2032 EREV Compact SUVs: Purchase Price, Efficiency, and Market Viability

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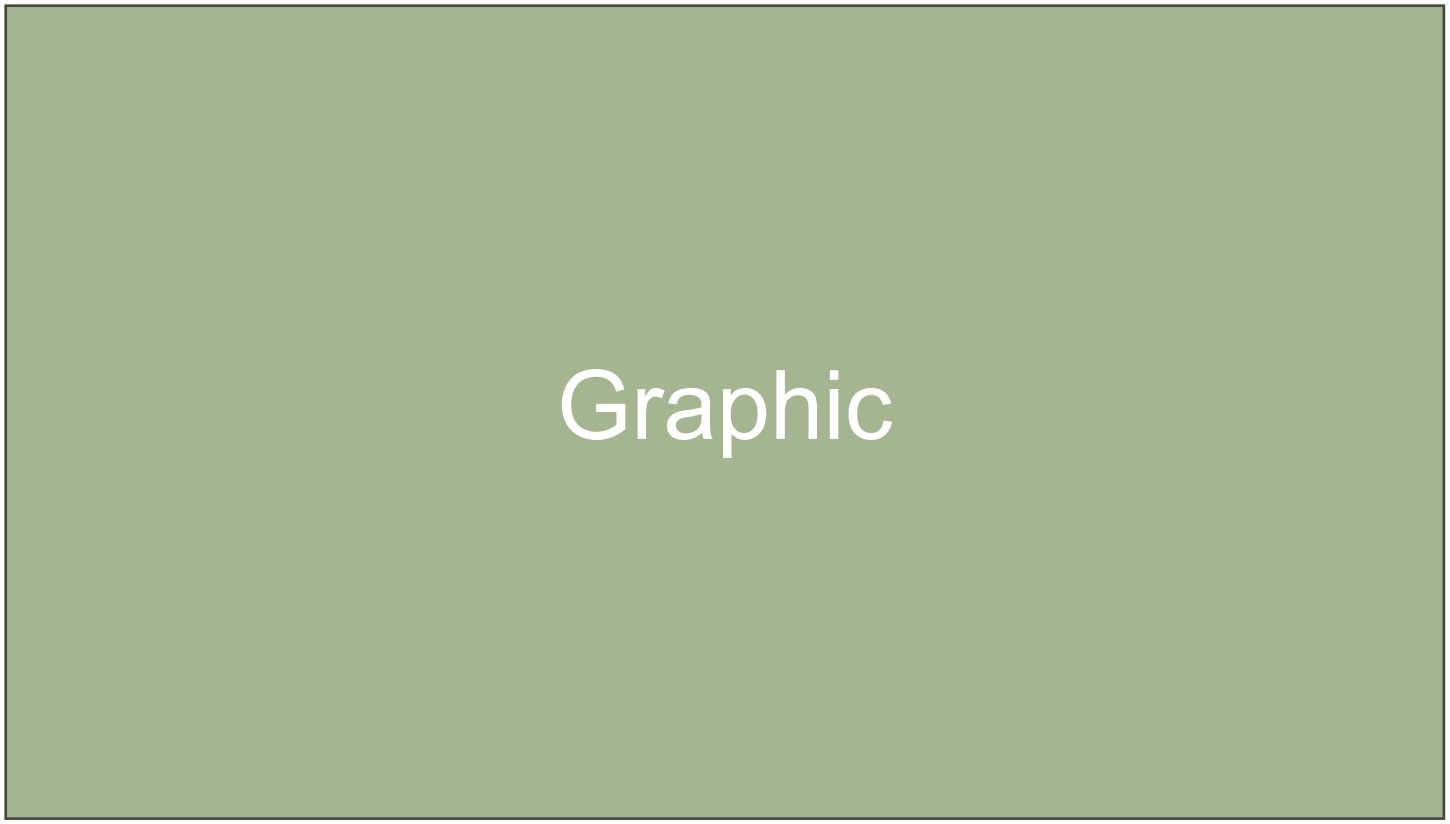


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Abbreviations and Acronyms

AWD	All-Wheel Drive
BEV	Battery Electric Vehicle
BEV300	300-Mile Range BEV
CAFE	Corporate Average Fuel Economy
CD	Charge-Depleting
CPI	Consumer Price Index
CS	Charge-Sustaining
DC-DC	DC-To-DC Converter
EPA	U.S. Environmental Protection Agency
EREV	Extended-Range Electric Vehicle
EREV100	100-Mile Electric Range EREV
EREV200	200-Mile Electric Range EREV
GaN	Gallium Nitride
ICE	Internal Combustion Engine
IM	Induction Motor
LFP	Lithium Ferro (Iron) Phosphate
MSRP	Manufacturer's Suggested Retail Price
MY	Model Year
NHTSA	National Highway Traffic Safety Administration
NVH	Noise Vibration and Harshness
OBC	On-Board Charger
OEM	Original Equipment Manufacturer
OMEGA	Optimization Model For Reducing Emissions of Greenhouse Gases for Automobiles
PHEV	Plug-In Hybrid Electric Vehicle
PHEV50	50-Mile Electric Range PHEV
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Motor
PMSyn-RM	Permanent Magnet Synchronous Reluctance Motor
RPE	Retail Price Equivalent
SiC	Silicon Carbide
SUV	Sport Utility Vehicle
USD	United States Dollar
WBG	Wide-Bandgap
WRSM	Wound Rotor Synchronous Motor

Revision Table

Version	Date	Comments
1.0	8/15/2025	Initial Release
2.0	9/10/2025	Updated figures, incorporated EDF feedback, added conclusion
3.0	9/19/2025	Incorporated additional EDF feedback, added ICE vehicle costs

Executive Summary

Study Overview

The electric vehicle market in the United States has been an increased area of focus in recent years. As of February 2025, the percentage of full electric new vehicle sales in the United States market was 7.9%, up from 1.6% in 2020 [1]. The rise of vehicle electrification has led to various technologies and architectures in the market, including parallel hybrids (PHEV), battery electric vehicles (BEV), and extended range electric vehicles (EREV).

Currently, BEVs typically have about 200-300 miles of range, depending on conditions [2]. Most Americans average less than 30 miles a day [3], so this range should be more than sufficient for most daily commutes; however, Americans also drive more distance than any other country on a per-year basis [4], so some users may desire additional range or better infrastructure such as fueling stations for the longer drives that are prevalent within the United States.

Despite the perceived drawbacks, electric vehicles are an appealing option to users for their lower maintenance and operating costs, and as the technologies advance and battery costs decrease, electric vehicles continue to become even more compelling. EREVs are a potential option for users who want the experience and benefits of an electric vehicle but desire the flexibility of a transitionary technology.

The scope of this study is to evaluate different potential EREV configurations for compact SUVs within the domestic United States market. This includes the manufacturing costs, purchase prices, and efficiencies, both within the electric-only mode and the range-extended mode of the EREVs, and how these specifications compare to equivalent BEVs and PHEVs for MY2025 and MY2032.

This study focuses on the compact SUV segment of the domestic market. This study considers a compact SUV to be a 2-row SUV with limited cargo space. Existing vehicles within this segment for both BEV and PHEV are considered when projecting the equivalent EREVs. AWD variations of each vehicle were considered for this study.

What is an EREV?

An EREV is a type of hybrid-electric vehicle containing a range extender: a unit that uses an ICE powertrain and a generator to provide additional range beyond what a battery alone would be able to achieve. The EREV has two modes: an electric-only mode where the EREV operates similarly to a BEV, driving the vehicle using the battery, and a range-

extended mode where the range extender system actively charges the battery during operation. In both modes, the vehicle is directly driven by the electric powertrain [5].

Difference between EREV and Conventional PHEV

An EREV shares similarities to a PHEV, both containing an electric and ICE powertrain, and both having the ability to charge the battery through plugging-in. However, there is one main difference: the EREV has a series hybrid architecture in which the ICE does not directly drive the wheels under any scenario, whereas the PHEV has a parallel hybrid architecture where it can drive the wheels directly through either the battery or the ICE powertrain. Because of this architecture, the EREV battery is typically larger than that of a PHEV and therefore provides more electric range than that of an PHEV, while also providing a driving experience more like a BEV than a PHEV [5].

Methodology

For this study, an EREV was assumed to be a BEV with a smaller electrical range, but with a range-extender to achieve additional combined vehicle range. Several vehicles across the domestic BEV market within the compact SUV segment were considered to define values for electric range, battery size, motor size, weight, and aerodynamic efficiency for a baseline BEV [6]. Once these specifications were defined, they were applied to determine the specifications of the representative EREVs. Once these representative EREVs were defined, their cost and efficiencies were determined, and these values were compared to an equivalent BEV and PHEV.

The battery of the baseline BEV was downsized to fit the use case of the EREV. Two range targets for electric mode operation were considered: 100 miles and 200 miles. The range and battery size of the baseline BEV [6] were used to determine what battery size was necessary for each EREV case. The efficiency assumed for the battery of the representative EREVs is 3.5 miles/kWh. The process and rationale for determining this battery efficiency is detailed in Section 2.4.1 The battery chemistry considered for the EREV was LFP. Rationale and methodology for the selection of an LFP battery is detailed in section 2.4.2.

A range extender was then added to the prospective downsized BEVs to allow for range-extended mode. This range extender consisted of an engine, motor generator, and traction inverter. Two engine types were considered: a 4-cylinder naturally aspirated engine and a 3-cylinder turbocharged engine.

The weight difference between batteries for the BEV and the EREVs was subtracted from the baseline BEV, and the weight of the range extender system was then added to that

value, giving a weight of the EREVs. A similar structural frame was assumed between the baseline BEV and the representative EREVs.

Once the representative EREVs were defined, the vehicles were costed for MY2025 and MY2032. Several price points of BEV SUVs on the current market were considered to form a baseline BEV price for MY2025 [7]. Retail price equivalent (RPE) was used to convert the retail price (MSRP) to an estimated manufacturing cost. RPE is the ratio of the purchase price of the vehicle to its manufacturing cost [8]. An RPE of 1.2 was applied to this BEV price to give a baseline BEV cost [9].

Once the cost of the baseline BEV was determined for MY2025, cost changes from the additions and reductions in the representative EREV were determined to cost the EREVs. The process was then repeated for MY2032 starting with a projected manufacturing cost of the baseline BEV for that year. Once manufacturing cost for the representative EREV was determined, an RPE of 1.2 could be applied to estimate the equivalent purchase price [9]. All prices and costs were normalized to 2025 USD using the United States Bureau of Labor Statistics CPI Inflation Calculator [10]. The process was repeated for MY2032. For MY2032, both global averages [9], [11] and domestic manufacturing costs [12], [13] were considered for batteries because of the increasing efforts in improving domestic manufacturing of LFP batteries by 2030 [13].

Figure 1 shows the overall costing methodology for going from the price of the baseline BEV to the cost of the representative EREV. It shows what components affected this change in prices and costs, and which components were assumed to be roughly the same. The same process was applied to each EREV configuration for MY2025 and MY2032.

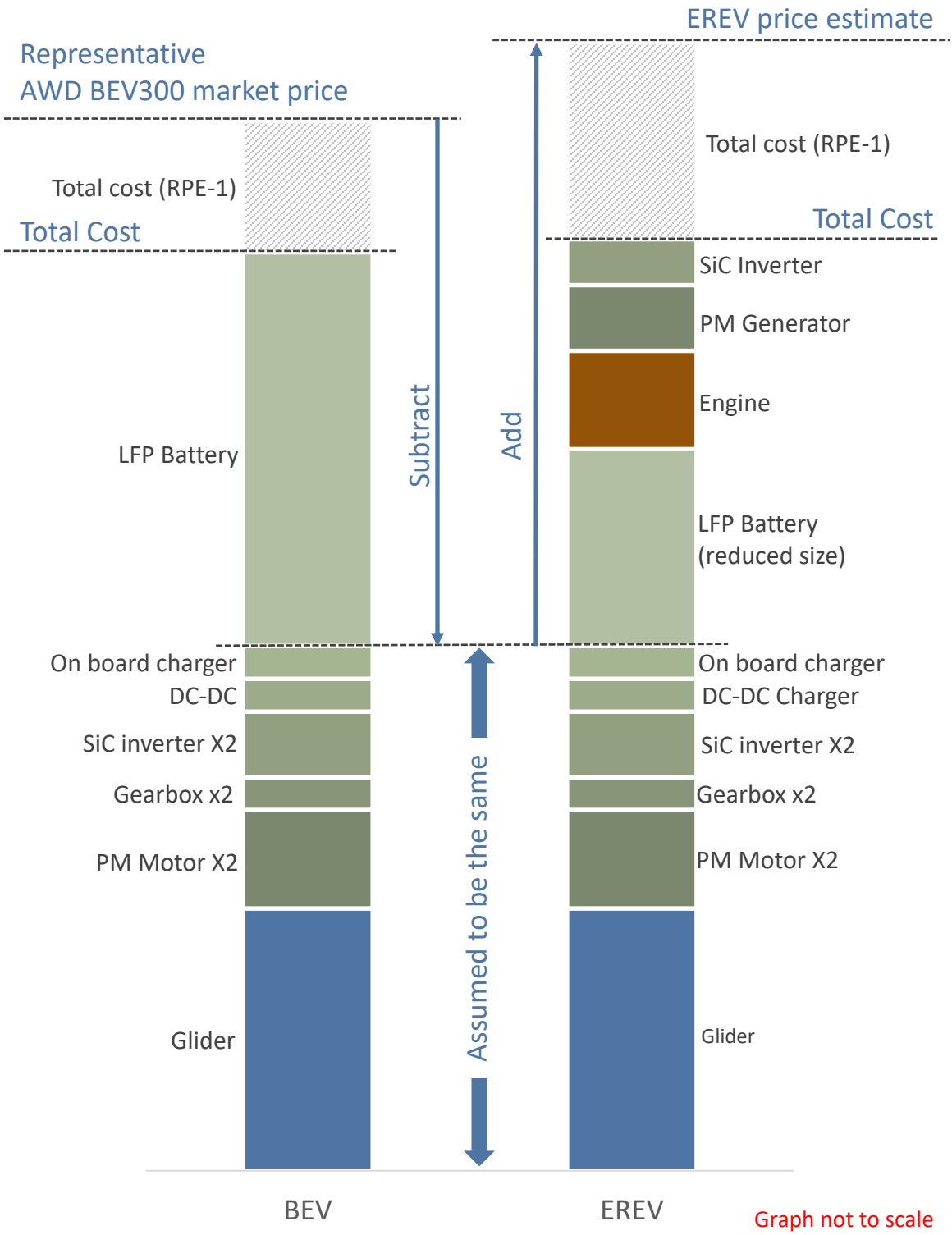


Figure 1: Methodology of Costing EREVs with the 2025 BEV Price as the Starting Point (RPE Assumed to be 1.2)

Once the representative EREVs were costed for MY2025 and MY2032, an equivalent PHEV was also costed for these years. This PHEV had the desired electric range of 50 miles. It was assumed that the PHEV battery was about 80% as efficient as the BEV and EREV batteries [12]. This efficiency difference can be attributed to the smaller battery of the PHEV and the efficiency losses from the transmission in the PHEV, as well as PHEVs being based on an ICE platform and therefore not optimized for electric driving. The equivalent PHEV battery size was determined to be 18 kWh. A torque converter was assumed to be removed from the BEV and a 4-cylinder naturally aspirated engine, a transmission, and a motor were assumed to be added to the BEV to characterize the equivalent PHEV.

Similarly to the EREVs, the PHEV was costed starting with the equivalent BEV cost. Similar costing considerations to the EREV were used: the battery costs, engine costs for the 4-cylinder naturally aspirated engine case, and the motor cost for 2025 and 2032 used for the EREV cases were also applied to the PHEV case. The torque converter was assumed to be about $100 [12]. The transmission cost was determined for both 2025 and 2032 using the NHTSA CAFE Model [14].

Results

Figure 2 depicts the manufacturing costs for the representative EREVs, BEV, and PHEV in the compact SUV market segment for MY2025. It was found that the EREV100 was a cheaper option than the equivalent BEV300 for MY2025, regardless of engine configuration. Both EREV100 cases had higher manufacturing costs than the PHEV50; however, the EREV100 with a 4-cylinder naturally aspirated engine had an almost identical manufacturing cost to the PHEV50. Each EREV200 case was found to have higher manufacturing costs and purchase prices than the equivalent BEV300. Ultimately, the most significant factor for the different costs between the equivalent vehicles was battery size. The costs of these vehicles can be compared to the manufacturing cost of an equivalent ICE vehicle in 2025, found to be approximately $31,600.

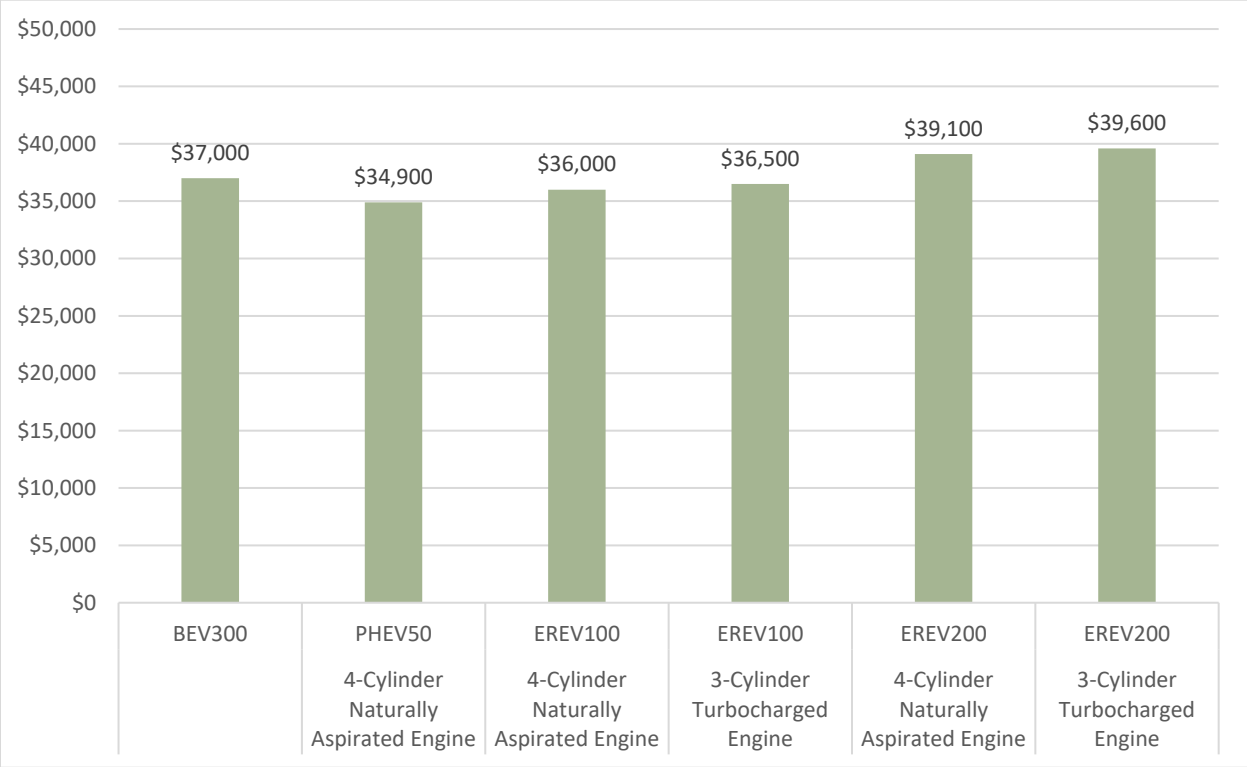


Figure 2: EREV, BEV, and PHEV Manufacturing Costs for MY2025 Compact SUVs

Figure 3 depicts the manufacturing costs for the representative EREVs, BEV, and PHEV in the compact SUV market segment for MY2032 if global battery costs are used. It was found that by 2032, battery costs will decrease enough to where all the EREV cases have higher manufacturing costs than the BEV300. The PHEV50 will still be a cheaper option than the EREVs in this case. The costs of these vehicles can be compared to the manufacturing cost of an equivalent ICE vehicle in 2032, found to be approximately $31,500.

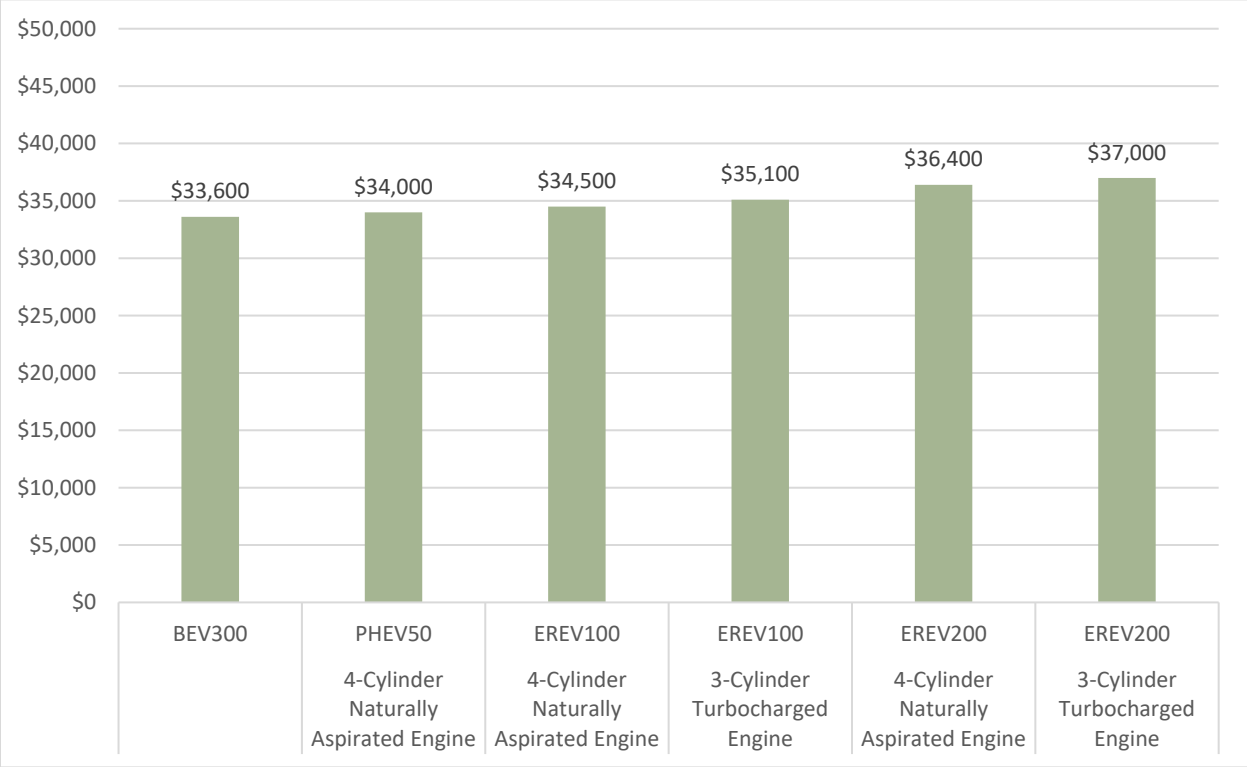


Figure 3: EREV, BEV, and PHEV Manufacturing Costs for MY2032 Compact SUVs Using Global Average Battery Costs

Figure 4 depicts the manufacturing costs for the representative EREVs, BEV, and PHEV in the compact SUV market segment for MY2032 if domestic battery costs are used. It was found that using the domestic battery costs still leads to the BEV becoming cheaper than all EREV options by 2032, just by a smaller margin than using the global costs for battery resulted in. This is because the difference between the global costs and the domestic costs is only around 15% [15], which leads to small changes when considering the battery sizes of these vehicles. The costs of these vehicles can be compared to the manufacturing cost of an equivalent ICE vehicle in 2032, found to be approximately $31,500.

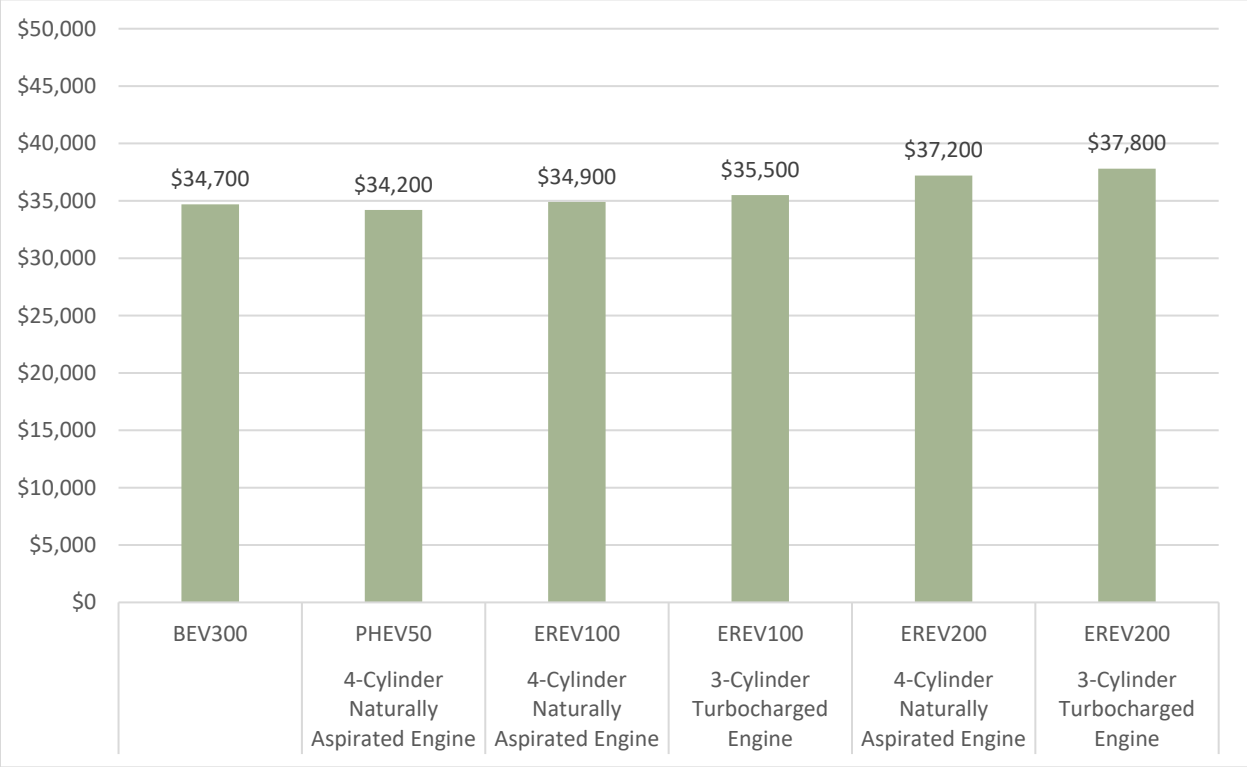


Figure 4: EREV, BEV, and PHEV Manufacturing Costs for MY2032 Compact SUVs Using Domestic Battery Costs

Figure 5 shows the estimated efficiency of the EREV100, EREV200, and PHEV50 in battery-electric (charge-depleting) mode. The BEV300, EREV100, and EREV200 share identical power torque-providing components: two motor drive units (each comprising a motor and reduction gearbox), one at the front and one at the rear.

For this report, it is assumed that the EREVs are based on an EV platform (BEV300), while the PHEVs are based on an ICE vehicle platform. The PHEV50 has significantly lower efficiency in CD mode because of its higher rolling resistance, greater drivetrain friction, and increased aerodynamic drag associated with the underlying ICE platform.

The marginally lower efficiency of the EREV200 is due to an additional 150 - 200 lb of weight. The EREV100 and EREV200 exhibit nearly identical efficiency despite the EREV100 being 400 lb lighter. The efficiency advantage of the EREV100 from reduced mass is offset by higher battery losses, approximately 2-3%, caused by its nearly doubled average battery C-rates over the cycle resulting in higher battery internal losses and increased cooling demands on the battery.

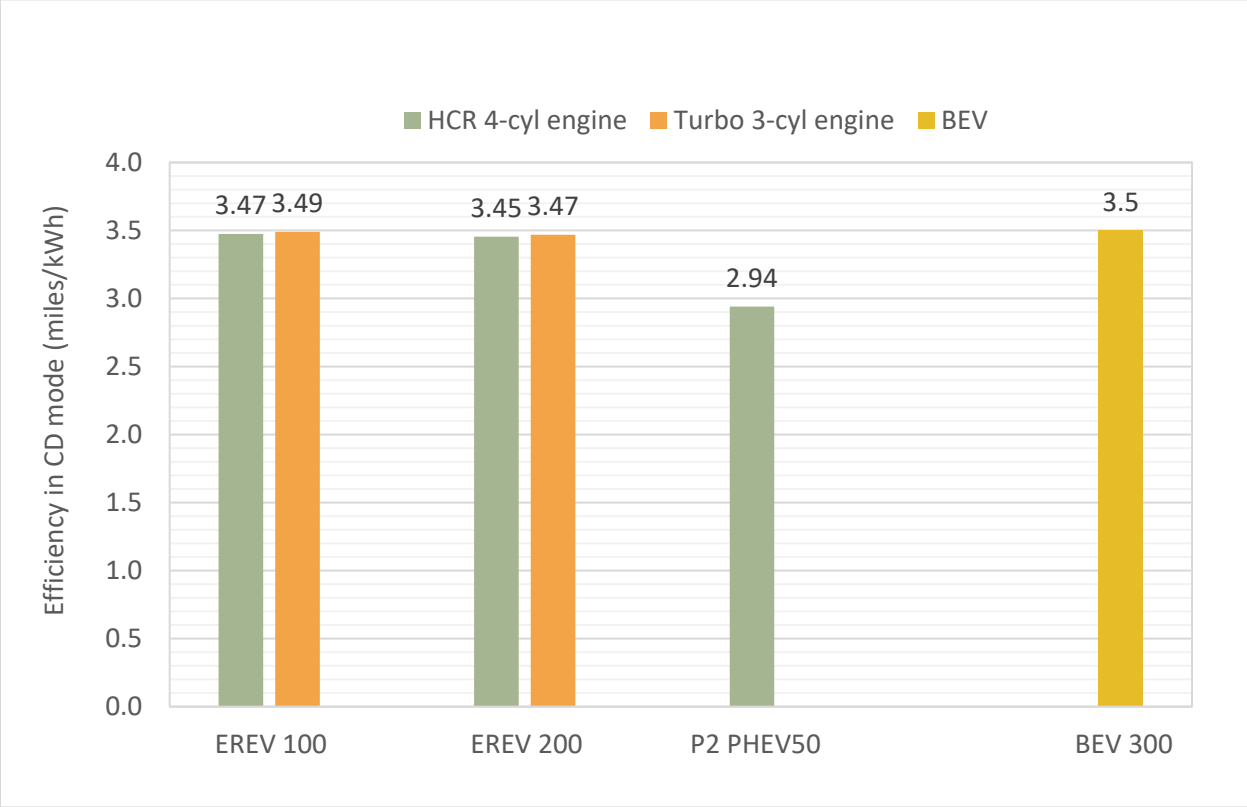


Figure 5: 2032 Estimated Efficiency (Miles/kWh) of the EREV and P2 PHEV in CD Mode

Figure 6 presents the estimated 2032 charge-sustaining fuel economy (mpg) of the EREV100, EREV200, and PHEV50. The PHEV50 achieves higher efficiency than the EREVs because the brake power produced by its ICE is used directly to drive the wheels. In an EREV, by contrast, the engine's brake power is first converted to electricity by the generator and associated power electronics, then converted back to mechanical power. The efficiency increase in being able to operate the engine at higher efficiency points in an EREV when compared to a PHEV, is not enough to negate these conversion losses

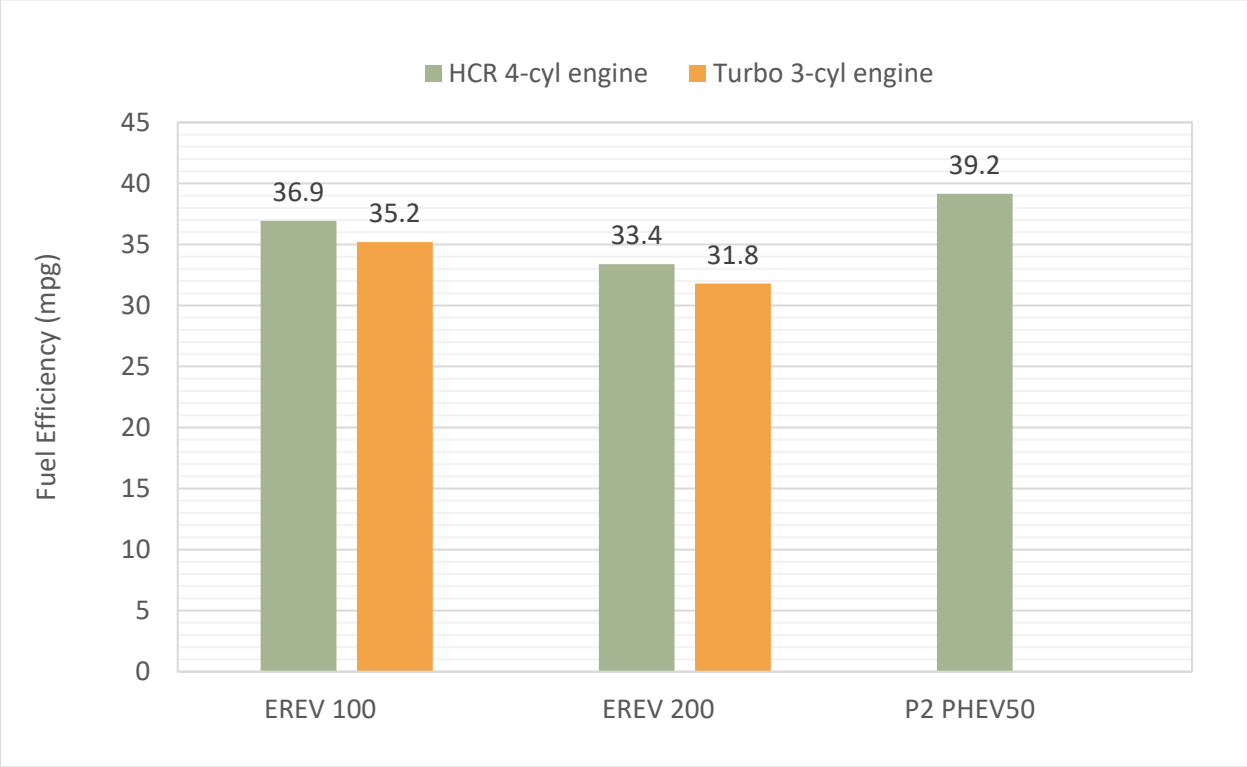


Figure 6: Estimated Efficiency (mpg) of the EREV and P2 PHEV in CS Mode

In Summary

As a result of this costing analysis, it was found that certain EREVs would be a cheaper option in the MY2025 when compared to an equivalent BEV300 and comparable to an equivalent PHEV50. By 2032, the equivalent BEV300 will provide more cost savings than the representative EREV100s, and the equivalent PHEV50 will remain cheaper than the representative EREV100s, suggesting no upfront savings for an EREV in the compact SUV market segment by 2032. Despite this, the cost difference between the EREV100 and the PHEV50 is marginal, so EREVs may be appealing to manufacturers or customers that desire more electric range. Equivalent purchase prices using an RPE of 1.2 can be found in section 4.2.

Further investigation into the appropriate engine sizing and efficiency optimization, battery sizing, vehicle architecture and design, and towing ability will provide a clearer picture of the best applications and vehicle classes for EREVs.

1. Introduction

1.1 Background

The electric vehicle market in the United States has been an increased area of focus in recent years. As of February 2025, the percentage of new full electric cars sold in the United States market was 7.9%, up from 1.6% in 2020 [1]. This focus on electrification has led to various electric vehicle technologies and architectures.

Currently, BEVs typically have about 200-300 miles of range, depending on conditions [2]. Most Americans average less than 30 miles a day [3], so this range should be more than sufficient for most daily commutes; however, Americans also drive more distance than any other country on a per-year basis [4], so some users may desire additional range for the longer drives that are prevalent within the United States.

Despite potential demand for extra range, electric vehicles are an appealing option to users, and as the technologies advance and costs decrease, electric vehicles could continue to become even more compelling. EREVs are a potential option for users who want the experience and benefits of an electric vehicle but desire the flexibility offered by the range extender.

1.2 EREV

An EREV is a type of hybrid-electric vehicle containing a range extender: a unit that uses an ICE powertrain and a generator to provide additional range beyond what a battery alone would be able to achieve. The EREV has two modes: an electric-only mode where the EREV operates similarly to a BEV, driving the vehicle using the battery, and a range-extended mode where the range extender system actively charges the battery during operation. In both modes, the vehicle is directly driven by the electric powertrain [5]. Figure 7 shows the architecture of a standard EREV compared to the architecture of the base BEV. As seen, there is no way for the ICE powertrain in the EREV to directly drive the wheels. Component size in Figure 7 is not necessarily to scale.

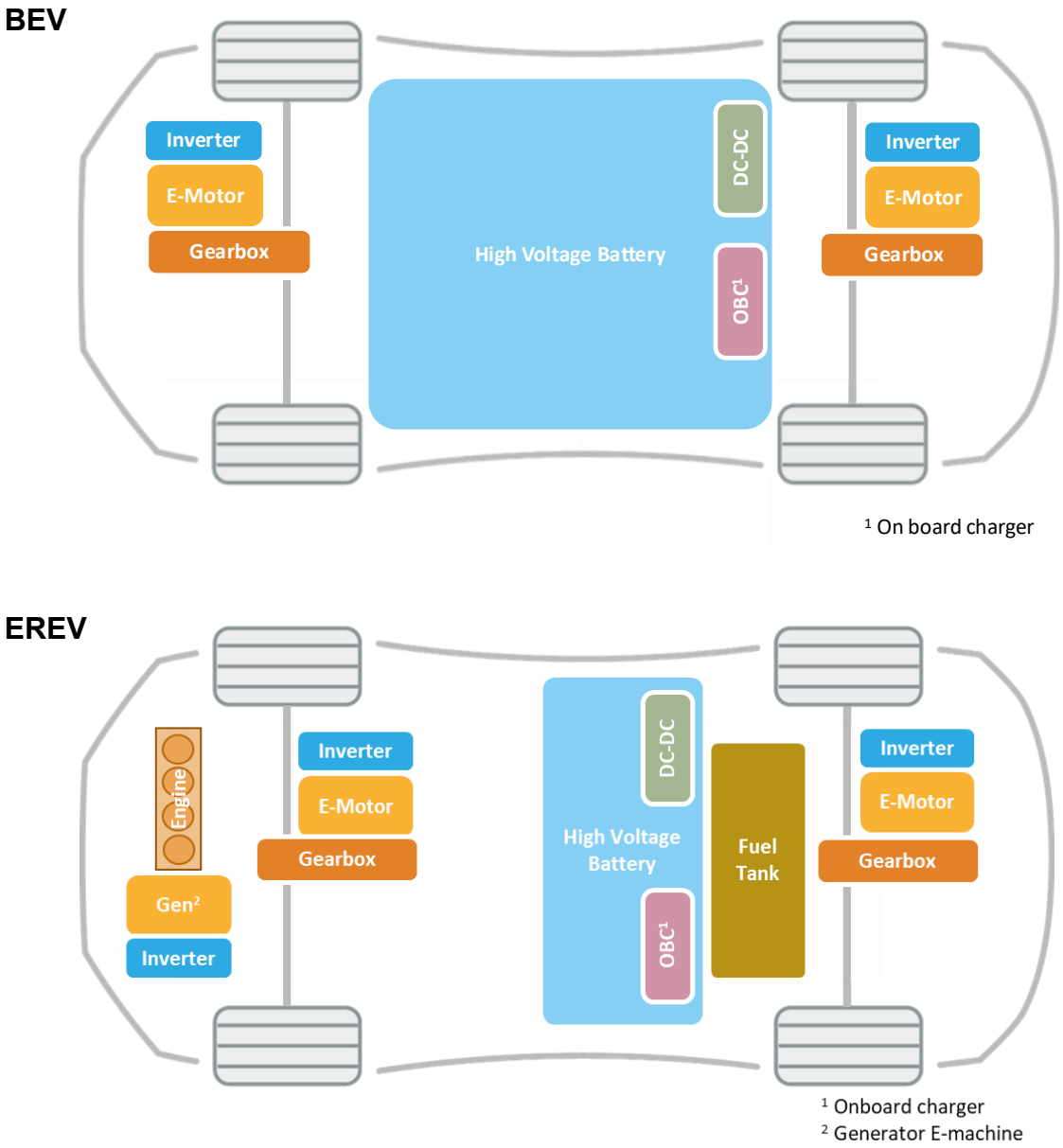


Figure 7: Architecture of an EREV (Exhaust, Aftertreatment, Fuel System etc. Not Shown for Simplicity) and Comparison to That of the Base BEV

An EREV shares similarities to a PHEV, both containing an electric and ICE powertrain, and both having the ability to charge the battery through plugging-in. However, there is one main difference: the EREV has a series hybrid architecture where the ICE powertrain does not directly drive the wheels under any scenario, whereas the PHEV has a parallel hybrid architecture where it can drive the wheels directly through either the battery or the ICE powertrain. Because of this use case, the EREV battery is typically larger than that

of a PHEV and therefore provides more electric range than that of an equivalent PHEV, while also providing a driving experience more similar to a BEV than a PHEV [5].

Figure 8 shows a side-by-side of the series hybrid architecture used by EREVs and the parallel hybrid architecture used by standard PHEVs. As seen, the PHEV has a direct connection from the engine to the gearbox. Component size in Figure 8 is not necessarily to scale.

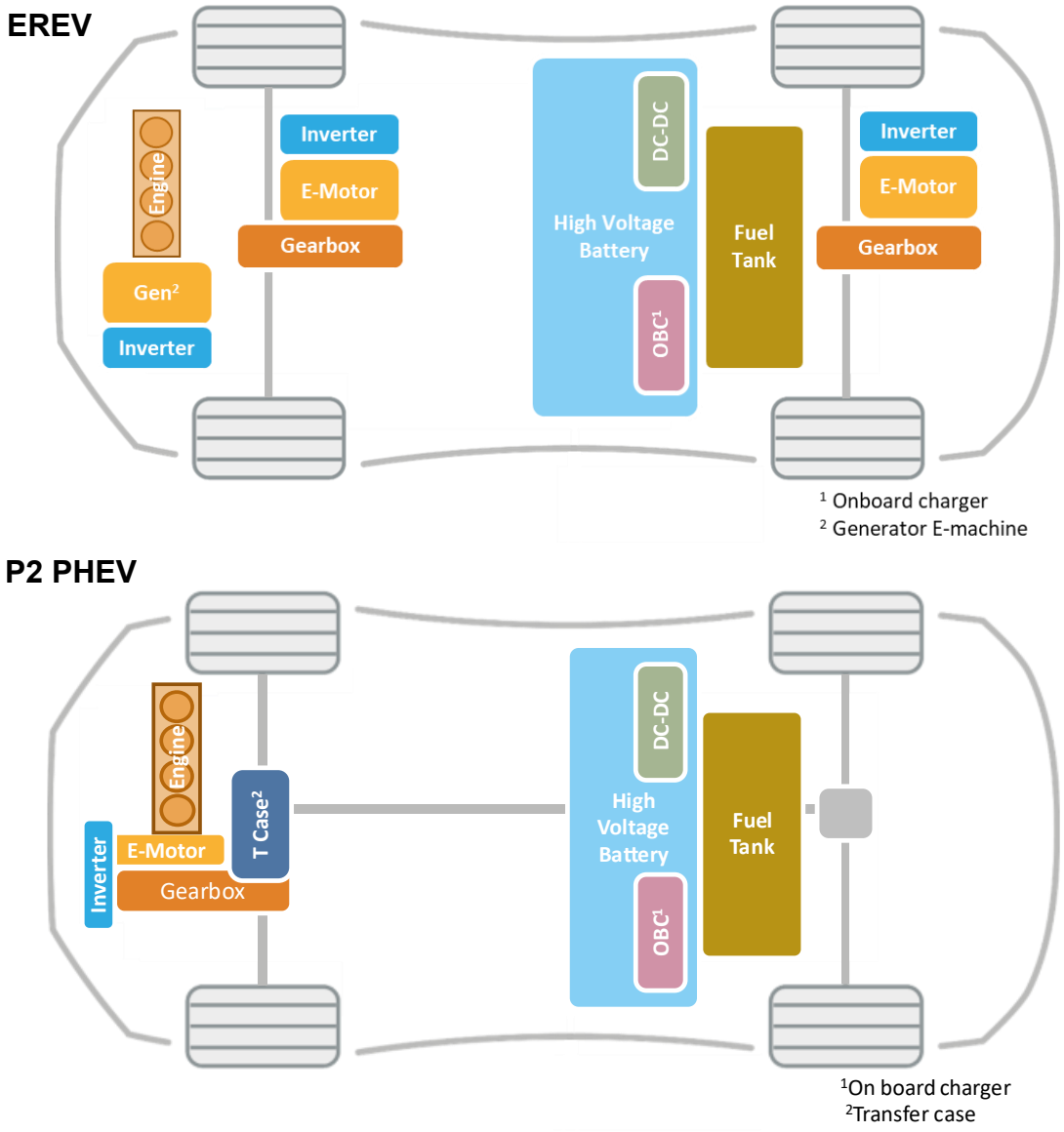


Figure 8: Series Hybrid Architecture used by EREVs and Parallel Hybrid Architecture used by P2 PHEVs (Exhaust, Aftertreatment, Fuel System etc. Not Shown for Simplicity)

1.3 Current State of the Market

As of 2025, there are no EREVs actively being produced in the United States market. There have been EREVs that have been sold in the United States market, but all were discontinued for lack of popularity or other shortcomings. This includes the BMW i3 REx, the Fisker Karma, and the Mazda MX-30 R-EV. Despite this, there are currently plans for EREVs returning in the future within the United States market, with Ram planning for an EREV truck and Scout Motors planning for EREVs in both the truck and midsize SUV segments [5]. Hyundai has announced plans to release its first EREV in 2027, with an announced 600 miles of total range [16]. Ford has also announced upcoming plans for an EREV variant of the Expedition and Explorer within the next few years [17]. These announcements from major OEMs regarding EREVs suggest that the EREV market share should see initial growth within the next few years.

While EREVs have not taken off yet within the United States market, EREVs make up a prominent share in the electrified vehicle market in China, showing the potential for EREV adoption at a large scale. In October 2024, EREVs made up 10.2% of the EV production within China. At that time, EREVs were on average about $4000 cheaper than EVs in the Chinese market [18]. Efforts to increase EREV production continue in this market, as from 2024 to 2025, EREV sales increased in China by 79%, as Chinese manufacturers see EREVs as an opportunity to provide additional range to electric vehicles [19].

1.4 Study Scope / Considerations

The scope of this study is to evaluate different potential EREV configurations for a compact SUV within the domestic United States market. This includes the manufacturing costs, purchase prices, and efficiencies, both within the electric-only mode and the range-extended mode of the EREVs, and how these specifications compare to equivalent BEVs and PHEVs for MY2025 and MY2032. This study focuses on the compact SUV segment of the domestic market. A compact SUV is considered to be a 2-row SUV with limited cargo space. Existing vehicles within this segment for both BEV and PHEV are considered when projecting the equivalent EREVs. AWD variations of each vehicle were considered for this study. This study is based on data drawn from a review of relevant literature, including but not limited to publications, press releases by organizations, news articles, and other similar sources. No modeling is performed as 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.

Cost and efficiency are the only potential benefits considered in this study. Other benefits, such as societal, social, health and environmental benefits, are not accounted for in this study. This study assumes that the long-term raw material supply grows simultaneously to meet the demand without any shortages. This study assumes the use of current

technologies within the conceptual vehicles, rather than independent development efforts for new technologies. While the study does assume there will be technological improvements that affect costing, it also assumes that architecture of the MY2032 vehicles is identical to that of the MY2025 vehicles. This study has not considered platform-level changes for any of the vehicles.

2. Methodology

For this study, an EREV was assumed to be a BEV with a smaller electrical range, but with a range-extender to achieve additional combined vehicle range. Several vehicles across the domestic BEV market within the compact SUV segment were considered to define values for electric range, battery size, motor size, weight, and aerodynamic efficiency for a baseline BEV [6]. Once these specifications were defined, they were applied to determine the specifications of the representative EREVs. Once these representative EREVs were defined, their cost and efficiencies were determined, and these values were compared to an equivalent BEV and PHEV.

2.1 Defining the Representative EREVs

The battery of the baseline BEV was downsized to fit the use case of the EREV. Two range targets for electric mode operation were considered: 100 miles and 200 miles. The range and battery size of the baseline BEV [6] were used to determine what battery size was necessary for each EREV case. The efficiency assumed for the battery of the representative EREVs is 3.5 miles/kWh. The process and rationale for determining this battery efficiency is detailed in Section 2.4.1 The battery chemistry considered for the EREV was LFP. Rationale and methodology for the selection of an LFP battery is detailed in section 2.4.2.

A range extender was then added to the prospective downsized BEVs to allow for range-extended mode. This range extender consisted of an engine, motor generator, and traction inverter. Two engine types were considered: a 4-cylinder naturally aspirated engine and a 3-cylinder turbocharged engine. The methodology and rationale for selecting these engine types is described in section 2.2.

The weight difference between batteries for the BEV and the EREVs was subtracted from the baseline BEV, and the weight of the range extender system was then added to that value, giving a weight of the EREVs. A similar structural frame was assumed between the baseline BEV and the representative EREVs.

Figure 9 gives the daily distance travelled by people in the US compiled from cell phone data. We removed all data points under 1 mile and 1-3 miles, assuming that a significant portion of those trips might not be automotive related. We also removed points where the daily distance travelled was above 500 miles, assuming that a significant portion of that might be air travel.

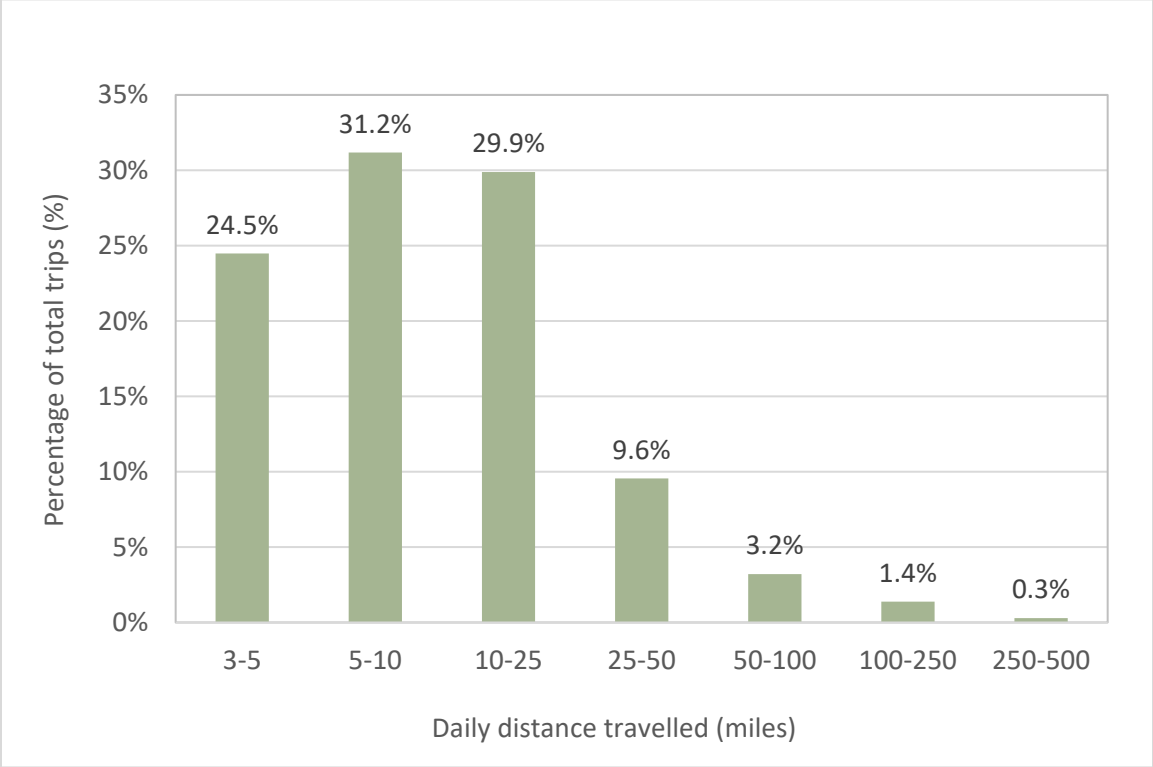


Figure 9: Daily Mobility Statistics Compiled by University of Maryland Based on Cellphone Data During 2019-2024, 6 Million Data Points [20] **Percentages are Based on Included Data Points. May Not Add to 100% Due to Rounding Errors.**

An EREV with 100 miles of electric range will cover more than 98% of people's daily travel needs. Increasing the electric range from 100 to 200 miles will only increase coverage of usage demand by less than 1.4%.

2.2 Combustion Engine for the 2032 EREV

In an EREV, unlike in an HEV or PHEV, the engine is not mechanically connected to the wheels. It is used to drive a generator that produces electricity for the traction motors and to charge the battery. We have selected a 2.5 liter four-cylinder, naturally aspirated, high compression ratio Atkinson cycle engine with direct injection (DI) and cooled exhaust gas recirculation (EGR) as the preferred option, due to its higher efficiency and lower cost when compared to a turbocharged gasoline engine (see section 2.5.1). A 1.5-liter turbocharged DI engine has also been evaluated as an alternative for comparison.

2.2.1 Technology Content of the Combustion Engine

In a conventional ICE powertrain, the engine's power output must closely follow the driver's pedal input. This requires the engine to deliver high torque response for drivability, as well as high brake thermal efficiency over a wide speed–load range to ensure good vehicle fuel economy. Technologies such as turbocharging can sacrifice peak engine

efficiency in exchange for improved efficiency at lower loads. This trade-off increases the average efficiency across engine operating points in various test cycles, thereby improving overall vehicle fuel economy.

Figure 11 compare the brake thermal efficiency of the Honda 1.5L L15B7 turbocharged DI engine (Figure 10) [21], [22] to the 2.5L Toyota A25FKS high compression ratio (HCR), NA, Atkinson engine with cooled EGR (Figure 11) [23], [24] used in competing compact SUVs (the Toyota RAV4 and the Honda CRV). The peak brake thermal efficiency of the Toyota engine is 39% while that of the Honda is 37%. But at 2000 rpm 50Nm, the efficiency of the Toyota engine is 30% while that of the Honda is 32.5 %. The Honda 1.5-liter turbo engine mated to a CVT gives an EPA rating of 28/34 (city/ highway) mpg in a CRV while the Toyota 2.5-liter NA engine mated to an 8-speed transmission gives an estimated 27/35 mpg in the RAV4. Two different powertrain strategies resulting in almost identical fuel economy.

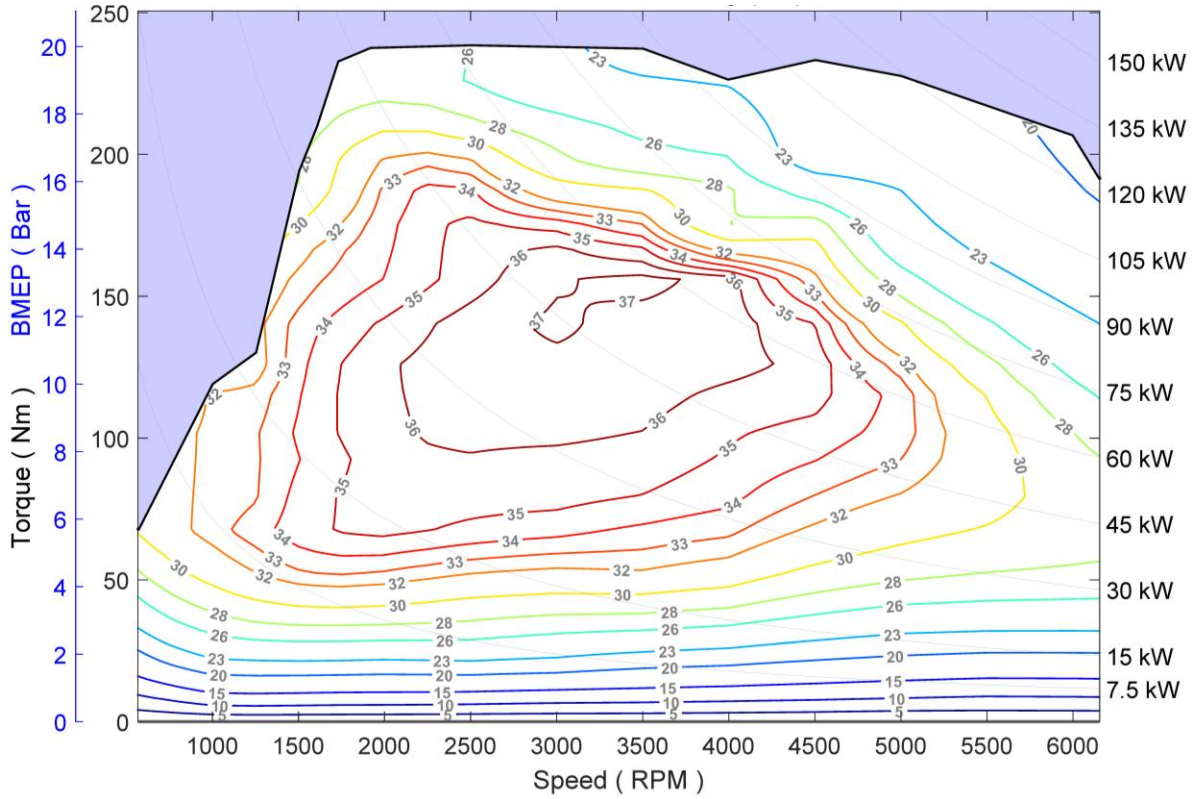


Figure 10: Brake Thermal Efficiency Map of the Honda L15B7 Engine – 1.5-Liter, 4-Cylinder, Turbo DI

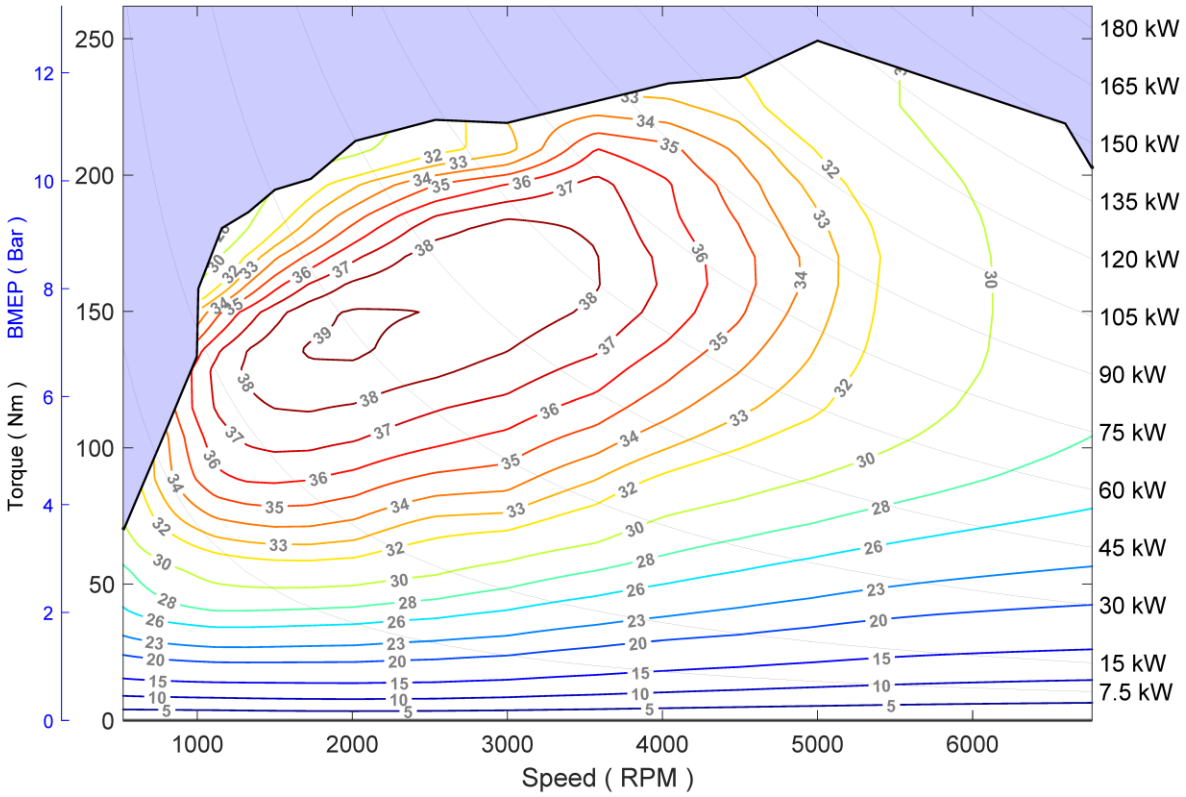


Figure 11: Brake Thermal Efficiency Map of the Toyota A25A-FKS Engine - 2.5-Liter, 4-Cylinder, DI HCR, Atkinson Cycle. Used in Conventional Powertrain Vehicles

In a hybrid vehicle, the power provided by the e-machine (and the battery) enables some decoupling of driver pedal command from the engine power output. Compared to an ICE powertrain this enables the engine in a hybrid powertrain to operate in a narrow speed-load range, with higher average efficiency, as shown in Figure 12.

The higher the power output of the e-machine and the greater the energy storage capacity of the battery pack, the more decoupling can be achieved between the driver's pedal input and the engine's power or torque output. As the powertrain moves from a mild hybrid to a full hybrid (including PHEV) and then to an EREV, the engine can be operated within a small, higher-efficiency region of the speed–load map. This narrow operating range favors engines with higher peak brake thermal efficiency.

Transitioning from a four-cylinder high compression ratio (HCR) engine to a three-cylinder turbocharged engine reduces peak engine efficiency and offers only negligible benefits in weight reduction and packaging. In contrast, in a large vehicle, moving from a V6 HCR engine to a four-cylinder turbocharged engine can result in a substantially greater reduction in weight and a notable improvement in packaging, which may make it a more attractive option despite the lower peak engine efficiency.

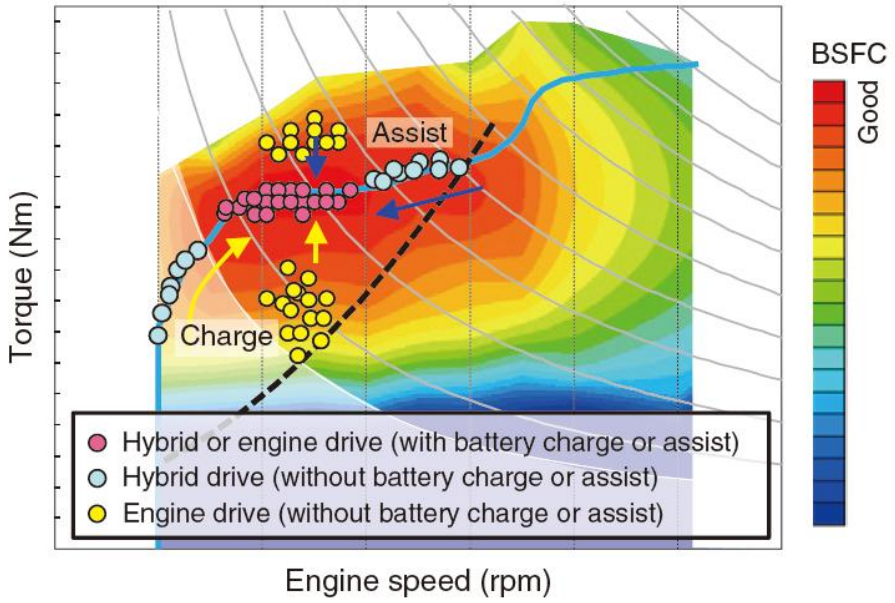


Figure 12: Illustration of Engine Operating Points in a Hybrid Powertrain [25], [26]

This narrow operation of the engine in an EREV allows the engine design to be optimized for higher efficiency in a narrow operating band. Figure 13 shows the brake thermal efficiency of the 2.5-liter A25A-FXS, [27], [28] used in the HEV and PHEV Vehicles, a version of the Toyota A25A-FKS engine used in the conventional ICE powertrain version of the RAV4 [23], [24] in Figure 11.

The two engines are compared in Table 1. The hybrid engine has a higher compression ratio of 14:1, compared with 13:1 for the engine used in the conventional ICE vehicle. This increase in compression ratio reduces the peak torque and peak power output of the hybrid engine by 13.25% and 11.6%, respectively. In a hybrid application, however, the e-machine compensates for this reduction in engine torque. The hybrid engine achieves a brake thermal efficiency of 40.9%, which is nearly two percentage points higher than that of the engine used in the conventional ICE powertrain.

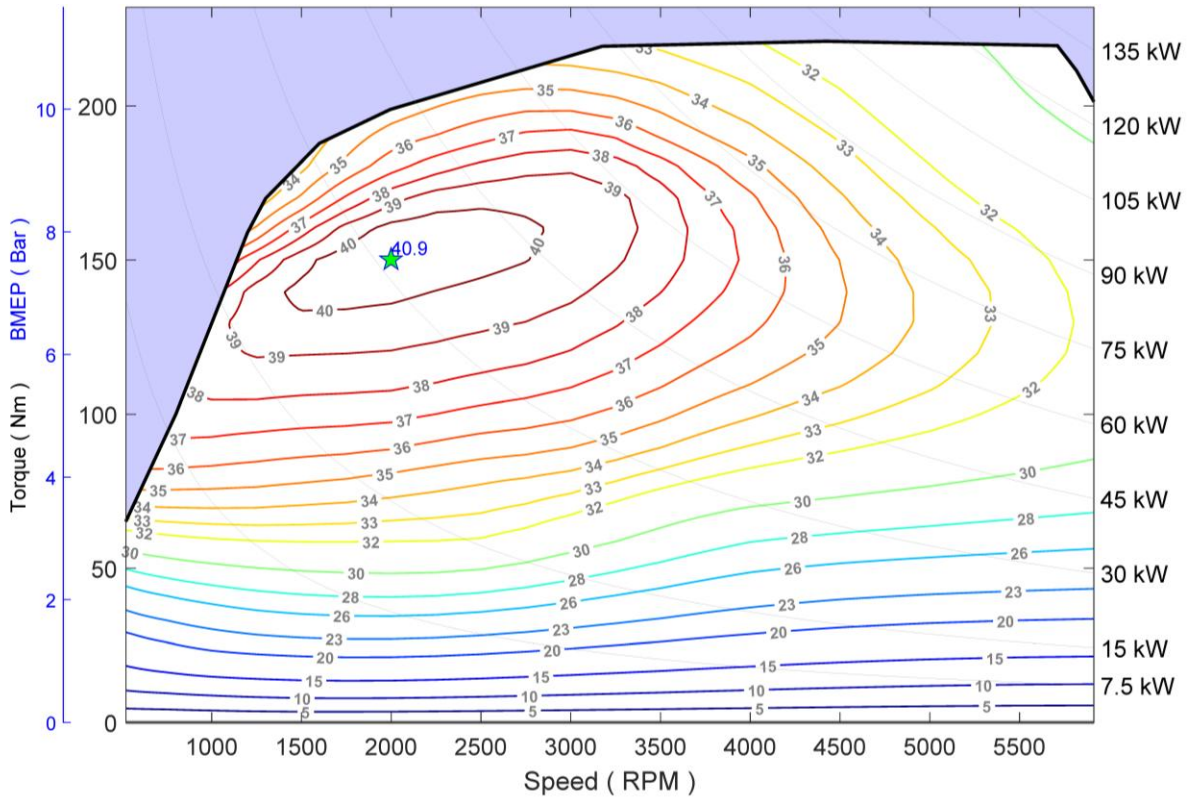


Figure 13: Brake Thermal Efficiency Map of the Toyota A25A-FXS Engine - 2.5-Liter, 4-Cylinder, DI HCR, Atkinson Cycle. Used in Hybrid Vehicles

Table 1: Comparison of the Different Versions of the Toyota A25A Engine [27], [28]

Engine	**Conventional**	**Hybrid/PHEV**
Engine Code	A25A-FKS	A25A-FXS
Engine Type	Inline-4 Cylinder	
Displacement [cc]	2487	
Bore × Stroke [mm]	Φ87.5×103.4	
Compression Ratio	13	14
Peak Efficiency (%)	39.0%	40.9%
Max. Power [kW/rpm]	151 / 6600	131/ 5700
Max. Torque [Nm/rpm]	250 / 5000	221 / 3600 - 5200
EGR System	Cooled EGR	
Fuel Injection System	D-4S (multi hole DI +PFI)	
After Treatment	2 catalytic converters, 2A/F sensors	
Emissions	SULEV30 (LEV III)	

Both engines employ direct injection (DI) and use the same aftertreatment system. Although the operating load and speed range of the hybrid or PHEV engine is narrower, the increased frequency of start–stop events in hybrid powertrain operation places additional demands on catalyst warm-up and overall aftertreatment performance. DI is necessary to maintain high combustion stability while allowing retarded combustion phasing during engine start conditions, which helps sustain high exhaust gas temperatures for rapid catalyst light-off. This ensures the catalyst quickly reaches the temperature required for effective NOx reduction and CO and HC oxidation. We expect that conventional PHEV and EREV engines will also use DI and the same aftertreatment system as the convention powertrain engine.

2.2.2 Engine Size and Power Output

The EREV's engine is assumed to provide the power required for highway cruise at real world speeds at or near its maximum break thermal efficiency. At cruise conditions, the power output of the generator is used as input to traction inverter minimizing the energy that is charged and discharged through the battery pack. This is because of the typical round-trip efficiency of sending energy though the battery pack is in the range of 90-95%. Figure 14 gives the maximum highway speed limits in various parts of the US. Most of the US has maximum speed limit of 70-80 mph. We assume a cruise speed of 80 mph to account for various driving behaviors. The range extender should also be able to supply indefinitely the power required to maintain the vehicle at top speed. The top speed of the EREV is assumed to be 110 mph, in line with other production vehicles in this market segment.

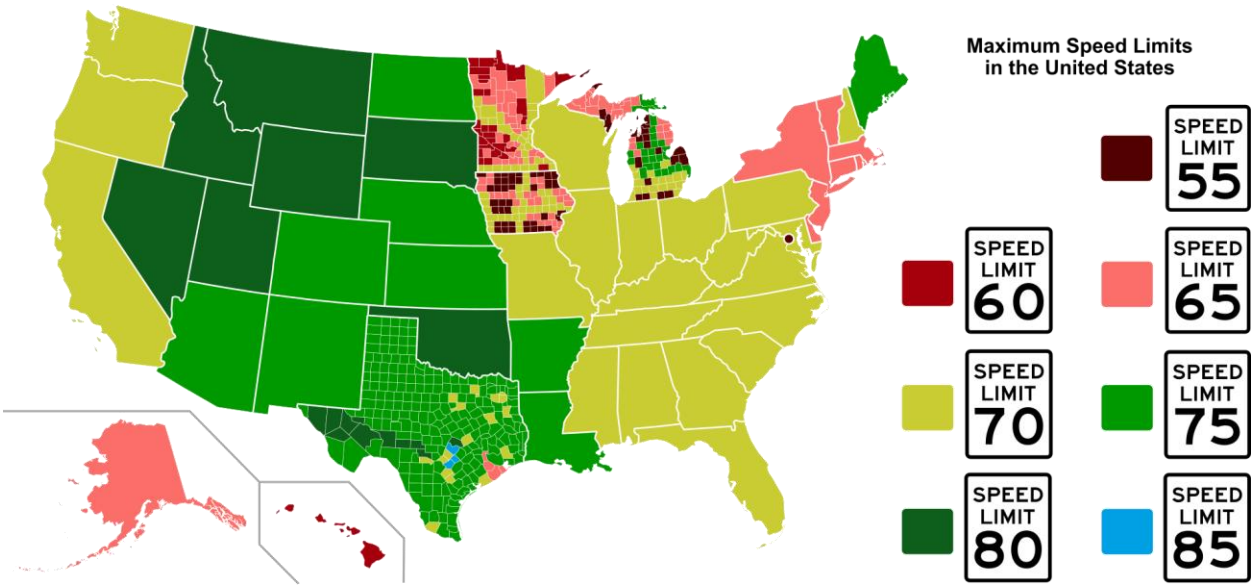


Figure 14: Map of the Highest Posted Speed Limits in Various Parts of the US [29]

Table 2 shows the traction power and the engine power estimate required to maintain the EREV at various speeds considering the efficiencies of the various components. The traction power required is calculated using ABC coefficients (coast down coefficients) published by the EPA [30]. These numbers will vary from vehicle to vehicle based on the coefficient of drag and vehicle frontal area (size and styling) drivetrain losses (efficiency of the motor and gearbox and friction in bearings and other components) and rolling resistance (size, aspect ratio and compound).

Table 2: Traction (At the Wheels) and Engine Power Requirements of an EREV at Highway and Top Speed

Vehicle Speed (mph)	70	80	110
Tractive Power Required (kW)	26.8	37.2	85.0
Mechanical Power Input to the Generator (kW)	30.9	42.9	98.2
Engine Brake Power Output (kW)	30.9	42.9	98.2

To estimate the efficiency of the EREV in charge-depleting mode, we have used the Toyota A25A-FXS engine, which is employed in the hybrid versions of the Camry and RAV4. Figure 15 shows the engine power requirements at 80 mph (1) and 115 mph (2) overlaid on the engine efficiency map. The 80-mph operating point, representative of highway driving, is close to the engine's peak efficiency region. In addition, this low-speed, moderate-load operating point offers favorable noise vibration and harshness (NVH) characteristics inside the cabin, which is particularly important for an EREV.

Because of its extended all-electric range, the EREV will operate in electric mode most of the time. As a result, consumers are likely to compare the NVH characteristics of the vehicle in engine-on (charge-sustaining) mode directly with those in pure electric (charge-depleting) mode. This contrast is more noticeable in an EREV than in a traditional hybrid, since drivers may experience long periods of near-silent electric operation before the engine starts, making any increase in noise, vibration, or harshness more perceptible.

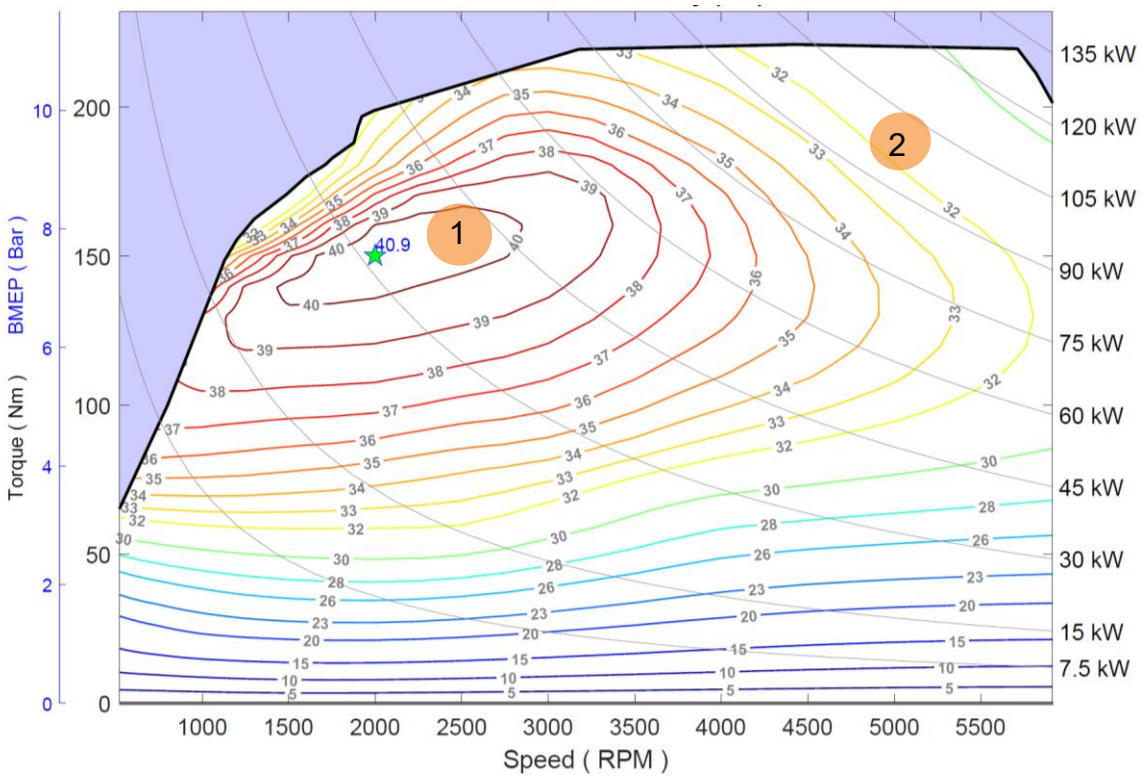


Figure 15: Engine Operating Points at 80 mph Superimposed on the Engine Efficiency Map of the Toyota A25A-FXS (2.5-Liter HCR, Atkinson Cooled EGR Dedicated Hybrid Engine) [27], [28]

2.3 Generator E-machine Selection and Sizing

In this report estimating the efficiency and cost of the EREV, we have chosen a permanent magnet e-machine for the generator due to its high maximum efficiency. The continuous mechanical power input of the generator e-machine to maintain the top speed of 110 mph is 98 kW (Table 2). Assuming a ratio of peak to continuous output of a motor generator as 0.65, the peak rating of the generator is 150 kW. The peak power is calculated since most costing studies of motors use the peak power output of the motor.

2.4 Estimating the Efficiency and battery size of a 2032 EREV

As a part of this study, we have estimated the charge-depleting and charge-sustaining efficiency of the EREV100, EREV200. and PHEV50. The traction portion of the EREV powertrain is assumed to be identical to that of the BEV300, with the EREV's front motor having the same power rating as the BEV300's front motor, and the EREV's rear motor having the same power rating as the BEV300's rear motor, providing all-wheel drive. The EREV is assumed to be based on the BEV with similar rolling resistance, drivetrain losses and aero efficiency.

The PHEV50 is assumed to use a P2 hybrid configuration, in which the torque converter of the automatic transmission is replaced with an electric motor. This is a generic architecture and differs from the Toyota Hybrid System (THS), which is proprietary to Toyota and Ford. The PHEV is assumed to be based on the base ICE platform with its rolling resistance, drivetrain losses and aero efficiency which are higher than the comparable BEV.

2.4.1 Basic Assumptions for 2032 Vehicle Efficiency Estimates

For this report, the 2032 BEV300 is assumed to have a test weight of 5,000 lb. and an efficiency of 3.5 kWh per mile (discussed in this section in detail). The weight of the EREV, used for estimating efficiency, is calculated as an offset from the weight of the BEV300 based on the revised battery size and range extender and supporting components (fuel system) that are added.

Figure 16 presents the range and gross battery capacity (kWh) of all electric compact SUVs available for sale in the United States in 2025. The iso-lines indicate efficiency in miles/kWh and show that most vehicles in this segment achieve between 3.0 and 3.5 miles/kWh. The Tesla Model Y is an outlier, with an efficiency close to 4.0 miles/kWh. Several factors contribute to the Model Y's higher efficiency, with its low coefficient of drag being a major contributor. This low drag is achieved in part through a car-like, sloping roofline, which may not align with the design language of other brands. As a result, the

Model Y is not representative of the broader segment, and a typical SUV will have higher aerodynamic drag and correspondingly higher energy consumption.

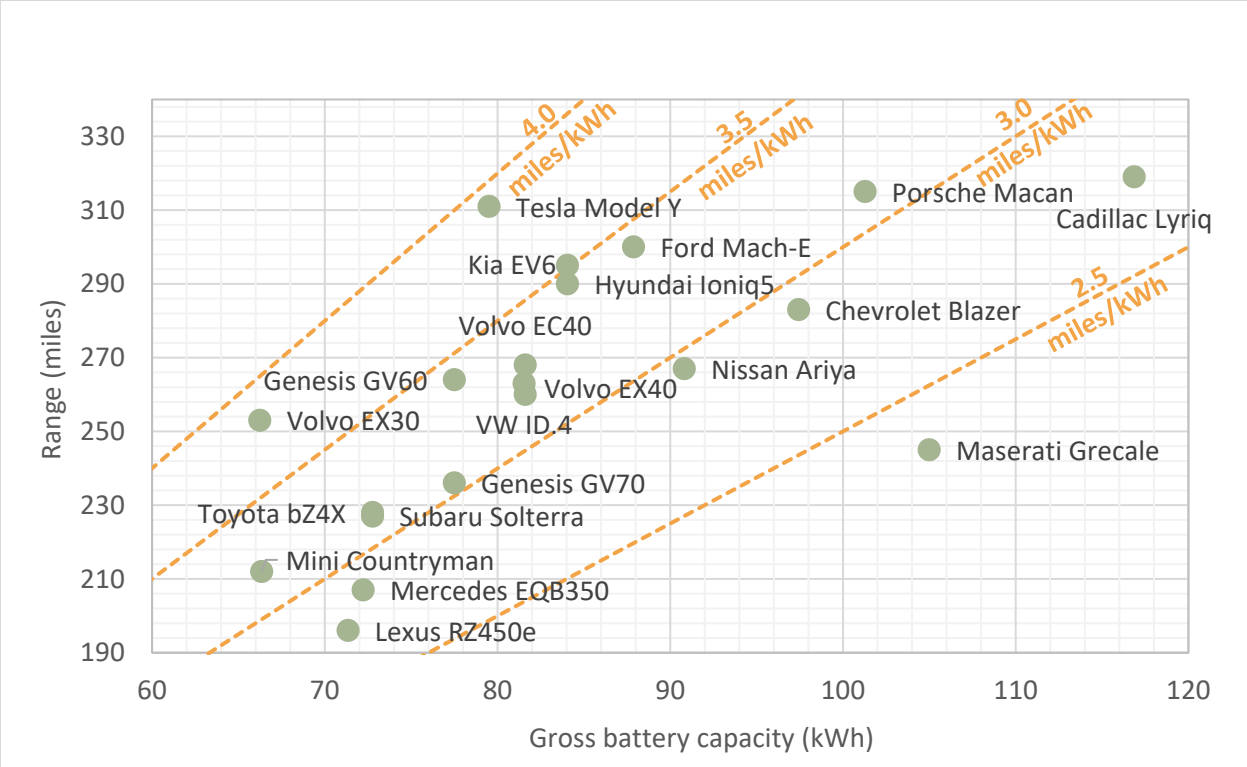


Figure 16: Gross Battery Capacity and EV Range of Compact BEV SUVs for Sale in 2025 [6]

Figure 17 shows the curb weight and efficiency of all compact battery-electric SUVs currently on sale in the United States [6]. Most EVs with a 300-mile range weigh between 4,700 and 5,000 lb. According to the 2024 EPA Trends Report, vehicle size and weight have increased steadily from 1970 to 2024 [31]. We expect this trend to continue through 2032, driven by growth in vehicle size, more stringent crash and safety requirements, additional hardware for autonomous driving, and increased infotainment and premium content. Based on these trends, we assume that a representative small battery-electric SUV in 2032 will have a curb weight of 5,000 lb. and an efficiency of 3.5 miles/kWh.

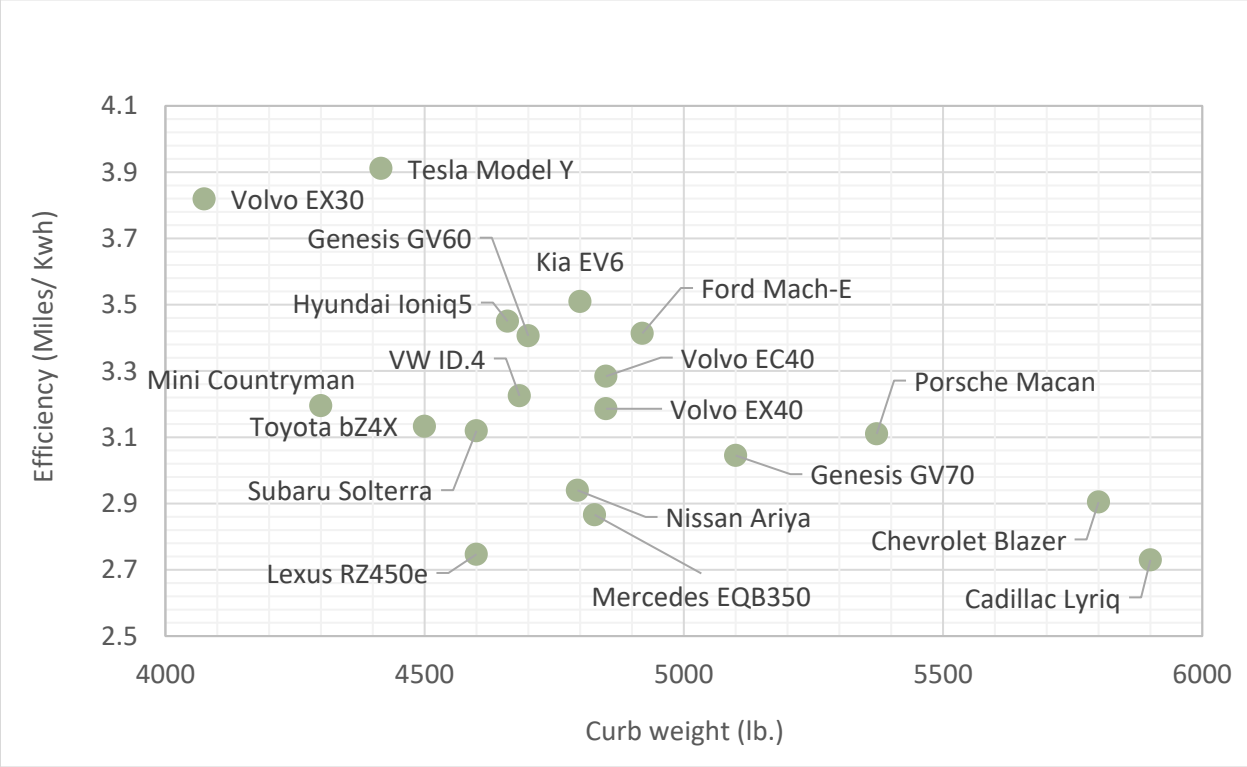


Figure 17: Curb Weight and the Efficiency of Compact BEV SUVs for Sale in 2025 [30]

Figure 18 presents the gross battery capacity and electric range of all compact SUV PHEVs available in the United States in 2025. When comparing Figure 18 to Figure 16, it is evident that PHEVs have a significantly lower efficiency, approximately 2.0 to 2.5 miles per kilowatt-hour, compared with 3.5 miles per kilowatt-hour for BEVs. This difference is primarily due to higher rolling resistance, greater drivetrain losses, and reduced aerodynamic efficiency in the ICE-based platforms on which most PHEVs are built.

As shown in Figure 19, these factors result in roughly 20% higher power traction demand for PHEVs compared with BEVs at 75 mph (calculated using ABC coast down coefficients published by the EPA [30]). We assume that a 2032 PHEV50 will be based on an ICE platform and will have a lower efficiency when compared to BEVs and EREVs

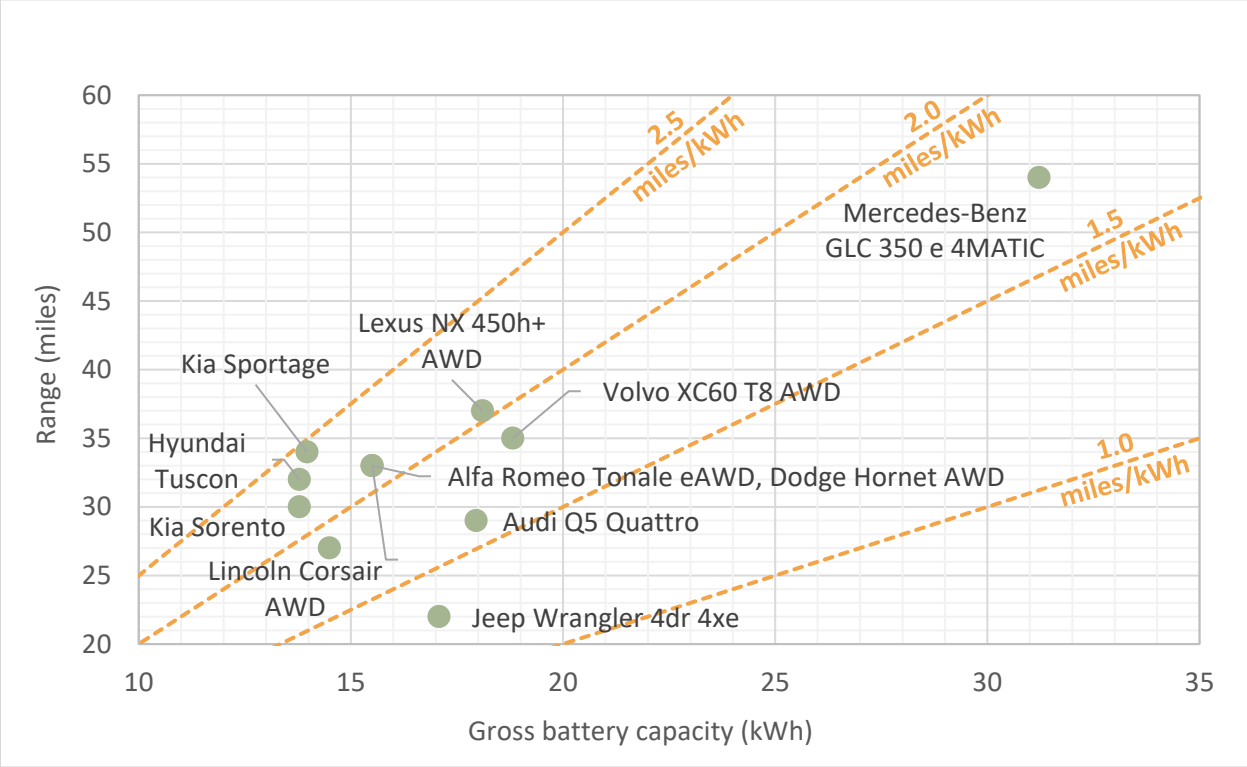


Figure 18: Gross Battery Capacity and EV Range of Compact PHEV SUVs for Sale in 2025 [6]

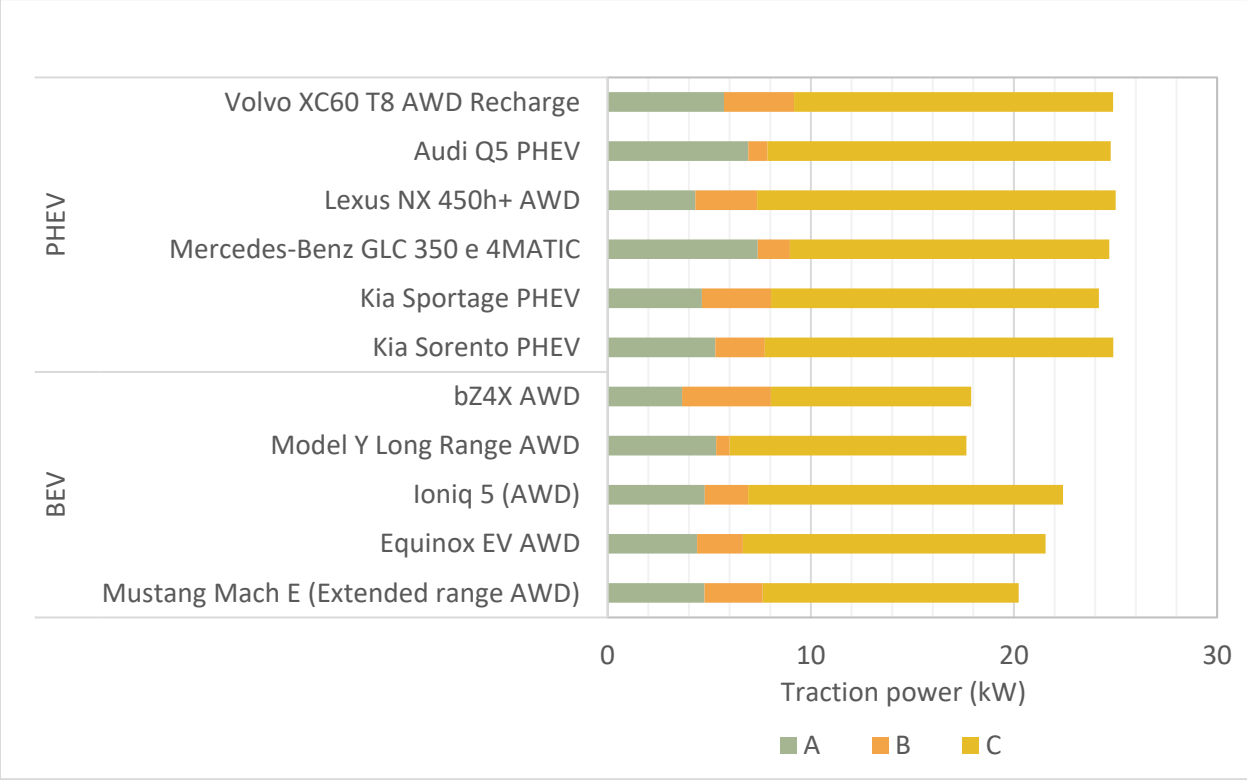


Figure 19: Traction Power Required for a Few BEV and PHEV SUVs at 75 mph

2.4.2 Battey Chemistry for BEVs, EREVs and PHEVs in 2032

We have chosen LFP batteries over NMC for all the vehicles in this report due to their lower costs, higher cycle life and the relatively smaller decrease in cycle life with increase in depth of discharge.

LFP batteries have a lower energy density when compared to NMC. Over the past decade, the energy density of the LFP packs has improved due to the following, making it feasible for them to power a compact BEV SUV with a 300-mile range.

1. Improvement of the energy density of the cells, 120-140 Wh/kg in 2015 to 205 Wh/kg in 2025.

2. Large form factor cells and optimized pack construction that increase the gravimetric cell to pack - GCTP (weight of the cells / weight of the pack) and volumetric cell to pack - VCTP (volume of the cells/ volume of the pack). BYDs blade battery pack achieves a GCTP and VCTP ratio of 0.85 and 0.62 [32]. This has enabled the LFP packs to close the energy density gap to NMC battery packs.

3. LFP packs can be frequently charged to 100% with minimal degradation of battery capacity when compared to NMC packs. This increases the effective usable capacity of the pack (increases the usable capacity/ gross capacity).

4. For an EREV100, the same driving distance or energy consumed represents a larger depth of discharge (DOD) of the pack when compared to that of a BEV300. Given their smaller battery packs, EREVs and PHEVs need a chemistry that has a higher cycle life at high depth of discharge. Figure 20 [33] compares the cycle life at various depths of discharge for LFP, NMC and NCA chemistries. LFP batteries have a much higher cycle life and a much lower decrease in cycle life as the depth of discharge is increased.

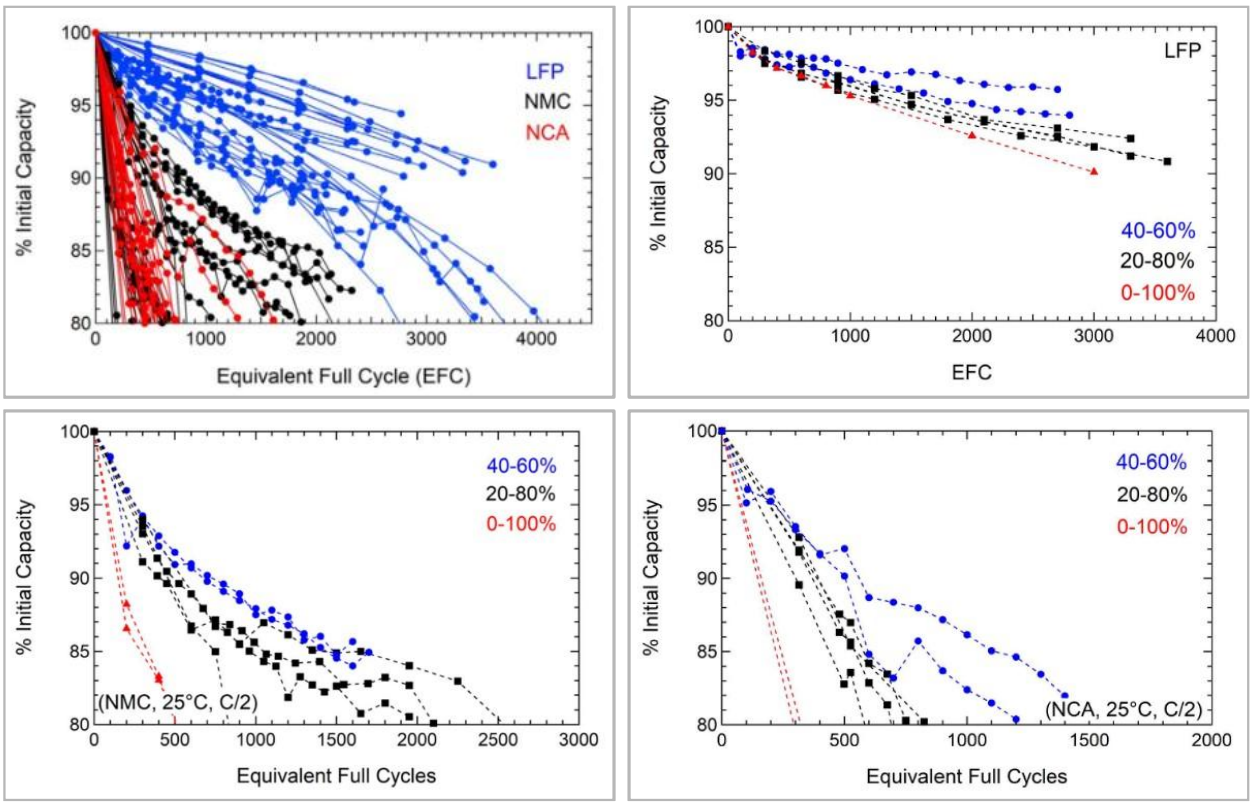


Figure 20: Effect of Depth of Discharge on Cycle Life of LFP, NMC and NCA batteries [33]

2.4.3 Battery Size and Weight Estimate for Various Vehicles in 2032

Figure 21 Figure 22 give the projected battery weights for EREV100 and EREV200 respectively for 2025 and 2032. The 2025 cell energy density and gravimetric cell to pack (GCTP) ratio is based on production BEVs. For 2032, the pack construction is assumed to be similar (similar GCTP ratio) with a projected cell energy density increase based on battery roadmaps of major suppliers and new electrode material that are currently scaling up production and are compatible with current battery manufacturing processes.

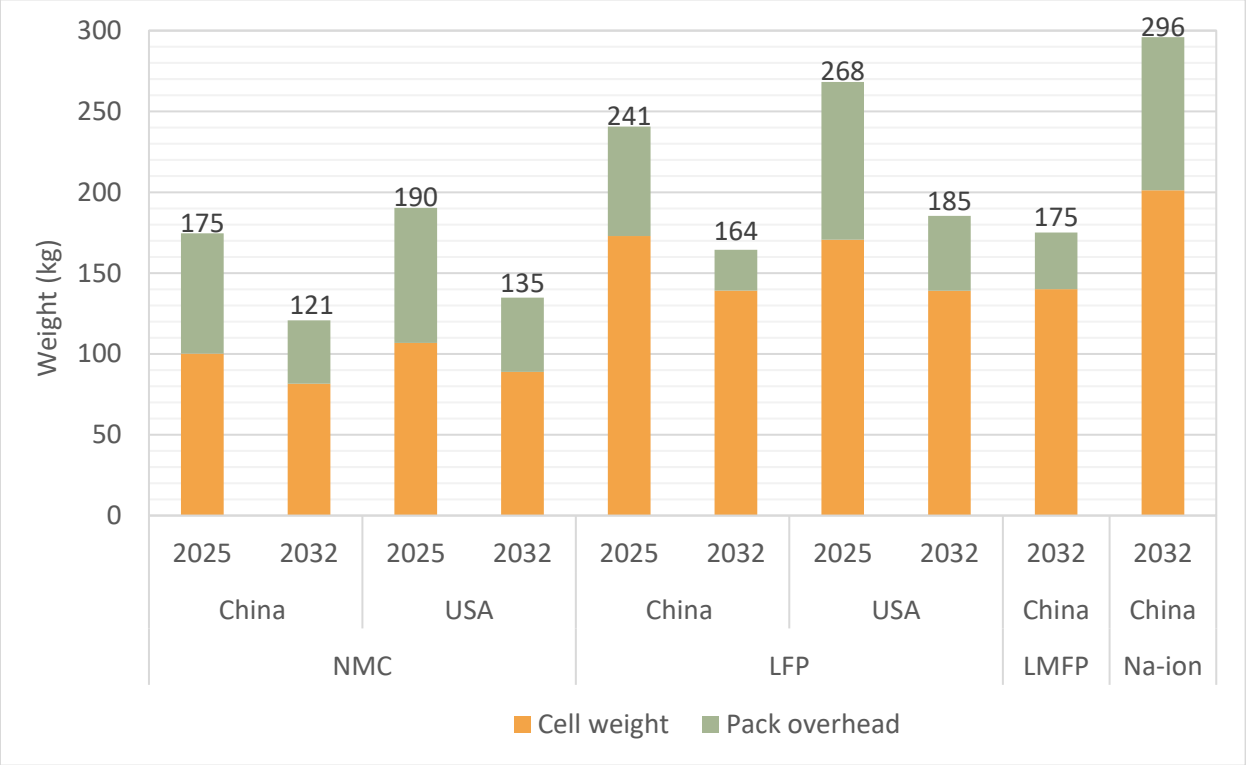


Figure 21: Battery Pack Weight of an EREV100 in 2025 and 2032

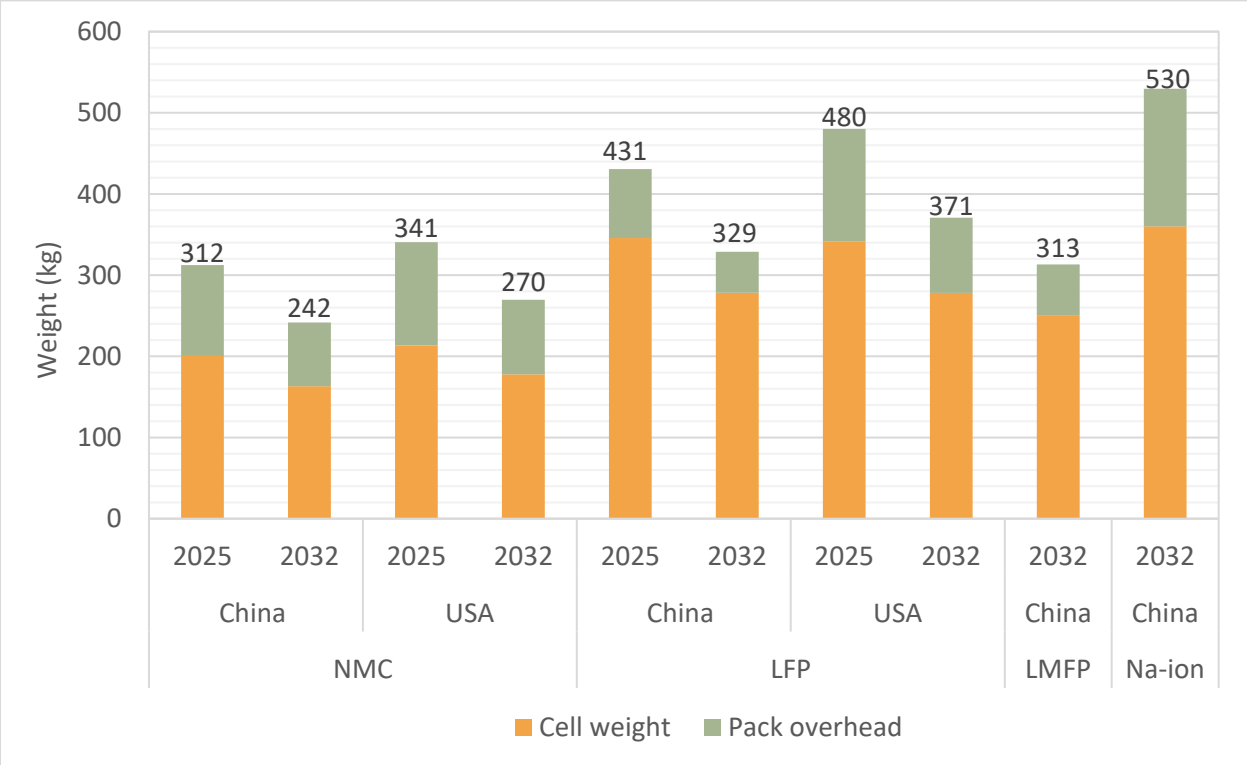


Figure 22: Battery Pack Weight of an EREV200 in 2025 and 2032

Figure 23 gives the vehicle weights calculated based on Figure 21 and Figure 22. These are used for estimating the energy consumption in CD and CS modes.

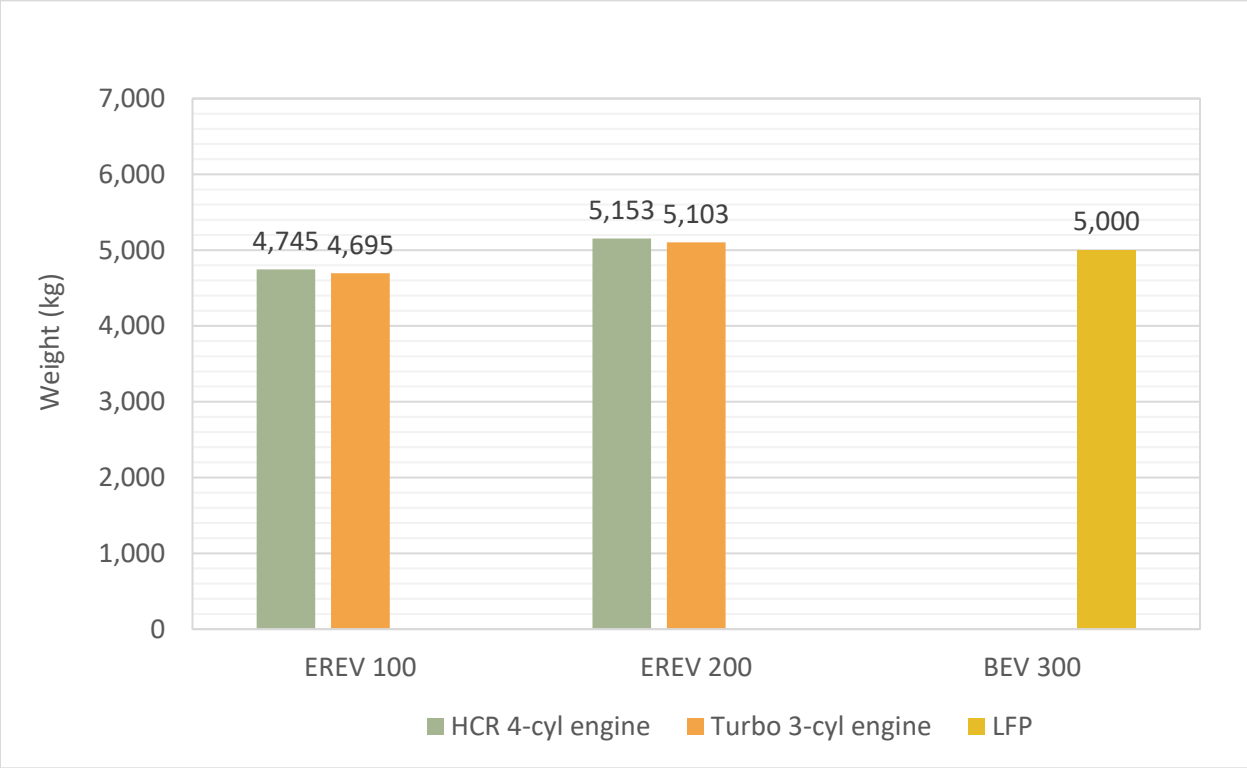


Figure 23: Vehicle Weights for Different EREV Powertrains

2.5 BEV, EREV, and PHEV Costing Methodology

Once the representative EREVs were defined, the vehicles were costed for MY2025 and MY2032. Several price points of BEV SUVs on the current market were considered to form a baseline BEV price for MY2025 [7]. Retail price equivalent (RPE) was used to convert the market MSRP to an estimated manufacturing cost. RPE is the ratio of the purchase price of the vehicle to its manufacturing cost [8]. An RPE of 1.2 was applied to this BEV price to give a baseline BEV cost [9].

Once the cost of the baseline BEV was determined for MY2025, cost changes from the additions and reductions in the representative EREV were determined to cost the EREVs. The process was then repeated for MY2032 starting with a projected manufacturing cost of the baseline BEV for that year. Once manufacturing cost for the representative EREV was determined, an RPE of 1.2 could be applied to estimate the equivalent purchase price [9]. All prices and costs were normalized to 2025 USD using the United States Bureau of Labor Statistics CPI Inflation Calculator [10].

Figure 24 shows the overall costing methodology for going from the price of the baseline BEV to the cost of the representative EREV. It shows what components affected this change in prices and costs, and which components were assumed to be roughly the same. The same process was applied to each EREV configuration for MY2025 and MY2032.

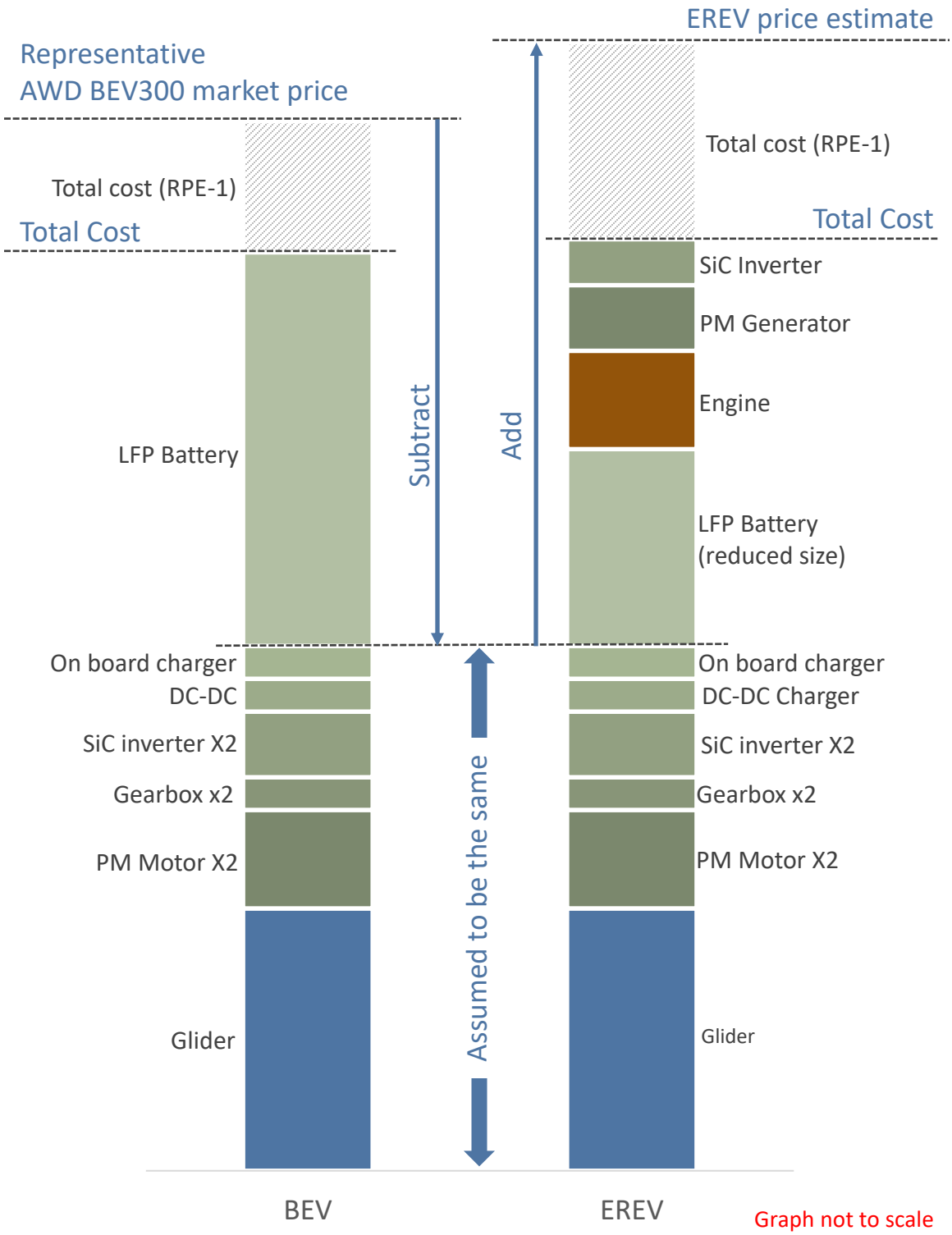


Figure 24: Methodology of Costing EREVs with the 2025 BEV Price as the Starting Point (RPE Assumed to be 1.2)

2.5.1 EREV Range Extender Costs

The range extender consisted of an engine, a motor generator, and a traction inverter. Two costing cases were considered for the engine: a 2.5L 4-cylinder Atkinson cycle engine and a 1.5L 3-cylinder turbocharged engine. Each of these engine types were costed for 2025 using the EPA OMEGA [34] and then cost improvements were applied to project costs for 2032 using the NHSTA CAFE Model [14]. Table 3 lists the engine costs used for each engine configuration for 2025 and 2032.

Table 3: Engine Costs Used for 2025 [34] **and 2032** [14]

Engine	2025 Cost ($)	2032 Cost ($)
4-Cylinder Naturally Aspirated	3,614	3,578
3-Cylinder Turbocharged	4,176	4,143

The motor generator and traction inverter were assumed to be 150 kW. The motor generator cost was estimated for 2025 based on max torque [35]. This max torque value, as well as the motor's power, were determined through the available motor options in the current BEV market within the SUV segment [7]. Max torque of the motor yielded a total motor cost for a single unit based on production volume. Comparing this total motor cost for multiple BEV motors to their power, the motor cost was able to be estimated in $/kWh [7]. Traction inverter was costed for 2025 based on power consumption [9]. For both motor generators and traction inverters, a large production supply was assumed. Manufacturing improvements were considered for forecasting the costs for 2032 [9]. Table 4 lists the motor and inverter costs used for 2025 and 2032.

Table 4: Motor and Inverter Costs Used for 2025 [9], [35] **and 2032** [9]

Component	2025 Cost ($/kW)	2032 Cost ($/kW)
Motor	3.41	3.41
Inverter	3.59	2.75

2.5.2 EREV Battery Cost Savings

Two battery sizes were considered for costing: a case that would give the EREV an electric range of 100 miles, and a case that would give the EREV an electric range of 200 miles. A battery size of 29 kWh was determined for the EREV100 and a battery size of 57 kWh was determined for the EREV200. The global average cost for batteries in 2025 [9], [11] was used to find the battery cost savings from the difference in the baseline BEV

battery to the two EREV cases for MY2025. For MY2032, both global averages [9], [11] and domestic manufacturing costs [12], [13] were considered for batteries because of the increasing efforts in improving domestic manufacturing of LFP batteries by 2030 [13]. Table 5 lists the battery costs used for 2025 and 2032.

Table 5: Battery Costs Used for 2025 [9], [11] **and 2032** [12], [13]

Component	2025 Cost ($/kWh)	2032 Global Cost ($/kWh)	2032 Domestic Cost ($/kWh)
Battery	107.20	66.43	80.00

2.5.3 PHEV Cost

Once the representative EREVs were costed for MY2025 and MY2032, an equivalent PHEV was also costed for these years. This PHEV had the desired electric range of 50 miles. It was assumed that the PHEV battery was about 80% as efficient as the BEV and EREV batteries [12]. This efficiency difference can be attributed to the smaller battery of the PHEV and the efficiency losses from the transmission in the PHEV, as well as PHEVs being based on an ICE platform and therefore not optimized for electric driving. The equivalent PHEV battery size was determined to be 18 kWh. The motors of the equivalent PHEV were assumed to be 100 kW. A 4-cylinder naturally aspirated engine and a transmission were assumed to be added to the BEV to characterize the equivalent PHEV. A torque converter was assumed to be removed from the transmission of the PHEV.

Similarly to the EREVs, the PHEV was costed starting with the equivalent BEV cost. Similar costing considerations to the EREV were used: the battery costs, engine costs for the 4-cylinder naturally aspirated engine case, and the motor cost for 2025 and 2032 used for the EREV cases were also applied to the PHEV case. The torque converter was assumed to be about $100 [12]. The transmission cost was determined for both 2025 and 2032 using the NHTSA CAFE Model [14]. Table 6 lists the transmission costs used for 2025 and 2032.

Table 6: PHEV Transmission Costs Used for 2025 and 2032 [14]

Component	2025 Cost ($)	2032 Cost ($)
PHEV SUV Transmission	1,857.10	1,839.20

3. Technology Review

3.1 Motor-Generator and Inverter Technology

Figure 25 shows the different types of motors used in production BEVs and OEMs or production applications.

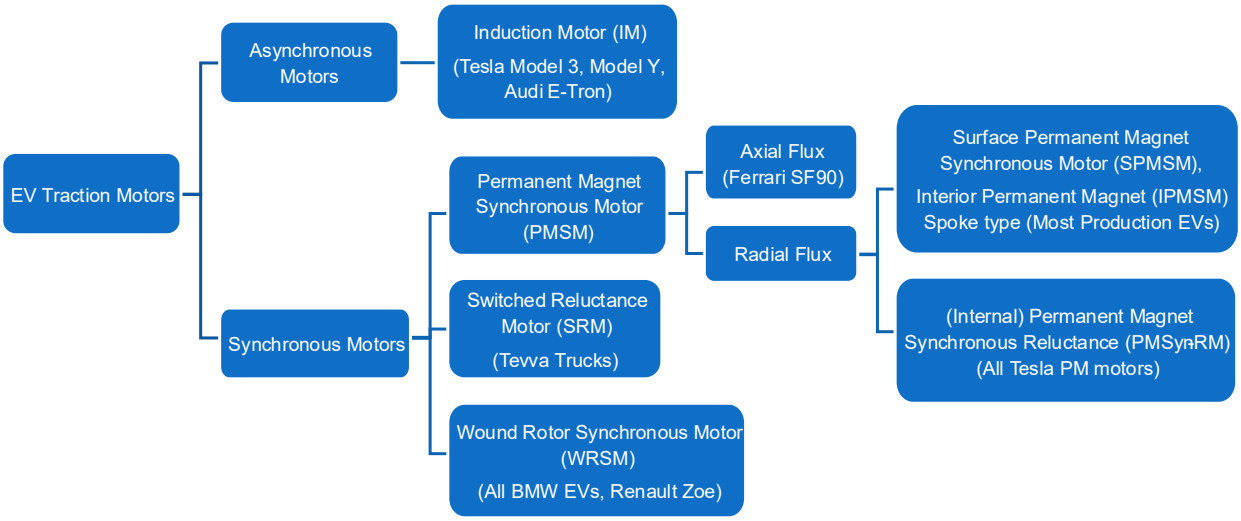


Figure 25: Different Types of Traction Motors in Production Battery Electric Vehicles [9]

3.1.1 Permanent Magnet Synchronous Motor (PMSM) and Permanent Magnet Assisted Synchronous Reluctance Motor (PMSyn-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. [9]

In a permanent magnet-assisted synchronous reluctance motor (PMSyn-RM), the reluctance torque is significant compared to the PM electrical torque [9]. 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 7 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 [36]. 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 7: Comparison of VW ID3 Motor and Tesla Model 3 Rear Motor [9]

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	g/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 [36]			

3.1.2 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 compared to >$4 per kW for PMSMs and PMSyn-RM [9]. Audi (Figure 26), 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.

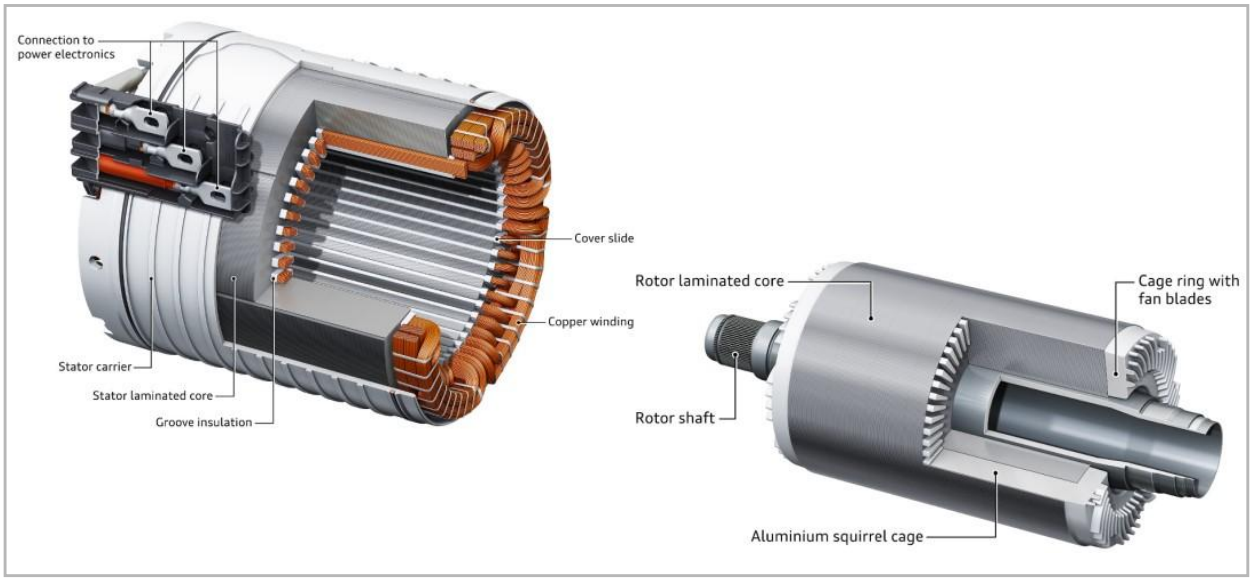


Figure 26: Audi APA250 Induction Motor with Cast Aluminum Rotor Conductors (125kW) [37]

3.1.3 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 [9]. 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 27 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.

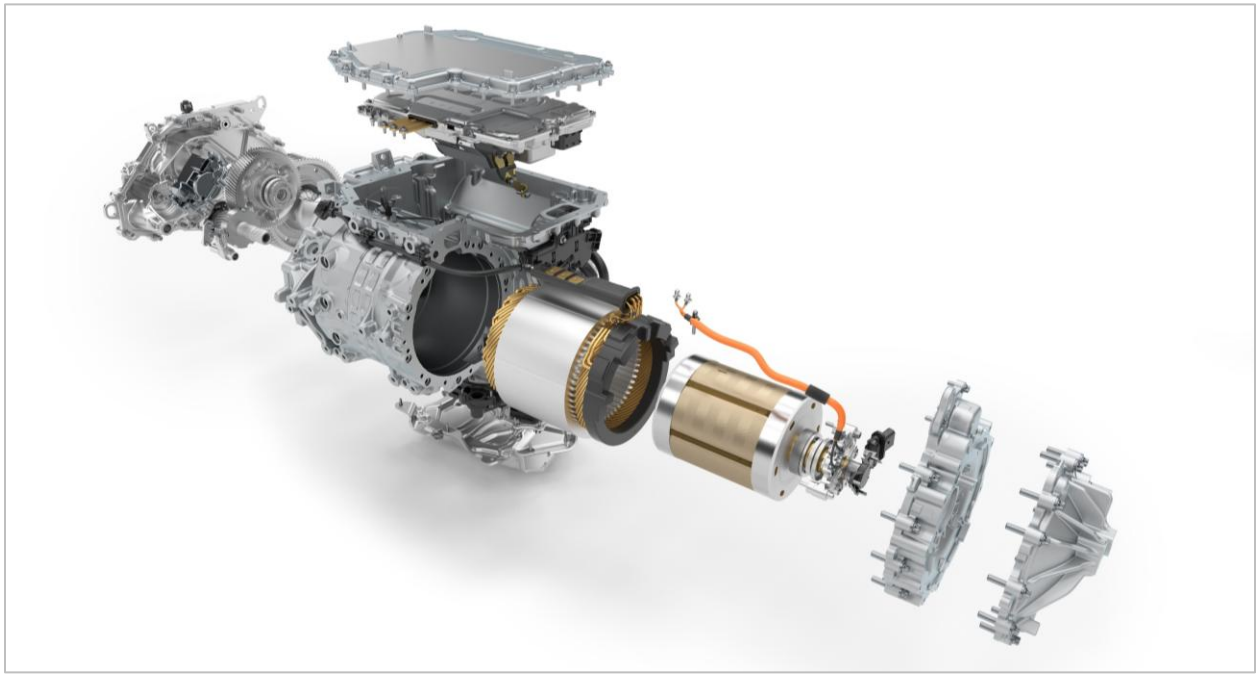


Figure 27: BMW "5th Gen E-drive Technology" Employing a Wound Rotor Synchronous Rotor. The New BMW iX3 – Drivetrain [38]

3.1.4 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) [9]. Over the past few years, all of these problems have been resolved, resulting in new motors having started limited production and being available for OEMs to test and integrate into their new product programs.

3.1.5 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, have become more widely available and cost-effective [9]. These newer technologies outperform traditional Si IGBTs in terms of power density, switching speed, and loss, making them appealing to electric car makers [39], [40], [41]. 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 [39], [41]. 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.

4. Results

This section presents the overall results of the cost analysis and the efficiency analysis for EREVs against a BEV and PHEV for the compact SUV segment in MY2025 and MY2032.

4.1 Cost of EREV, BEV, and PHEV

Figure 28 depicts the manufacturing costs for the representative EREVs, BEV, and PHEV in the compact SUV market segment for MY2025. It was found that the EREV100 was a cheaper option than the equivalent BEV300 for MY2025, regardless of engine configuration. Both EREV100 cases had higher manufacturing costs than the PHEV50; the EREV100 with a 4-cylinder naturally aspirated engine being only about $1,000 more. Each EREV200 case was found to have higher manufacturing costs than the equivalent BEV300. Ultimately, the most significant factor for the different costs between the equivalent vehicles was battery size. The costs of these vehicles can be compared to the manufacturing cost of an equivalent ICE vehicle in 2025, found to be approximately $31,600.

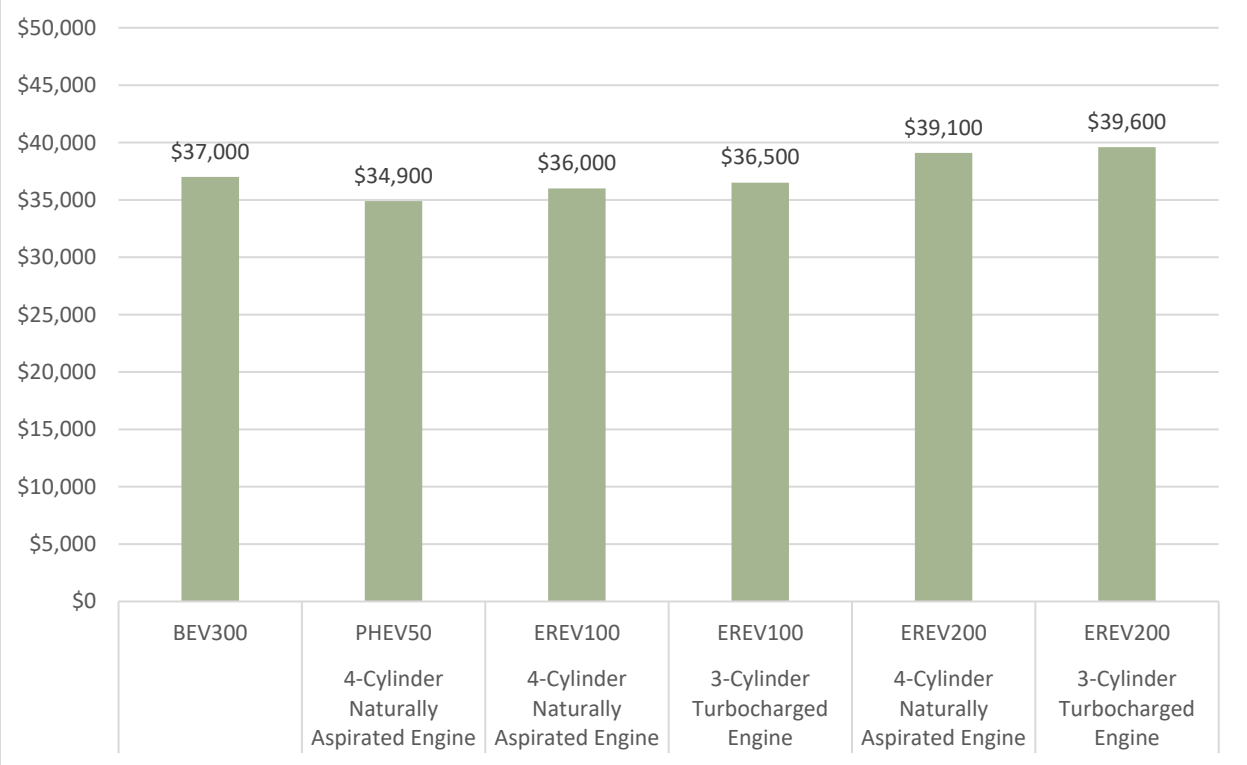


Figure 28: EREV, BEV, and PHEV Manufacturing Costs for MY2025 Compact SUVs

Figure 29 depicts the manufacturing costs for the representative EREVs, BEV, and PHEV in the compact SUV market segment for MY2032 if global battery costs are used. It was found that by 2032, battery costs will decrease enough to where all the EREV cases have higher manufacturing costs than the BEV300. The PHEV50 will still be a more affordable option than the EREVs in this case, but the additional range provided by EREVs may maintain their attractiveness to consumers and manufacturers. The costs of these vehicles can be compared to the manufacturing cost of an equivalent ICE vehicle in 2032, found to be approximately $31,500.

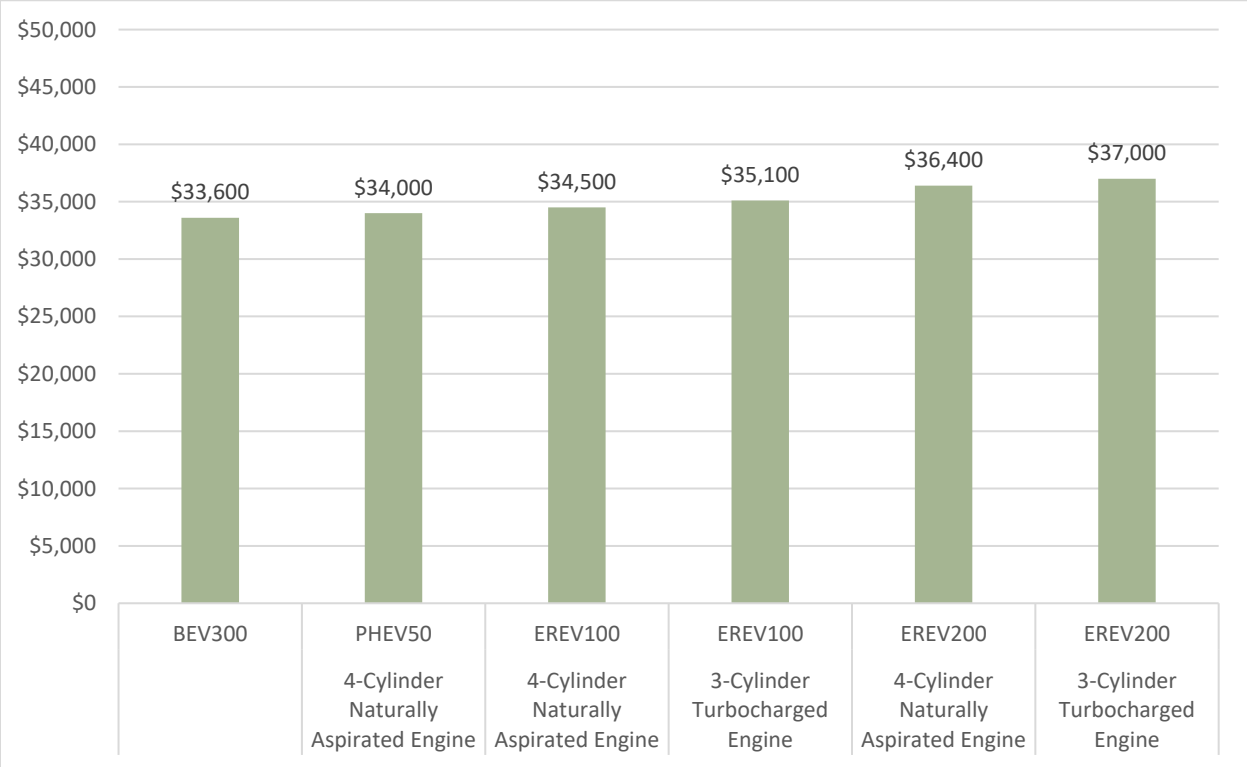


Figure 29: EREV, BEV, and PHEV Manufacturing Costs for MY2032 Compact SUVs Using Global Average Battery Costs

Figure 30 depicts the manufacturing costs for the representative EREVs, BEV, and PHEV in the compact SUV market segment for MY2032 if domestic battery costs are used. It was found that using the domestic battery costs still leads to the BEV becoming less expensive than all EREV options by 2032, just by a smaller margin than using the global costs. This is because the difference between the global costs and the domestic costs is only around 15% [15], which leads to small changes when considering the battery sizes of these vehicles. The costs of these vehicles can be compared to the manufacturing cost of an equivalent ICE vehicle in 2032, found to be approximately $31,500.

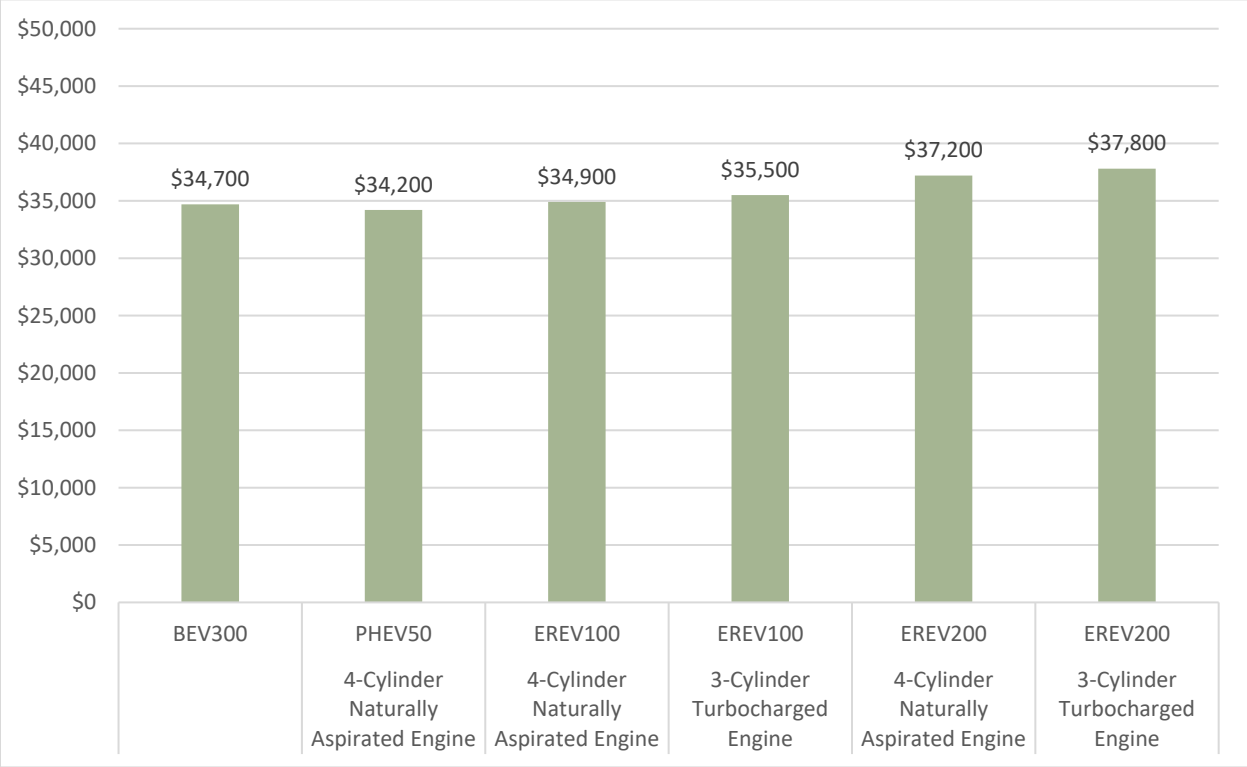


Figure 30: EREV, BEV, and PHEV Manufacturing Costs for MY2032 Compact SUVs Using Domestic Battery Costs

As a result of this costing analysis, it was found that certain EREVs would be a cheaper option in MY2025 when compared to an equivalent BEV300 and comparable to an equivalent PHEV50. By 2032, the equivalent BEV300 will provide more cost savings than the representative EREV100s, and the equivalent PHEV50 will remain cheaper than the representative EREV100s, suggesting no upfront savings for an EREV in the compact SUV market segment by 2032. Despite this, the cost difference between the EREV100 and the PHEV50 is marginal, so EREVs may be appealing to manufacturers or customers that desire more electric range.

4.2 Purchase Prices of EREV, BEV, and PHEV

Figure 31 depicts the purchase prices for the representative EREVs, BEV, and PHEV in the compact SUV market segment for MY2025. It was found that the EREV100 could be purchased at a lower price point than the equivalent BEV300, regardless of engine configuration. However, the EREV100 would fall at a slightly higher price point than the equivalent PHEV50. The ERV200, regardless of engine configuration, falls at significantly higher purchase price than the equivalent BEV300.

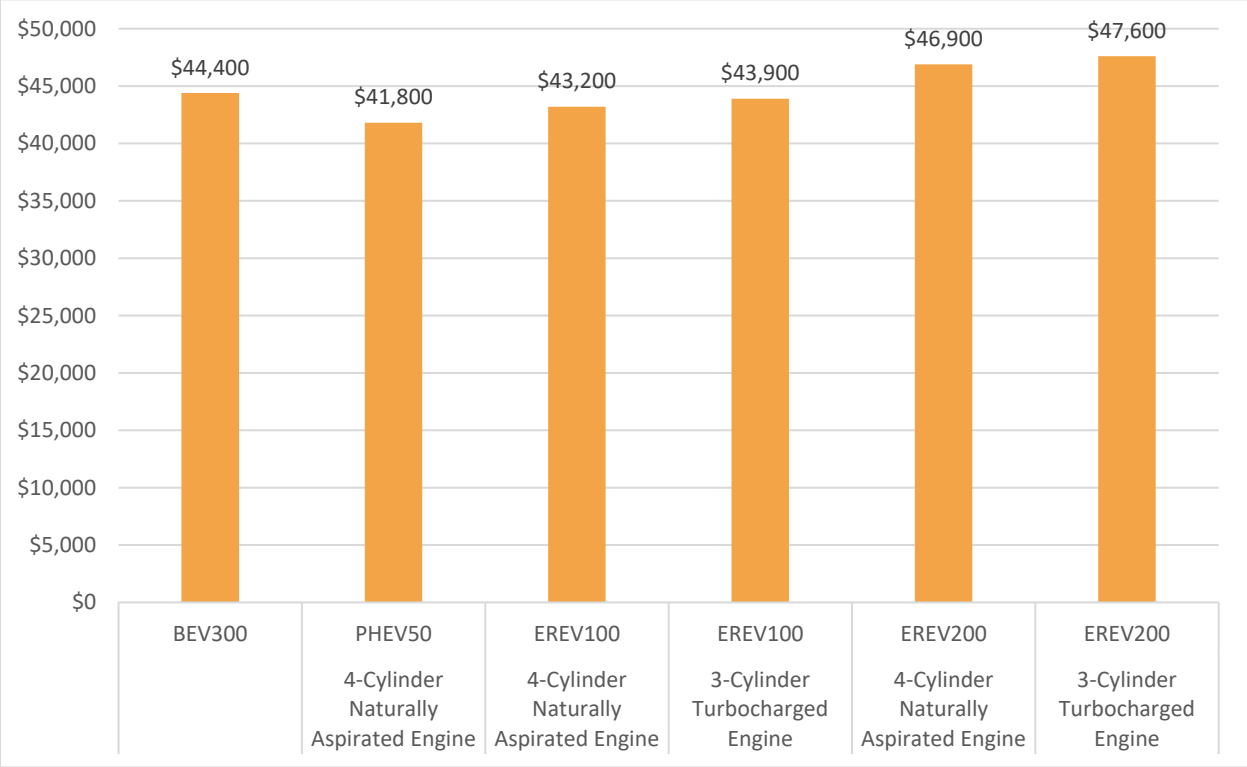


Figure 31: EREV, BEV, and PHEV Purchase Prices for MY2025 Compact SUVs

Figure 32 depicts the purchase prices for the representative EREVs, BEV, and PHEV in the compact SUV market segment for MY2032 if global battery costs are used. It was found that by 2032 that EREVs, regardless of configuration, would fall at a higher purchase price than the equivalent BEV300 and remain at a higher purchase price than the PHEV50.

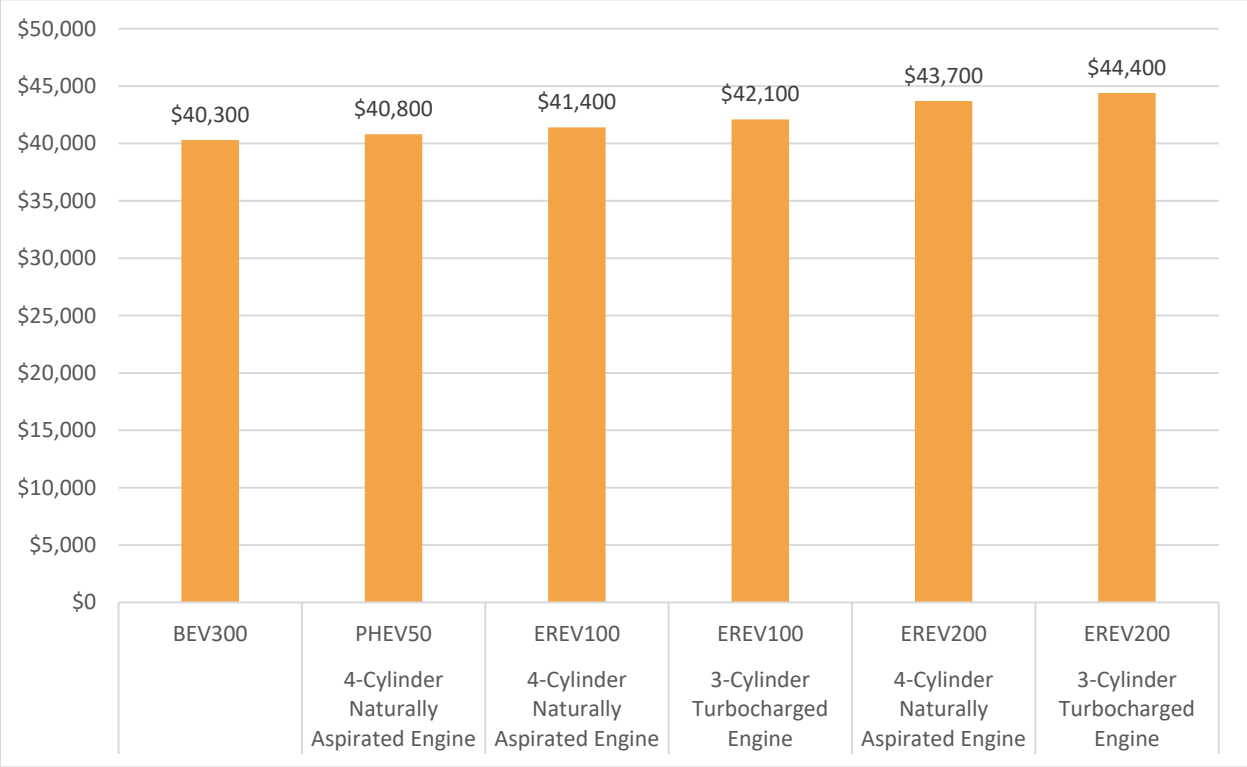


Figure 32: EREV, BEV, and PHEV Purchase Prices for MY2032 Compact SUVs Using Global Average Battery Costs

Figure 33 depicts the purchase prices for the representative EREVs, BEV, and PHEV in the compact SUV market segment for MY2032 if domestic battery costs are used. It was found that regardless of global or domestic battery costs in 2032, the EREVs go for a higher purchase price than the equivalent BEV300 and the PHEV50 by 2032.

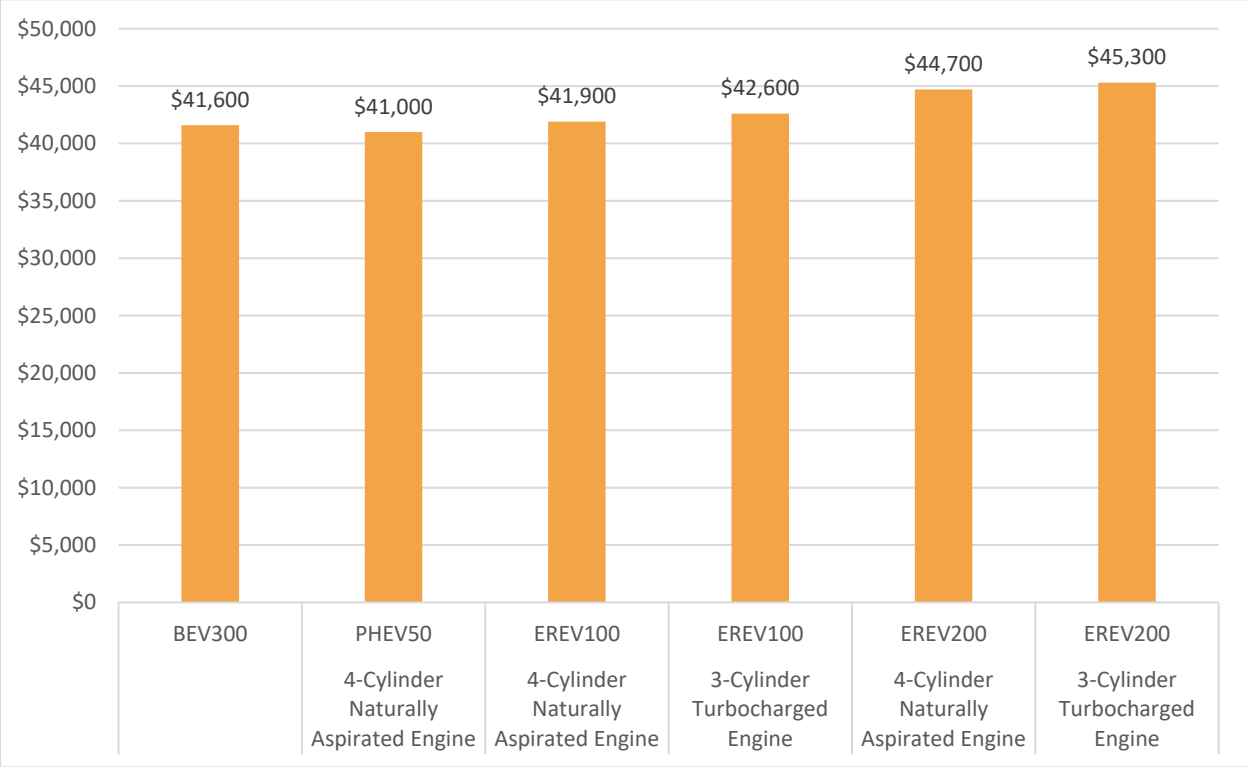


Figure 33: EREV, BEV, and PHEV Purchase Prices for MY2032 Compact SUVs Using Domestic Battery Costs

As a result of this analysis, the same conclusions found in the manufacturing costs analysis results in section 4.1 can be derived from the purchase prices of the vehicles. This is because the prices derive from applying an RPE of 1.2 to each vehicle's manufacturing cost. This further shows that EREVs are a more affordable alternative to equivalent BEVs in MY2025 but will fall at a higher price point than the BEV by MY2032 and will fall at a higher price point than the PHEV50 in both 2025 and 2032, suggesting no upfront savings for an EREV by 2032 when compared to the equivalent BEV and PHEV.

4.3 Efficiency of EREV, BEV and PHEV

This section presents estimated efficiencies for representative 2032 EREV100 and EREV200 configurations and compares them with a PHEV50. These values represent estimates for a representative vehicle. As with BEVs and PHEVs available in the 2025 market (Figure 16, Figure 18, a range of efficiencies is expected for 2032 vehicles in both charge-deplete and charge-sustain modes. The variation will depend on factors such as vehicle size and design (weight, frontal area, and aerodynamic drag coefficient), drivetrain design (drivetrain friction), engine and e-motor technology (efficiency), performance targets (motor sizing and its influence on where the operating points lie on the motor

map), tire (width, aspect ratio and compound), battery chemistry (internal resistance and associated losses), and thermal management system design (parasitic power demand for battery cooling).

Figure 34 gives the curb weight of the 2032 EREVs with 100 and 200 miles of electric range with the two engine options - the 4-cylinder HCR engine and the 3-cylinder turbocharged engine. The estimated curb weight of the 2032 BEV with 300-mile range is also shown for comparison. All vehicles are assumed to use LFP battery chemistry.

The difference in weight between the naturally aspirated high HCR engine and the 3-cylinder turbocharged engine is marginal. The EREV200 weighs 100 -150 lb more than the BEV300 since the weight saving from the smaller battery pack is less than the weight added by the engine, generator, power electronics, fuel system and the modifications to the chassis for taking the extra weight of the engine and other components in the front. The EREV100 saves about 250-300 lb compared to the BEV300.

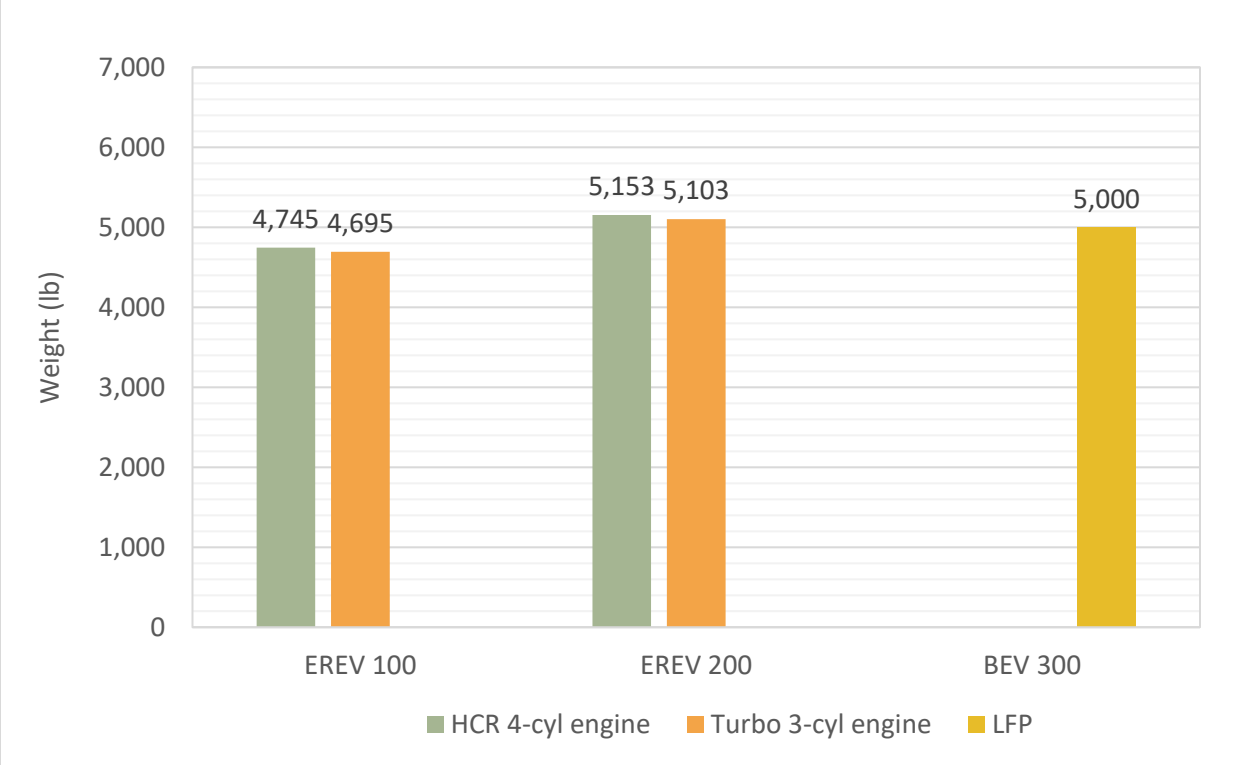


Figure 34: 2032 Vehicle Weights for Different EREV Powertrains.

Figure 35 shows the estimated efficiency of the EREV100, EREV200, and PHEV50 in battery-electric (charge-depleting) mode. The BEV300, EREV100, and EREV200 share identical torque-providing components: two motor drive units (each comprising a motor and reduction gearbox), one at the front and one at the rear, with identical power outputs.

The slightly lower efficiency of the EREV200 is due to an additional 150 - 200 lb of weight. The EREV100 and EREV200 exhibit nearly identical efficiency despite the EREV100 being 400 lb lighter. The efficiency advantage of the EREV100 from reduced mass is offset by higher battery losses, approximately 2-3%, caused by its nearly doubled average battery C-rates over the cycle (both traction and regenerative braking) and increased cooling demands on the battery. For all three vehicles, we have assumed the same LFP battery chemistry.

The PHEV50 has significantly lower efficiency because it is based on an underlying ICE platform with higher rolling resistance, greater drivetrain friction, and increased aerodynamic drag.

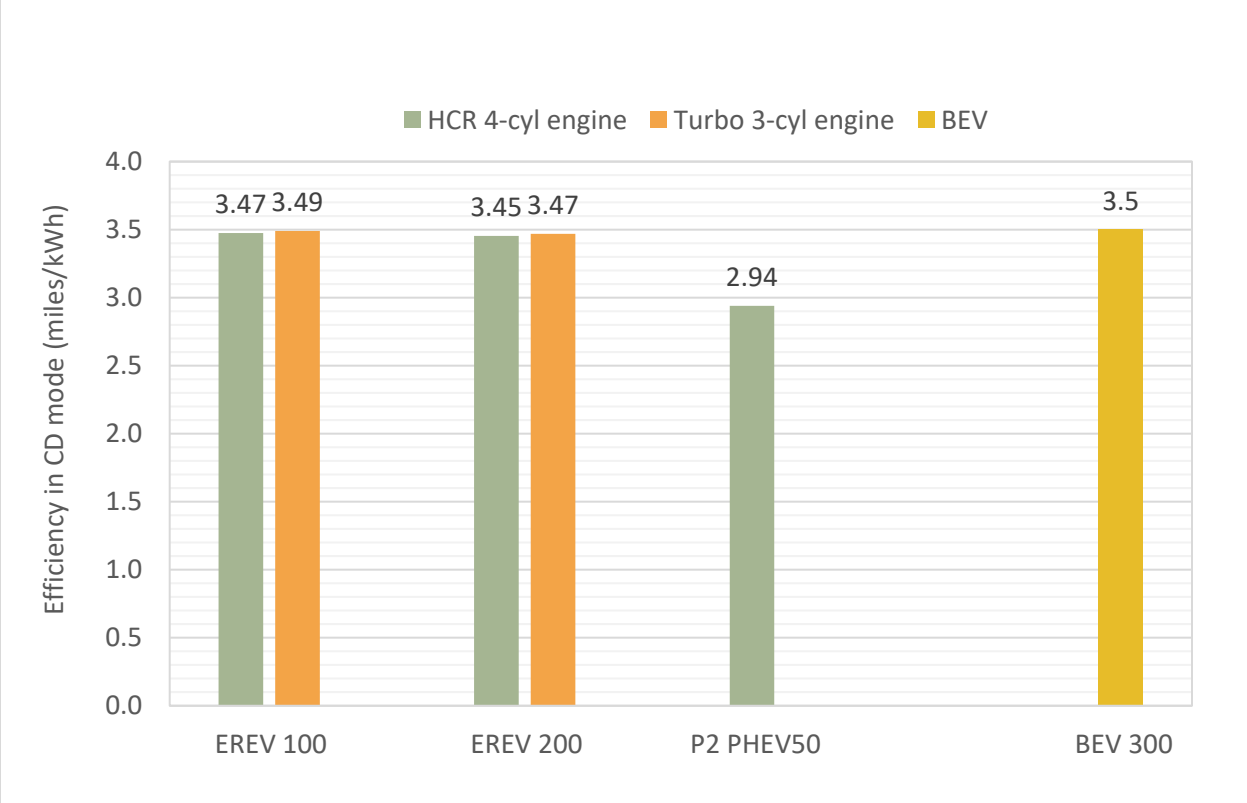


Figure 35: 2032 Estimated Efficiency (Miles/kWh) of the EREV and P2 PHEV in CD Mode

Figure 36 presents the estimated 2032 charge-sustaining fuel economy (mpg) of the EREV100, EREV200, and PHEV50. The PHEV50 achieves higher efficiency than the EREVs because the brake power produced by its ICE is used directly to drive the wheels. In an EREV, by contrast, the engine's brake power is first converted to electricity by the generator and associated power electronics, then converted back to mechanical power

by the traction motor and inverter. In addition, a portion of the energy is routed through the battery, introducing further losses.

In the EREV powertrain, these additional conversion and storage losses exceed the efficiency benefit gained from operating the engine in a narrow, high-efficiency speed–load range. The EREV100 is more efficient than the EREV200 due to being 400 lb lighter. Furthermore, the naturally aspirated high compression ratio Atkinson cycle engine is more efficient than the turbocharged engine because of its higher peak brake thermal efficiency. Since the engine operates within a narrow speed–load band, peak efficiency is more important than part-load efficiency.

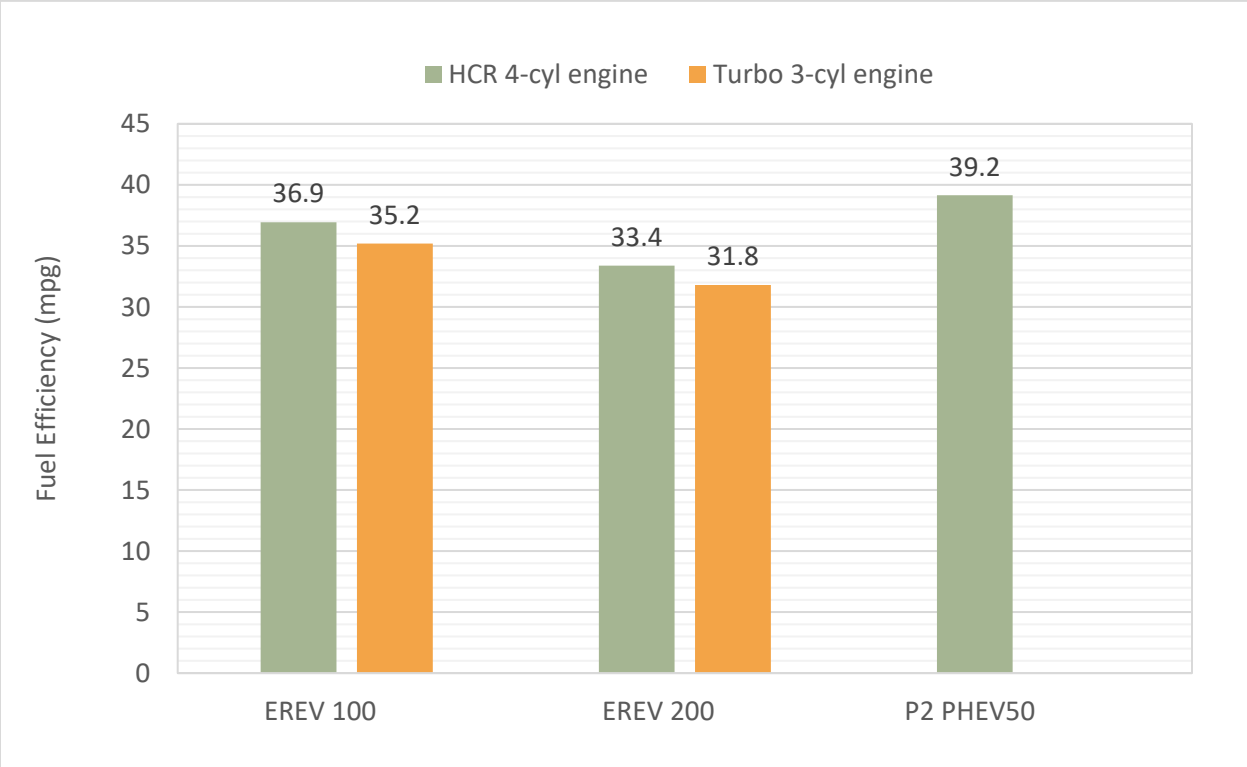


Figure 36: Estimated Efficiency (mpg) of the EREV and P2 PHEV in CS Mode

5. Conclusions and Future Work

In the compact SUV class, EREVs are eclipsed by BEVs and PHEVs in up-front cost and efficiency now and in MY 2032. Thus, the appeal to the consumer may lie elsewhere: electric-only commuting with regular long trips enabled by the range extender, increased towing range or capability not possible in a BEV, or the familiarity of a gasoline car and its associated infrastructure. The difference in cost between an EREV and an equivalent BEV or PHEV is marginal, so these additional factors may be attractive over the limited savings. Furthermore, there is opportunity for cost savings within EREVs as more efforts go into the technology. Factors such as engine optimization and platform redesigns may drive cost down in EREVs as this study assumed borrowing those technologies from other vehicle variants.

Further study of the cost and efficiency of EREVs for these cases, such as a full-size SUV or a class 2b pickup truck, may reveal advantages not shown in this study. As mentioned in section 1.3, Ram has announced the Ramcharger, a full-size EREV pickup advertised to have more towing capacity, range, and payload than any electric truck, indicating a potential market in these vehicle classes over BEV or PHEV. Expanding this study to other vehicle classes and use cases is recommended.

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