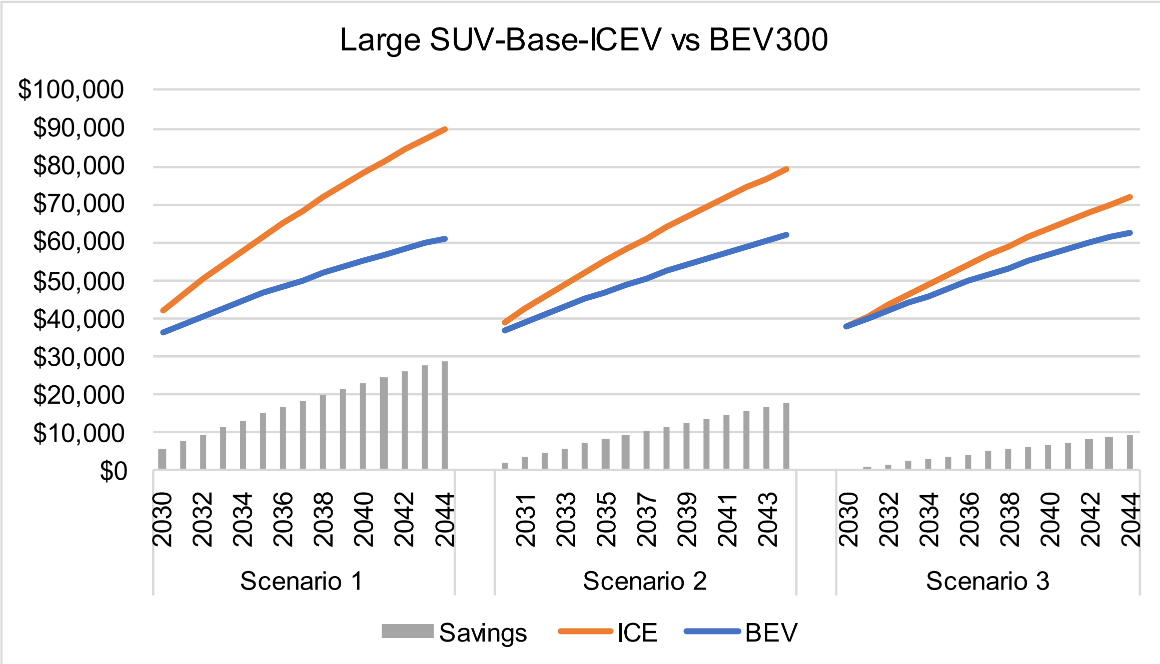

Figure 91: TCO parity of large SUV in the base segment with residential charging

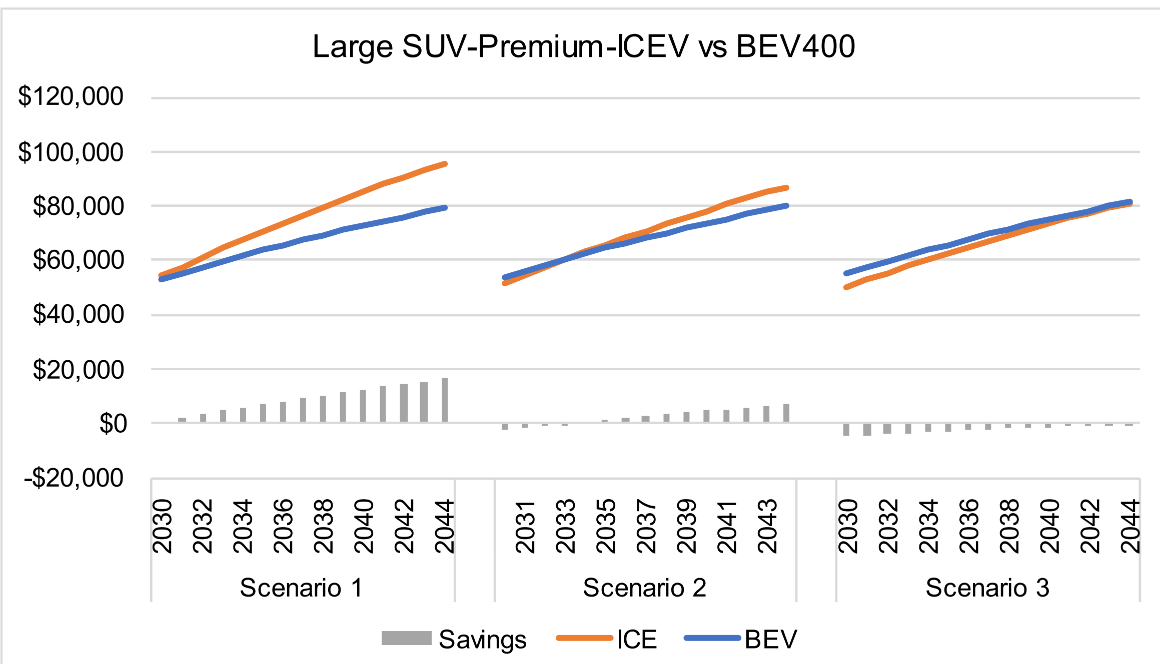

Figure 92: TCO parity of large SUVs in the premium segment with residential charging

8.3.6 Pickup Truck

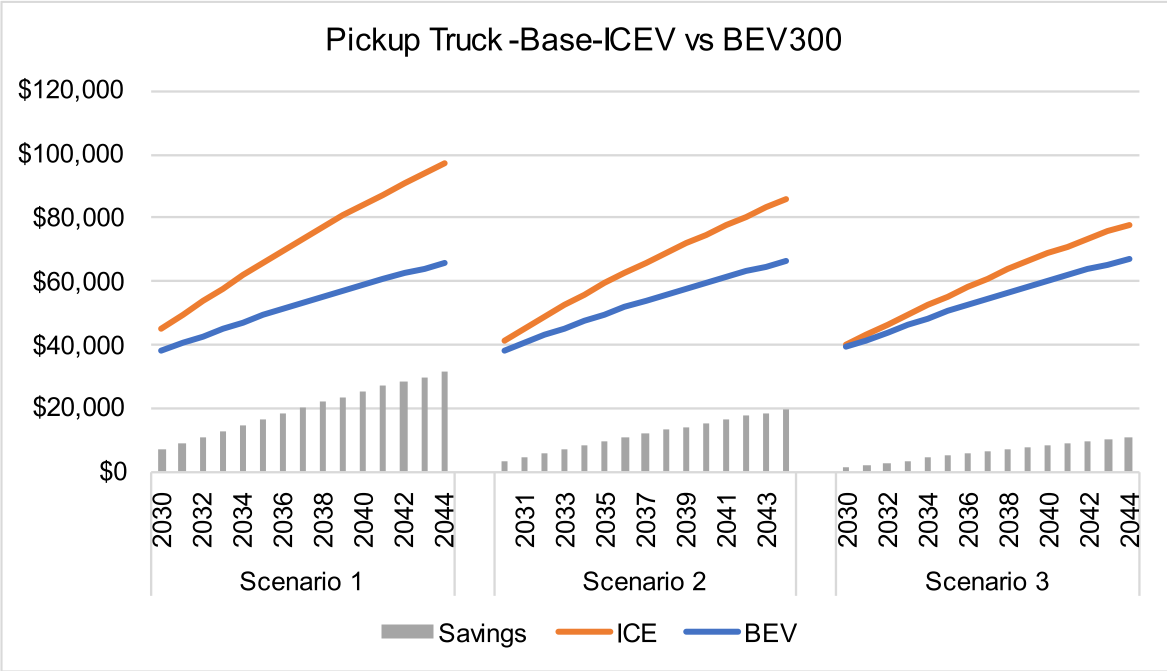

Figure 93: TCO parity of pickup truck in the base segment with residential charging

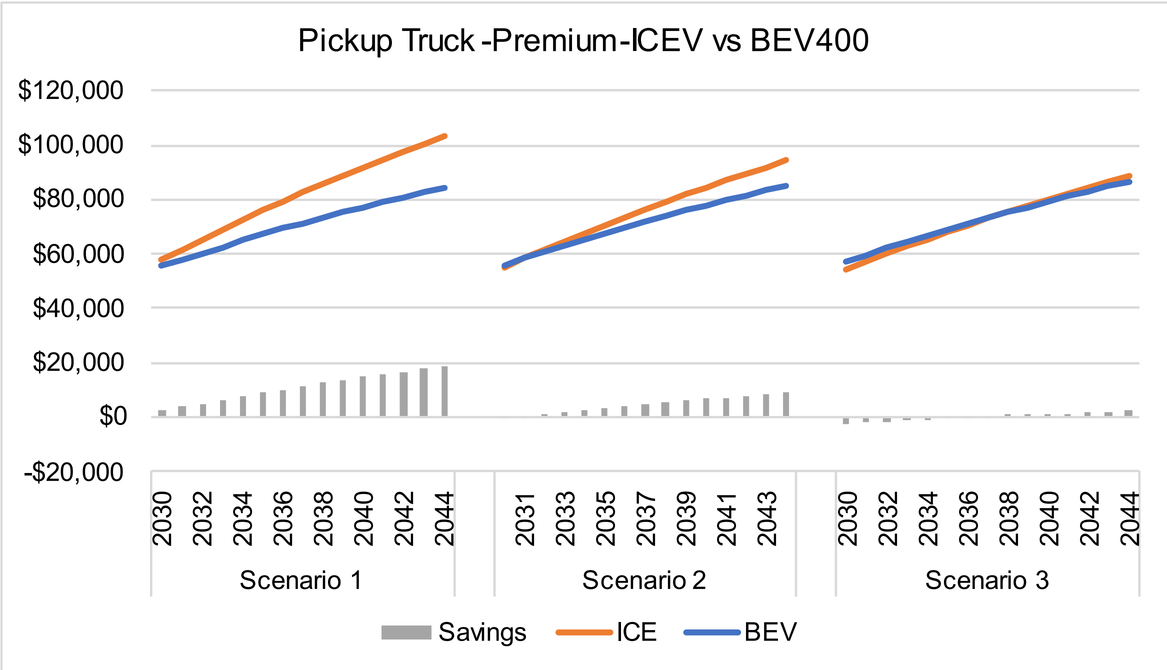

Figure 94: TCO parity of pickup trucks in the premium segment with residential charging

8.4 Total Cost of Ownership Parity with Demand Charging Scenario

8.4.1 Small Car

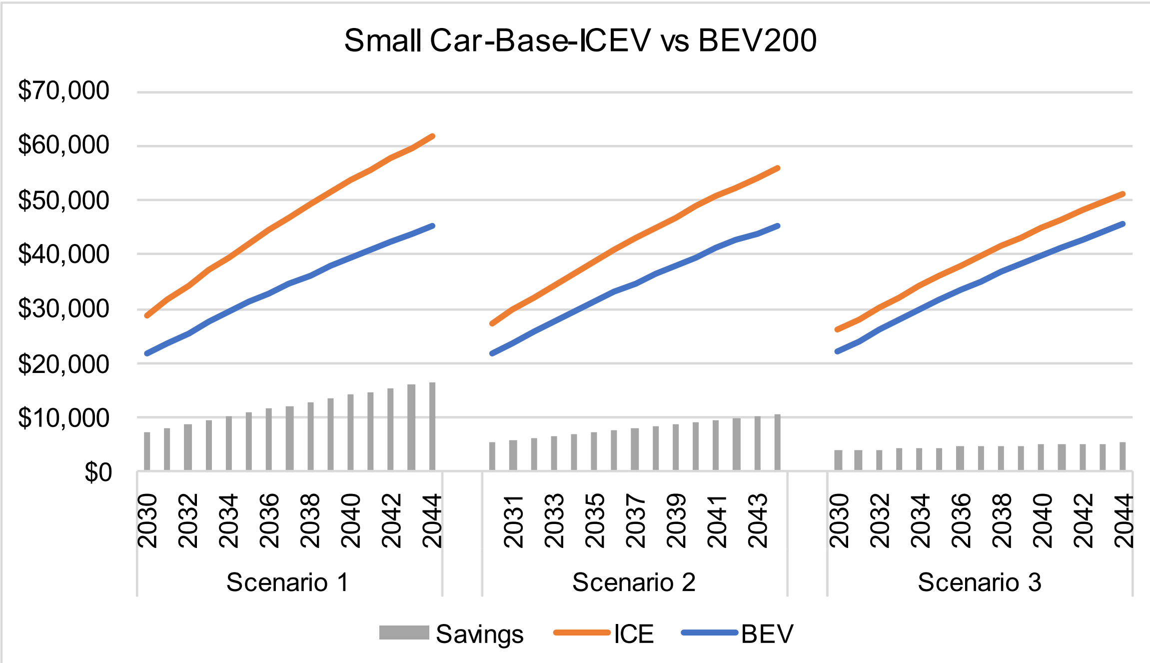

Figure 95: TCO parity of small cars in the base segment with demand charging

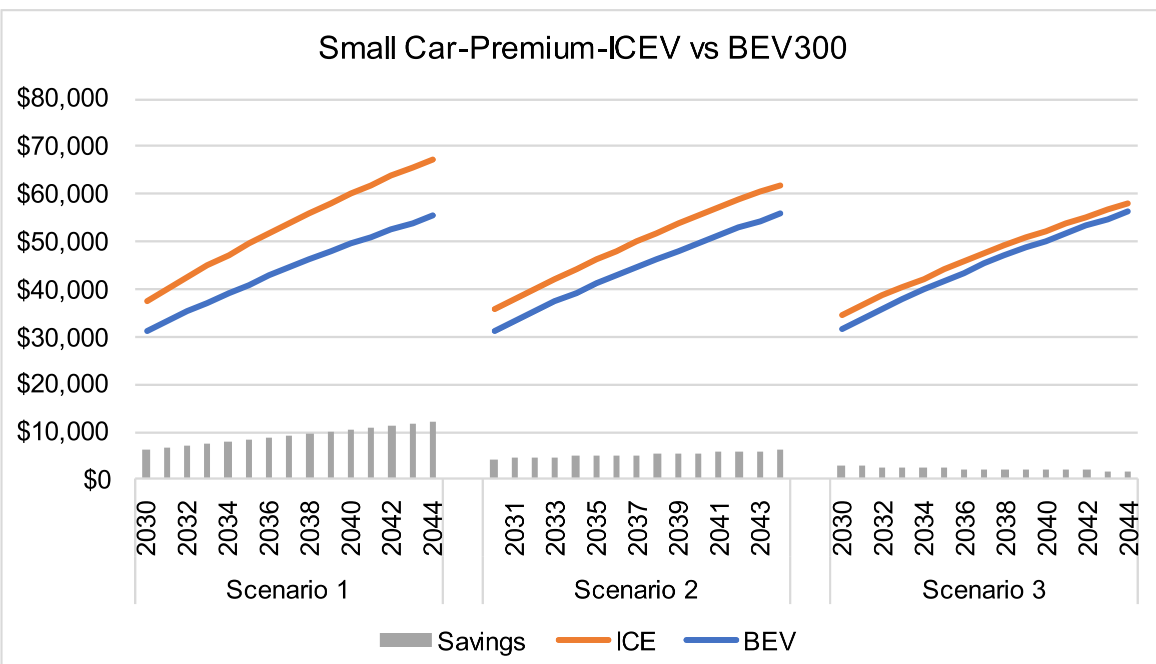

Figure 96: TCO parity of small cars in the premium segment with demand charging

8.4.2 Medium Car

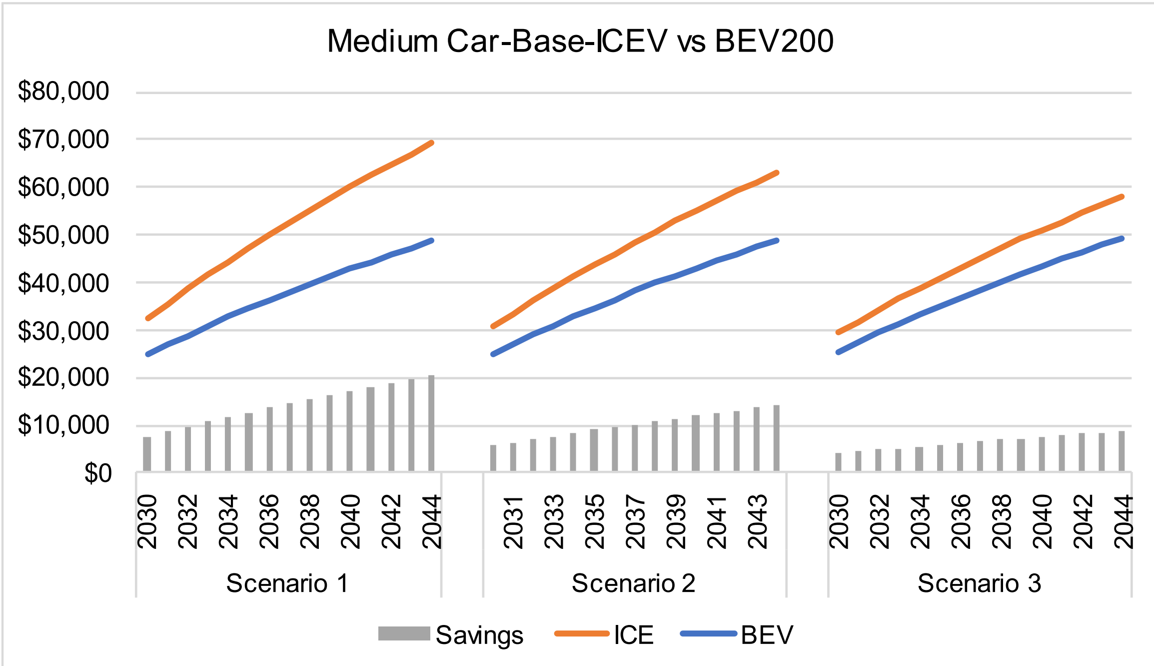

Figure 97: TCO parity of medium car in the base segment with demand charging

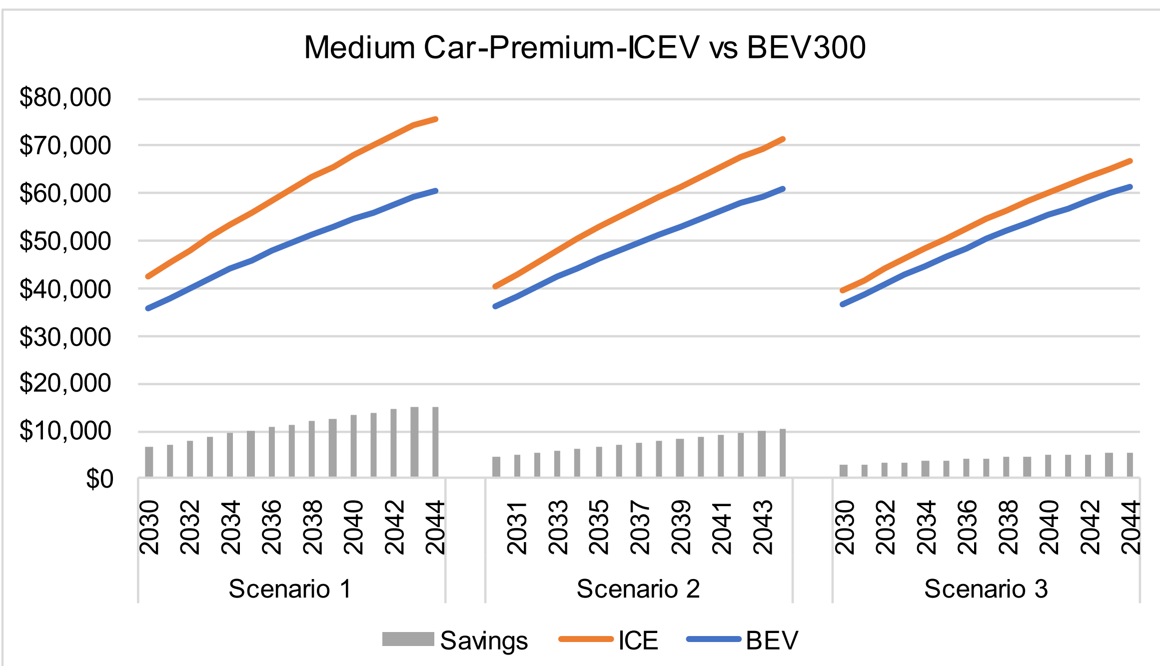

Figure 98: TCO parity of medium car in the premium segment with demand charging

8.4.3 Small SUV

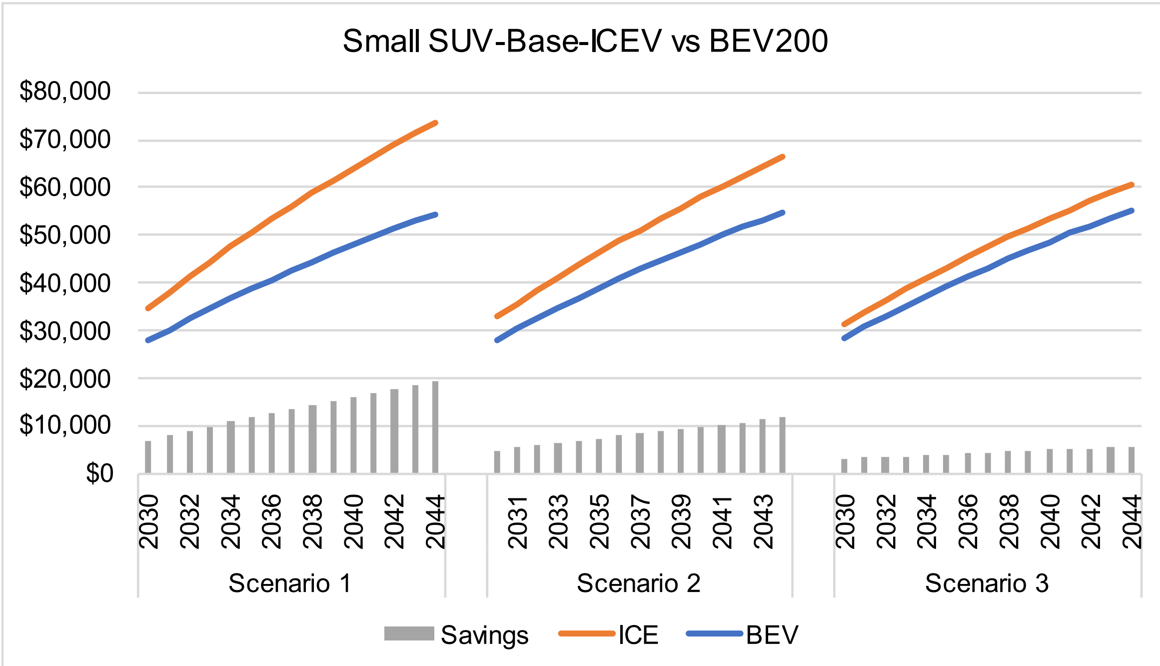

Figure 99: TCO parity of small SUVs in the base segment with demand charging

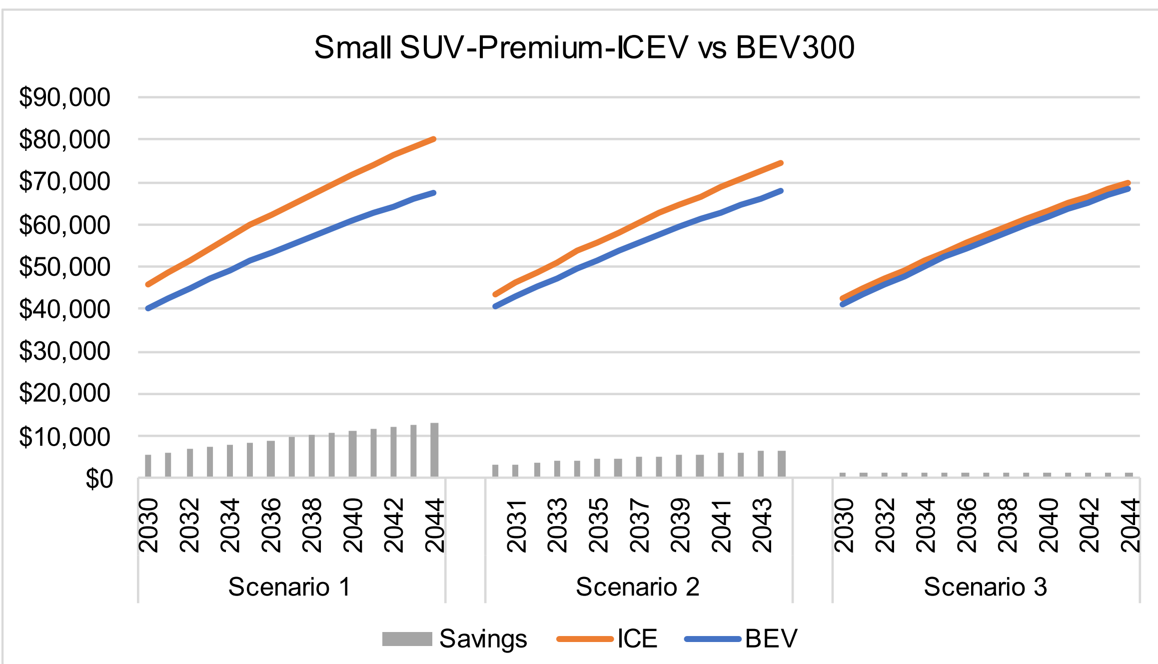

Figure 100: TCO parity of small SUVs in the premium segment with demand charging

8.4.4 Midsize SUV

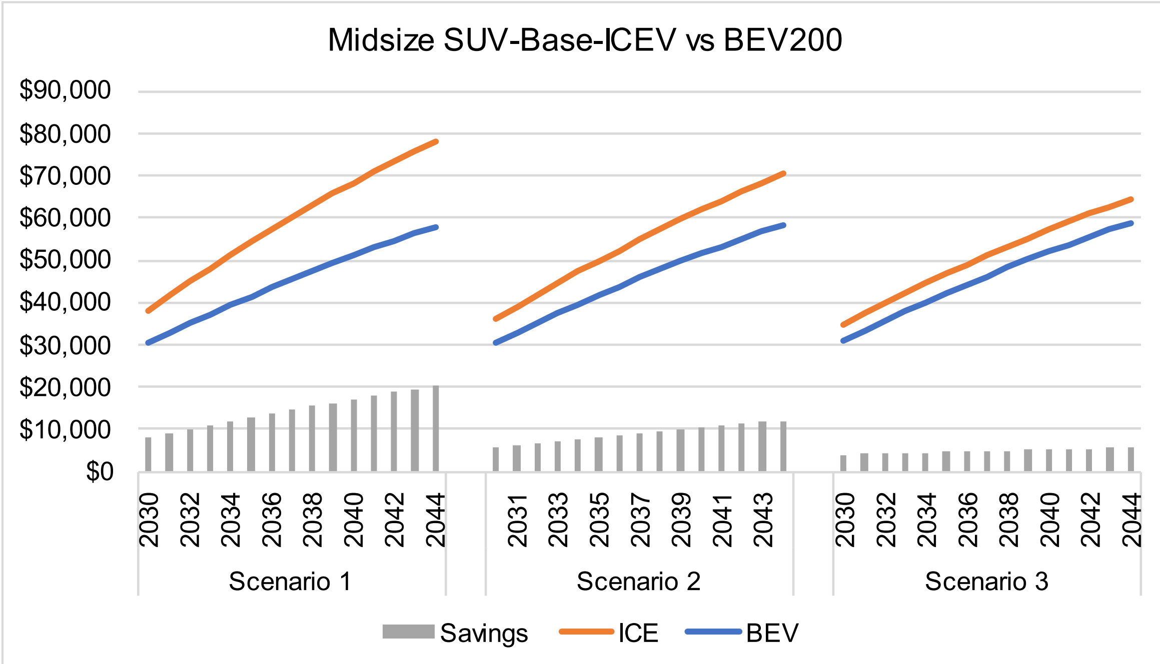

Figure 101: TCO parity of midsize SUV in the base segment with demand charging

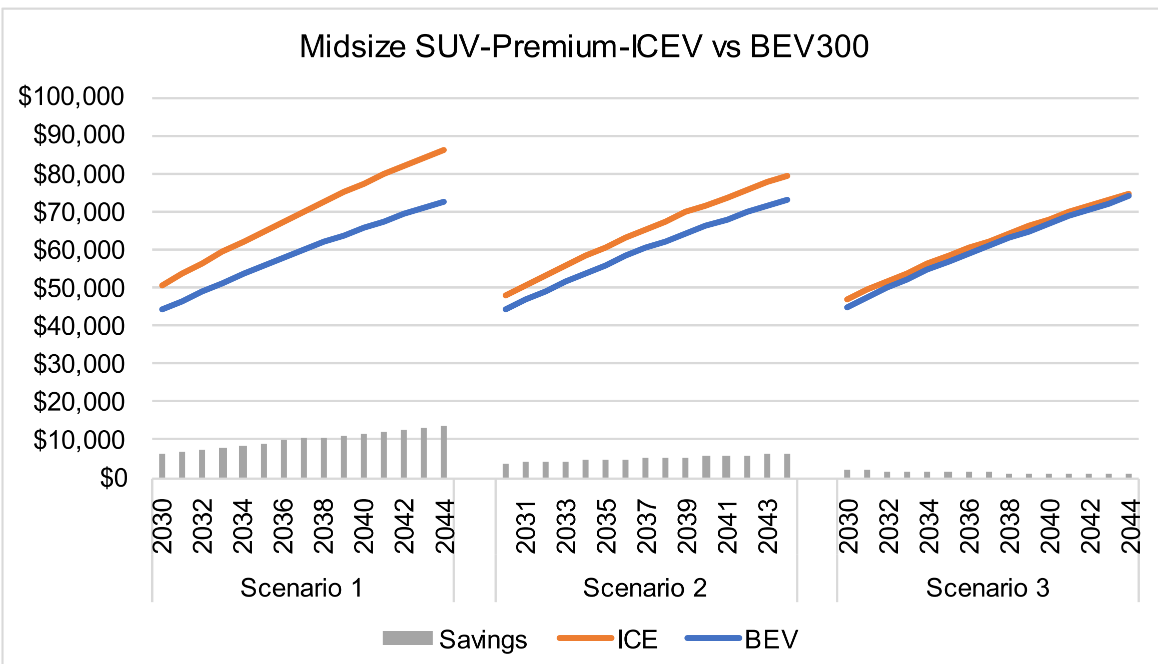

Figure 102: TCO parity of midsize SUV in the premium segment with demand charging

8.4.5 Large SUV

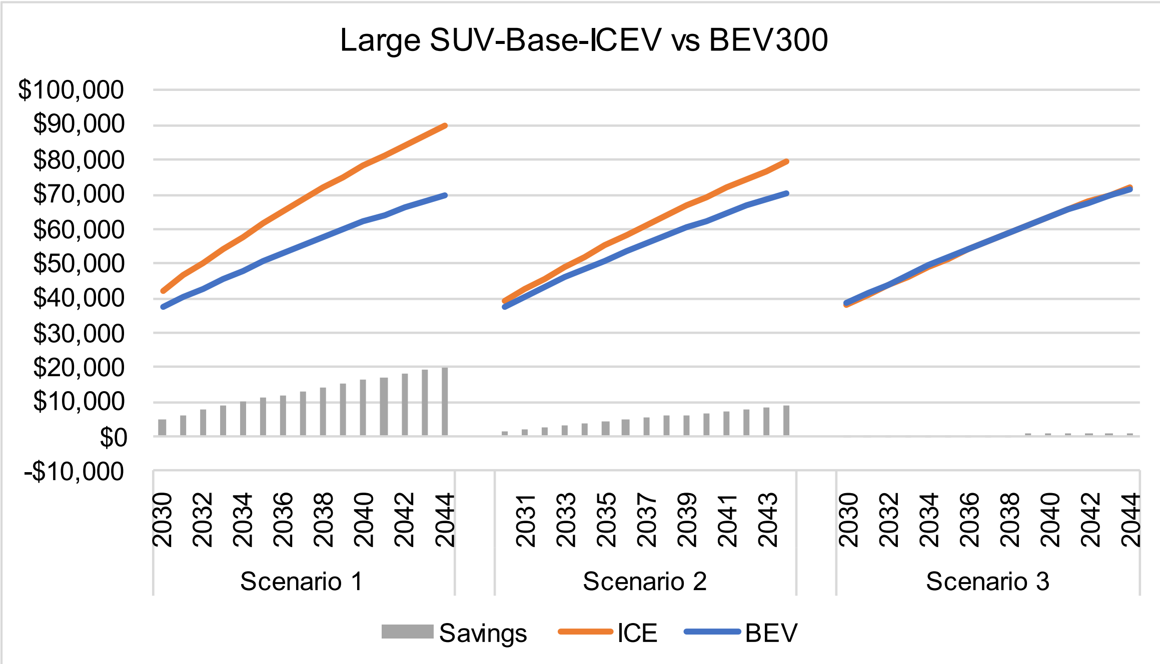

Figure 103: TCO parity of large SUV in the base segment with demand charging

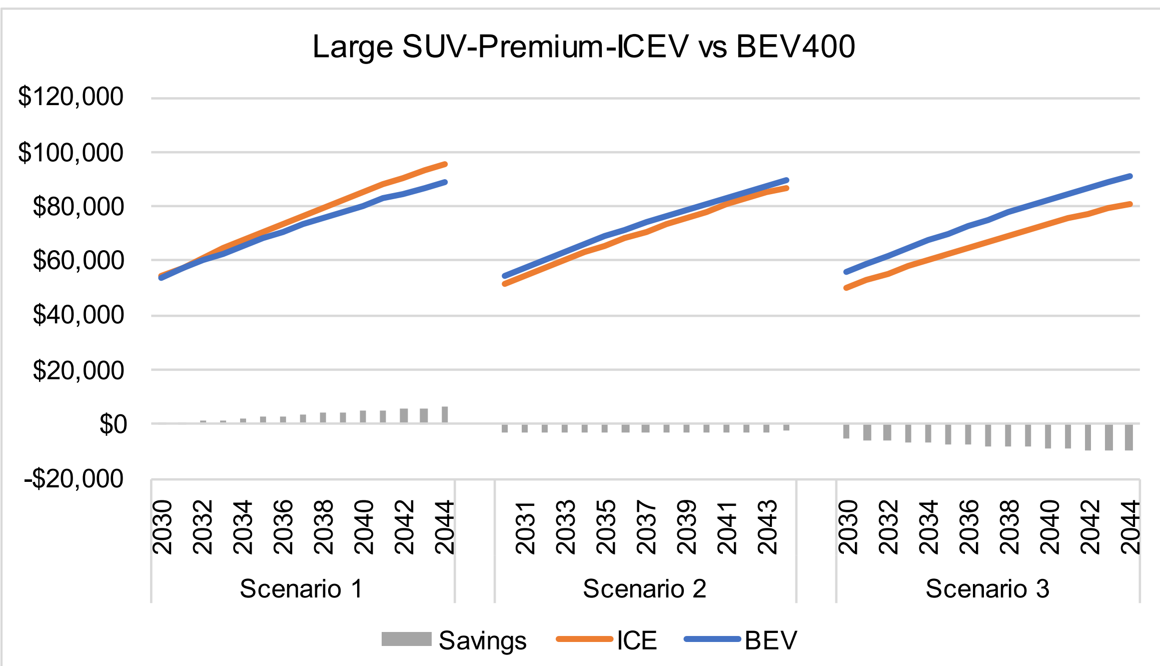

Figure 104: TCO parity of large SUVs in the premium segment with demand charging

8.4.6 Pickup Truck

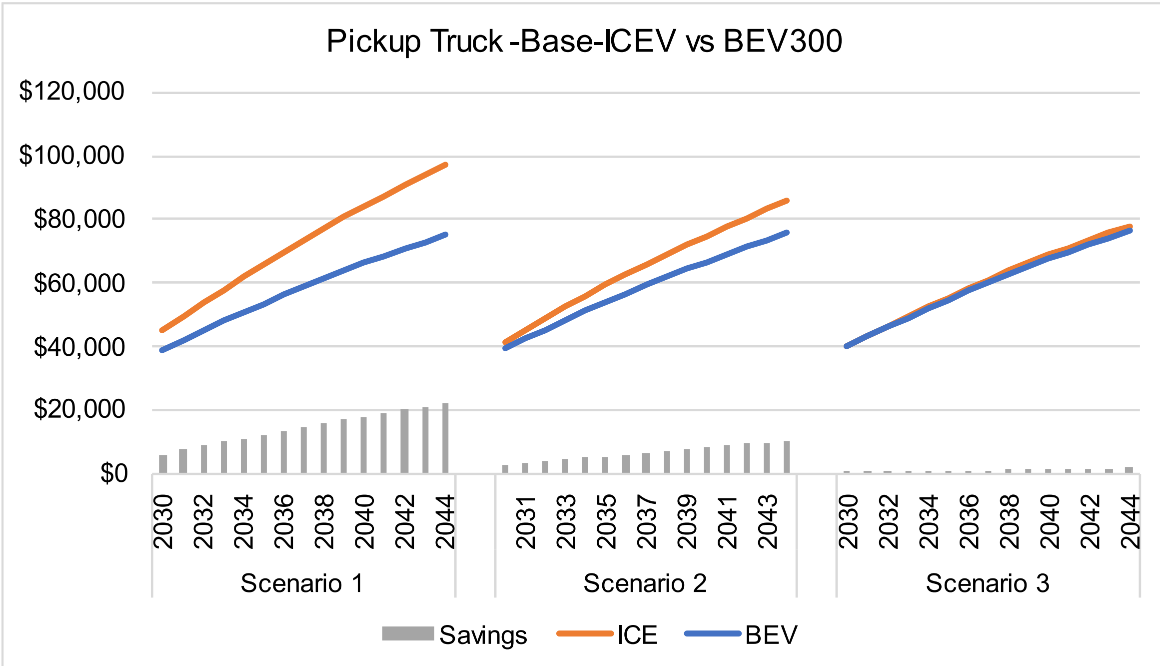

Figure 105: TCO parity of pickup truck in the base segment with demand charging

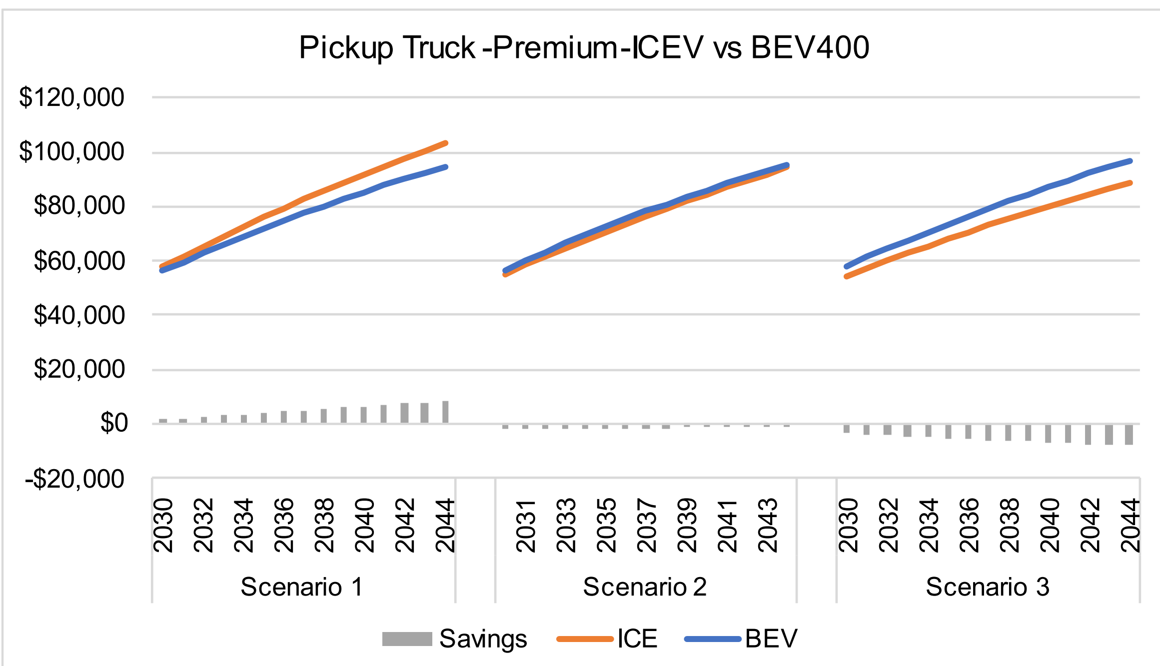

Figure 106: TCO parity of pickup trucks in the premium segment with demand charging

8.5 Fleetwide Sales-Weighted Average Cost

SS12V is equally split between CONV and BISG for simplifying the projections and analysis. HCR and TURBO are the engine pathways while CONV, BISG, and SHEV are the electrification pathways. For the LTs, the HCR engine pathway is considered for all scenarios. They are two separate pathways and have overlapping numbers, and therefore should be considered separately. The ICE sales considered from the vehicles_report_FRM_PrimaryRuns for MY 2029 is 12,248,135, with the breakup as follows:

a) Conventional (+50% SS12V): 6,733,032
b) BISG (+50% SS12V): 2,940,676
c) SHEV: 2,574,427

Table 49: Penetration rates from technology utilization in Scenario 0

Pathway	LT	PC	Total % share	Sale numbers
HCR + TURBO	75%	75%	75%	11,564,972
CONV (+50% SS12V)	28%	58%	42%	6,521,407
BISG (+50% SS12V)	23%	14%	19%	2,924,955
SHEV	27%	6%	17%	2,560,664

Table 50: Normalized sales of light trucks (LT) and passenger cars (PC) in Scenario 0

Powertrain	LT	PC
	HCR + TURBO	HCR + TURBO
Conventional	34%	68%
BISG	27%	17%
SHEV	32%	7%

Table 51: Penetration rates from technology utilization in Scenario 1 all migration from CONV to BISG with SHEV remaining unchanged

Pathway	LT	PC	Total % share	Sale numbers
HCR + TURBO	75%	75%	75%	11,564,972
CONV (+50% SS12V)	0%	0%	0%	0
BISG (+50% SS12V)	65%	91%	77%	9,446,362
SHEV	34%	7%	21%	2,560,664

Table 52: Normalized sales for the light trucks (LT) and passenger cars (PC) in Scenario 1,

Powertrain	LT	PC
	HCR + TURBO	HCR + TURBO
Conventional	0%	0%
BISG	61%	85%
SHEV	32%	7%

Table 53: Penetration rates from technology utilization in Scenario 2 with all migration from CONV to BISG and SHEV with a 60:40 split, respectively.

Pathway	LT	PC	Total % share	Sale numbers
HCR + TURBO	75%	75%	75%	11,564,972
CONV (+50% SS12V)	0%	0%	0%	0
BISG (+50% SS12V)	51%	62%	56%	6,837,800
SHEV	48%	36%	42%	5,169,227

Table 54: Normalized sales for the light trucks (LT) and passenger cars (PC) in Scenario 2.

Powertrain	LT	PC
	HCR + TURBO	HCR + TURBO
Conventional	0%	0%
BISG	48%	58%
SHEV	45%	34%

Table 55: Powertrain costs used in the study.

Powertrain	LT	PC
	HCR + TURBO	HCR + TURBO
Conventional	$7,696	$6,606
BISG	$8,122	$7,201
SHEV	$9,600	$8,181

The steps to compute the sales-weighted average cost are:

a) Using the percentage breakup of the electrification pathway, split the CONV, BISG, and SHEV into the HCR and TURBO engine pathways, respectively.

b) Compute the sales-weighted average cost using the formula, $(\Sigma \text{ Costs} \times \text{Sales})_{\text{technology}} \div (\Sigma \text{ Sales})$

8.5.1 Total Cost of Ownership Parity using Fleetwide Sales-Weighted Average Cost of each Subclass

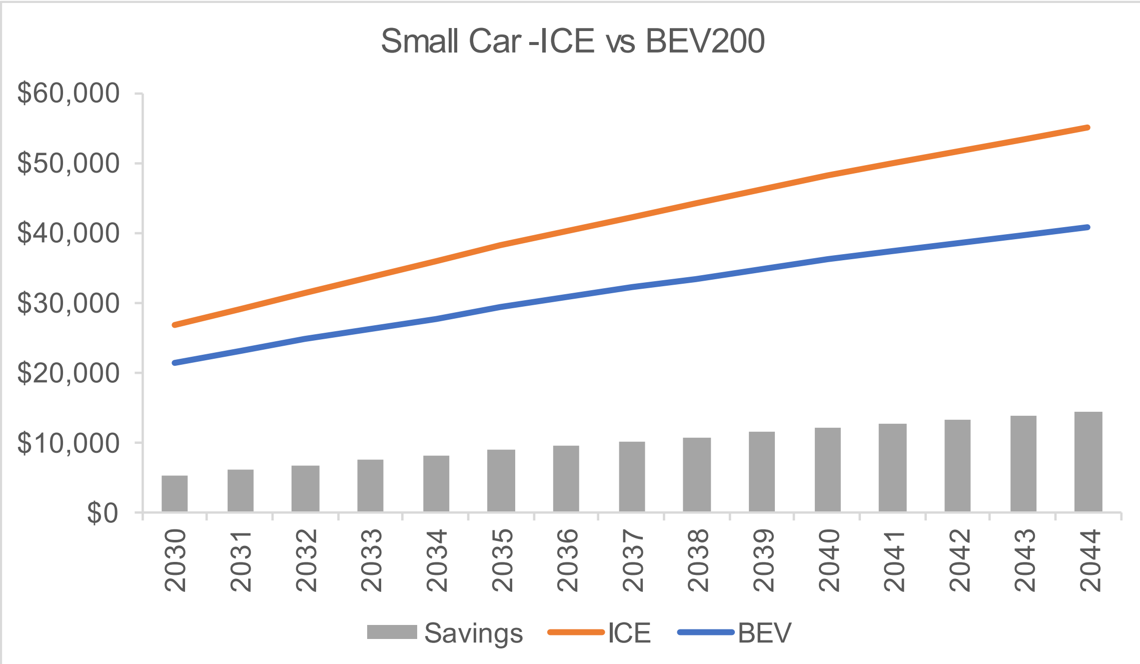

Figure 107: TCO parity of fleetwide sales-weighted small car ICE vs BEV200.

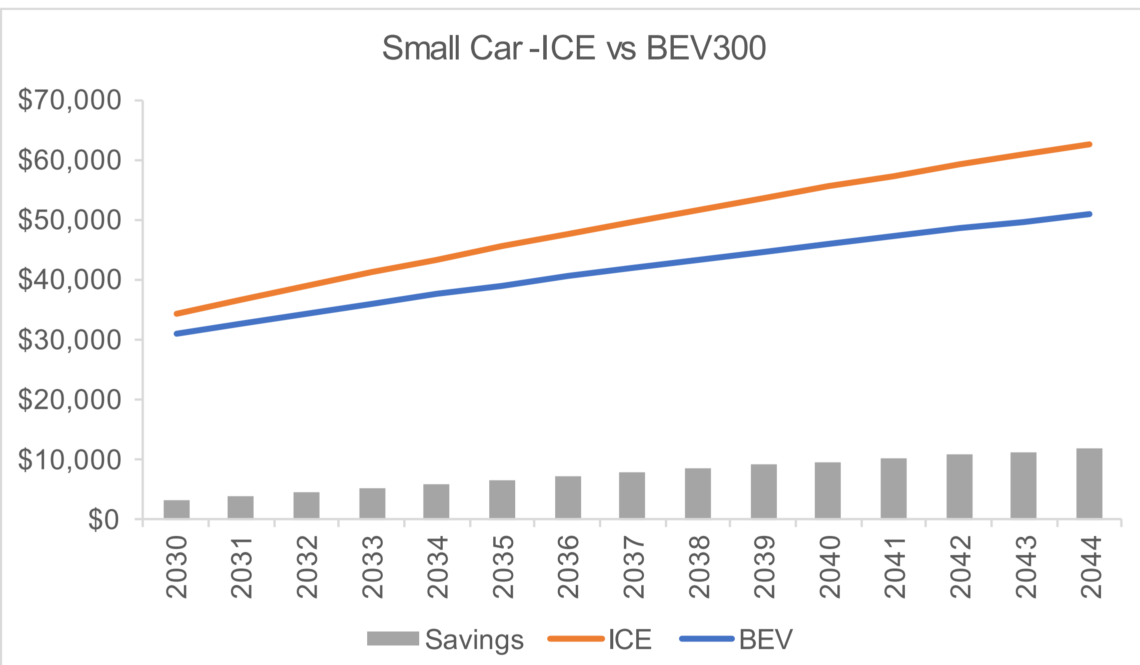

Figure 108: TCO parity of fleetwide sales-weighted small car ICE vs BEV300.

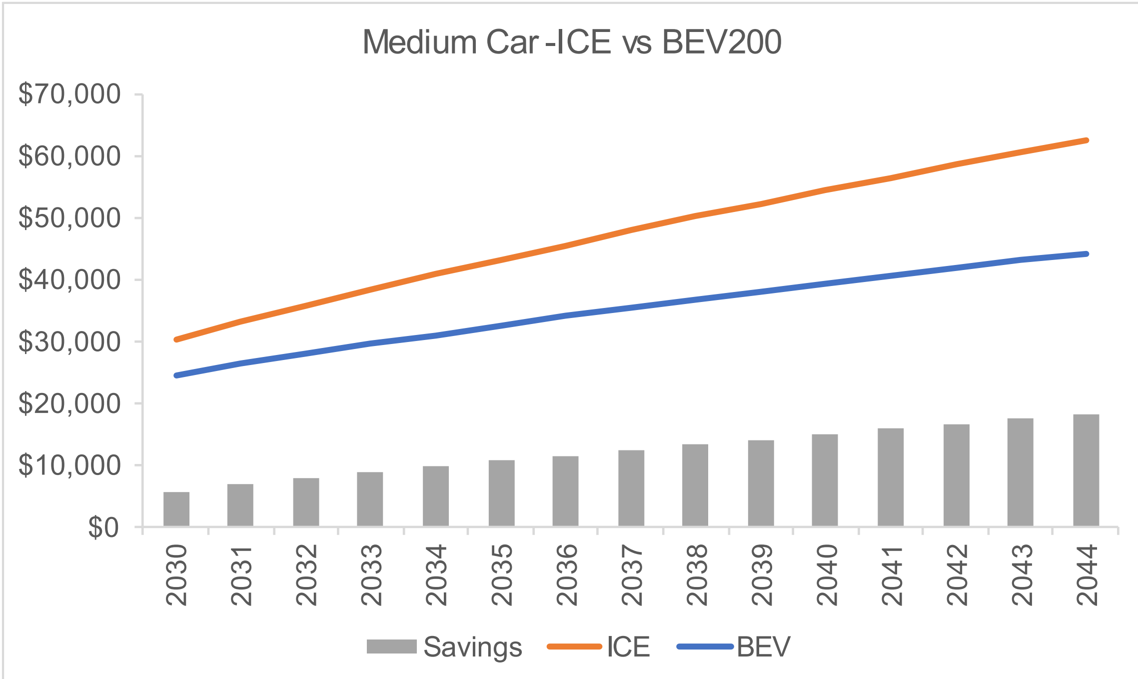

Figure 109: TCO parity of fleetwide sales-weighted medium car ICE vs BEV200.

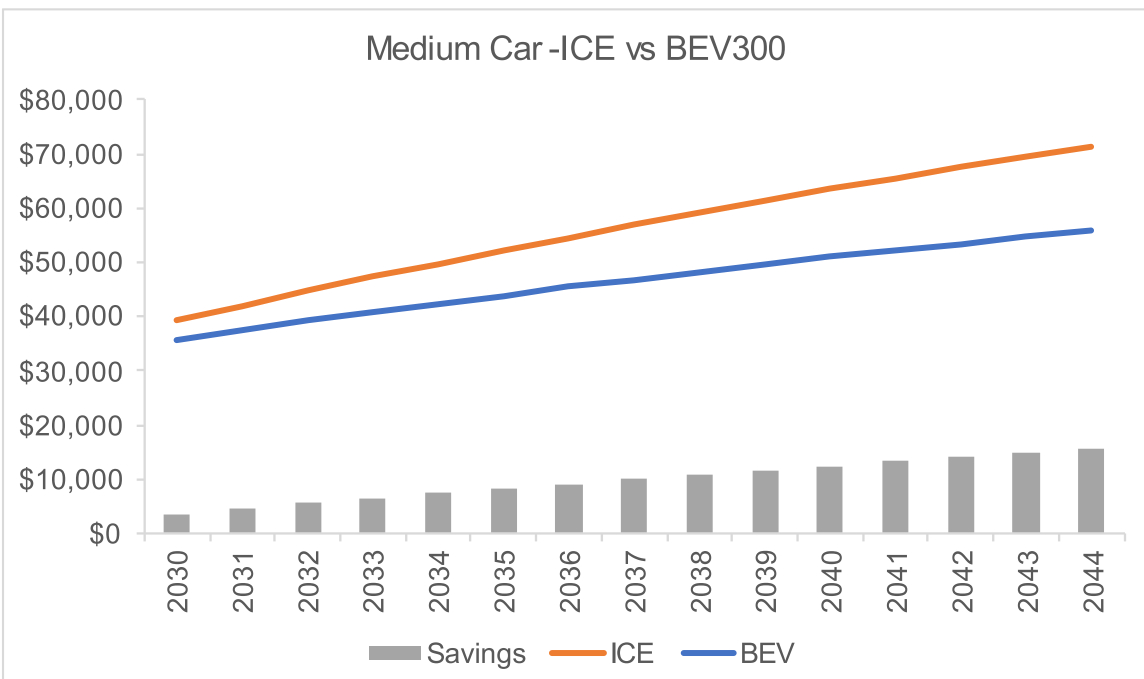

Figure 110: TCO parity of fleetwide sales-weighted medium car ICE vs BEV300.

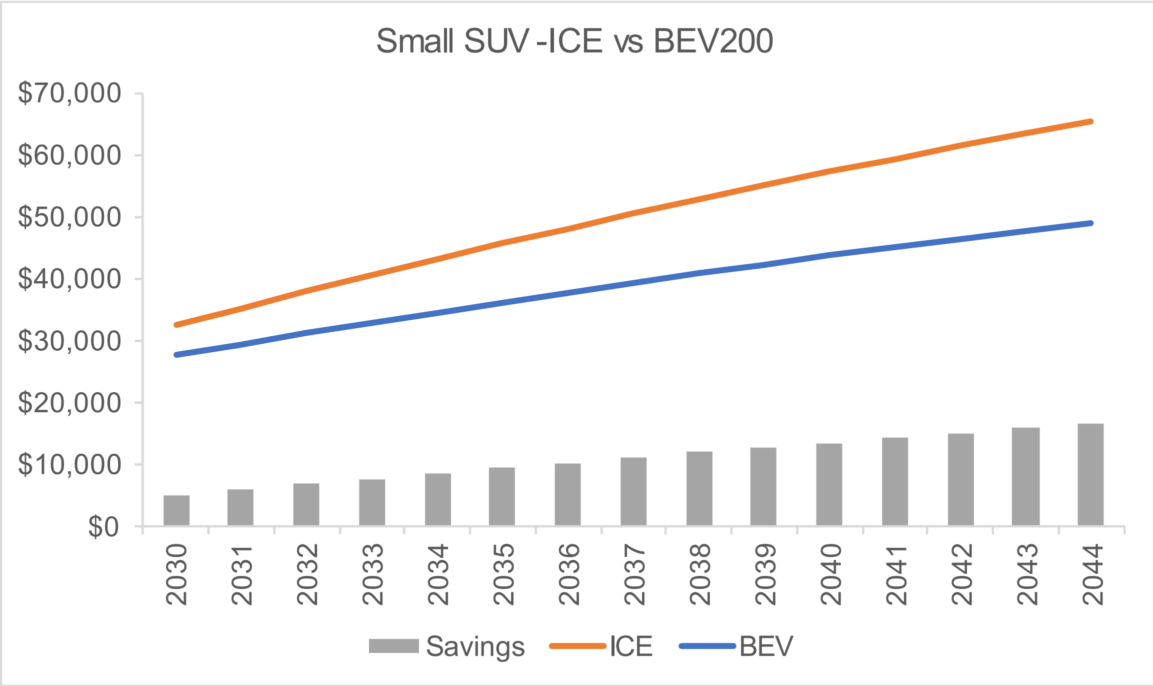

Figure 111: TCO parity of fleetwide sales-weighted small SUV ICE vs BEV200.

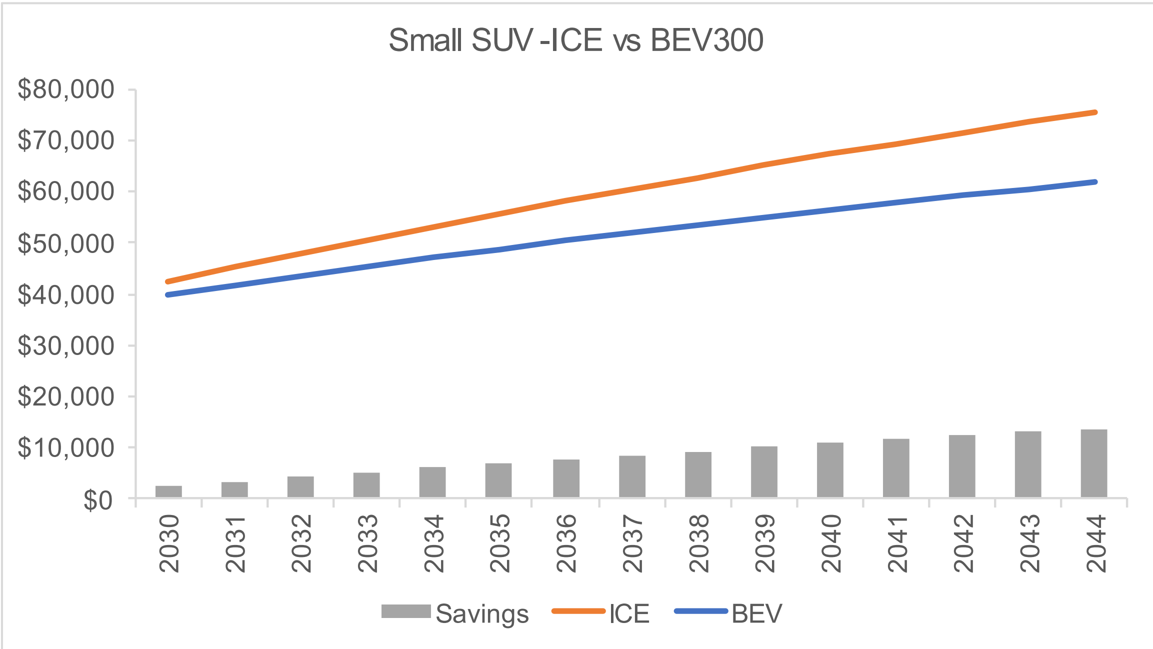

Figure 112: TCO parity of fleetwide sales-weighted small SUV ICE vs BEV300.

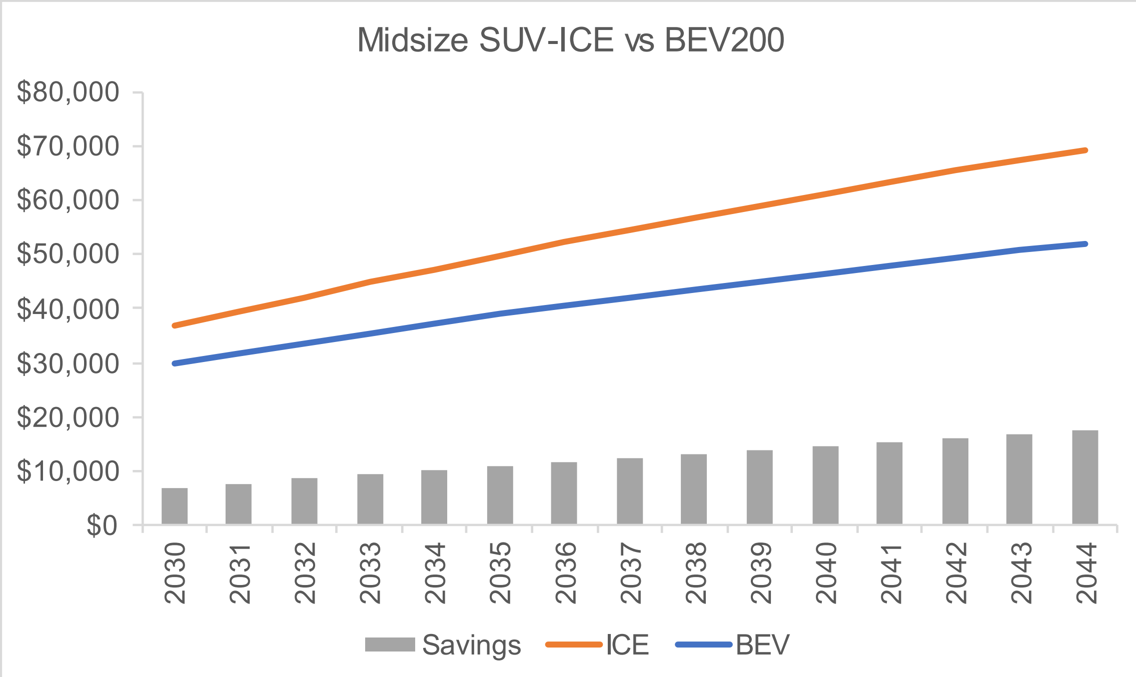

Figure 113: TCO parity of fleetwide sales-weighted midsize SUV ICE vs BEV200.

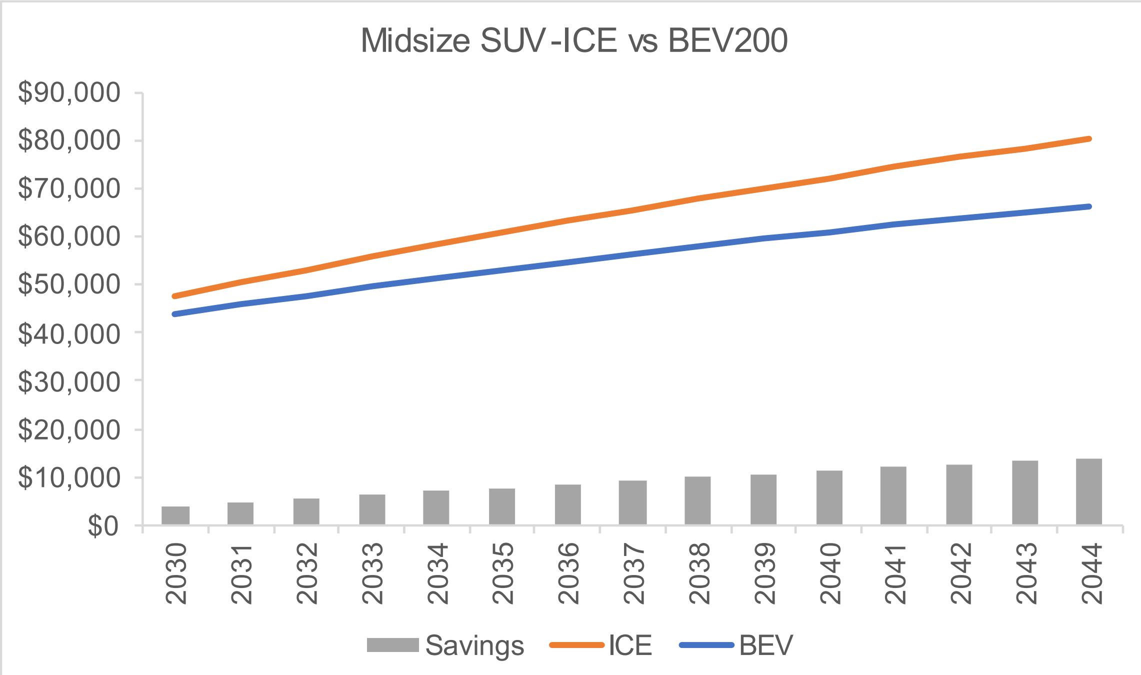

Figure 114: TCO parity of fleetwide sales-weighted midsize SUV ICE vs BEV300.

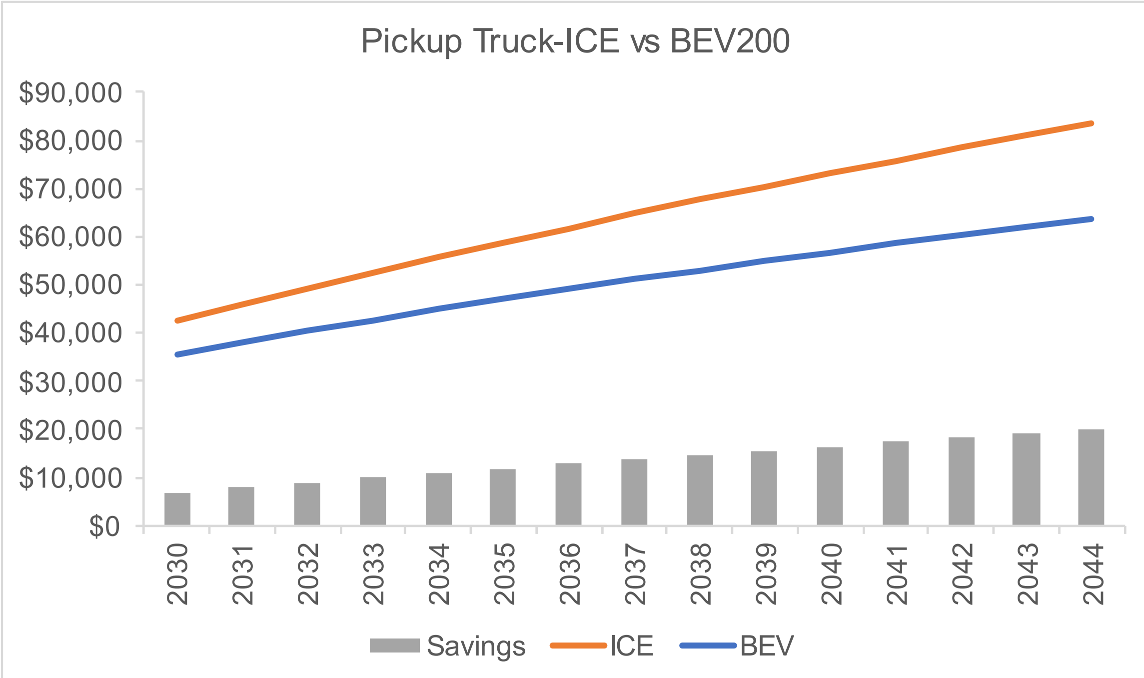

Figure 115: TCO parity of fleetwide sales-weighted pickup truck ICE vs BEV200.

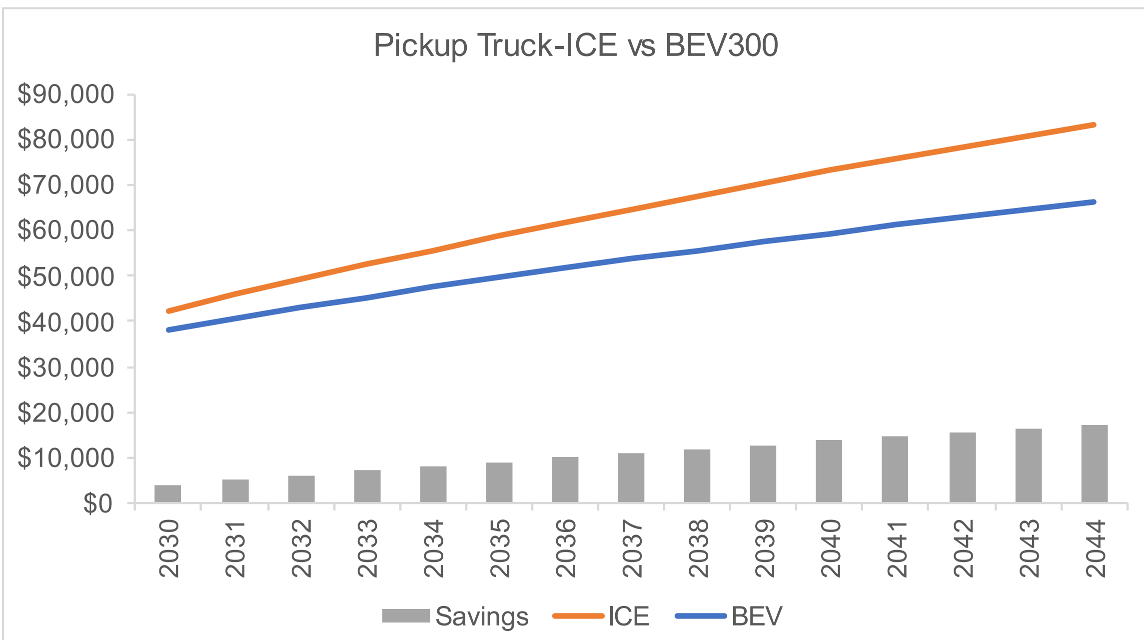

Figure 116: TCO parity of fleetwide sales-weighted small SUV ICE vs BEV300.

8.6 Total Cost of Ownership Parity with Fuel Price Sensitivity

8.6.1 Small Car

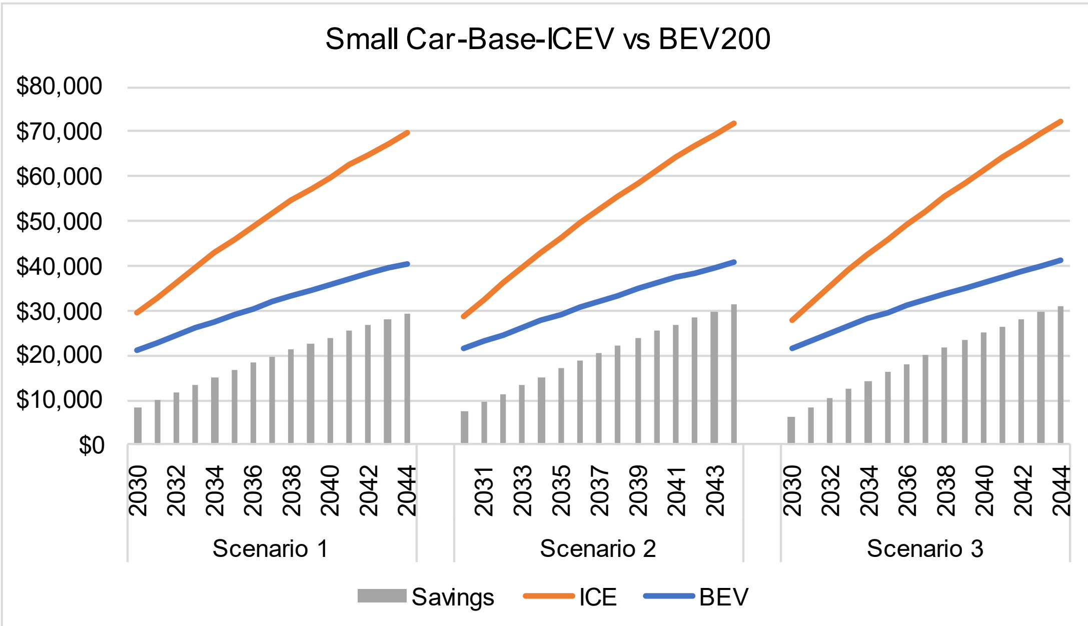

Figure 117: TCO parity of small cars in the base segment in a high gasoline price scenario.

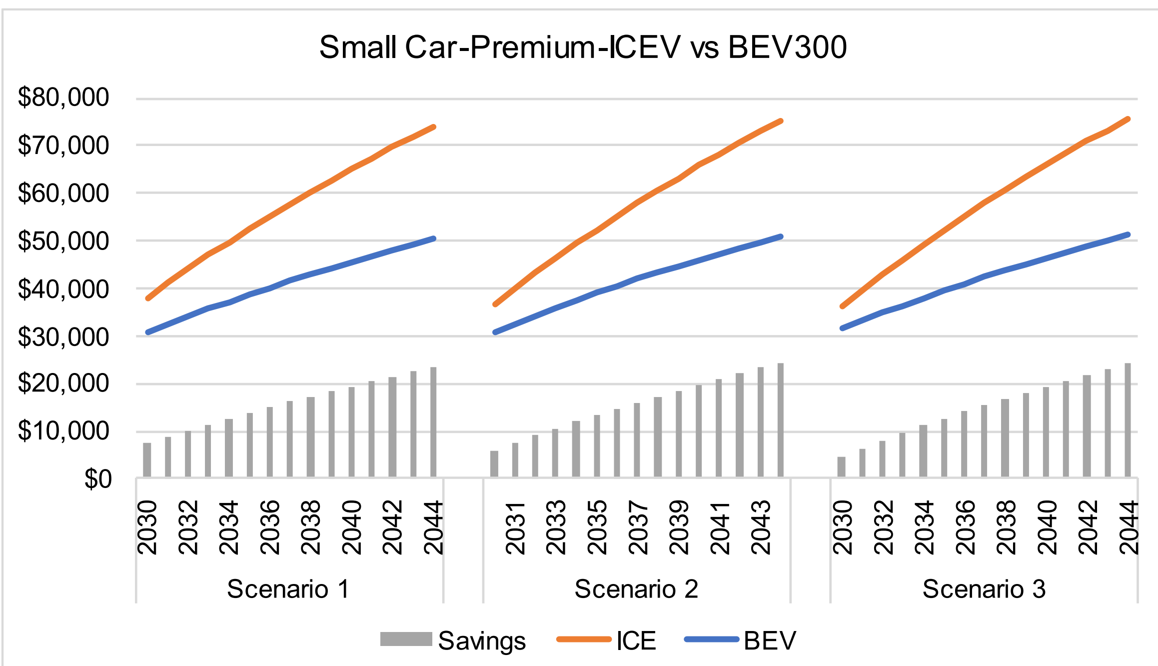

Figure 118: TCO parity of small cars in the premium segment in a high gasoline price scenario.

8.6.2 Medium Car

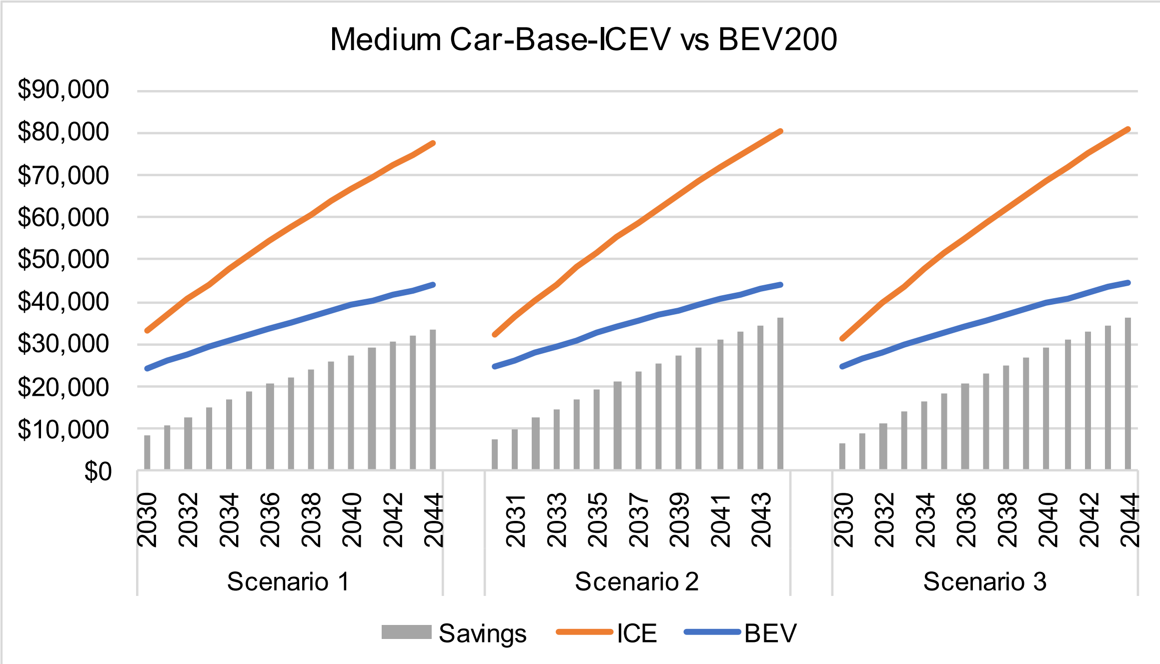

Figure 119: TCO parity of medium car in the base segment in a high gasoline price scenario.

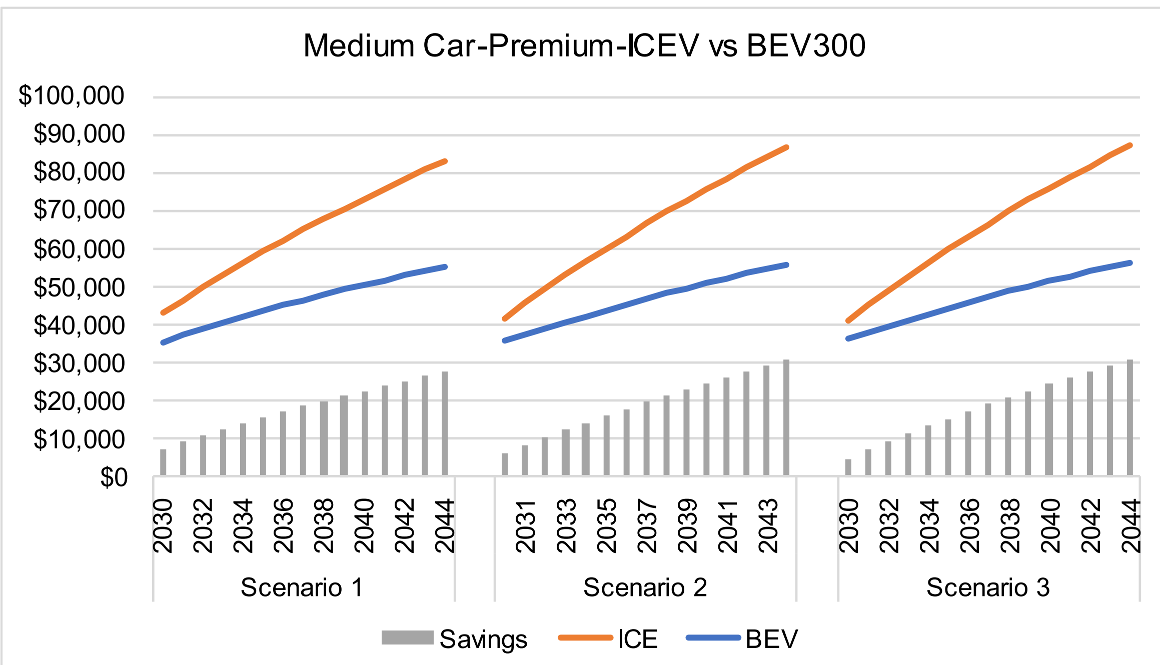

Figure 120: TCO parity of medium car in the premium segment in a high gasoline price scenario.

8.6.3 Small SUV

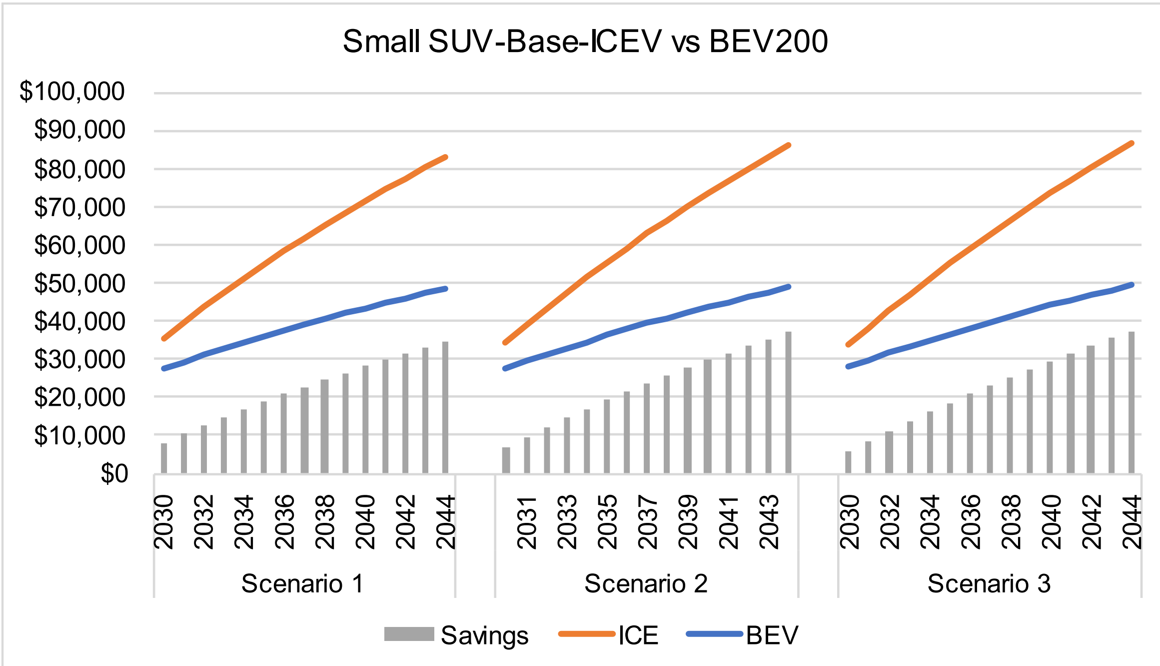

Figure 121: TCO parity of small SUVs in the base segment in a high gasoline price scenario.

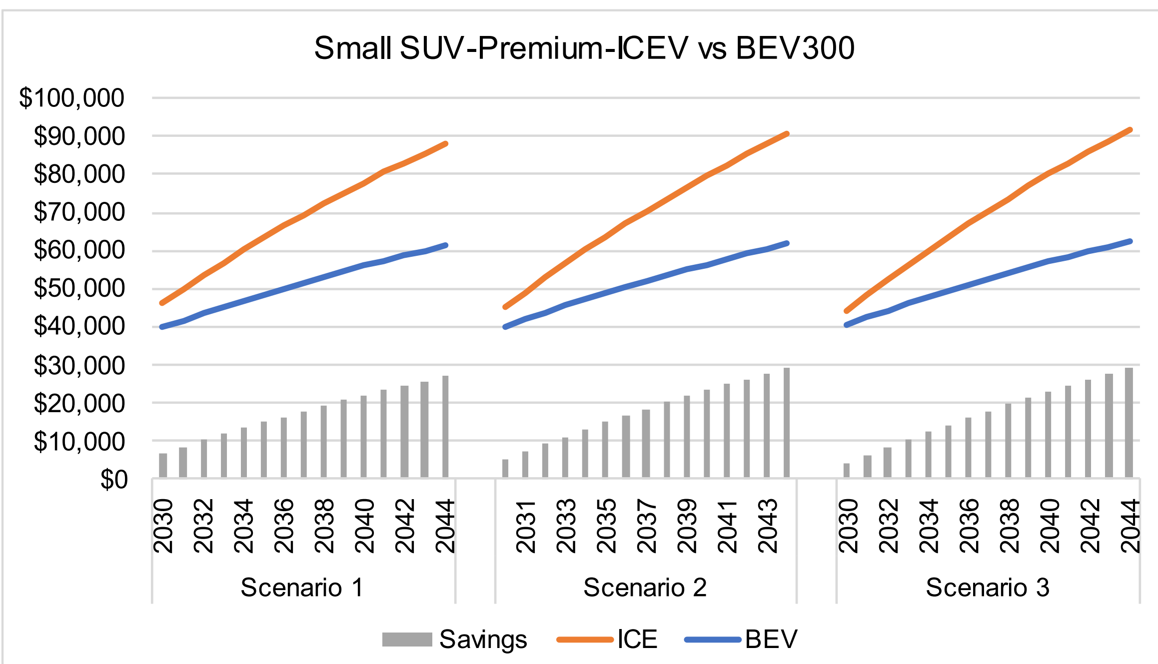

Figure 122: TCO parity of small SUVs in the premium segment in a high gasoline price scenario.

8.6.4 Midsize SUV

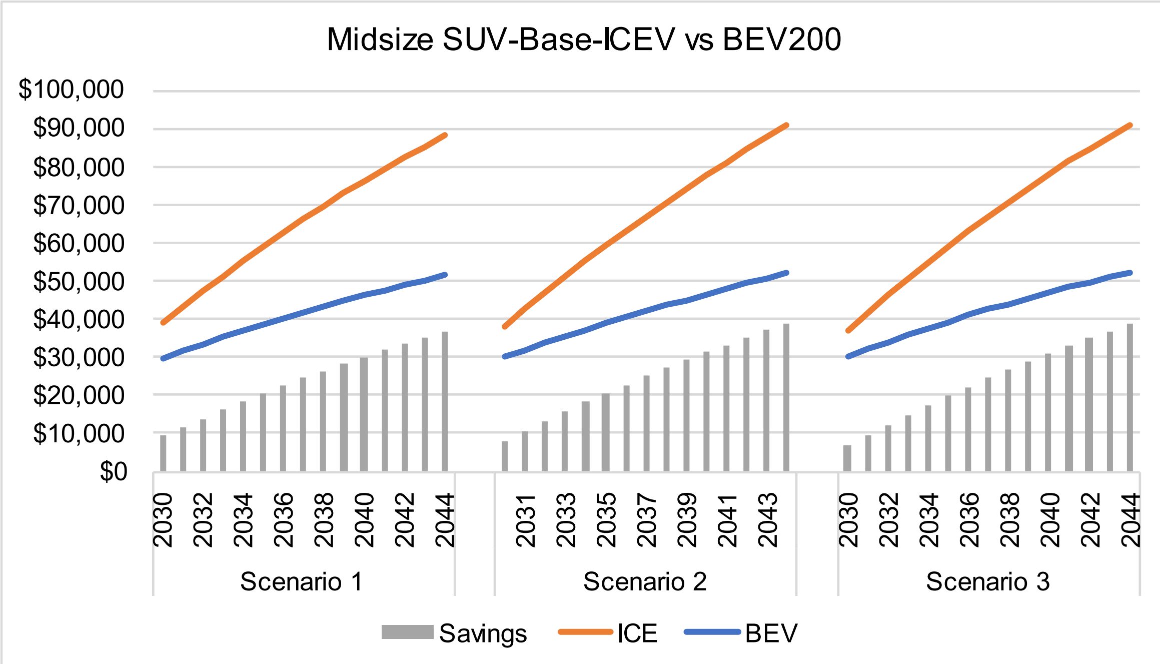

Figure 123: TCO parity of midsize SUV in the base segment in a high gasoline price scenario.

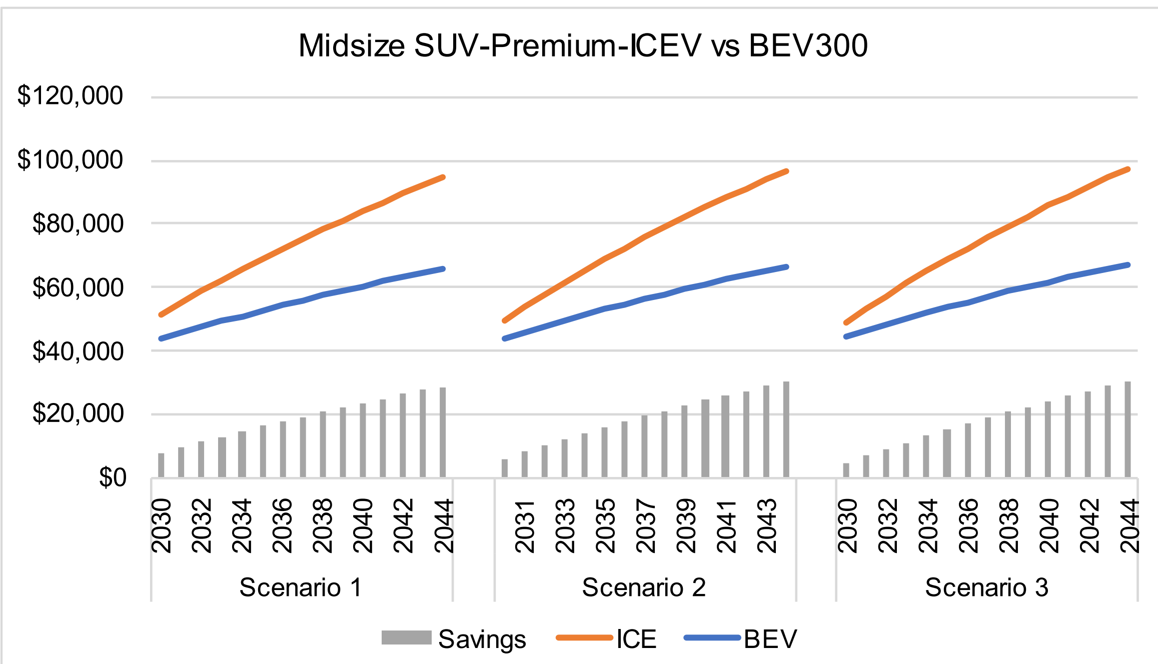

Figure 124: TCO parity of midsize SUV in the premium segment in a high gasoline price scenario.

8.6.5 Large SUV

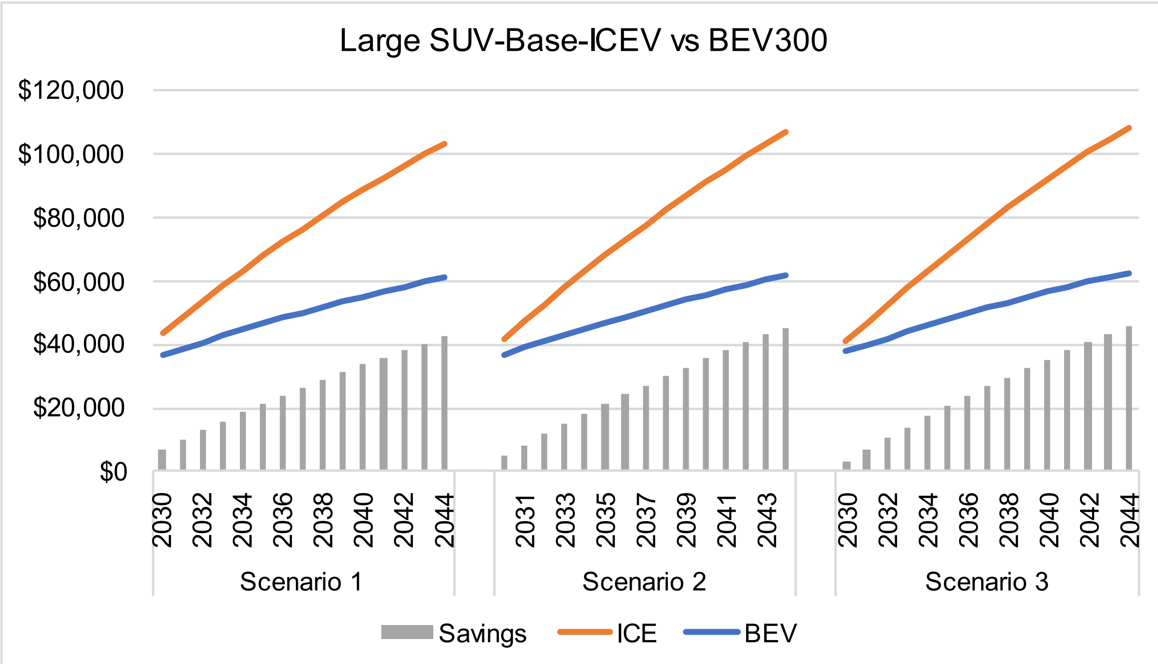

Figure 125: TCO parity of large SUVs in the base segment in a high gasoline price scenario.

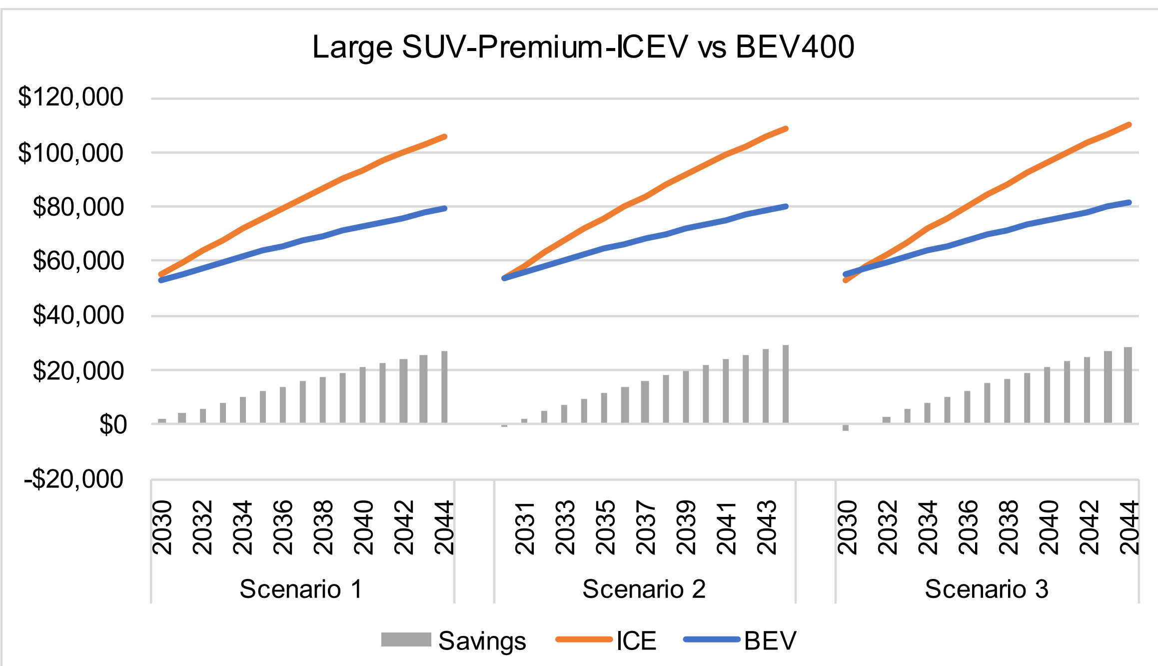

Figure 126: TCO parity of large SUVs in the premium segment in a high gasoline price scenario.

8.6.6 Pickup Truck

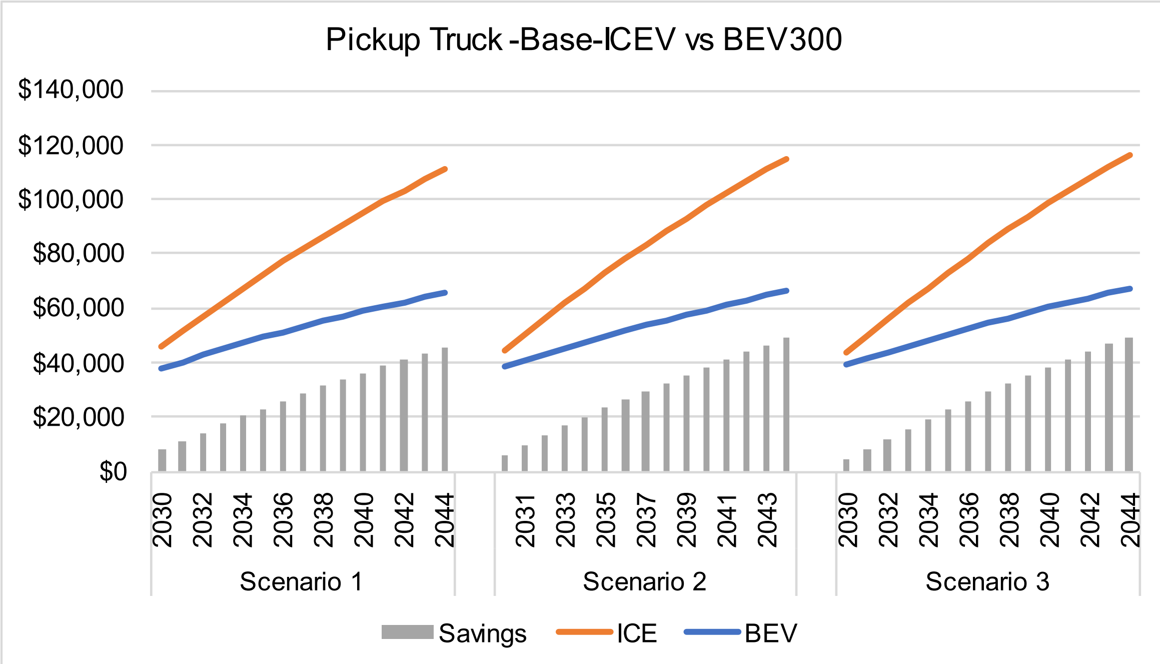

Figure 127: TCO parity of pickup trucks in the base segment in a high gasoline price scenario.

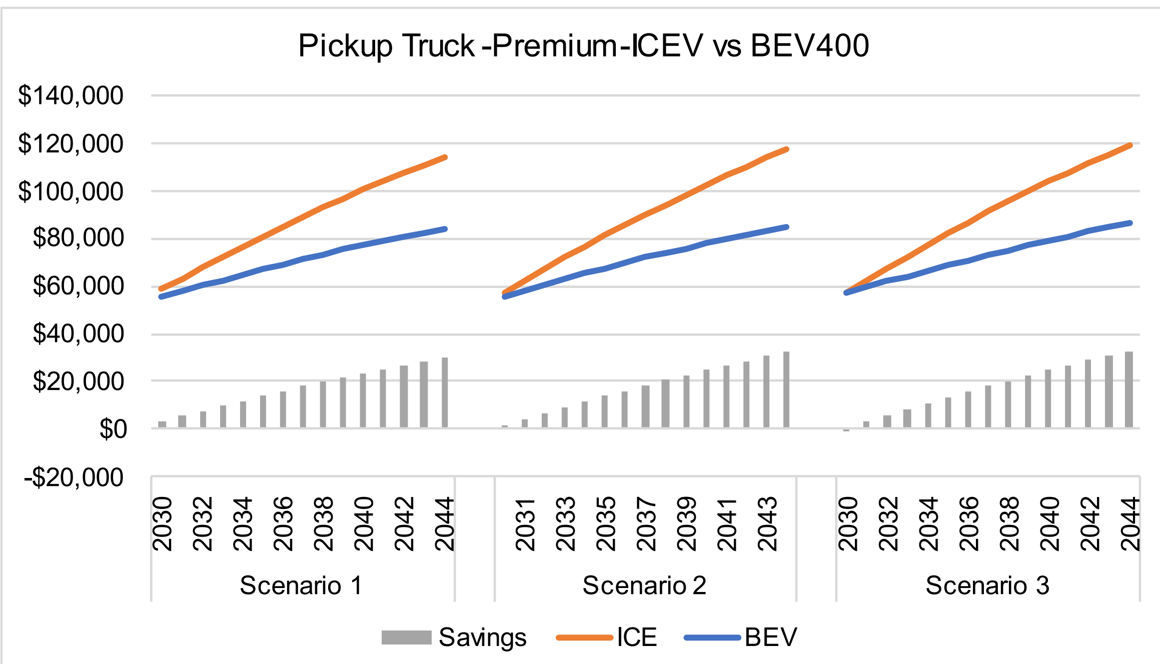

Figure 128: TCO parity of pickup trucks in the premium segment in a high gasoline price scenario.

8.7 Total Cost of Ownership Parity with Electricity Price Sensitivity

8.7.1 Small Car

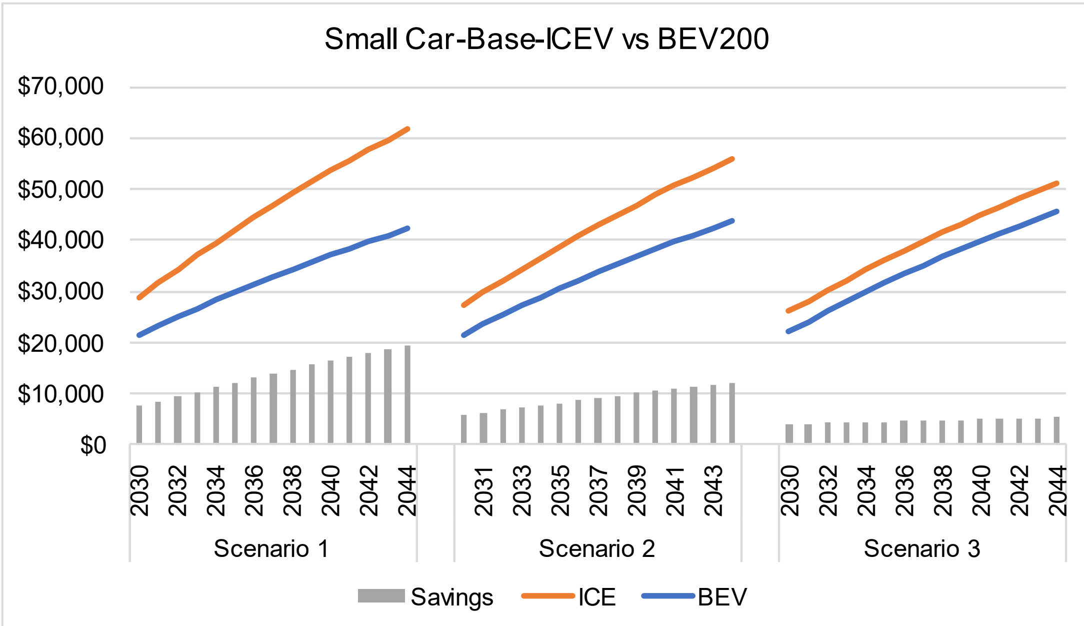

Figure 129: TCO parity of small cars in the base segment with state-based electricity prices.

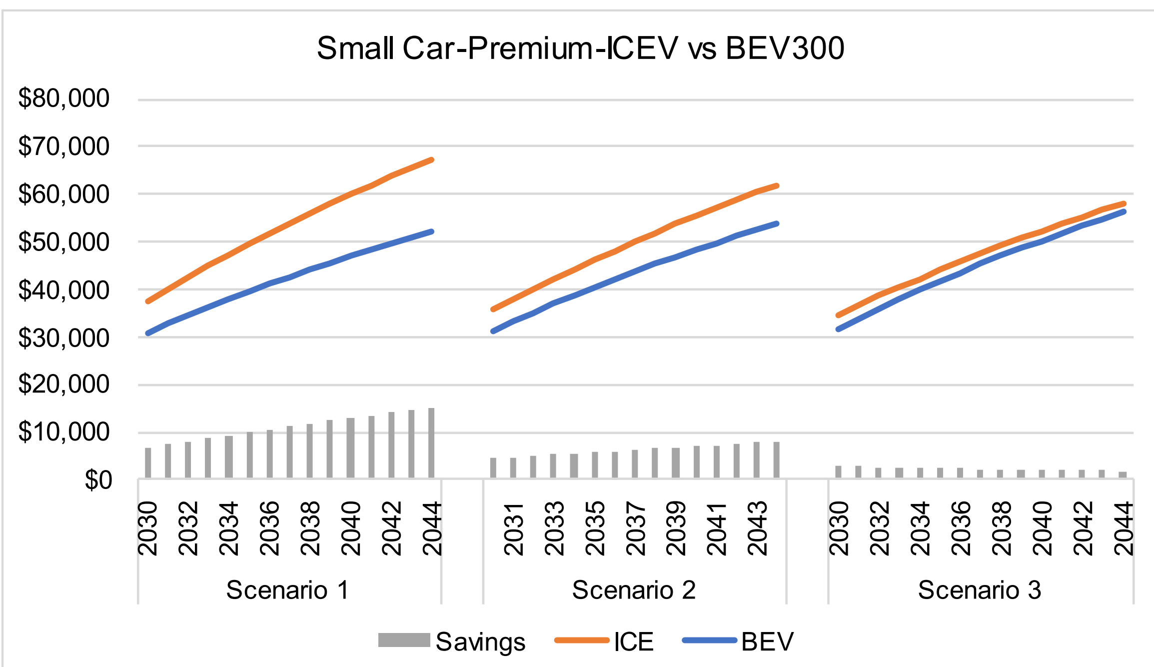

Figure 130: TCO parity of small cars in the premium segment with state-based electricity prices.

8.7.2 Medium Car

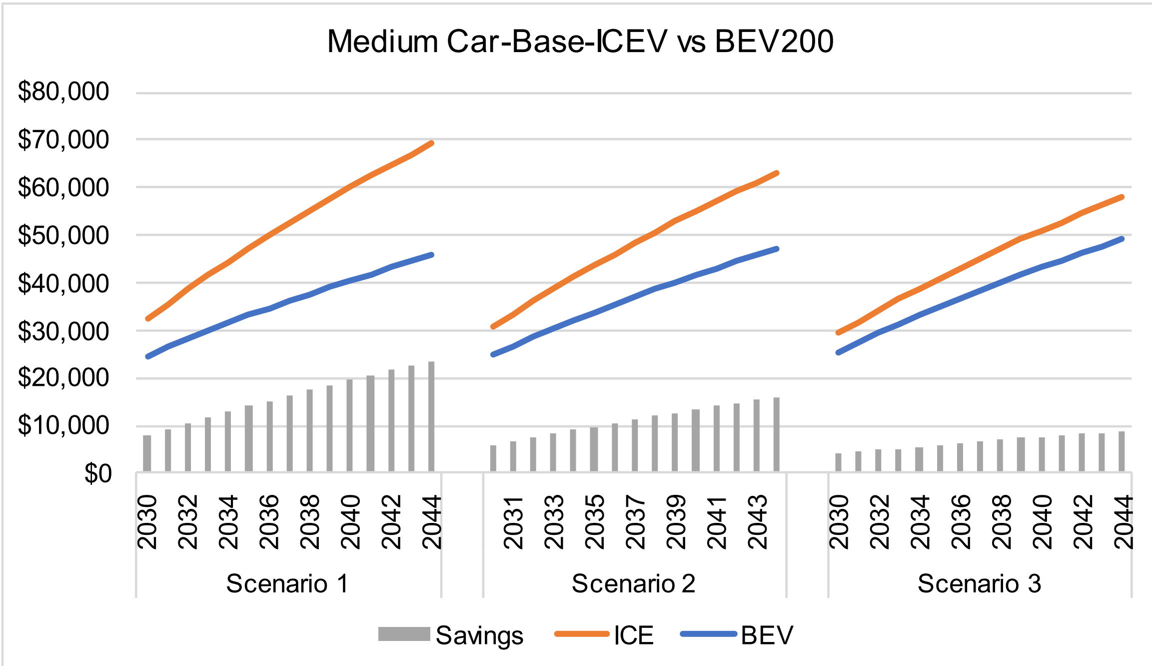

Figure 131: TCO parity of medium car in the base segment with state-based electricity prices.

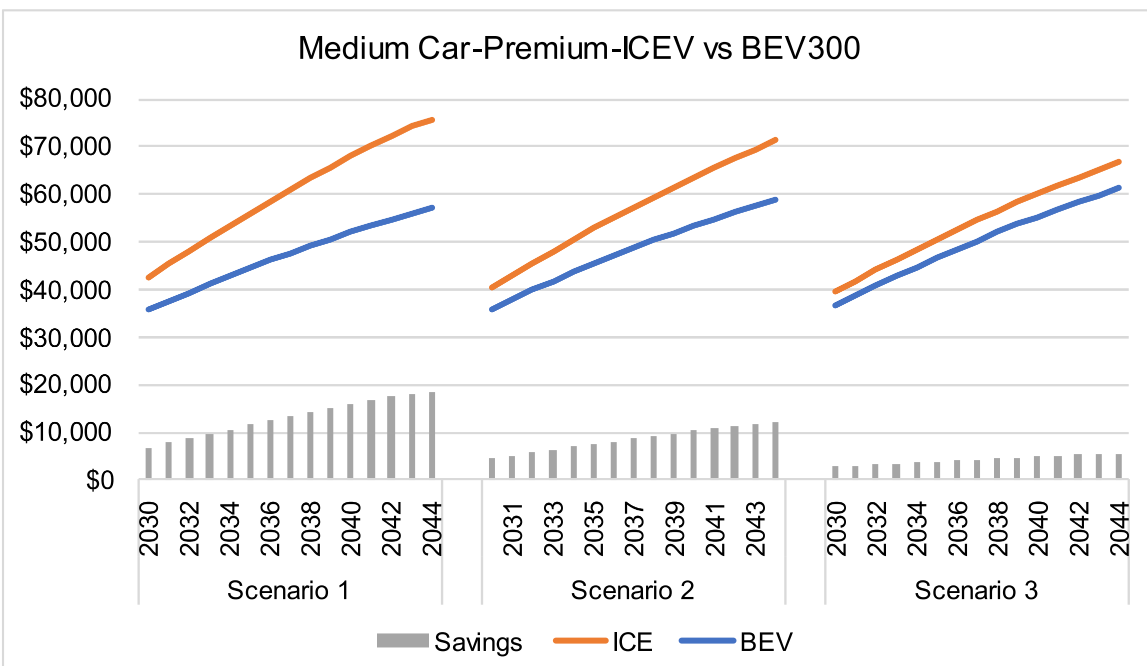

Figure 132: TCO parity of medium car in the premium segment with state-based electricity prices.

8.7.3 Small SUV

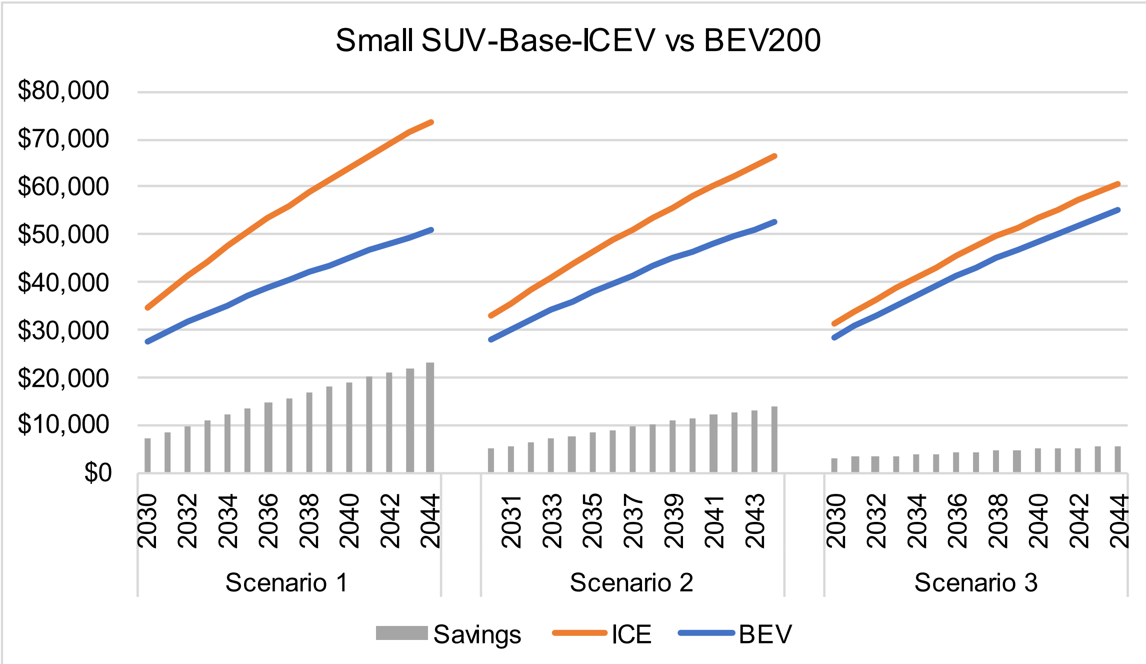

Figure 133: TCO parity of small SUVs in the base segment with state-based electricity prices.

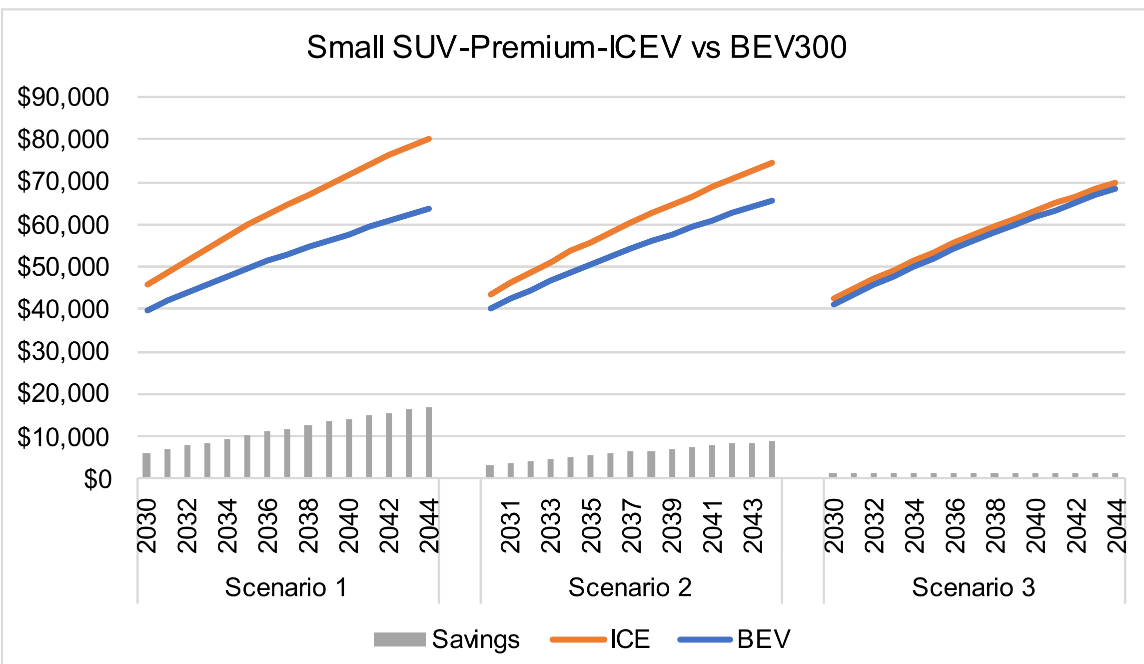

Figure 134: TCO parity of small SUVs in the premium segment with state-based electricity prices.

8.7.4 Midsize SUV

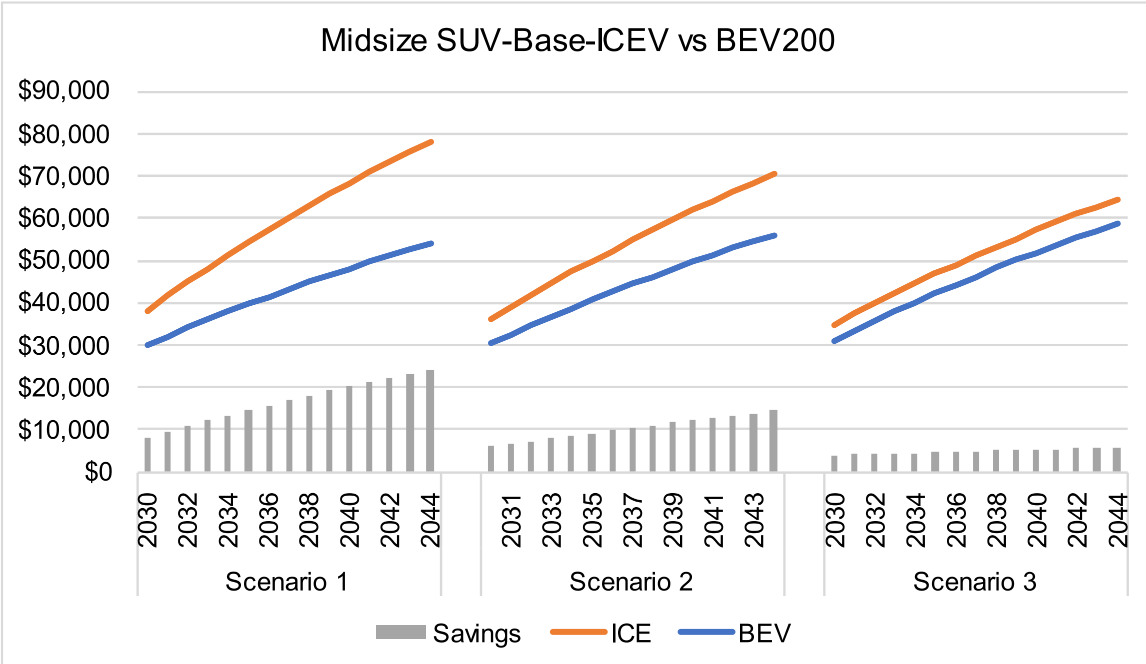

Figure 135: TCO parity of midsize SUV in the base segment with state-based electricity prices.

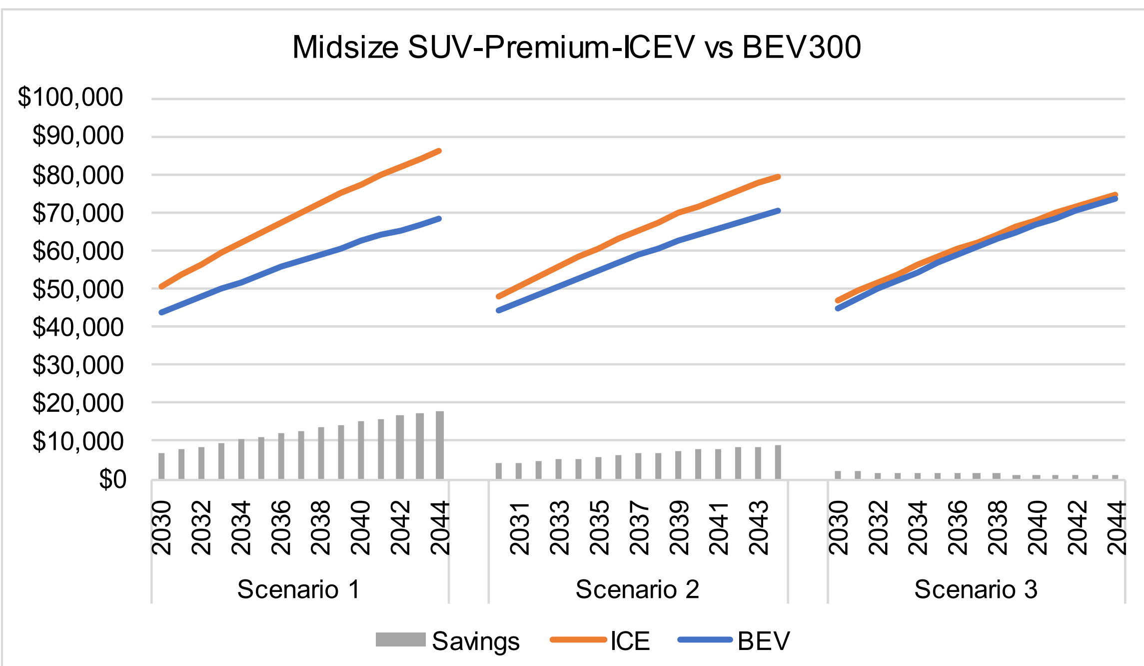

Figure 136: TCO parity of midsize SUV in the premium segment with state-based electricity prices.

8.7.5 Large SUV

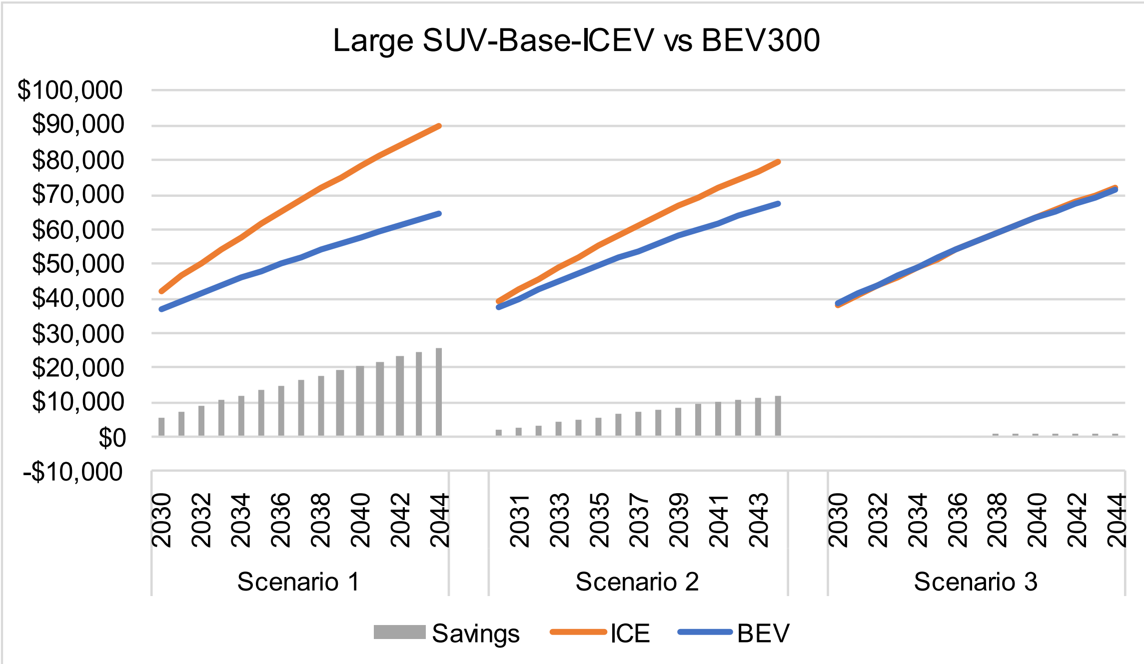

Figure 137: TCO parity of large SUVs in the base segment with state-based electricity prices.

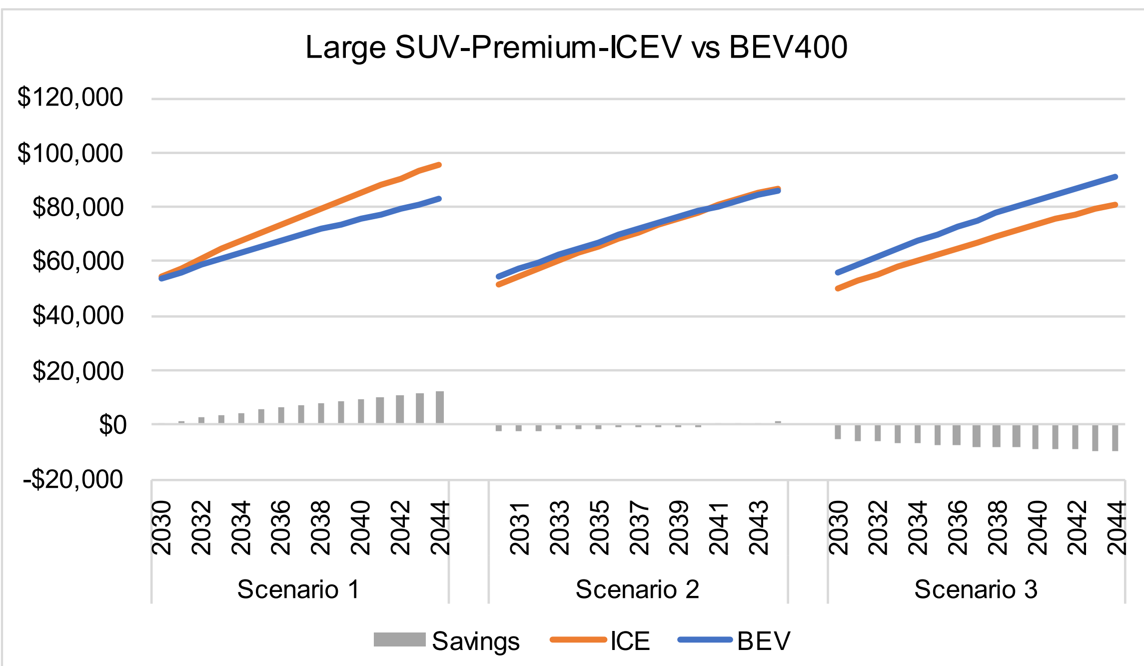

Figure 138: TCO parity of large SUVs in the premium segment with state-based electricity prices.

8.7.6 Pickup Truck

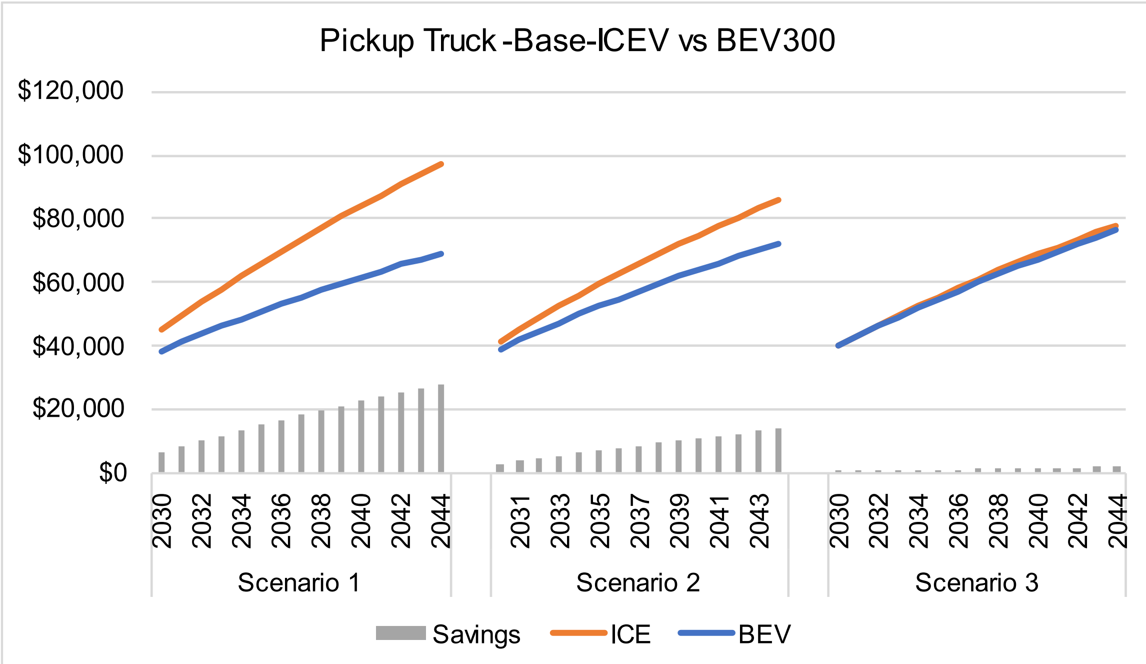

Figure 139: TCO parity of pickup trucks in the base segment with state-based electricity prices.

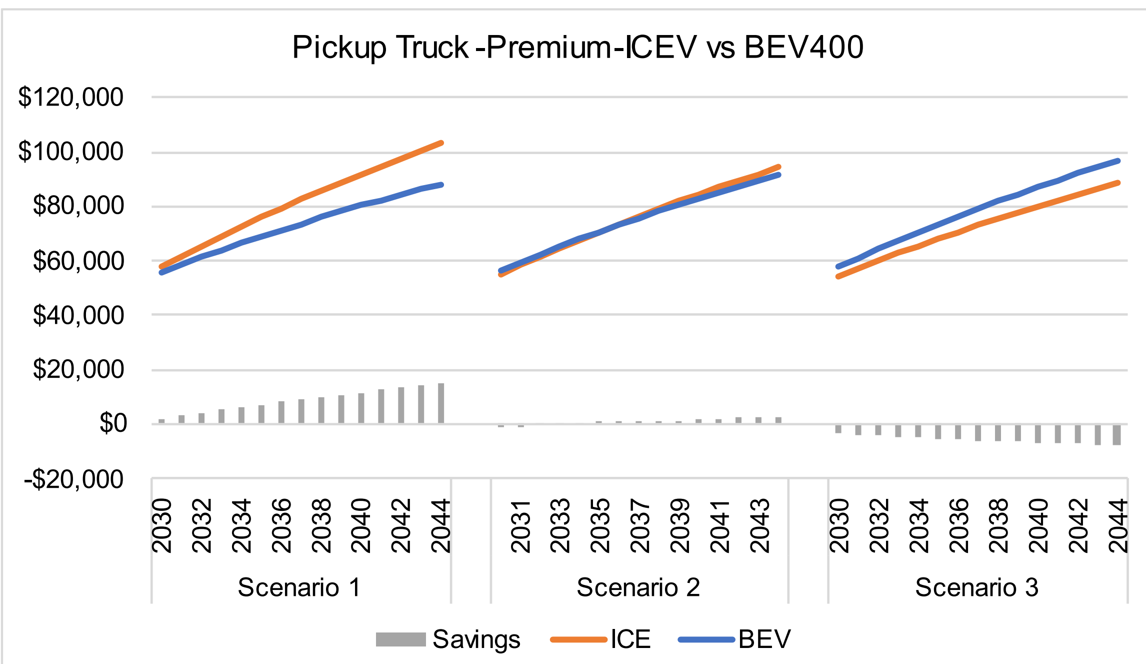

Figure 140: TCO parity of pickup trucks in the premium segment with state-based electricity prices.