California Air Resources Board

Appendix G

ACC II ZEV Technology Assessment

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I. Introduction

Since the adoption of the Advanced Clean Cars (ACC) regulations in 2012, zero-emission vehicle technology developments – for battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and plug-in hybrid electric vehicles (PHEVs) – have progressed quickly. This has led to the introduction of zero-emission vehicles (ZEVs) with longer all-electric driving ranges and more efficient and capable drivetrains far earlier than expected. Looking to the future of ZEV and PHEV technologies in the 2026 to 2035 timeframe, even greater efficiency improvements, longer ranges, and vehicle offerings across all passenger car and truck categories with comparable capabilities as conventional gasoline vehicles is anticipated.

ZEVs produce no exhaust emissions of any criteria pollutant under any possible operational modes and conditions (BEVs and FCEVs). BEVs utilize batteries to store energy needed to power electric motors, and FCEVs use hydrogen stored on board to create electricity from a fuel cell in combination with a traction battery to power the electric motor(s). These electric vehicles have instant torque response, low noise, regenerative braking that greatly reduces brake wear and generally have a simple mechanical drivetrain, often with no transmission.

Similarly, plug-in hybrid electric vehicles use batteries to power an electric motor, but they also use another fuel, such as gasoline, to power an internal combustion engine (ICE).[1] A PHEV is defined as a vehicle that can draw propulsion power from multiple on-board sources including a combustible fuel and a traction battery, with the ability to charge the battery from an off-vehicle power source, such as the electric power grid. PHEVs can also be blended or non-blended, where blended PHEVs refer to those that require the engine to meet the full power demands of the vehicle before the battery has been depleted and non-blended PHEVs are those that can drive fully electric even during high-power demand. BEVs, FCEVs, and PHEVs collectively are referred to as electric vehicles.

By the end of 2020, the number of electric passenger vehicles reached 10 million units worldwide, an increase of 42 percent from 2019.[2] China maintained the largest electric vehicle fleet in the world with a total of 4.5 million electric vehicles, but for the first time Europe had the largest annual increase in electric vehicles to reach a total of 3.2 million by the end of 2020. The United States had about 1.8 million ZEV and PHEV registrations by the end of 2020, with about 78 percent of newly registered electric cars in 2020 being BEVs.[3] While the ongoing health and economic crisis of the COVID-19 pandemic caused conventional and new car registrations to fall in 2020, the global electric vehicle sales share

[1] U.S. Department of Energy Alternative Fuels Data Center. n.d. *How Do Plug-In Hybrid Electric Cars Work?* Accessed March 1, 2022. https://afdc.energy.gov/vehicles/how-do-plug-in-hybrid-electric-cars-work.

[2] Hongyang, Cui, Dale Hall, Jin Li, and Nic Lutsey. 2021. *Update on the global transition to electric vehicles through 2020.* International Council on Clean Transportation. Accessed March 1, 2022. https://theicct.org/sites/default/files/publications/global-update-evs-transition-oct21.pdf.

[3] International Energy Agency. 2021. *Global EV Outlook 2021: Accelerating ambitions despite the pandemic.* International Energy Agency. Accessed March 1, 2022. https://iea.blob.core.windows.net/assets/ed5f4484-f556-4110-8c5c-4ede8bcba637/GlobalEVOutlook2021.pdf.

rose 70 percent from 2019 levels as electric vehicle sales declined less than the overall market.[4]

In the United States, a large fraction of the electric vehicle sales occurs in California due to strong consumer demand, regulatory mechanisms, and ZEV market support policies in the state. New ZEV and PHEV sales in 2020 reached 145,099, which was a slight decline from 2019 sales given the impact of the global health and economic crisis, but sales rebounded to 250,279 in 2021. Table 1 shows details of new ZEVs and PHEVs sold over the last five years, indicating that the California electric vehicle market continues to grow. Roughly 1,054,100 electric vehicles were sold cumulatively by the end of 2021, with California hitting its first electric vehicle deployment goal of 1 million ZEVs and PHEVs by 2023 two years early.[5][6] This puts California on track to reach the second goal of 1.5 million ZEVs on the road sooner than the 2025 target as directed in Executive Order B-16-12.[7] These promising market signals in combination with the Advanced Clean Cars II regulations will help California reach the goal of 5 million ZEVs by 2030 as directed by Executive Order B-48-18 and reach the goal of all new passenger car and truck sales being electric by 2035 as directed by Executive Order N-79-20.[8][9]

Table 1. New BEV, FCEV, and PHEV Annual Sales and Market Share in California[10][11]

Metric	2017	2018	2019	2020	2021
PHEV New Sales	45,492	59,699	50,660	38,153	63,141
BEV and FCEV New Sales	48,095	97,444	96,687	106,946	187,138
Total New ZEV and PHEV Sales	93,587	157,143	147,347	145,099	250,279
Total New Vehicle Sales	2,183,293	2,251,593	2,153,747	1,864,164	2,016,192
PHEV Market Share	2.08%	2.65%	2.35%	2.05%	3.13%
BEV and FCEV Market Share	2.20%	4.33%	4.49%	5.74%	9.28%

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[4] International Energy Agency, *Global EV Outlook 2021*

[5] California Energy Commission. 2022. "New ZEV Sales." *California Energy Commission Zero Emission Vehicle and Infrastructure Statistics Data*. January 31. Accessed March 2, 2022. https://www.energy.ca.gov/files/zev-and-infrastructure-stats-data.

[6] SB 1275 (De León, Chapter 530, Statute of 2014) established the Charge Ahead California Initiative with the goal of placing one million zero-emission and near zero-emission vehicles in California by 2023

[7] Governor Edmund G. Brown, Jr. 2012. *Executive Order B-16-2012*. March 23. Accessed March 1, 2022. https://www.library.ca.gov/wp-content/uploads/GovernmentPublications/executive-order-proclamation/39-B-16-12.pdf.

[8] Governor Edmund G. Brown, Jr. 2018. *Executive Order B-48-18*. January 26. Accessed March 1, 2022. https://www.library.ca.gov/wp-content/uploads/GovernmentPublications/executive-order-proclamation/39-B-48-18.pdf.

[9] Governor Gavin Newsom. 2020. *Executive Order N-79-20*. September 23. Accessed March 1, 2022. https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf

[10] California Energy Commission, "New ZEV Sales"

[11] California Energy Commission. 2021. "Vehicle Population." *California Energy Commission Zero Emission Vehicle and Infrastructure Statistics Data.* April 30. Accessed March 2, 2022. https://www.energy.ca.gov/files/zev-and-infrastructure-stats-data.

Metric	2017	2018	2019	2020	2021
Total ZEV and PHEV Market Share	4.29%	6.98%	6.84%	7.78%	12.41%

The electric vehicle market share of new light-duty vehicle sales in California has continued to grow. California ZEV and PHEV market share held steady at about 7 percent of the new light-duty vehicle sales from 2018 to 2020 before accelerating sharply in 2021. The growing number of ZEV and PHEV models, continued expansion of California's charging and hydrogen fueling network, and the state's commitment to strong electric vehicle incentives has helped maintain a robust electric vehicle market. Figure 1 below shows the growth of ZEV and PHEV market share in California from 2012 to 2021, with BEVs seeing a much larger market share than other technologies from 2018 onward. The California electric vehicle market share is expected to continue to increase rapidly as more ZEV and PHEV model *offerings en*ter the market and in vehicle segments not previously offered before.

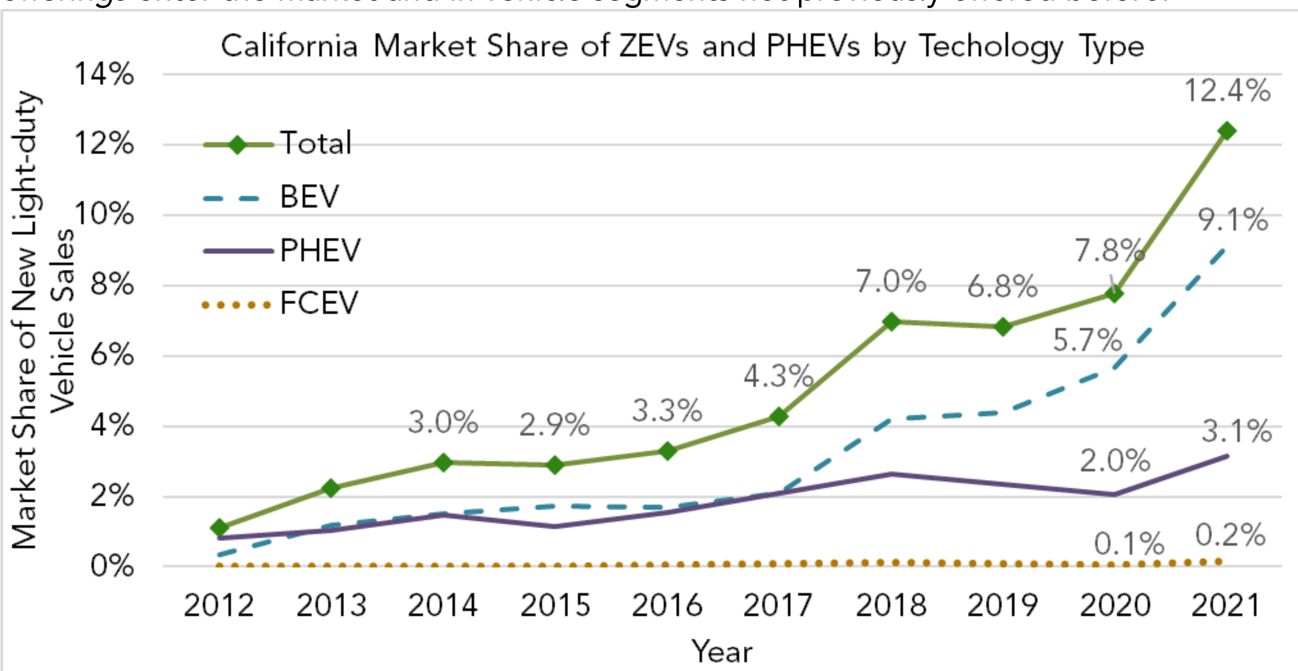

Figure 1. California New Vehicle Market Share of ZEVs and PHEVs from 2012 to 2021[12][13]

Supportive ZEV policies, such as funding for ZEV infrastructure and purchase incentives, have helped a growing electric vehicle market in California as technology costs continue to come down. Despite impressive cost reductions in batteries and ongoing technology development, BEVs, FCEVs, and PHEVs are projected to continue to have cost premiums relative to future conventional internal combustion engine vehicles (ICEVs) in the early model years of the ACC II regulations. In 2016, the Joint Agency Draft Technical Assessment Report (TAR) projected

[12] California Energy Commission, "New ZEV Sales"
[13] California Energy Commission, "Vehicle Population"

an incremental cost of $6,500 to $14,200 for PHEV40[14] and BEV200s[15] over an equivalent ICE vehicle in the 2025 model year.[16] Incremental cost analysis recently completed by CARB staff projects an incremental cost of $2,454 to $6,262 for 300-mile range BEVs for small cars to pickup trucks respectively in the 2026 model year. These changes in incremental cost projections represent updated ZEV technology innovations, including increased battery energy storage performance, lower battery costs per kWh, and improved component efficiency, collectively reducing system costs even while battery pack sizes increased. While BEV costs are anticipated to reach cost parity with ICEV costs by 2030 for most vehicle classes, PHEV and FCEV manufacturing costs are projected to continue to have a cost premium over ICEVs through 2035. Costs for non-battery components are also declining due to improvements in design and integration, demonstrated by several vehicle and component teardowns. Integration and developments in non-battery components are expected to continue, resulting in cost improvements of roughly 10 percent from the 2026 to 2035 model year.

This appendix provides an assessment of the current state of the ZEV market, the progress of BEV, PHEV, and FCEV technologies, and implications for the economic analysis of the ACC II regulations.

II. Electric Vehicle Technology: Status and Trends

ZEV and PHEV technology continues to change rapidly as the industry responds to evolving market pressures, consumer demands, and California, U.S., and other global regulatory requirements. Manufacturers are now accelerating plans to bring more ZEVs and highly capable PHEVs to the market while indicating plans to phase out new ICE vehicles. These electrified vehicles utilize various technologies that continue to improve with ongoing development. There have been several broader trends in ZEV technology taking place within the industry: battery packs with increased energy capacity, vehicles with more electric range, and expanding electric vehicle technology into various vehicle segments. These technology improvements are leading to a wider range of ZEV and PHEV models that offer customers more utility.

A. Current and Future ZEVs and PHEVs

The electric vehicle market has seen a significant increase in available models since the Nissan Leaf and Chevrolet Volt 2010 market introductions. Currently, the market has

[14] PHEV40 means a 40 mile all electric range (label) PHEV (non-blended)

[15] BEV200 means a 200 mile all electric range (label) BEV

[16] U.S. Environmental Protection Agency, U.S. National Highway Traffic Safety Administration, California Air Resources Board. 2016. *Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025.* July 2016. Accessed March 1, 2022. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100OXEO.PDF?Dockey=P100OXEO.PDF

increased from one[17] to 60 models offered through 2021.[18] This rapid market growth and expansion of product offerings over the past decade is expected to accelerate significantly in the next five years.

Consumers have different needs and expectations, especially when it comes to vehicles. Vehicle choice and model availability across market segments is a critical decision-making factor for new car shoppers, and a diverse selection of makes and models is an indicator for market growth. According to research by the International Council on Clean Transportation (ICCT), cities with more ZEV models available to consumers had higher electric vehicle registrations.[19] Table 2 lists the 2021 model year ZEVs and PHEVs available by technology type across different vehicle classes in the U.S. market.[20]

Table 2. Electric Vehicles Available by Manufacturer, Model Year 2021[21]

Make	Model	Vehicle Type	Electric Range[22]	EPA Size Class
Audi	e-tron	BEV	222	Standard Sport Utility Vehicle 4WD
Audi	e-tron Sportback	BEV	218	Standard Sport Utility Vehicle 4WD
BMW	i3 / i3s	BEV	153	Subcompact Cars
Chevrolet	Bolt EV	BEV	259	Small Station Wagons
Ford	Mustang Mach-E	BEV	211-305	Small Station Wagons
Hyundai	Ioniq Electric	BEV	170	Midsize Cars
Hyundai	Kona Electric	BEV	258	Small Sport Utility Vehicle 2WD
Jaguar	I-Pace EV400	BEV	234	Small Sport Utility Vehicle 4WD
Kandi	K27	BEV	59	Compact Cars
Kia	Niro Electric	BEV	239	Small Station Wagons
MINI	Cooper SE Hardtop 2 door	BEV	110	Subcompact Cars
Nissan	LEAF (S/SV/SL)	BEV	149-226	Midsize Cars
Polestar	2	BEV	233	Midsize Cars
Porsche	Taycan (4/4S/Turbo/Perf)	BEV	199-227	Large Cars
Tesla	Model 3	BEV	263-353	Midsize Cars

[17] One model from a manufacturer subject to the ZEV regulation in 2010.
[18] Models here are defined as a unique vehicle offering, excluding trim versions of that model. For example, the Nissan Leaf is offered in the S, SV, and SL trims, but the Leaf is only counted as one model.
[19] International Council on Clean Transportation. 2019. *The surge of electric vehicles in United States cities.* International Council on Clean Transportation. June. Accessed March 1, 2022. https://theicct.org/sites/default/files/publications/ICCT_EV_surge_US_cities_20190610.pdf
[20] If trim levels of models are accounted for, there were 108 different models and trim varieties on the market in 2021.
[21] U.S. Department of Energy and U.S. Environmental Protection Agency. 2022. *Fuel Economy Guide: Model Year 2021.* March 2. Accessed March 4, 2022. https://www.fueleconomy.gov/feg/pdfs/guides/FEG2021.pdf
[22] The electric range value represents the approximate number of miles that can be travelled in combined city and highway driving before the vehicle must be recharged (assumes 55% city and 45% highway). The EPA estimates are meant to be a general guideline for consumers when comparing vehicles; however, range will vary depending on factors like cold weather, accessory use (such as A/C), and high-speed driving, which can lower the vehicle’s range significantly.

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Tesla	Model S	BEV	334-405	Large Cars
Tesla	Model X	BEV	300-371	Standard Sport Utility Vehicle 4WD
Tesla	Model Y	BEV	244-326	Small Sport Utility Vehicle 4WD
Volkswagen	ID.4	BEV	240-260	Small Sport Utility Vehicle 2WD
Volvo	XC40 AWD BEV	BEV	208	Small Sport Utility Vehicle 4WD
BMW	i3 / i3s with Range Extender	BEVx	126	Subcompact Cars
Honda	Clarity Fuel Cell	FCEV	360	Midsize Cars
Hyundai	Nexo / Blue	FCEV	354, 380	Standard Sport Utility Vehicle FWD
Toyota	Mirai Limited / XLE	FCEV	357	Compact Cars
Audi	A7 quattro	PHEV	24	Midsize Cars
Audi	A8 L	PHEV	18	Large Cars
Audi	Q5	PHEV	19	Small Sport Utility Vehicle 4WD
BMW	330e	PHEV	23	Compact Cars
BMW	330e xDrive	PHEV	20	Compact Cars
BMW	530e	PHEV	21	Compact Cars
BMW	530e xDrive	PHEV	19	Compact Cars
BMW	745e xDrive	PHEV	17	Large Cars
BMW	X3 xDrive30e	PHEV	18	Small Sport Utility Vehicle 4WD
BMW	X5 xDrive45e	PHEV	31	Standard Sport Utility Vehicle 4WD
Bentley	Bentayga	PHEV	18	Standard Sport Utility Vehicle 4WD
Chrysler	Pacifica Hybrid	PHEV	32	Minivan - 2WD
Ferrari	SF90 Stradale Coupe	PHEV	9	Two Seaters
Ford	Escape FWD PHEV	PHEV	37	Small Sport Utility Vehicle 2WD
Honda	Clarity Plug-in Hybrid	PHEV	48	Midsize Cars
Hyundai	Ioniq Plug-in Hybrid	PHEV	29	Midsize Cars
Jeep	Wrangler 4dr 4xe	PHEV	22	Small Sport Utility Vehicle 4WD
Karma	GS-6	PHEV	54, 61	Subcompact Cars
Karma	GT	PHEV	54, 61	Subcompact Cars
Kia	Niro Plug-in Hybrid	PHEV	26	Small Station Wagons
Land Rover	Range Rover / Sport PHEV	PHEV	19	Standard Sport Utility Vehicle 4WD
Lincoln	Aviator PHEV AWD	PHEV	21	Standard Sport Utility Vehicle 4WD
Lincoln	Corsair AWD PHEV	PHEV	28	Small Sport Utility Vehicle 4WD
MINI	Cooper SE Countryman	PHEV	18	Midsize Cars
Mitsubishi	Outlander PHEV	PHEV	24	Small Sport Utility Vehicle 4WD
Polestar	1	PHEV	52	Minicompact Cars
Porsche	Cayenne	PHEV	15, 17	Standard Sport Utility Vehicle 4WD
Porsche	Panamera 4 e-Hybrid	PHEV	17, 19	Large Cars
Subaru	Crosstrek Hybrid AWD	PHEV	17	Small Sport Utility Vehicle 4WD
Toyota	Prius Prime	PHEV	25	Midsize Cars
Toyota	RAV4 Prime 4WD	PHEV	42	Small Sport Utility Vehicle 4WD
Volvo	S60 AWD PHEV	PHEV	22	Compact Cars
Volvo	S90 AWD PHEV	PHEV	21	Midsize Cars
Volvo	V60 AWD PHEV	PHEV	22	Small Station Wagons
Volvo	XC60 AWD PHEV	PHEV	19	Small Sport Utility Vehicle 4WD
Volvo	XC90 AWD PHEV	PHEV	18	Standard Sport Utility Vehicle 4WD

Currently available electric vehicle models span platforms from subcompact cars to large cars and from small sport utility vehicles (SUVs) to minivans, confirming the technology is available for a large portion of the light-duty market segment. The 60 available ZEVs and PHEVs in the 2021 model year spanned across ten EPA vehicle size classes and many came with all-wheel drive capabilities.[23] Figure 2 below shows the number of ZEV and PHEV models offered by technology type and EPA size class for existing model year 2021 vehicles. However, more choices in larger vehicle categories like large SUVs and pick-up trucks in the electric vehicle market are needed to attract more consumers and for ZEVs and PHEVs to become more competitive with the ICEV market. This is critical in the United States where crossovers, sport utility vehicles, light pickup trucks and vans (collectively defined as light-duty trucks) represented over 76 percent of new sales in 2020 and 2021.[24] Within the light-truck sector, the crossover segment accounted for 45 percent of all new light-vehicle sales.[25] New vehicle models entering the market in the upcoming model years should begin to fill this gap, with several light-duty truck products, including full-size pick-ups.

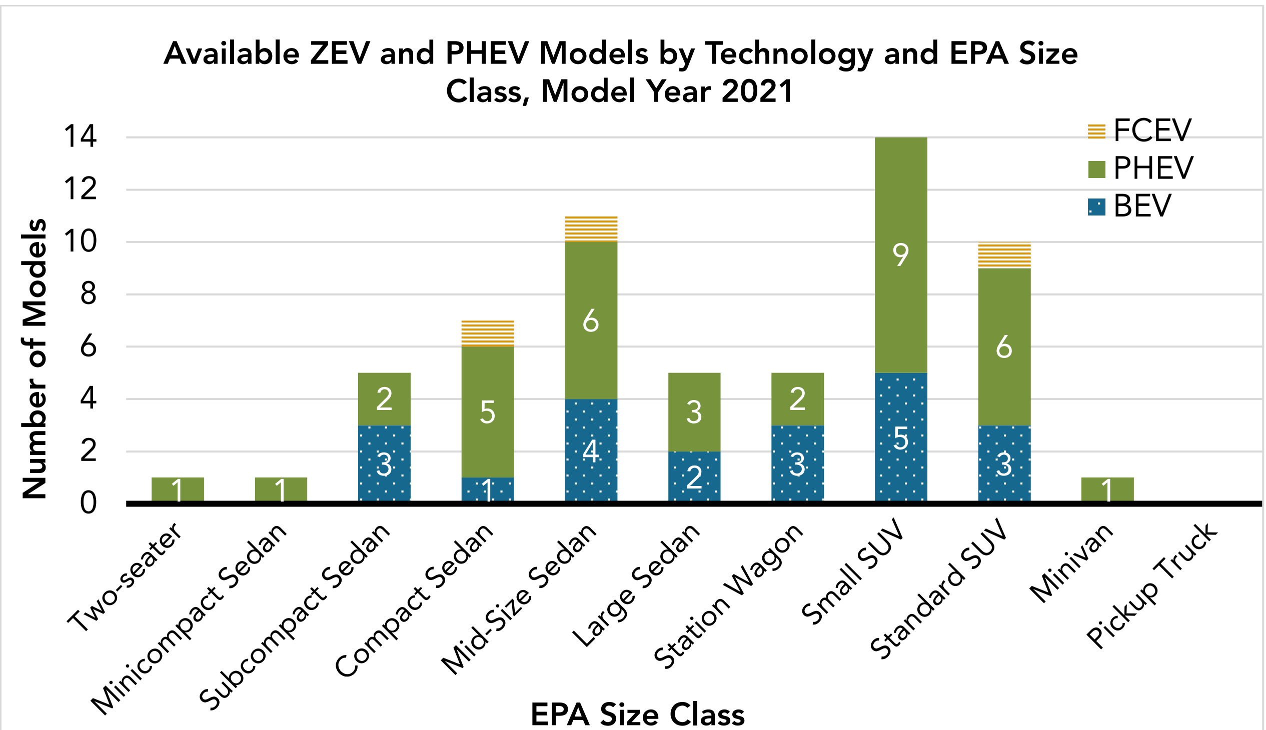

Figure 2. 2021 ZEV and PHEV Models by Class Size

While new vehicle sales in California are less dominated by light-duty trucks than in other states, in California light-duty trucks' share of the industry in 2020 and 2021 was

[23] U.S. Department of Energy and U.S. Environmental Protection Agency. n.d. *www.fueleconomy.gov: Frequently Asked Questions.* Accessed March 4, 2022. https://www.fueleconomy.gov/feg/info.shtml.
[24] California New Car Dealers Association. 2022. *California Auto Outlook: Comprehensive information on the California vehicle market.* February. Accessed March 4, 2022. https://www.cncda.org/wp-content/uploads/Cal-Covering-4Q-21.pdf
[25] Manzi, Patrick. 2021. "NADA Market Beat: December 2021." National Automobile Dealers Association. December. Accessed March 3, 2022. https://www.nada.org/WorkArea/DownloadAsset.aspx?id=21474865289.

approximately 65 percent.[26] In 2021, nonluxury SUVs made up about 34 percent of all new vehicle sales in California, with pickups and vans a distant second at 17 percent.[27] As more ZEV models are introduced in varying vehicle classes and with more diverse and higher-range BEVs, it is likely that market share will continue to increase. Manufacturers have announced many additional vehicle introductions anticipated over the next several years specifically in larger vehicle classes.

Figure 3 shows 179 available and expected ZEV and PHEV models by the 2025 model year. CARB staff compiled an extensive list of all the currently available models (Table 2) and all the future models that are expected to be released using publicly available news articles and DOE/EPA data (Table 3).[28] In developing this figure, staff assumed that each vehicle model, once introduced, would be offered for at least six model years aligned with the design cycle of vehicles.

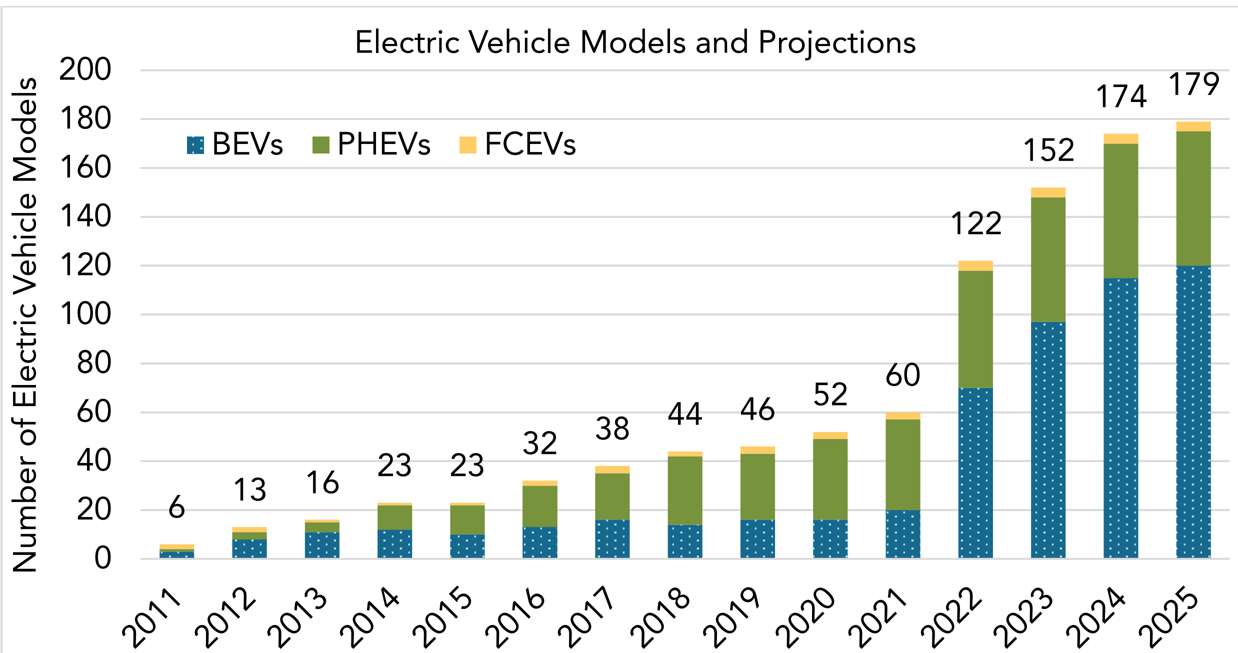

Figure 3. Aggregate ZEV and PHEV Models Projected by Model Year Through 2025

Vehicle diversity is also anticipated to grow significantly over the next few years with several pick-up trucks, SUVs, and crossovers coming to market starting in 2022 and continuing to grow from there. Figure 4 indicates that new ZEV and PHEV product offerings are expected in broader market segments than currently available through the 2021 model year as indicated prior in Figure 2.

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[26] California New Car Dealers Association, *California Auto Outlook*
[27] California New Car Dealers Association, *California Auto Outlook*
[28] M.J. Bradley & Associates. 2021. *Electric Vehicle Market Status – Update, Manufacturer Commitments to Future Electric Mobility in the U.S. and Worldwide*. Accessed March 3, 2022. https://www.mjbradley.com/sites/default/files/EDF_EV_Market_Report_April_2021_Update.pdf.

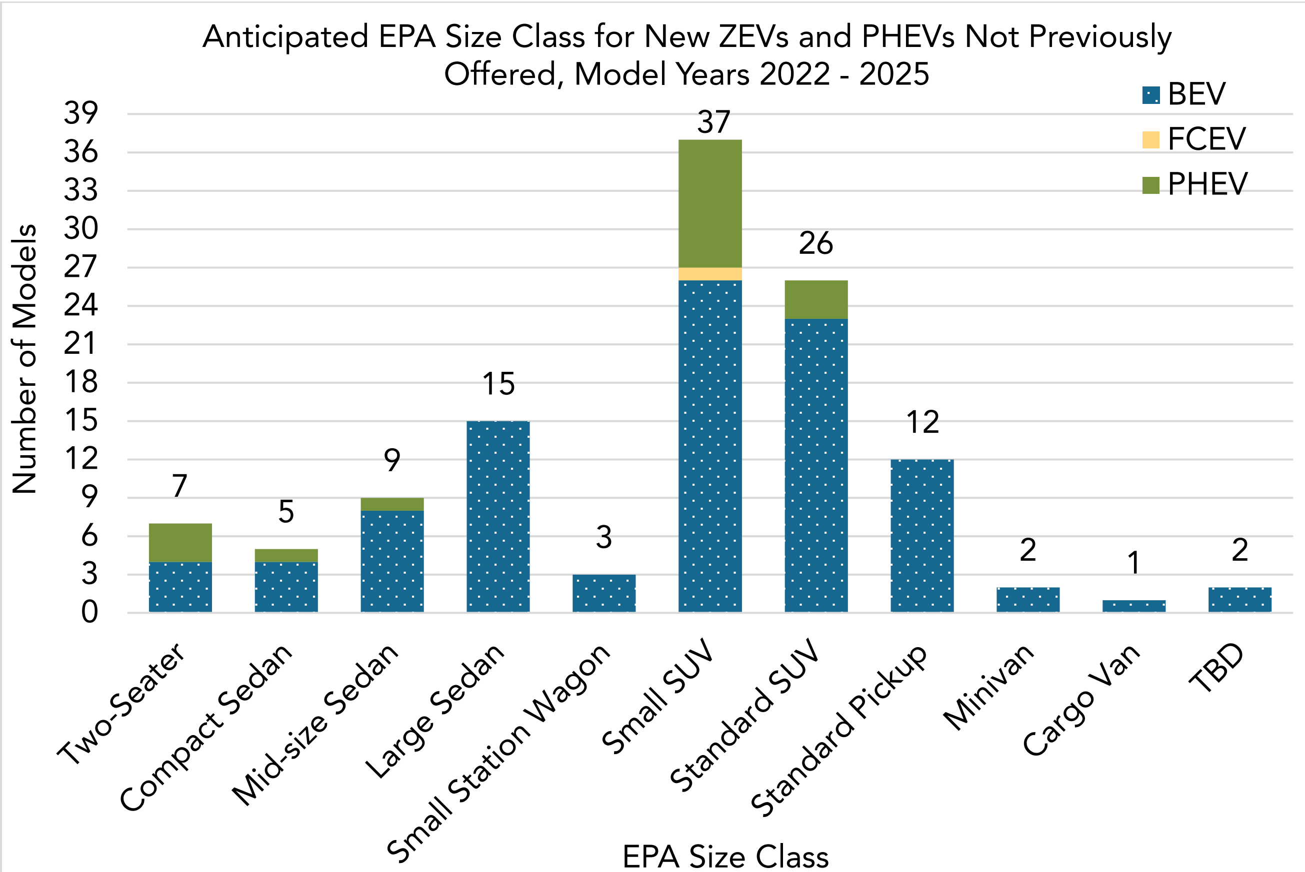

Figure 4. Anticipated ZEV and PHEVs Available by EPA Size Class for New Model Year 2022-2025 Offerings

A list of new ZEVs and PHEVs by model year is provided in Table 3, which are additional to the 60 existing electric vehicle offerings that will continue to be offered in later model years, as well. Staff utilized the EPA Size Classification for vehicle size as this is information is publicly available as a reference for all current EPA certified vehicles. In most cases the stated vehicle range is assumed to be the EPA label range unless otherwise noted. By 2026, the ZEV and PHEV market will have expanded rapidly, with more platform offerings and increased capability of vehicles to support continued ZEV sales growth.

Table 3. Anticipated New ZEVs and PHEVs Introduced in Model Years 2022 to 2025

Make	Model	Vehicle Type	Electric Range	EPA Size Class
Alfa Romeo	Tonale[i]	PHEV	50	Midsize
Aston Martin	DBX PHEV[ii]	PHEV	TBD	Standard SUV
Aston Martin	Sportscar (DBS/DB11/Vantage)[iii]	BEV	372+	Two Seaters
Audi	A6 e-tron[iv]	BEV	400 (WLTP)	Large
Audi	e-tron GT[v]	BEV	238	Standard SUV
Audi	e-tron S (20, 21, 22in)[v]	BEV	181, 208	Standard SUV

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Make	Model	Vehicle Type	Electric Range	EPA Size Class
Audi	e-tron S Sportback (20, 21, 22in wheels) [v]	BEV	185, 212	Standard SUV
Audi	Q4 e-tron & sportback quattro[v]	BEV	241	Small SUV
Audi	RS e-tron GT[v]	BEV	232	Midsize
Audi	A4 e-tron[vi]	BEV	TBD	Large
Automobili	Battista hyper GT[vii]	BEV	310 (WLTP)	Two Seaters
Bentley	Flying Spur[viii]	PHEV	25	Compact
BMW	i4 (4 Series) [v]	BEV	227-301	Large
BMW	iX xDrive50[v]	BEV	305-324	Standard SUV
BMW	iX3[ix]	BEV	286 (WLTP)	Standard SUV
BMW	X5 (Hydrogen NEXT)[x]	FCEV	311	Small SUV
BMW	i5[xi]	BEV	250	Midsize
BMW	i7[xii]	BEV	380	Large
BMW	i8 M[xiii]	PHEV	TBD	Two Seaters
Buick	Electra[xiv]	BEV	300	Standard SUV
Cadillac	Lyriq SUV[xv]	BEV	300	Standard SUV
Cadillac	Celestiq sedan[xvi]	BEV	400+	Large
Cadillac	Escalade[xvii]	BEV	400+	Standard SUV
Canoo	Lifestyle Vehicle[xviii]	BEV	230	Large
Canoo	Electric AWD Pickup Truck[xix]	BEV	200	Standard Pickup
Canoo	Electric Van[xix]	BEV	250	Standard Pickup
Chevrolet	Blazer[xx]	BEV	300	Standard SUV
Chevrolet	Equinox[xxi]	BEV	200	Small SUV
Chevrolet	Silverado[xxii]	BEV	400	Standard Pickup
Chrysler	Airflow Concept[xxiii]	BEV	350+	Large
Dodge	eMuscle[xxiv]	BEV	500	TBD
Faraday Future	FF 91[xxv]	BEV	378	Large
Fisker	Ocean Crossover[xxvi]	BEV	250, 340, 350+	Small SUV
Ford	E-Transit[xxvii]	BEV	125	Cargo Van
Ford	F-150 Lightning[xxviii]	BEV	230, 300	Standard Pickup
Ford	Explorer SUV[xxix]	BEV	TBD	Standard SUV
Genesis	Electrified G80[xxx]	BEV	265-310	Large
Genesis	Electrified GV70[xxxi]	BEV	249 (Korean)	Small SUV
Genesis	GV60[xxxii]	BEV	229, 249, 280	Small SUV
GMC	Hummer EV Edition 1[xxxiii]	BEV	329	Standard Pickup
GMC	Sierra Denali[xxxiv]	BEV	400	Standard Pickup
GMC	Sierra SUV[xxxv]	BEV	400	Standard Pickup
GMC	Hummer EV SUV[xxxvi]	BEV	300	Standard SUV
Honda	Acura ADX SUV[xxxvii]	BEV	TBD	Small SUV
Honda	Prologue SUV[xxxviii]	BEV	300	Small SUV
Hyundai	Ioniq 5 SUV[v]	BEV	220, 256, 303	Small SUV
Hyundai	Ioniq 6 Sedan[xxxix]	BEV	300	Midsize
Hyundai	Santa Fe Plug-in Hybrid[v]	PHEV	31	Small SUV
Hyundai	Tucson Plug-in Hybrid[v]	PHEV	33	Small SUV

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Make	Model	Vehicle Type	Electric Range	EPA Size Class
Hyundai	Ioniq 7 SUV[xl]	BEV	300+	Standard SUV
Infiniti	QX Inspiration SUV Concept[xli]	BEV	TBD	Small SUV
Jaguar Land	Range Rover P440e[xlii]	PHEV	48	Standard SUV
Jeep	Compass 4xe PHEV[xliii]	PHEV	29-30 (WLTP)	Small SUV
Jeep	Grand Cherokee PHEV[v]	PHEV	26	Small SUV
Jeep	Renegade 4xe PHEV[xliv]	PHEV	26 (WLTP)	Small SUV
Jeep	Wrangler Magneto[xlv]	BEV	250	Small SUV
Kandi	K32[xlvi]	BEV	60, 150	Standard Pickup
Karma	GSe-6[xlvii]	BEV	230	Midsize
Kia	EV6[v]	BEV	232, 274, 310	Midsize
Kia	Sorento Plug-in Hybrid[v]	PHEV	32	Small SUV
KIA	EV9[xlviii]	BEV	300	Standard SUV
Lamborghini	Urus PHEV[xlix]	PHEV	TBD	Standard SUV
Lamborghini	Aventador[l]	PHEV	TBD	Two Seaters
Lamborghini	Huracan[li]	PHEV	TBD	Two Seaters
Land Rover	Range Rover[lii]	BEV	300	Standard SUV
Lexus	NX 450h Plus AWD[v]	PHEV	37	Small SUV
Lexus	RZ 450e[liii]	BEV	250	Small SUV
Lincoln	Mark E[liv]	BEV	300-350	Standard SUV
Lordstown	Endurance[lv]	BEV	250	Standard Pickup
Lordstown	Van Concept[lvi]	BEV	350	Minivan
Lotus	Evija Hypercar[lvii]	BEV	250 (WLTP)	Two Seaters
Lotus	Type 132[lviii]	BEV	TBD	Standard SUV
Lotus	Unnamed Coupe-Sedan[lix]	BEV	TBD	Compact
Lotus	Unnamed Smaller SUV[lx]	BEV	TBD	Small SUV
Lucid	Air Dream (all trims) [v]	BEV	451-520	Large
Lucid	Air Grand Touring (all trims)[v]	BEV	469, 516	Large
Lucid	Air Pure[lxi]	BEV	406	Large
Maserati	Grecale PHEV SUV[lxii]	PHEV	TBD	Small SUV
Maserati	Levante GT PHEV SUV[lxiii]	PHEV	33	Small SUV
Maserati	GranCabriolet[lxiv]	BEV	TBD	Compact
Maserati	GranTurismo[lxv]	BEV	TBD	Compact
Maserati	Grecale EV[lxvi]	BEV	TBD	Standard SUV
Maserati	Levante SUV[lxvii]	BEV	TBD	Standard SUV
Maserati	MC20[lxviii]	BEV	TBD	Two Seaters
Mazda	MX-30[v]	BEV	100	Small SUV
Mazda	MX-30 PHEV[lxix]	PHEV	TBD	Small SUV
Mercedes-Benz	EQA (GLA class)[lxx]	BEV	200-250	Small SUV
Mercedes-Benz	EQB (GLB class)[lxxi]	BEV	240	Small SUV
Mercedes-Benz	EQE (C class)[lxxii]	BEV	370	Midsize
Mercedes-Benz	EQS 450 Plus[v]	BEV	350	Large
Mercedes-Benz	EQS 580 4matic[v]	BEV	340	Large
Mercedes-Benz	EQG[lxxiii]	BEV	400	Small SUV

Make	Model	Vehicle Type	Electric Range	EPA Size Class
Mercedes-Benz	Vision EQXX[lxxiv]	BEV	620	Large
Mercedes-Benz	EQC (GLC class)[lxxv]	BEV	272 (WLTP)	Small SUV
Nissan	Ariya crossover[lxxvi]	BEV	210, 300	Small SUV
Polestar	3[lxxvii]	BEV	310	Standard SUV
Polestar	4[lxxviii]	BEV	300	Small SUV
Polestar	5[lxxix]	BEV	TBD	Standard SUV
Porsche	Macan EV[lxxx]	BEV	227	Small SUV
Ram	1500 Electric[lxxxi]	BEV	500	Standard Pickup
Rivian	R1S[v]	BEV	316	Standard SUV
Rivian	R1T[v]	BEV	314	Standard Pickup
Rolls-Royce	Spectre[lxxxii]	BEV	TBD	TBD
Subaru	Solterra CUV[lxxxiii]	BEV	220	Small Station Wagon
Tesla	Cybertruck[lxxxiv]	BEV	250, 300, 500	Standard Pickup
Tesla	Roadster[lxxxv]	BEV	620	Midsize
Toyota	bZ4X[lxxxvi]	BEV	250	Small SUV
VinFast	VF 8[lxxxvii]	BEV	313 (WLTP)	Small SUV
VinFast	VF 9[lxxxvii]	BEV	342 (WLTP)	Midsize
Volkswagen	ID. 5[lxxxviii]	BEV	320	Small SUV
Volkswagen	I.D. Buzz[lxxxix]	BEV	300+	Minivan
Volkswagen	ID. Space Vizzion[xc]	BEV	300	Small Station Wagon
Volkswagen	ID. Vizzion[xci]	BEV	413	Small Station Wagon
Volkswagen	ID.6 Crozz / ID.6 X[xcii]	BEV	270, 365 (NEDC)	Standard SUV
Volkswagen	ID Life[xciii]	BEV	200	Compact
Volvo	C40 Recharge twin[v]	BEV	226	Small SUV
Volvo	Embla (XC90 Replacement)[xciv]	BEV	TBD	Small SUV
Volvo	Polestar 2 Single, Dual [v] Motor[xcv]	BEV	249, 270	Small SUV
Volvo	XC60[xcvi]	BEV	TBD	Standard SUV

Additional expansion of vehicle model offerings is also expected after 2025 based on manufacturers announced longer-term, broad reaching electrification plans that will affect model years 2025 and beyond. Five years ago, manufactures made public announcements on electrification plans that are now coming to light, such as Daimler's announcement of the creation of the Mercedes-Benz sub-brand "EQ", which has since brought dedicated all-electric vehicles to market.[29] Similarly, the proliferation of recent announcements from manufacturers signals a rapid shift toward high levels of planned electrification for the light-duty vehicle market and away from ICE technologies. Many manufacturers have announced goals to produce only electric vehicles within the next ten to fifteen years: Volvo announced

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[29] Mercedes-Benz Group AG. 2016. "Next step in electric offensive: Mercedes-Benz to build first electric car of the new EQ product brand in its Bremen plant." *Mercedes-Benz Group Media.* October 27. Accessed March 4, 2022. http://media.daimler.com/marsMediaSite/ko/en/14353750.

plans to make only fully electric cars by 2030,[30] General Motors announced their goal to shift its light-duty vehicles entirely to zero-emissions by 2035,[31] and Fiat announced a move to all electric vehicles by 2030[32] (along with Fiat's parent corporation Stellantis announcing an intensified focus on electrification across all of its brands[33]). Similarly, Mercedes-Benz announced that all their new architectures would be electric-only from 2025 onward.[34]

Other manufacturers have announced sales goals for electric vehicles over the next decade or two. Volkswagen announced that it expects half of its U.S. vehicle sales to be all-electric by 2030.[35] Honda announced a full electrification plan to take effect by 2040, with 40 percent of its North American vehicle sales expected to be zero-emission by 2030 and 100 percent by 2040.[36] Ford announced they expect 40 percent of their global light-duty vehicle sales to be all-electric by 2030.[37]

These announcements continue a pattern from the past several years of many manufacturers taking steps to introduce a wide range of zero-emission technologies while reducing their reliance on the internal-combustion engine in various markets around the globe.[38,39] Table 4 provides a list of key manufacturer announcements related to ZEV goals and investments

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[30] Volvo Car USA. 2021. "Volvo Cars to be fully electric by 2030." *Volvo Newsroom*. March 2. Accessed March 4, 2022. https://www.media.volvocars.com/us/en-us/media/pressreleases/277409/volvo-cars-to-be-fully-electric-by-2030.

[31] General Motors. 2021. "General Motors, the Largest U.S. Automaker, Plans to be Carbon Neutral by 2040." *GM Corporate Newsroom*. January 28. Accessed March 4, 2022. https://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2021/jan/0128-carbon.html

[32] Stellantis. 2021. "World Environment Day 2021 – Comparing Visions: Olivier Francois and Stefano Boeri, in Conversation to Rewrite the Future of Cities." June 4. Accessed March 4, 2022. https://www.media.stellantis.com/em-en/fiat/press/world-environment-day-2021-comparing-visions-olivier-franois-and-stefano-boeri-in-conversation-to-rewrite-the-future-of-cities.

[33] Stellantis. 2021. "Stellantis Intensifies Electrification While Targeting Sustainable Double-Digit Adjusted Operating Income Margins in the Mid-Term." July 8. Accessed March 4, 2022. https://www.stellantis.com/en/news/press-releases/2021/july/stellantis-intensifies-electrification-while-targeting-sustainable-double-digit-adjusted-operating-income-margins-in-the-mid-term#:~:text=Financial%20Performance&text=As%20a%20result%2C%20Stellantis%20is,customers%20on%20a%20global%20basis.

[34] Mercedes-Benz AG. 2021. "Mercedes-Benz prepares to go all-electric." July 22. Accessed March 4, 2022. https://mercedes-benz-media.co.uk/en-gb/releases/1431.

[35] Volkswagen. 2021. "Strategy update at Volkswagen: The transformation to electromobility was only the beginning." *Volkswagen Newsroom.* March 5. Accessed March 4, 2022. https://www.volkswagen-newsroom.com/en/stories/strategy-update-at-volkswagen-the-transformation-to-electromobility-was-only-the-beginning-6875.

[36] Honda. 2021. "Summary of Honda Global CEO Inaugural Press Conference," April 23. Accessed March 4, 2022. https://global.honda/newsroom/news/2021/c210423eng.html.

[37] Ford Motor Company. 2021. "Superior Value From EVs, Commercial Business, Connected Services is Strategic Focus of Today's 'Delivering Ford+' Capital Markets Day." *Ford Media Center*. May 26. Accessed March 4, 2022. https://media.ford.com/content/fordmedia/fna/us/en/news/2021/05/26/capital-markets-day.html.

[38] M.J. Bradley & Associates, *Electric Vehicle Market Status*

[39] Wappelhorst, Sandra. 2020. "The end of the road? An overview of combustion-engine car phase-out announcements across Europe," Briefing, International Council on Clean Transportation. Accessed March 3, 2022. https://theicct.org/wp-content/uploads/2021/06/Combustion-engine-phase-out-briefing-may11.2020.pdf.

which are supported by increasing availability of electric vehicle models that offer improved performance and handling.[40] [41] Automakers representing one-third of California's market have already announced targets for greater than 50% ZEV sales by 2030, as well as significant financial commitments to electrification and sustainability. This is being driven not only by California's push toward electrification, but jurisdictions around the world.

Table 4. Public Announcements of Manufacturer Long-Term ZEV and PHEV Targets and Production Goals

Vehicle Manufacturer	Public Announcements
BMW	10 million BEVs on the road within the next 10 years. 50% global sales to be battery electric by 2030; 2 million BEVs delivered by the end of 2025. BEVs available for 90% of market segments from compact class to ultra-luxury segment (i.e., Rolls-Royce) in 2023, with BEVs available for 100% of market segments by 2030. Mini to be all-electric in the early 2030s.[xcvii] [xcviii]
Canoo	Plans to produce 14K to 17K BEVs a year by the end of 2023; production targets of 70K to 80K units by 2025. Production of 3 pod like vehicles – a pickup truck, delivery van, and minivan [xcix] [c]
Fisker	4 new BEVs by 2025[ci]
Ford	40% to 50% of global vehicle volume to be fully electric by 2030. 40 EV models (26 BEVs); Increase production to 150,000 Lightning EVs by mid-2023. Fully "electrified" Lincoln lineup by 2030, with half of the 4 Lincoln models fully electric in 5 years [cii] [ciii] [civ] [cv] [cvi]
General Motors	30 new global electric vehicle models by 2025. Offer only electric vehicles by 2035, increase GM's North American production capacity for building electric vehicles to 1 million units by 2025. All Cadillac models to be electric by 2030; no new models with gas engines now. [cvii] [cviii][cix]
Honda	40% of North American vehicle sales to be zero-emission by 2030 and 100% by 2040. Plans to introduce 2 large-sized EV models in 2024 model year – one from Honda brand and the other from Acura. [cx]
Hyundai	Hyundai to fully electrify its lineup in major global markets by 2040, 670K annual EV sales by 2025. 23 types of EVs and hydrogen cars by 2025. [cxi] [cxii]
Jaguar Land Rover	All models fully electric by 2025, carbon neutral by 2039, 6 electric Land Rovers over the next 5 years. By 2030, about 60% of Land Rover models sold will be zero-emissions vehicles [cxiii] [cxiv]
Kia	500,000 global sales of electric vehicles by 2026, 25% EV sales/7 dedicated BEVs by 2027, 11 fully electric cars [cxv]
Lucid Motors	By 2023, the Phase II completion allows for their annual production to increase from 34K to 90K BEVs. The Lucid Air will be released with 4 Different Variations (8 trims) [cxvi]

[40] Consumer Reports. 2020. "Electric Cars 101: The Answers to All Your EV Questions," November 5. Accessed March 4, 2022. *https://www.consumerreports.org/hybrids-evs/electric-cars-101-the-answers-to-all-your-ev-questions/.*

[41] Muratori et al. 2021. "The rise of electric vehicles—2020 status and future expectations." *Progress in Energy.* Accessed March 5, 2022. https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/pdf.

Vehicle Manufacturer	Public Announcements
Mazda	By 2030, all models will be EV or hybrid. First battery EV is the MX-30, 13 electric car models available by around 2025[cxvii]
Mercedes-Benz	By 2022, BEV in all segments the company serves. All newly launched architectures will be electric-only from 2025 onwards. Investments into combustion engines and plug-in hybrid technologies will drop by 80% between 2019 and 2026. Joining forces with Factorial Energy to jointly develop next-generation solid-state battery technology. [cxviii] [cxix] [cxx]
Mitsubishi	25% carbon reduction by 2030, will focus on PHEVs [cxxi]
Nissan	8 EVs on the road by the end of 2023. Nissan has promised 15 new all-electric models and 8 more new "electrified" models by 2030. It also wants to reach 40% "electrified" vehicles in the US by 2030, and a 50% "electrified" mix globally by the same year.[cxxii] [cxxiii] [cxxiv]
Rivian Automotive	New factory in Georgia by 2024, capacity to produce 400K vehicles a year; also expand Illinois factory. 6 New BEV models by 2025 [cxxv]
Stellantis	All models fully electric by 2028, BEVs and PHEVs will account for more than 40 percent of sales in North America and 70 percent in Europe. 55 electrified cars and trucks for sale in the U.S. and Europe by 2025. $35.5 billion in EV spending through 2025 [cxxvi] [cxxvii]
Subaru	Electrify all models by 2030. Model year 2023 Solterra SUV is Subaru's first EV [cxxviii] [cxxix]
Tesla	Planning to sell 20 million vehicles a year by 2030 [cxxx]
Toyota	8 million electric vehicles by 2030, 40 percent electric by 2025 and 70 percent by 2030; plan to roll out 30 battery EV models by 2030, globally offering a full lineup of battery EVs in the passenger and commercial segments. 70 electrified models (BEVs/PHEVs) by 2025, 15 of them battery EVs [cxxxi] [cxxxii]
VinFast	All electric production by the end of 2022, targeting global electric vehicle sales of 42,000 in 2022, new Gigafactory planned in the U.S. Two SUV models in the U.S. are VF 8 and VF 9 [cxxxiii] [cxxxiv]
Volkswagen Group	50% fully electric sales in the U.S. by 2030. By 2030, Volkswagen will have launched about 70 all-electric models across the Group. Audi aims to have 30 electric models (BEVs and PHEVs) on sale by 2025; 20 of those being pure BEVs. First Bentley BEV by 2025, and a total of five new electric models between 2025 and 2030. Porsche to be carbon neutral by 2030, with 80% of the cars and SUVs it makes either electric or plug-in hybrids. [cxxxv] [cxxxvi] [cxxxvii]
Volvo	1 million total EV sales, by 2025, half of global sales are fully electric, carbon neutral by 2040. All fully electric models will be available online only[cxxxviii]

Momentum has been building around electrification worldwide. Countries around the world have already been taking action on 100% vehicle electrification commitments (or an outright ban of gasoline sales) as early as 2025. In addition to these commitments, several large markets where passenger vehicles are sold have adopted policies and regulations that will additionally call for higher and higher volumes of electrified vehicles. On September 23, 2020, Governor Newsom signed Executive Order N-79-20 establishing a goal for 100 percent of in-state sales of new passenger cars and trucks to be zero-emission by 2035.[42] Such an ambitious goal is the first in the United States and complements what others are doing around the world. The specifics of each national target vary slightly in that some explicitly require 100 percent sales of electric vehicles while others require the opposite of no new gasoline, diesel, or fossil fuel vehicles. Timelines for these targets also vary widely. Norway has the most aggressive target of 100 percent electric vehicle sales by 2025, while other countries such as Costa Rica and Germany are aiming for these levels by 2050 (see Table 5 for full listing of countries and target dates). These are a combination of announcements, alongside policy documents and binding agreements/laws. Such targets send strong policy signals to the market. France and Spain have codified these targets as formal laws that would make these targets legally binding and enforceable requirements.

Table 5. Jurisdictions with 100% ZEV Sales or Phase-Outs of Gasoline, Diesel, or Fossil Fuels[43] [44]

Target Year	Country/Jurisdiction (target type)
2025	• Norway (EV only)
2030	• Austria (no gasoline/diesel vehicles) • Denmark (no gasoline/diesel vehicles; PHEVs until 2035) • Iceland (no gasoline/diesel vehicles) • Ireland (no fossil fuel vehicles) • Israel (no gasoline/diesel vehicles) • Netherlands (EV only) • Slovenia (no gasoline/diesel vehicles; includes PHEVs) • Sweden (no gasoline/diesel vehicles) • United Kingdom (no gasoline/diesel vehicles)
2035	• California (no ICE vehicles) • Canada (no ICE vehicles) • Cape Verde (no ICE vehicles) • New York (no ICE vehicles) • Japan (no ICE vehicles, mid-2030s; includes HEVs) • Thailand (ZEV only)

[42] Governor Gavin Newsom, *Executive Order N-79-20*

[43] International Council for Clean Transportation. 2021. Global passenger car market share of countries planning to phase out new sales of internal combustion engine vehicles. October. Accessed March 1, 2022. *https://theicct.org/sites/default/files/publications/pvs-global-phase-out-FS-oct21.pdf.*

[44] IEA. 2021. *Global EV Policy Explorer: Electric vehicle deployment policies and measures.* International Energy Agency, Paris. Accessed March 1, 2022. https://www.iea.org/articles/global-ev-policy-explorer.

Target Year	Country/Jurisdiction (target type)
2040	• Egypt (no ICE vehicles) • France (no fossil fuel vehicles) • Singapore (no ICE vehicles; includes PHEVs) • Sri Lanka (EV/HEV only) • Spain (EV only) • Taiwan (no gasoline/diesel vehicles)
2050	• Costa Rica (EV only) • Germany (EV only) • Portugal (no ICE vehicles)

B. Increase in All Electric Range

Industry is expanding its BEV and PHEV product offerings with more range than previously anticipated. In the 2012 ACC rulemaking, CARB staff assumed that all BEVs produced in compliance (from 2018 through 2025 model year) would have a 100-mile test cycle range[45] (approximately 70 mile 'label range'), all PHEVs would have 22-40 miles of test cycle range (~14-30 mile label range), and all FCEVs would have at least 350 miles of test cycle range (maxing out the number of credits that could be earned within the program).[46] Since then, manufacturers have announced 300-mile (or more) label range BEVs and multiple PHEVs at various ranges. Vehicle all-electric range has been steadily increasing since 2012 due to decreased batteries costs, battery pack capacity increases, and efficiency improvements made to drivetrains and associated components.

The jump in BEV range since the 2012 rulemaking is large. The median driving range of 2021 model year BEVs was 239 miles compared to a median range of 68 miles in 2011. Additionally, the maximum range for any BEV offered in the 2021 model year was 405 miles, and there are already BEV models offered for the 2022 model year achieving a maximum range of 520 miles. While the median range for gasoline vehicles was 403 miles, as more long range BEVs become available the discrepancy in range between gasoline powered vehicles and BEVs is likely to continue to narrow.[47] Figure 5 below shows the trend in median and maximum BEV EPA label ranges from model year 2011 to 2022. The maximum BEV range in model year 2021 is attributed to the Tesla Model S Long Range (405 miles) while the max BEV range in model year 2022 is attributed to the Lucid Air Dream (520 miles).

[45] Test cycle range means all electric range on the urban dynamometer drive schedule (UDDS).

[46] California Air Resources Board. 2011. Initial Statement of Reasons: 2012 Proposed Amendments to The California Zero-Emission Vehicle Program Regulations. December 7. Accessed February 11, 2021. http://www.arb.ca.gov/regact/2012/zev2012/zevisor.pdf

[47] U.S. DOE. U.S Department of Energy Vehicle Technologies Office. 2022. "FOTW #1221, Model Year 2021 All-Electric Vehicles Had a Median Driving Range about 60% That of Gasoline Powered Vehicles" January 17. Accessed February 24, 2022. https://www.energy.gov/eere/vehicles/articles/fotw-1221-january-17-2022-model-year-2021-all-electric-vehicles-had-median.

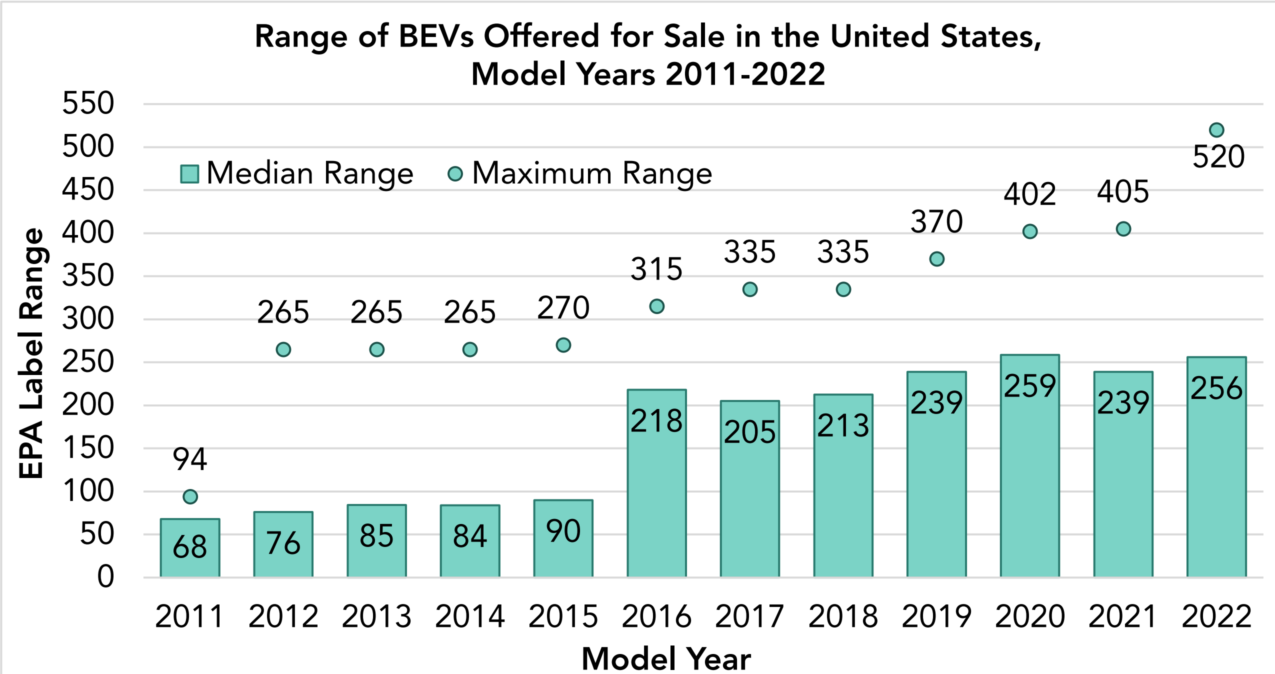

Figure 5. Battery Electric Vehicle Maximum and Median Ranges from Model Year 2011 to 2021

PHEVs with increased ranges are also anticipated due in part to consumer demand for a more all-electric driving experience. Second generation PHEVs that are now in the market offer more range than earlier generation vehicles. The maximum PHEV all-electric range in model year 2021 and 2022 is attributed to the Karma GS-6 (61 all-electric miles). While the maximum PHEV all-electric range increased in a stepwise pattern from 35 miles in 2011 to 61 miles in 2022, the median range for PHEVs has decreased from 35 miles to 23 miles in the last 11 years due to an increase in PHEV model availability. Figure 6 below shows the trend in median and maximum PHEV EPA label ranges from model year 2011 to 2022.

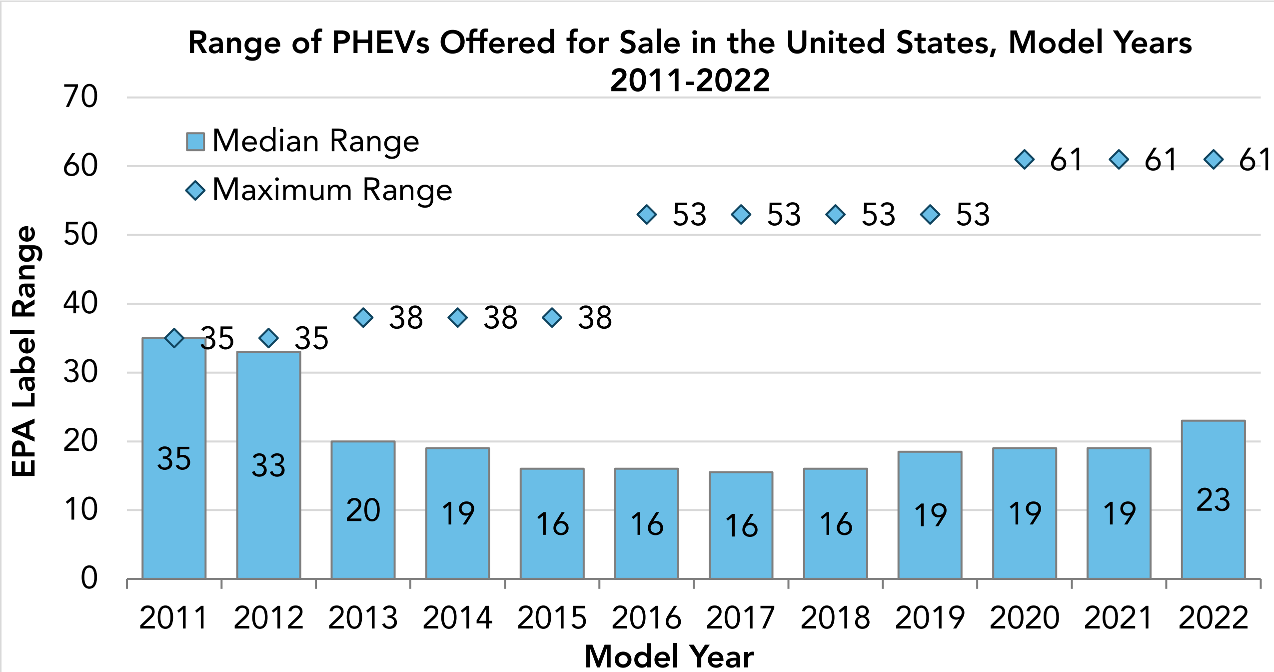

Figure 6. Plug-in Hybrid Electric Vehicle Maximum and Median Ranges from Model Year 2011 to 2022 [48]

C. Battery Electric Vehicle Improvements

BEV technology has progressed quickly since the market introduction of the Nissan Leaf in 2010. The Leaf itself has increased in range by 310 percent since its first model year.[49] Range increases have come from several technology advancements, including manufacturers moving to dedicated BEV platforms that have further improved total vehicle efficiency, mass, and available space for larger battery packs. Details of these trends are described below.

1. Increase in Battery Pack Energy Capacity

Battery pack capacities continue to increase in BEVs, supporting longer range and faster recharge times, replacing more miles of range per hour. Battery packs as large is 200 kWh have now entered in the market in larger vehicles like the GMC Hummer EV truck with a 329-mile range.[50] Other models like the Tesla Model 3 Long Range have increased battery capacity on an existing product in the market as battery energy density (Wh/liter) improved,

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[48] The BMW i3 Range Extender and BMW i3S Range Extender models were excluded in this analysis since they are not true PHEVs.

[49] U.S. Department of Energy and the U.S. Environmental Protection Agency. n.d. Fueleconomy.gov - 2011 and 2022 Nissan Leaf. Accessed February 25, 2022. https://www.fueleconomy.gov/feg/Find.do?action=sbs&id=30979&id=44447.

[50] Edelstein, Stephen. 2021. Motor Authority - 2022 GMC Hummer EV Edition 1 to have 329 miles of range, too heavy for official EPA rating. November 24. Accessed February 25, 2022. https://www.motorauthority.com/news/1134272_2022-gmc-hummer-ev-edition-1-to-have-329-miles-of-range-too-heavy-for-official-epa-rating.

enabling the battery pack to expand from 75kWh to 82kWh partway through the 2021 model year. Nissan has introduced a 62kWh battery option for the 2021 model year Leaf and Chevrolet has increased its Bolt battery packs from 60kWh to 64kWh even though the vehicle platform did not change.[51]

2. Dedicated BEV platforms

Earlier in the development of plug-in electric vehicles (PEVs, representing both BEVs and PHEVs), manufacturers used both shared and dedicated platforms for their PEV offerings; however, most manufacturers have shifted to dedicated platforms as they electrify their fleets. Use of a global shared platform allows commonality across models and international markets for increased volumes and reduced costs, while a dedicated platform allows for a higher level of optimization specifically for the PEV technology.

Dedicated BEV platforms eliminate provisions for ICE powertrain, exhaust emissions, evaporative emissions, and fuel systems that would otherwise need to be accommodated on platforms that are shared between BEV, PHEV, hybrid electric vehicle (HEV), and conventional ICEV models. This dedicated BEV platform approach typically allows integration of the battery pack entirely within the vehicle floor structure, reduces vehicle weight, reduces manufacturing costs, increases available passenger and cargo volume, and in some cases, has the battery pack integrated as part of the vehicle's crash mitigation structure.

Manufacturers have recently introduced a growing number of dedicated battery electric vehicle platforms, such as the GM Ultium platform, the VW MEB platform, and the Hyundai E-GMP platform which underpin products like the GMC Hummer EV, VW iD.4, and Hyundai Ioniq 5, respectively.[52] The VW Group is continuing to expand its BEV specific platforms under the name Project Artemis for Audi, Project Trinity for VW, and the jointly developed Premium Platform Electric (PPE) platform between Audi and Porsche.[53] [54] [55] Nissan has also

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[51] Nissan USA. n.d. *2022 Nissan LEAF Range, Charging & Battery.* Accessed January 25, 2022. https://www.nissanusa.com/vehicles/electric-cars/leaf/features/range-charging-battery.html.
[52] Oreizi, Darya. 2021. Charged Future - Overview of Electric Vehicle Platforms in 2021. February 9. Accessed February 25, 2022. https://www.chargedfuture.com/electric-vehicle-platforms-in-2021/.
[53] Volkswagen AG. 2020. Markus Duesmann launches “Artemis” project. May 29. Accessed February 25, 2022. https://www.volkswagenag.com/en/news/2020/05/Artemis.html#.
[54] Audi AG. 2021. "UBS Investor Meeting." Audi.com. January 7. Accessed February 25, 2022. https://www.audi.com/content/dam/gbp2/company/investor-relations/events-and-presentations/investor-presentations/2021/2021-07-07-UBS-PPE-deep-dive.pdf.
[55] Volkswagen AG. 2021. “Project Trinity: With high range, extremely short charging times and revolutionary production, the sedan will launch in 2026.” March 5. Accessed March 4, 2022. https://www.volkswagen-newsroom.com/en/press-releases/project-trinity-with-high-range-extremely-short-charging-times-and-revolutionary-production-the-sedan-will-launch-in-2026-6879.

debuted a new all-electric platform that will be introduced with its Ariya.[56] Daimler has introduced its new Electric Vehicle Architecture (EVA) that underpins the new EQS sedan.[57]

BEV specific platforms allow for further integration of battery packs into dedicated platforms such that battery modules can be eliminated and battery cells themselves can become an integrated structural member of the vehicle chassis. Those developments enable even greater vehicle efficiencies by reducing structural material in the chassis and battery pack and by increasing battery cell packing efficiency without the need for battery module-specific materials. Tesla, during their 2020 Annual Shareholder Meeting and Battery Day, presented a breakdown of what they think their advanced batteries can contribute to vehicle efficiency, battery cost on a dollar per kilowatt-hour (kWh) basis, and the investment required on a $/GWh basis to produce those new batteries.[58] The structural battery shown was projected by Tesla to increase vehicle range by 14 percent which would equate to an additional 46 miles on a 2022 Tesla Model Y Long Range on 19" wheels.[59] Efficiency increases from a structural battery pack are only fully realized on a BEV-specific platform and demonstrates that there are further efficiency improvements to be had over existing vehicles.

D. Plug-in Hybrid Electric Vehicle Improvements

PHEV technology continues to evolve as manufacturers introduce different architectures and all electric capabilities. Toyota increased the equivalent all-electric range of the Prius plug-in hybrid that was introduced for the 2012 model year (MY) by 127 percent in five years with the introduction of the 2017 MY Prius Prime that is also capable of completing the US06 drive cycle under electric power alone. Four model years later, Toyota introduced the larger 2020 MY RAV4 Prime with a 68 percent equivalent all-electric range (EAER) improvement over the Prius Prime and 281 percent improvement over the original Prius Plug-in Hybrid.[60] The RAV4 Prime also includes all-wheel drive (AWD) and even more all-electric power than the Prius Prime.

Ford has also improved their PHEVs with their second-generation products. The C-MAX and Fusion Energi plug-in hybrids both debuted for the 2013 MY with 20 miles of EAER. The larger Ford Escape PHEV debuted for the 2020 MY with 37 of EAER, an increase of 85

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[56] Nissan Motor Corporation. 2021. Nissan Ariya world debut: an all-electric crossover for a new era. Accessed February 25, 2022. https://usa.nissannews.com/en-US/releases/2021-nissan-ariya-press-kit#.

[57] Randall, Chris. 2021. Daimler to exclusively introduce EV platforms from 2025. *electrive.com*. July 22. Accessed February 25, 2022. https://www.electrive.com/2021/07/22/daimler-to-exclusively-introduce-ev-platforms-from-2025/.

[58] Tesla. 2020. Tesla Battery Day. Fremont, CA, September 22. Accessed March 3, 2022. https://tesla-share.thron.com/content/?id=96ea71cf-8fda-4648-a62c-753af436c3b6&pkey=S1dbei4

[59] Motley Fool Transcribing. 2022. Tesla (TSLA) Q4 2021 Earnings Call Transcript. January 27. Accessed March 3, 2022. https://www.fool.com/earnings/call-transcripts/2022/01/27/tesla-tsla-q4-2021-earnings-call-transcript/.

[60] U.S. Department of Energy and the U.S. Environmental Protection Agency. n.d. Fueleconomy.gov - 2012 Toyota Prius Plug-in Hybrid, 2017 Toyota Prius Prime, 2021 Toyota RAV4 Prime 4WD. Accessed February 25, 2022. https://www.fueleconomy.gov/feg/Find.do?action=sbs&id=32484&id=38531&id=42793.

percent.[61] The much larger Lincoln Aviator PHEV also debuted for the 2020 MY with three rows of seating and 21 miles of EAER. Other manufacturers have also increased range in their PHEV offerings, like Volvo with their T8 variants (XC60, XC90, V60, S60, and S90 vehicles), Karma with its Revero GT, BMW with its 'e' variants of the X5, 3 series, and 7 series, Hyundai with its Ioniq, Santa Fe, and Tucson, and Kia with their Sorento and Niro. Jaguar Land Rover also recently announced the Range Rover P440e with 48 miles of EAER for the 2023 MY.[62]

Those improvements stem from some of the same areas that BEVs have benefited from. Improved electric motors and power electronics are being utilized to further enhance all-electric operation efficiency to extend range. Heat pumps have also been integrated into PHEV designs like with the Toyota Prius Prime and RAV4 Prime to increase all-electric efficiency in inclement weather.[63] [64] PHEVs have also gained from many of the same battery improvements that BEVs have. As PHEV batteries increase in energy capacity, power to energy ratio becomes less of a factor, and PHEVs can use more energy dense cells which further increase capacity for a given volume which will assist in packaging those packs onto future vehicle designs.

E. Fuel Cell Electric Vehicle Improvements

FCEVs are full electric drive vehicles where the propulsion energy is supplied by hydrogen and a fuel cell stack that transforms the chemical energy stored in hydrogen into electricity as needed for motive power. The inputs of the electrochemical process for the fuel cell stack are oxygen and hydrogen, with the byproducts being electricity, water, and heat. The major components of the fuel cell system include the fuel cell stack, the hydrogen storage tank, balance of plant (valves, safety release, vent, fill tubes, etc.), and a battery pack for dynamic load balancing/response, moving the motor directly, capturing braking regeneration, and energy storage. Additionally, the system includes coolant subsystems, an air handling subsystem with compressor-expander module (CEM) precooling, and humidification.

The fuel cell stack is much like a battery in that it consists of an anode, a cathode, and dividing electrolyte membrane (thus the name of the type used for light-duty applications: proton exchange membrane fuel cell).[65] Additional stack components include the gas

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[61] U.S. Department of Energy and the U.S. Environmental Protection Agency. n.d. FuelEconomy.gov - 2013 Ford C-MAX Energi Plug-in Hybrid, 2013 Ford Fusion Energi Plug-in Hybrid, 2020 Ford Escape FWD PHEV. Accessed February 25, 2022. https://www.fueleconomy.gov/feg/Find.do?action=sbs&id=33336&id=33398&id=42743.
[62] Land Rover. 2022. New Range Rover: Orders Open for Flagship SV Model and Extended Range Plug-In Hybrid With 48 Miles of EV Range. January 27. Accessed February 25, 2022. https://media.landrover.com/en-us/news/2022/01/new-range-rover-orders-open-flagship-sv-model-and-extended-range-plug-hybrid-48-miles.
[63] Szymkowski, Sean. 2017. How does the heat pump work in a Toyota Prius Prime plug-in hybrid? *Green Car Reports*. May 24. Accessed February 25, 2022. https://www.greencarreports.com/news/1110627_how-does-the-heat-pump-work-in-a-toyota-prius-prime-plug-in-hybrid.
[64] Halvorson, Bengt. 2020. 2021 Toyota RAV4 Prime first drive review: The way a plug-in hybrid should be. *Green Car Reports*. July 1. Accessed February 25, 2022. https://www.greencarreports.com/news/1128706_2021-toyota-rav4-prime-first-drive-review-the-way-a-plug-in-hybrid-should-be.
[65] EPA, NHTSA, and CARB, *Draft Technical Assessment Report.*

diffusion layer (GDL) that helps transport hydrogen and oxygen from flow channels to the anode and cathode surfaces, as well as bipolar plates that divide each individual cell, integrate the channels through reactant and product gases flow, and conduct the electricity generated by the fuel cell stack to the vehicle's battery and motor.

An on-board hydrogen storage system for LDVs consists of a 700 bar (70MPa or 10,000psi) hydrogen pressure vessel and the balance of plant (BOP). The tank is typically wound carbon fiber construction with a polymer liner. The BOP consists of devices such as the fill tube and port, temperature sensor, pressure gauge, pressure relief device, rupture disc, solenoid control valve, primary pressure regulator, manual ball valve, a check valve, and related data communications hardware.

At the time of the ACC rulemaking in 2012, there were no light-duty mass-produced fuel cell vehicles available on the market, but that quickly changed with introduction of the Hyundai Tucson Fuel Cell in the 2015 model year. It was subsequently followed by the releases of the Toyota Mirai and Honda Clarity Fuel Cell.

Fuel cell systems utilized in FCEVs have significantly improved in recent years. The DOE reports that fuel cell stack costs have fallen 70 percent since 2008 (at high production volumes).[66] Hyundai Motor Group reports a similar cost reduction of 98 percent between prototype systems developed in 2003 and their next-generation fuel cell systems set for commercial introduction in the near future. [67]

Durability of Hyundai fuel cells are also reported to have increased from 3,000 hours/100,000 km (62,000 miles) in their first-generation system to a target 500,000 km (310,000 miles) in their next-generation fuel cell system for commercial applications. Durability across the FCEV fleet has also improved over the past 15 years. The National Renewable Energy Lab (NREL) assessed data from FCEVs to measure progress and compared it to the durability targets set by the DOE.[68] NREL revealed that 22 percent of the vehicles had over 2,000 operation hours and a maximum operation time of 5,648 hours. It was also shown that from 2006 through 2016 the average fleet durability went from 1,000 hours to 2,000 hours and the maximum fleet average durability saw an increase from 2,000 hours to 4,000 hours. Using this data, NREL projected 4,130 hours as a maximum fleet average durability with a 10 percent voltage degradation. The increase in durability hours is an indicator that technology advancements are enabling higher durability times in FCEVs; however, as indicated by NREL, meeting the targets set by DOE may take a few years. For fuel cell power systems, the DOE targeted durability for 5,000 hours, which is approximately 150,000 driving miles, with 10 percent

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[66] Satyapal, Sunita. 2021. "2021 AMR Plenary Session" presentation, 2021 US Department of Energy Hydrogen Technology Office Annual Merit Review, Online, June 7.
[67] Hyundai Motor Group. 2021. "Hyundai Motor Group's next-generation fuel cell system, a key technology for popularizing hydrogen energy." September 7. Accessed February 17, 2022. https://tech.hyundaimotorgroup.com/article/hyundai-motor-groups-next-generation-fuel-cell-system-a-keytechnology-for-popularizing-hydrogen-energy/.
[68] Kurtz, Jennifer, Sam Sprik, Genevieve Saur, and Shaun Onorato. 2019. "Fuel Cell Electric Vehicle Durability and Fuel Cell Performance". Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-73011. https://www.nrel.gov/docs/fy19osti/73011.pdf.

degradation by 2020.[69] Ultimately, the DOE aims for 8,000 hours with 150,000 driving miles and 10 percent degradation.[70]

The fuel cell systems have also increased total power over time while becoming more compact due to increasing system power density. Toyota has reported similar gains between its first and second generation Mirai. The second-generation model, released in model year 2021, is 20 percent smaller, 50 percent lighter, and 12 percent more powerful than the fuel cell in the first generation Mirai[71]. The second-generation Mirai list price was also approximately $9,000 less than its predecessor.

III. Battery Technology for ZEVs and PHEVs: Status and Trends

Lithium-ion batteries are used in virtually every ZEV and PHEV application. Lithium-ion technology provides the best balance of energy density and cost of any rechargeable battery technology available today, allowing manufacturers to pack more energy into a battery pack at a lower cost.

A. Lithium-ion Battery Overview

Lithium-ion batteries consist of the following main components: a cathode, an anode, current collectors, a separator, electrolyte, and a case of some kind to contain those components. Lithium-ion encompasses several different technologies and variations that use lithium ions as the transport mechanism for electrons. Ions shuttle between the cathode and anode during charging and discharging. Upon discharge, the oxidation of the anode occurs (loss of electrons), and the cathode is reduced (gains electrons). The reverse of those phenomena takes place during charging.[72] Battery cells typically account for most of the total battery weight and contain a number of minerals in the active cathode material (e.g., lithium, nickel, cobalt, and manganese), anode (e.g., graphite), and current collector (e.g., copper).[73] The remaining modules and pack components consist mostly of aluminum, steel, coolants, and electronic parts.

It is important to highlight the individual components of lithium-ion batteries because increases in energy or power density often are not from equal improvements in each

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[69] Kurtz, Jennifer, Sam Sprik, Genevieve Saur, and Shaun Onorato. 2019. "On-Road Fuel Cell Electric Vehicles Evaluation: Overview". Golden, CO: National Renewable Energy Laboratory. NREL/TP-5400-73009. https://www.nrel.gov/docs/fy19osti/73009.pdf.

[70] U.S. Department of Energy. 2017. "Hydrogen and Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan." Section 3.4: Fuel Cells. May. Accessed March 4, 2022. https://www.energy.gov/sites/prod/files/2016/06/f32/fcto_myrdd_fuel_cells_0.pdf.

[71] Toyota. 2020. "Toyota Introduces Second-Generation Mirai Fuel Cell Electric Vehicle as Design and Technology Flagship Sedan." *Toyota Pressroom*. December 16. Accessed February 17, 2022. https://pressroom.toyota.com/toyota-introduces-second-generation-mirai-fuel-cell-electric-vehicle-as-design-and-technology-flagship-sedan/.

[72] Battery University. 2022. "BU-204: How do Lithium Batteries Work?" February 22. Accessed March 4, 2022. *http://batteryuniversity.com/learn/article/lithium_based_batteries*.

[73] IEA. 2021. *The Role of Critical Minerals in Clean Energy Transitions*, International Energy Agency, Paris. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

component. Improvements from technology advancements most often occur within an individual component and result in corresponding changes made to the other components to appropriately handle that change. Batteries need advancements in the capacity of the cathode, capacity of the anode, and specific mass of all the other components for energy density and specific energy to increase at a rate similar to increases in energy capacity of the individual components. If one component sees several large increases and the other two portions do not, those large increases become less and less effective at increasing the total cell energy density or the specific energy of the battery cell. Increases in cell energy density and specific energy result in reductions to the mass and volume of a battery pack for a given range which would improve vehicle efficiency. Or, those density or specific energy improvements could be used to increase battery energy capacity of a battery pack relative to one with older cells without growth in volume or mass.

Lithium-ion batteries used in electric vehicles are composed of battery cells manufactured in various formats and contained in battery modules within a battery pack. Lithium-ion batteries for electric vehicles are packaged in cylindrical, prismatic, and pouch formats. Typically, cylindrical cells come in the '18650' format, which is an industry adopted cell standard that has the nominal dimensions of 18 millimeters (mm) in diameter and 65.0mm in length (for reference, a conventional AA size alkaline battery is typically 14mm in diameter by 50mm in length). Consumer electronics, particularly laptops and battery-operated power tools, have made the '18650' battery cell the most widely produced lithium-ion battery format. The demand has driven development, optimization, and volume cost reductions for those cells, which helped the '18650' cells in Tesla's Model S and Model X vehicles achieve some of the highest energy density and specific energy measurements on the market at the time of their introduction.

Tesla has iterated on the cylindrical format starting with the Tesla Model 3 by codeveloping a larger '2170' cell that is 21mm in diameter and 70mm long with Panasonic. That cell is also used in the more recently introduced in the Model Y. Rivian announced that their R1T and R1S truck and SUV products also utilize the 2170 cell format and Lucid Motors is another manufacturer that is using 2170 cylindrical cells in its new Air large sedan.[74] Other battery manufacturers like Samsung and LG Chem Power have also announced 2170 cells.[75] [76]

During its Battery Day in 2020, Tesla announced that it was working on an even bigger cell, the '4680', which is 46mm in diameter and 80mm long.[77] Tesla claims that the format has the best blend of energy density and cost. Tesla is also working on several other enabling

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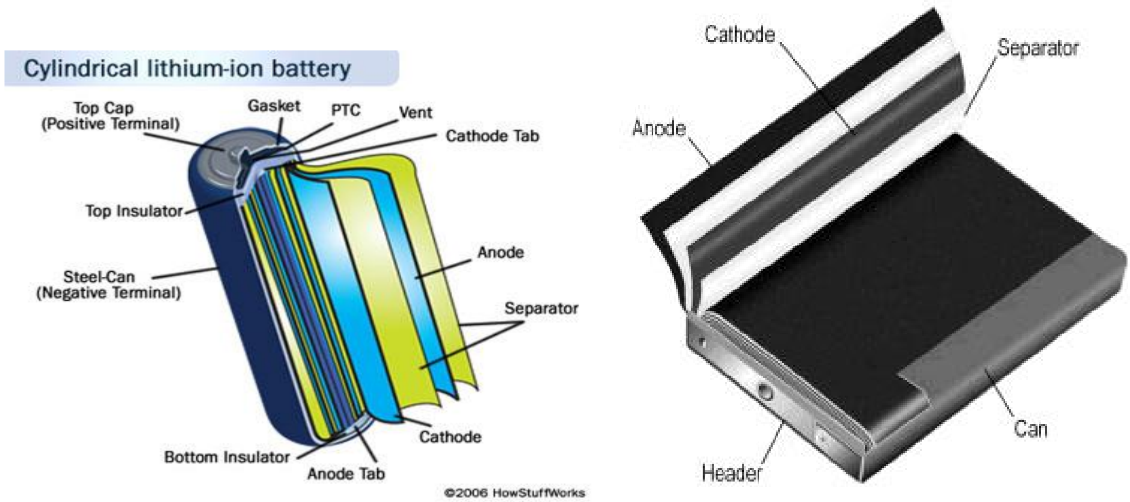
[74] Halvorson, Bengt. 2021. Are cylindrical cells the reason Lucid, Tesla, and Rivian lead in range? October 15. Accessed February 28, 2022. https://www.greencarreports.com/news/1133877_cylindrical-cells-advantages-tesla-lucid-rivian-range.
[75] Abuelsamid, Sam. 2021. LG Chem Commits $4.5 Billion to Expand EV Battery Production In U.S. *Forbes.* March 11. Accessed February 28, 2022. https://www.forbes.com/sites/samabuelsamid/2021/03/11/lg-chem-commits-45b-to-expand-ev-battery-production-capacity-in-us-by-70-gwh/?sh=7974735ca026.
[76] Samsung SDI. 2017. Samsung SDI Presents an Innovative Next Generation Battery with Fast Charging Capability and High Energy Density that enables Electric Vehicles (EV) to Drive 600km. *SDI News.* January 9. Accessed February 28, 2022. https://www.samsungsdi.com/sdi-news/1502.html?pageIndex=3&idx=1502&searchCondition=0&searchKeyword=.
[77] Tesla, *Tesla Battery Day*.

technologies for the larger cells like tab-less electrodes for lower resistance, so the cell generates less internal heat, which is important on a larger diameter cylindrical cell because the larger size makes the removal of internal heat more difficult.

Figure 7. Cylindrical and Prismatic lithium-ion battery[78] [79]



Prismatic battery cells have been designated as such due to their rectangular prismatic shape, as seen in Figure 7. Prismatic cells have been used in cell phones and some low-profile laptops, but also have seen implementations in HEVs, PHEVs, and BEVs. The prismatic container is designed in such a way that it manages the natural swelling of the components of the cell during charging and discharging.[80] Pressure build-up due to gassing of the components that may occur during cycling of the cell is usually managed through a vent of some kind. While prismatic cells are generally considered to be the safest cell containment design, they give up both specific energy capacity and energy density to cylindrical and pouch cells.

Pouch cells can be described just like their name indicates. The contents of the cell are sealed within a foil pouch. The pouch is designed to handle the swelling of the components and outgassing, but its external dimensions will change in doing so. This creates additional challenges for packaging considerations when designing battery modules and packs. LG Chem designed and manufactured pouch cells that are more exposed within the pack to allow for higher packing density and to better accommodate the liquid cooling design General Motors implemented in the Volt's battery pack. Since then, General Motors has continued to codevelop cells with LG Chem and announced a more holistic approach to

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[78] Marshall, Brain. 2021. "How Lithium-ion Batteries Work" HowStuffWorks.com. February 11. Accessed March 4, 2022. *http://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery.htm*.
[79] Battery University. 2019. BU-301a: Types of Battery Cells. Compare the pros and cons of the cylindrical cell, button cell, prismatic cell and pouch. April 24. Accessed March 3, 2022. https://batteryuniversity.com/article/bu-301a-types-of-battery-cells
[80] Landini, Stefano. 2019. A Review of Phase Change Materials for the Thermal Management and Isothermalisation of Lithium-Ion Cells. The Journal of Energy Storage. 25. 1000887. 10.1016/j.est.2019.100887.

platform and battery cell design with its Ultium platform.[81] A common cell format of 23 inches long by 4 inches tall by 0.4 inches thick will be used in all of GM's Ultium-based EV products. The packs can range from 50kWh to 200kWh and the common cell will allow for higher cell volume throughput at manufacturing centers. Many vehicle manufacturers and battery manufacturers are continuing to develop the pouch style cell.

Current lithium-ion technologies are mostly agnostic to physical cell design. However, it is yet to be seen if advanced lithium-ion batteries like those with lithium or silicon-based anodes, solid state-based systems, lithium-sulfur, or even sodium-ion will remain agnostic to physical cell design. For example, possible issues could arise with solid-state separators conforming to the tight bend radii required of separators within a cell or dimensional constraints that arise from battery cell's tendency to swell during charging. For instance, Tesla noted that lithium iron phosphate is better suited to formats other than 4680 due to edge case physics-based differences to other chemistries.[82] These considerations could dictate the physical formats of batteries that incorporate advanced battery technologies.

Manufacturers must decide on battery pack topologies, specifically in terms of the number of cells connected in parallel and series. This can be dependent upon several factors. Understanding what manufacturers chose to do is critical to knowing what power demands the drivetrain will place on individual battery cells, and the voltage range that the battery pack will operate within. Equipment that will operate on the high voltage bus must interface with that voltage, which will affect the cost of that equipment. Increasing the voltage on packs could require voltage isolation specifications of existing equipment to be upgraded to handle the higher voltage.

B. Battery Durability

BEVs rely on lithium-ion batteries to operate; however, these batteries do not have an unlimited lifespan. To measure the lifespan of these batteries, battery durability is considered for assessing the useful life of a battery and how different elements impact the battery degradation process. The DOE Vehicle Technologies Office (VTO) has put forth electric vehicle targets and goals for batteries at the pack and cell level including: 15 years of calendar life, 1,000 cycles of deep discharge cycle life, and greater than 70 percent of useable energy for nominal capacity discharged over three hours at –20 degrees Celsius (C) for low temperature performance.[83] The United States Advanced Battery Consortium subsequentially put forth a battery test procedure to verify battery performance in comparison to the DOE VTO targets for electric vehicles for an equivalent electric range of

[81] Morris, Charles. 2021. Charged Electric Vehicles Magazine - GM reveals more technical details of its Ultium battery packs. July 12. Accessed February 28, 2022. https://chargedevs.com/newswire/gm-reveals-more-technical-details-of-its-ultium-battery-packs/.

[82] Motley Fool Transcribing, *Tesla (TSLA) Q4 2021 Earnings Call Transcript*

[83] U.S. Department of Energy. 2020. "Batteries: 2020 Annual Progress Report." Office of Energy Efficiency & Renewable Energy Vehicle Technologies Office. https://www1.eere.energy.gov/vehiclesandfuels/downloads/VTO_2020_APR_Batteries_compliant_.pdf

200 miles based on an Urban Dynamometer Driving Schedule (UDDS) cycle operating at 30 degrees Celsius.[84]

To define battery durability and degradation, metrics such as cycle life, range, usable energy, and capacity provide explanations as to how these factors impact battery life. Cycle life is the number of charge and discharge cycles that can occur before a battery begins to fail meeting performance needs. Cycle life is dependent on the depth of discharge, which is the percentage of the battery that has been discharged, with higher depth of discharges resulting in a lower cycle life.[85] Battery capacity of a vehicle is the accumulated electric charge a battery has and is measured in ampere-hours whereas usable energy is the energy a battery has available to use for vehicle operations and is measured in kilowatt-hours. Capacity is the measure of charge independent of voltage, while usable energy depends on the voltage the battery operates at. Usable energy and capacity impact vehicle range – as these factors decrease, the available range of a vehicle decreases as well. When a battery has 80 percent usable energy, it is considered to have reached its end-of-life. Capacity fade can be further categorized into calendar and cycle capacity loss.

Battery degradation can be separated into two categories which both can be affected by several factors. The first is cycle based aging where a battery degrades from energy in and out of the battery. Cycle capacity loss is dependent on the frequency of use of the battery, the level of charging the battery experiences, and electrochemical aging due to the growth of an internal solid-electrolyte interphase (SEI) layer caused by various factors such as high temperature and high current.[86] [87] The second is calendar aging where a battery degrades based on the conditions the battery experiences over a period of time when the battery is storing energy rather than charging or discharging. Calendar capacity loss is significant to battery durability as electric vehicles are generally idling for longer periods of time rather than operating. Calendar aging contributes more to capacity loss than cycle aging, with an average capacity loss of 31 percent after 10 years with most of the loss occurring in earlier years.[88] Some factors that contribute to calendar capacity loss include state of charge, temperature the vehicle battery is exposed to, and time. One of the primary degradation mechanisms is the time a battery spends at elevated temperatures. Another is the time a battery spends close to its upper and lower voltage limits. These degradation factors are

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[84] U.S. Department of Energy Vehicle Technologies Program. 2020. "United States Advanced Battery Consortium Battery Test Manual for Electric Vehicles." U.S. Department of Energy: Energy Efficiency and Renewable Energy (EERE). October 2020.
[85] MIT Electric Vehicle Team. 2008. "A Guide to Understanding Battery Specifications." December. https://web.mit.edu/evt/summary_battery_specifications.pdf
[86] Yang, Fan, Yuanyuan Xie, Yelin Deng, and Chris Yuan. 2018. "Predictive modeling of battery degradation and greenhouse gas emissions from U.S. state-level electric vehicle operation." *Nature Communications*. doi:10.1038/s41467-018-04826-0.
[87] Edge, Jacqueline S, Simon O'Kane, Ryan Prosser, Niall S Kirklady, Anisha N Patel, Alastair Hales, Abir Ghosh, et al. 2021. "Lithium ion battery degradation: what you need to know." *Physical Chemistry Chemical Physics* 23 (14): 8200-8221. doi:10.1039/d1cp00359c.
[88] Yang, Fan, Yuanyuan Xie, Yelin Deng, and Chris Yuan. 2018. "Considering Battery Degradation in Life Cycle Greenhouse Gas Emission Analysis of Electric Vehicles." *25th CIRP Life Cycle Engineering (LCE) Conference* 505-510. doi:10.1016/j.procir.2017.12.008

constantly being evaluated to better understand how to mitigate them and improve battery durability.

1. Factors Impacting Battery Durability and Degradation

Battery durability and degradation are dependent upon various factors, such as fast charging, ambient temperature, state of charge of the battery, driving cycles, battery thermal management, and vehicle-to-grid connectivity.

The level of charging a vehicle battery receives can accelerate battery degradation. Studies have shown that more DC fast charging use, particularly in hot climates, could lead to quicker degradation and decreased usable energy compare to BEVs that do not use fast charging.[89] [90] When two 2012 Nissan Leaf battery packs rated at 24 kWh were tested for charging impacts on the battery, the pack charged with a Level 2 charger showed a capacity fade of 23.1 percent and the DC fast charged pack had a capacity fade of 28.1 percent.[91] Optimization of charging can help mitigate the impacts of fast charging to the battery, which can help reduce capacity fade.[92]

Ambient temperature also has an influence on battery durability and degradation both for calendar and cycle aging. Environmental, charging, and operating temperatures independently and combined can affect the longevity of vehicle battery life. To increase battery life, batteries should operate between 25C and 30C as the rate of degradation tends to increase with temperature increase.[93] [94] Other studies have shown that operating temperatures can impact aging, and battery operating temperatures should be between 15C and 35C to minimize battery degradation. Charging the battery at low temperatures can also lead to lithium deposition which can accelerate degradation of the battery. As for calendar aging, environmental temperatures also have a significant impact, as storing the battery at temperatures outside the range of 15C to 35C can be harmful to battery life.[95] With increasing temperatures, battery cycle life is significantly impacted and reduced, as

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[89] Argue, Charlotte. 2020. “What can 6,000 electric vehicles tell us about EV battery health?” Geotab. July 7. Accessed July 16, 2021. https://www.geotab.com/blog/ev-battery-health/.
[90] Transport Canada. 2017. “Electric Vehicle Battery Durability Testing and Evaluation.” October. Accessed March 3, 2022. https://wiki.unece.org/download/attachments/51973240/EVE-24-09-rev1e.pdf?api=v2.
[91] Tanim, Tanvir R., Matthew G. Shirk, Randy L. Bewley, Eric J. Dufek, and Bor Yann Liaw. 2018. The implications of fast charge in lithium ion battery performance and life: cell vs. pack. Study, Energy Storage and Advanced Vehicles Department, Idaho National Laboratory, Idaho Falls, Idaho.
[92] Hoke, Anderson, Alexander Brissette, Kandler Smith, Annabelle Pratt, and Dragan Maksimovic. 2014. "Accounting for Lithium-Ion Battery Degradation in Electric Vehicle Charging Optimization." IEEE Journal of Emerging and Selected Topics in Power Electronics 691-700. doi:10.1109/JESTPE.2014.2315961.
[93] Eider, Markus, and Andreas Berl. 2018. "Dynamic EV Battery Health Recommendations." e-Energy '18: Proceedings of the Ninth International Conference on Future Energy Systems. New York, NY: ACM. 586-592. doi:10.1145/3208903.3213896.
[94] Yanh, Fan, Yuanyuan Xie, Yelin Deng, and Chris Yuan. 2018. "Predictive modeling of battery degradation and greenhouse gas emissions from U.S. state-level electric vehicle operation." Nature Communications, June 21. doi:10.1038/s41467-018-04826-0.
[95] Han, Xuebing, Languang Lu, Yuejiu Zheng, Xuning Feng, Zhe Li, Jianqiu Li, and Minggao Ouyang. 2019. "A review on the key issues of the lithium ion battery degradation among the whole life cycle." eTransportation 1. doi:10.1016/j.etran.2019.100005.

increasing the number of charge and discharge cycles reduces battery capacity which is further impacted by increasing temperatures.[96] Other research has shown that a combination of low temperature and high state of charge shows highest capacity fade, with moderate temperatures of 25C showing the lowest capacity fade.[97] Both low and high temperature extremes can therefore adversely impact vehicle range.[98] [99] [100]

Battery degradation is further impacted by driving patterns, storage, and charging. Pulling too much current from a battery over a certain amount of time such as through aggressive driving patterns can have detrimental effects on battery life.[101] Current flow through a battery creates heat and can cause side reactions that reduce battery life. The smaller the current flow, the longer the battery life.[102] Battery state of charge (SoC) can also impact battery life. A higher SoC indicates higher terminal voltage and a lower anode potential relative to a higher cathode potential, which can result in solid-electrolyte interphase thickening. This SEI thickening causes the battery to age quicker. Cycle aging occurs when the battery is charging or discharging and can be induced by current flow and SoC levels and is accelerated by high internal temperatures. To maximize battery life, batteries should not be stored at high SoC, but rather be maintained at 80 percent or lower while minimizing the depth of discharge.[103] [104] In other words, draining most of a battery's capacity frequently, or completely draining a battery, reduces battery capacity over time. Similarly, charging an electric vehicle beyond its voltage limit can cause internal resistance in the battery; however, most batteries have built-in battery management systems, so overcharging is rarely an issue. When combined with temperature impacts, SoC can aggravate battery degradation further.[105]

While temperature can greatly impact battery degradation, battery thermal management can provide some aid in battery longevity with a system that can engage and disengage in thermal management when needed. Thermal management systems are important for batteries since temperature impacts various parameters related to battery longevity, performance, and discharge rate of the battery. Vehicles with a liquid cooling system, such as the 2015 Tesla Model S, have shown a lower average degradation rate than vehicles with a

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[96] Carnovale, Andrew, and Xianguo Li. 2020. "A modeling and experimental study of capacity fade for lithium-ion batteries." Energy and AI. doi:10.1016/j.egyai.2020.100032.
[97] Keil, Peter, and Andreas Jossen. 2015. "Aging of Lithium-Ion Batteries in Electric Vehicles: Impact of Regenerative Braking." World Electric Vehicle Journal 7.
[98] Argue, "What can 6,000 electric vehicles"
[99] American Automobile Association, Inc. 2019. AAA Electric Vehicle Range Testing. AAA. https://www.aaa.com/AAA/common/AAR/files/AAA-Electric-Vehicle-Range-Testing-Report.pdf.
[100] Sacramento Metropolitan Air Quality Management District. 2020. "Electric vehicle charging and extreme heat." Urban Heat Island Project. Accessed March 15, 2022. https://www.airquality.org/LandUseTransportation/Documents/UHI%20EV%20charging%20and%20extreme%20heat.pdf.
[101] Eider et al., "Dynamic EV Battery Health Recommendations"
[102] Han et al., "A Review of lithium-ion battery degradation"
[103] Eider et al., "Dynamic EV Battery Health Recommendations"
[104] Keil, Peter, Simon F. Schuster, Jörn Wilhelm, Julian Travi, Andreas Hauser, Ralph C. Karl, and Andreas Jossen. 2016. "Calendar Aging of Lithium-Ion Batteries." Journal of the Electrochemical Society 163 (9)
[105] Kostopoulos, Emmanouil D., George C. Spyropoulos, and John K. Kaldellis. 2020. "Real-world study for the optimal charging of electric vehicles." Energy Reports 6: 418-426. doi:10.1016/j.egyr.2019.12.008.

passive air-cooling system, such as the 2015 Nissan Leaf.[106] Batteries with adequate thermal management can provide the battery with needed cooling to decrease operating temperatures as well as battery degradation.

Lastly, implementing vehicle-to-grid (V2G) connectivity or bidirectional charging with electric vehicle batteries can further deplete battery life while the vehicle odometer or vehicle age may not reflect this utilization. A recent study assessed costs and impacts of V2G on battery degradation in 20 new Nissan Leaf vehicles with optimization that ran over three years in 1-hour intervals. The projected remaining battery capacity after three years ranged from 67.8 to 75.6 percent.[107] Another experiment conducted laboratory testing of commercial 18650 Li-ion cells which included cycling experiments for V2G impacts and calendar aging experiments for temperature and SoC impacts. Results showed that V2G use can increase the capacity loss by 33 percent when V2G charging is performed once a day. [108] Batteries with lower SoC limits of 50-90 percent could reduce battery degradation.[109] These results indicate that V2G could decrease battery life when not properly managed.

2. Battery Electric Vehicle Durability Improvements

Electric vehicles on the road today are already able to maintain 80 percent of the vehicle's original battery capacity for 10 years or 150,000 miles. When looking at the United States Advanced Battery Consortium electric vehicle battery goals for battery life of 15 years, an analysis conducted on lithium-ion cells of Panasonic NCR18650PD revealed capacity loss was well within the 80 percent benchmark even at different temperatures.[110] Tesla's fleet of over 1 million Tesla Model S and X vehicles have also shown less than 15 percent battery degradation for vehicles that drove between 150,000 and 200,000 miles.[111] Tesloop, which is a Tesla rental company in Southern California, operated a Tesla Model X 90D with 350,000 miles on an original battery while only experiencing a 13 percent capacity fade, which translated to a range reduction from 247 miles to 215 miles at 95 percent charge.[112]

Similarly, state of health data for Nissan Leaf's from the 2013 through 2019 model years have shown that the Nissan Leaf has improved state of health throughout the years. The 2013 model had 3 percent degradation the first year and 8.9 percent degradation by the third year whereas the 2016 model had 2.3 percent degradation the first year and 6.9 percent

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[106] Argue, "What can 6,000 electric vehicles"

[107] Gowda, Shashank Narayana, Basem Eraqi, Hamidreza Nazaripouya, and Rajit Gadh. 2021. "Assessment and Tracking Electric Vehicle Battery Degradation Cost using Blockchain." Innovative Smart Grid Technologies Conference (ISGT). *Virtual: IEEE Power & Energy Society.* 1-5. doi:10.1109/ISGT49243.2021.9372218.

[108] Dubarry, Matthieu. 2017. Electric Vehicle Battery Durability And Reliability Under Electric Utility Grid Operations. *Hawaii Natural Energy Institute.* http://publications.energyresearch.ucf.edu/wp-content/uploads/2018/06/FSEC-CR-2064-17.pdf.

[109] Tchagang, Alain, and Yeong Yoo. 2020. "V2B/V2G on Energy Cost and Battery Degradation under Different Driving Scenarios, Peak Shaving, and Frequency Regulations." *World Electric Vehicle Journal* 11 (1): 14. doi:10.3390/wevj11010014.

[110] Keil et al., "Aging of Lithium-Ion Batteries in Electric Vehicles"

[111] Tesla. 2019. Impact Report. Tesla. https://www.tesla.com/ns_videos/2019-tesla-impact-report.pdf.

[112] Kane, Mark. 2019. Insideevs.com - Tesloop Explains Various Causes For Tesla Battery Degradation. April 22. Accessed March 2, 2022. https://insideevs.com/news/345589/tesloop-reasons-cause-battery-degradation/.

degradation by the third year. [113] The 2017 model had 2 percent degradation the first year showing improvement from previous years. An average decline across 21 vehicle models indicated a 2.3 percent degradation per year, which can translate to a 150-mile range vehicle losing 17 miles after 5 years.[114] From these real-world examples, 80 percent battery degradation can support vehicles that have travelled up to 150,000 miles before reaching a critical point of excessive range loss. And with automakers putting forth vehicles with higher battery capacity, the degradation should be less when compared to a smaller battery size. Furthermore, electric vehicle batteries may be able to provide necessary range even after 70-80 percent battery degradation. [115] [116]

C. Battery Trends and Future Improvements

Conventional lithium-ion batteries like those with nickel manganese cobalt (NMC), nickel cobalt aluminum (NCA), and nickel manganese cobalt aluminum (NMCA) cathodes have continued to improve year over year trending towards reductions in cobalt and increases in nickel for higher energy density.[117] [118] Some of those improvements have slowed recently due to impacts in material availability. Several companies, including Tesla, have prioritized lithium iron phosphate (LiFePO4) chemistries, despite the lower energy density relative to nickel and cobalt based chemistries to meet demand in the lower range versions of vehicles.

Although the technology and cost analysis for the ACC II proposal relied on conventional lithium-ion batteries, the 2021 National Academies of Sciences, Engineering, and Medicine report on light-duty vehicle technologies identified several pathways for advanced battery technologies that go beyond conventional lithium-ion based systems including lithium anodes, solid-state separators, lithium sulfur designs, lithium air designs, and magnesium-based batteries.[119] With these advanced battery technologies possible reduction in mass, charging times, and cost for future ZEVs has the potential to be transformative for the industry. Several companies have moved some advanced technologies out of the lab phase and are now working on making the batteries durable, manufacturable, and cheap enough for the light-duty automotive market.

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[113] Argue, "What can 6,000 electric vehicles"

[114] Argue, "What can 6,000 electric vehicles"

[115] Casals, Lluc Canals, Marta Rodriguez, Cristina Corchero, and Rafeal E. Carrillo. 2019. "Evaluation of the End-of-Life of Electric Vehicle Batteries According to the State-of-Health." World Electric Vehicle Journal 10 (4): 63. doi:10.3390/wevj10040063.

[116] Saxena, Samveg, Caroline Le Floch, Jason MacDonald, and Scott Moura. 2015. "Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models." Journal of Power Sources 282: 265-276. doi:10.1016/j.jpowsour.2015.01.072.

[117] Tesla, *Tesla Battery Day*.

[118] GM. 2020. *GM Reveals New Ultium Batteries and a Flexible Global Platform to Rapidly Grow its EV Portfolio.* March 4. Accessed March 4, 2022. https://media.gm.com/media/us/en/gm/home.detail.print.html/content/Pages/news/us/en/2020/mar/0304-ev.html.

[119] National Academies of Sciences, Engineering, and Medicine. 2021. Assessment of Technologies for Improving Light-Duty Vehicle Economy - 2025-2035. Consensus Study, Washington D.C.: The National Academies. doi:10.17226/26092.

The International Council on Clean Transportation (ICCT) identified three advanced battery companies and their announced cell energy densities in Table 6, and there are many other companies working to create next generation battery technologies.[120] Many of those companies have announced partnerships with vehicle manufacturers, new breakthroughs in preproduction cells, or even cells that are going into production in consumer products with durability requirements that are lower than the light-duty automotive sector. But those consumer product batteries provide an important steppingstone to demonstrate manufacturing capability while the companies work to improve cycle durability and calendar life.

Table 6. Energy Density of Battery Technologies

Company	Technology	Energy density (Wh/kg)	Reference
Existing	Lithium-ion (various)	100-260	121
SES	Lithium metal	417	122
Solid power	Lithium metal	440	123
Solid power	High content silicon	390	124
Quantumscape	Lithium metal	380-500	125

Silicon anode technologies can greatly improve energy density over conventional graphite anodes. Graphite has a maximum theoretical specific capacity of 372 (mAh/g) while silicon has a maximum of 3,600 (mAh/g).[126] Unfortunately, lithium alloys with silicon swells more than 300 percent, which severely limits the use of silicon as an anode without specific mitigation methods to ensure appropriate cycle life. Several companies like Amprius Technologies, Inc (Amprius), Enovix Corporation (Enovix), and Sila Nanotechnologies, Inc. (Sila) are

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[120] Slowik, Peter, Michael Nicholas, Anh Bui, Logan Pierce, and Stephanie Searle. 2021. Memorandum Re: Advanced Clean Cars (ACC) II ZEV Cost Modeling Workbook. December 23.

[121] Yang, Gene et al. (2020) Advances in Materials Design for All-Solid-state Batteries: From Bulk to Thin Films. Journal of Applied Sciences. https://www.researchgate.net/publication/342821920_Advances_in_Materials_Design_for_All-Solid-state_Batteries_From_Bulk_to_Thin_Films

[122] Business Wire. 2021. Business Wire - SES Unveils World's First 100 Plus Ah Li-Metal Battery, Announces New Gigafactory at First SES Battery World. November 3. Accessed March 4, 2022. https://www.businesswire.com/news/home/20211103005931/en/SES-Unveils-World%E2%80%99s-First-100-Plus-Ah-Li-Metal-Battery-Announces-New-Gigafactory-at-First-SES-Battery-World.

[123] Solid Power. 2022. *A New Breed of Battery.* Accessed March 4, 2022. https://solidpowerbattery.com/.

[124] Solid Power, *A New Breed of Battery.*

[125] QuantumScape. 2021. *Electric vehicles are here. The future is solid.* Accessed March 4, 2022. https://web.archive.org/web/20211224000843/https://www.quantumscape.com/

[126] Scott, Alex. 2019. Chemical & Engineering News - In the battery materials world, the anode's time has come. April 7. Accessed February 28, 2022. https://cen.acs.org/materials/energy-storage/battery-materials-world-anodes-time/97/i14.

demonstrating promising developments in silicon-based technologies towards the goal of placing that technology into electric vehicles.

Amprius recently announced that they shipped their first commercially available 450 Wh/kg and 1150 Wh/L cells for use in high-altitude pseudo-satellites. Enovix announced in September of 2021 that they hit a major milestone with start of production of their first battery cells from its automated manufacturing line and had shipped custom cells to a top-tier consumer electronics company for augmented reality glasses.[127] Sila's technologies are being utilized in a health and fitness tracker, the WHOOP 4.0 wristband, that is now available to consumers. The integration of Sila's advanced battery technology improved energy density by 17 percent and reduced the size of the WHOOP 4.0 over its previous generation.[128] These announcements and products demonstrate that the technology is developing according to the respective battery manufacturer's plans towards mass manufactured versions for light-duty automotive applications.

Solid state battery companies have received a lot of attention in the last few years. Solid state batteries, which are generally lithium-ion based, replace the electrolyte and separator in a battery cell with a solid material. That material is usually a type of polymer or ceramic. Solid Power has stated that they intend to bring all solid-state designs to production.[129] SES and QuantumScape have stated that they will be pursuing a hybrid pathway that has a solid-state separator, but the cathode side utilizes a liquid or gel electrolyte, otherwise known as a catholyte.[130] [131] Other companies like Factorial and Prologium are pursuing an all-solid-state approach and now have agreements and investments with several vehicle manufacturers. Another battery company based out of Berkeley, California, PolyPlus Battery Company (PolyPlus), has been working on solid state battery technology for some time with its glass-protected lithium metal battery. PolyPlus signed a joint development agreement with SK Innovation Co. Ltd. (SK) in 2019 to focus on solid-state lithium anode laminate that has the potential to double the energy density and cycle life of rechargeable batteries.[132] Solid state cells potentially can work with a variety of different anodes and cathodes and have several potential technical advantages, including for battery safety.

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[127] Enovix Corporation. 2021. Enovix Achieves Major Milestones: U.S.-Based Factory Produces First Battery Cells Off Its Automated Manufacturing Line and Ships Custom Design for AR Glasses. September 22. Accessed February 15, 2022. https://ir.enovix.com/news-releases/news-release-details/enovix-achieves-major-milestones-us-based-factory-produces-first.

[128] Sila Nanotechnologies, Inc. 2021. *Unlocking Radical Product Innovation from the Inside Out*. September 7. Accessed March 4, 2022. https://www.silanano.com/news/unlocking-radical-product-innovation-from-the-inside-out.

[129] Solid Power. n.d. *Solid Power's All-Solid-State Battery Cell Technology.* Accessed February 17, 2022. https://solidpowerbattery.com/batteries/.

[130] Donnelly, Grace. 2021. Emerging Tech Brew: SES says its next-gen battery could be in cars by 2025. November 3. Accessed March 4, 2022. https://www.morningbrew.com/emerging-tech/stories/2021/11/03/ses-says-its-next-gen-battery-could-be-in-cars-by-2025.

[131] QuantumScape. 2021. *Solid-State Battery Landscape.* February 16. Accessed February 28, 2022. https://www.quantumscape.com/resources/blog/solid-state-battery-landscape/.

[132] PolyPlus Battery Company. 2019. PolyPlus Battery Company. February 18. Accessed February 11, 2022. https://polyplus.com/polyplus-and-sk-enter-into-joint-development-agreement-for-glass-protected-lithium-metal-battery/.

Battery and automotive manufacturers are continuing to further improve battery safety, and new technologies like solid state batteries can bring significant improvements in this regard. Liquid based electrolytes in most lithium-ion batteries are flammable under extreme conditions and are likely the first part of a cell to ignite.[133] Solid electrolytes do away with that hazard by replacing that electrolyte with a solid material that is not flammable, making the batteries inherently safer. Solid Power has stated that third-party safety tests of its development cells in 2021, which included a nail penetration test, demonstrated better resistance to fire than conventional lithium-ion battery safety results.[134]

While there have been incidences of vehicle battery fires and recalls for BEVs, this does not mean that BEVs pose greater risks than hybrid and conventional vehicles.[135] [136] Conventional ICE and hybrid vehicles continue to have fire risks.[137] A recent study of recalls and on-road incidents demonstrated that hybrid and conventional ICE vehicles have much higher fire related incidence rates than BEVs.[138] While BEVs arguably pose similar or less risk of fire than hybrid and conventional vehicles, solid-state batteries could help to further reduce battery related fire risks altogether. This may make future BEVs even safer than the data suggests current BEVs already are.

D. Energy Efficiency Improvements

In conjunction with increases in battery pack energy capacity, the energy efficiency of BEVs is also increasing. Several vehicle models that have been in the market for more than one or two model years have seen year-over-year energy efficiency increases since they were first introduced. Tesla's Model 3 long range AWD model variants started in 2018 with 116 MPGe and in less than four years are now achieving an efficiency of 131 MPGe.[139] The Model S has increased 35 percent from 89 MPGe to 120 MPGe in the ten years since it was first introduced for the 2012 model year.[140] New models like the 2022 model year Lucid Motors

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[133] Hess, Steffen, Margret Wohlfahrt-Mehrens, and Mario Wachtler. 2015. "Flammability of Li-Ion Battery Electrolytes: Flash Point and Self-Extinguishing Time Measurements." Journal of The Electrochemical Society 162: A3084.
[134] Solid Power. 2021. *Are Solid-State Cells Safer?* December 8. Accessed February 28, 2022. https://solidpowerbattery.com/solid-state-safety/.
[135] NHTSA. 2021. Consumer Alert: GM Expands Recall, All Chevrolet Bolt Vehicles Now Recalled. August 20. Accessed February 17, 2022. https://www.nhtsa.gov/press-releases/recall-all-chevy-bolt-vehicles-fire-risk.
[136] NHTSA. 2021. "Part 573 Safety Recall Report 21V-127." NHTSA. March 1. Accessed March 4, 2022. https://static.nhtsa.gov/odi/rcl/2021/RCLRPT-21V127-1095.PDF.
[137] Barry, Keith. 2022. *Nissan Rogue Recalled for Fire Risk and Electrical Issues.* January 26. Accessed February 17, 2022. https://www.consumerreports.org/car-recalls-defects/nissan-rogue-recalled-for-fire-risk-and-electrical-issues-a4879259490/
[138] Bodine, Rachel. 2022. *AutoInsuranceEZ.com: Gas vs. Electric Car Fires [2021 Findings].* January 21. Accessed February 17, 2022. https://www.autoinsuranceez.com/gas-vs-electric-car-fires/.
[139] U.S. Department of Energy and the U.S. Environmental Protection Agency. n.d. Fueleconomy.gov - 2018 Tesla Model 3 Long Range AWD and 2022 Tesla Model 3 Long Range AWD. Accessed March 1, 2022. https://www.fueleconomy.gov/feg/Find.do?action=sbs&id=40385&id=45011.
[140] U.S. Department of Energy and the U.S. Environmental Protection Agency. n.d. Fueleconomy.gov - 2012 Tesla Model S, 2022 Tesla Model S. Accessed March 1, 2022. https://www.fueleconomy.gov/feg/Find.do?action=sbs&id=32557&id=45014.

Air large sedan are also debuting with impressive efficiencies for the vehicle's size and power, indicating that further gains in efficiency can be achieved by better reducing mass and better optimizing for efficiency rather than performance. Lucid Motors submitted comments in response to CARB's May 2021 Workshop stating that their Air sedan is "17 percent more efficient than other leading electric cars and gets an additional 100 miles out of the same sized battery pack as a leading competitor."[141]

The ICCT submitted comments concerning CARB's ZEV cost modeling used for generating incremental costs in the ACC II SRIA demonstrating CARB's estimates of BEV efficiencies were too conservative.[142] The ICCT provided an extensive table of existing models' efficiencies like the Tesla Model 3 and Kia EV6 which shows those vehicles to be more efficient than what CARB was projecting for similar vehicles starting in the 2026 model year. The ICCT additionally analyzed Argonne National Laboratory's (ANL) outputs from its Autonomie model runs completed for ANL's 2021 Light-Duty Vehicle Technology report to the DOE.[143] [144] Their analysis showed that the Autonomie outputs for BEV efficiencies could be representative of 2026 model year BEVs with an eleven percent upward adjustment to those efficiencies to account for how far current vehicles have already come. In response to those comments and presented data, CARB staff adjusted BEV efficiencies, which are outlined in Section X.A.1.a of the Initial Statement of Reasons (ISOR).

Manufacturers have realized those full vehicle efficiency improvements through several areas, some of which are specific to electrical components. Further optimizations in electric motors have increased both their power density and efficiency. Inverter efficiencies have benefited appreciably from the introduction of silicon carbide (SiC) based semiconductors into the industry. Additional efficiency gains have also come from high levels of integration. Munro's Model 3 and Model Y teardown reports demonstrated that Tesla has maintained its strategy of continual improvements that are forcing other manufacturers to be nimbler and iterate on their products more quickly than many have historically done. Ford is planning several incremental changes to its Mustang Mach-E prior to a standard mid-cycle refresh cadence that will increase range and efficiency.[145]

Other improvements in efficiency have come from vehicle level design decisions, many of which have been made possible by BEV specific platforms. Manufacturers continue to iterate

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141 Witt, Daniel - Lucid Motors. 2021. *RE: Lucid Comments on May 6, 2021 Advanced Clean Cars II Workshop.* Comment letter submitted to CARB by Lucid Motors. June 11, 2021.

142 Slowik, Peter et. al., 2021.

143 Islam, Ehsan Sabri, Ram Vijayagopal, Ayman Moawad, Namdoo Kim, Benjamin Dupont, Daniela Nieto Prada, and Aymeric Rousseau. 2021. ANL/ESD-21/10 - A Detailed Vehicle Modeling & Simulation Study Quantifying Energy Consumption and Cost Reduction of Advanced Vehicle Technologies Through 2050. Energy Systems Division, Argonne National Laboratory, October. Accessed March 1, 2022. https://vms.es.anl.gov/case-studies/u-s-doe-vto-hfto-r-d-benefits/.

144 Autonomie is a computer model for assessing the energy consumption and cost of multiple advanced powertrain technologies, developed by ANL and partners. *See* Autonomie Vehicle System Simulation Tool | Argonne National Laboratory (anl.gov) for more information.

145 Edelstein, Stephen. 2022. *CEO: Ford Plans to "Reengineer" Mustang Mach-E Incrementally, Won't Save Improvements for Mid-Cycle Refresh*. Green Car Reports. February 7. Accessed February 15, 2022. https://www.greencarreports.com/news/1134986_ceo-ford-plans-to-reengineer-mustang-mach-e-incrementally-wont-save-improvements.

on those BEV platforms and bodies to improve aerodynamic efficiency. It has been reported that Lucid Motors' new Air sedan achieves a drag coefficient of 0.200.[146] Mercedes claims that its EQS sedan has a coefficient of drag of 0.20.[147] Tesla states a drag coefficient of 0.208 for its latest Model S sedan iteration.[148] These gains in aerodynamic efficiency demonstrate that manufacturers are leveraging BEV-specific platforms to further enhance range and overall vehicle efficiency and will likely do so across all vehicle types.

Manufacturers have also developed innovative drivetrain strategies to mitigate potential efficiency losses from adding a second motor for AWD capability. Tesla, with its AWD versions of its vehicles, introduced the Model 3 with a permanent magnet motor at the rear axle, and an AC induction electric motor at the front axle such that when the motor is not powered there is no inherent magnetism of a permanent magnet motor to overcome. Lucid Motors has developed a front axle disconnect for their Air large sedan which disconnects the front permanent magnet motor when it is not being utilized by the vehicle for tractive power or regeneration, thereby reducing any magnetic drag.

As discussed, battery developments are also moving forward. Should advanced battery technologies like solid state designs, silicon anodes, lithium anodes, or others become viable for light-duty automobile use, those technologies will likely reduce the total vehicle mass significantly. In a vehicle like the Tesla Model Y, an advanced battery cell with an energy density of 400 Wh/kg would likely result in a reduction of battery pack mass of about 35 percent compared to the current battery pack without counting any of the additional downstream mass reduction effects from moving to a solid-state cell, like the ability to utilize bipolar stacking.[149]

E. Critical Materials for Electric Vehicle Batteries

Lithium batteries depend on a short list of materials with unique properties and few substitutes. As mentioned, lithium-ion batteries typically combine lithium with nickel, manganese, cobalt, aluminum, or iron for the cathode, use aluminum for packaging and the cathode's current collector, and have an anode consisting of graphite and a copper current collector.[150] Of the materials used in lithium-ion battery cells, the US government deems many to be critical. Because the supply of these materials is crucial for their performance but may also be constrained or put at risk due to natural, geopolitical, and economic forces, they are referred to as critical materials. In 2018, the U.S. Department of Interior identified a range of lithium-ion battery materials as critical materials to the economic and national security of

[146] Markus, Frank. 2021. *How the Lucid Air's Aerodynamic Tricks Gain It Access to the .200 Club.* Motor Trend. November 15. Accessed January 27, 2022. https://www.motortrend.com/news/2022-lucid-air-luxury-ev-design-aero-tricks/.
[147] Mercedes-Benz Group Media. 2021. *The new EQS: Aerodynamics.* April 15. Accessed March 1, 2022. https://group-media.mercedes-benz.com/marsMediaSite/en/instance/ko/The-new-EQS-Aerodynamics.xhtml?oid=49581781.
[148] Tesla. 2022. Tesla Model S. Accessed January 27, 2022. https://www.tesla.com/models.
[149] With cell mass of 69g and assumed 18.25Wh per cell.
[150] Union of Concerned Scientists. 2021. Electric Vehicles Batteries: Addressing Questions about Critical Materials and Recycling. February. Accessed March 3, 2022. https://www.ucsusa.org/sites/default/files/2021-02/ev-battery-recycling-fact-sheet.pdf.

the United States, including lithium, cobalt, manganese, and aluminum.[151] In 2022, the final list of critical minerals was revised, which maintained that many of the minerals used in electric vehicle batteries are critical minerals.[152] Of those, lithium and cobalt are generally considered to have the most significant supply risk due to the high geographic concentration of production.[153] Recycling batteries reduces the need for extracting, refining, and transporting new minerals, recycling batteries domestically presents an opportunity to recover critical materials while reducing reliance on imports and mitigating supply risk and reducing the environmental and social burden of raw material production.[154]

F. Battery Recycling and Reuse

As described earlier, ZEVs and PHEVs are powered by high-voltage traction batteries. As electric vehicles retire from service, retired traction batteries will be created. Traction batteries are large format, long-lived, rechargeable devices which contain a range of high-value materials with limited natural availability.

Automakers in the U.S. market typically warrant traction or high-voltage batteries for BEVs for 8 years or 100,000 miles.[155] Meanwhile, the traction batteries on PHEVs certified to CARB's transitional ZEV standard are warranted for 10 years or 150,000 miles. As battery technology progresses, and to maximize BEV benefits, increasing the battery warranty on these vehicles to cover more vehicle mileage for an extended period ensures the vehicles have a reliable battery for a longer period of the vehicles' lifespan. Once battery capacity drops below 70 percent of the initial range, or if the vehicle is out of warranty and the battery pack or individual modules are replaced, those batteries would enter end of life management processes. Retired traction batteries can be reused, repurposed, recycled, or ultimately discarded in a hazardous waste landfill.

1. Battery Reuse and Repurposing

Electric vehicle batteries will be retired from their primary application either when the vehicle itself is physically damaged or when the range and/or performance is no longer acceptable to the driver. Retired battery systems are likely to enter a range of applications based on

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[151] U.S. Department of the Interior. 2018. "Final List of Critical Minerals 2018." Office of the Secretary, Interior. Federal Register Vol. 83, No. 97. May 18. Accessed March 3, 2022. https://www.govinfo.gov/content/pkg/FR-2018-05-18/pdf/2018-10667.pdf.

[152] Burton, Jason. 2022. *U.S. Geological Survey Releases 2022 List of Critical Minerals.* U.S. Geological Survey, Department of the Interior. February 22. Accessed March 7, 2022. https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals.

[153] Olivetti, Elsa A., Gerbrand Ceder, Gabrielle G. Gaustad, Xinkai Fu. 2017. "Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals." *Joule 2017, 1 (2),* 229– 243. https://doi.org/10.1016/j.joule.2017.08.019.

[154] Kendall, Alissa, Margaret Slattery, and Jessica Dunn. 2021. *Lithium-ion Car Battery Recycling Advisory Group: DRAFT Report.* AB 2832 Advisory Group. December 1. Accessed March 3, 2022. https://www.calepa.ca.gov/wp-content/uploads/sites/6/2021/12/Materials-Meeting-16-Lithium-ion-Car-Battery-Recycling-Advisory-Group-AB-2832-Draft-Policy-Recommendations-as-of-12.01.2021.pdf.

[155] Office of Energy Efficiency & Renewable Energy, 2016. "Fact #913: February 22, 2016 The Most Common Warranty for Plug-In Vehicle Batteries is 8 Years/100,000 Miles". Posted February 22, 2016.

their physical characteristics, state of health, and performance. Some modules with minimal degradation and absent defects or damage could likely be refurbished and reused directly as replacement battery packs for the same model vehicle. Major automakers, including Nissan and Tesla, have offered rebuilt or refurbished battery packs for purchase or warranty replacement of original battery packs.[156] When retired after its vehicle life, electric vehicle batteries are expected to retain as much as 80 percent of their initial capacity, though the actual condition will vary from vehicle to vehicle.[157]

After use in a vehicle, lithium battery packs could deliver an additional 5-8 years of service in a stationary application. To be used as stationary storage, used batteries must undergo several processes that are currently costly and time intensive. Each pack must be tested to determine the remaining state of health of battery modules, as it will vary for each retired system depending on factors that range from climate to individual driving behavior. The batteries must then be inspected, fully discharged, and reconfigured to meet the energy demands of their new application. In many cases, packs are disassembled before modules are tested, equipped with a battery management system, and re-packaged. The key barrier to the second-life battery industry stems from the process of testing and repurposing used battery systems, which makes it difficult for used systems to compete with new battery storage given the rapidly falling cost and improving performance of new lithium-ion battery systems.

Given the growing market for electric vehicles, second-life batteries could represent an important resource for stationary energy storage applications. Examples of stationary energy storage applications include backup power for homes or cellular towers, or, in larger arrays, for large buildings like arenas or even in utility grid applications.[158] Second-life batteries may be 30 to 70 percent less expensive than new ones in energy storage applications in 2025.[159] By 2030, the second-life battery supply from the burgeoning PEV market could exceed 200 gigawatt-hours per year, which could exceed demand by almost 25 percent.[160] Second-life batteries would also reduce the demand for virgin materials used in the production of new energy storage batteries.[161]

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[156] Avarts, Eric C. 2018. *Nissan begins offering rebuilt Leaf battery packs*. Green Car Reports. May 14. Accessed March 1, 2022. https://www.greencarreports.com/news/1116722_nissan-begins-offering-rebuilt-leaf-battery-packs.

[157] Hossain et al. 2019. "A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers & Potential Solutions, Business Strategies, and Policies." *IEEE*. June 18. Accessed March 3, 2022. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8718282

[158] [158] Wentworth, Adam. 2018. *Amsterdam Arena installs major new battery storage*. ClimateAction. July 02. Accessed March 1, 2022. https://www.climateaction.org/news/amsterdam-arena-installs-major-new-battery-storage.

[159] Engel, Hauke, Patrick Hertzke, and Giulia Siccardo. 2019*. Second-life EV batteries: The newest value pool in energy storage*. McKinsey & Company. April 30. Accessed April 30, 2022. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage.

[160] Engel, *Second-life EV batteries*

[161] Casals, Lluc Canals, B. Amante Garcia, and Camille Canal. 2019. "Second life batteries lifespan: Rest of useful life and environmental analysis." *Journal of Environmental Management,* February 15: 354-363. https://www.sciencedirect.com/science/article/pii/S0301479718313124.

The economic potential for battery second life could help to further decrease the upfront costs of electric vehicle batteries by increasing the value of a used electric vehicle. In a stationary setting, distributed energy storage resources can provide a range of services both behind and in-front of the electricity meter. For private customers, battery energy storage can provide back-up power and decrease electricity costs. For utility customers, storage can provide a range of services including frequency regulation, deferral of investments in transmission and distribution infrastructure, and energy arbitrage.

2. Battery Recycling

Recycling is the process of taking packs and reducing them to their base materials. Lithium-ion battery recycling can be broken down into three general stages:

- Pre-treatment, which primarily consists of mechanical shredding and sorting out plastic fluff, metal-enriched liquid, and metal solids.[162]
- Secondary treatment, which involves separating the cathode from the aluminum collector foil with a chemical solvent.
- Recovery of the cathode materials through hydrometallurgy, which relies on chemical leaching, or pyrometallurgy, which relies on high temperatures to enable electrolytic reaction processes.

There are a limited number of large-scale facilities that recycle lithium batteries today and the technological approaches can be broken down into three general categories:

Pyrometallurgical Recycling

A smelting process is used to heat the batteries to high temperatures, driving off organics like separators and plastics as waste gases. Pyrometallurgical plants (i.e., smelters) use high temperatures (~1500°C) to burn off impurities and recover cobalt, nickel, and copper. The remaining nickel, cobalt, and copper is recovered in a mixed alloy that can be further separated using hydrometallurgy. The lithium and aluminum remain in a slag by-product. It is not economically viable to separate out the lithium via hydrometallurgy, so instead, it is typically sold for use as an additive in concrete or as an insulation material.[163] There is no ability to recycle the electrolyte or plastics. Pyrometallurgy is energy intensive and costly and can potentially emit hazardous gases. However, it has been an economically viable way to recover cobalt and nickel from batteries with high contents of one or both metals.

Hydrometallurgical Recycling

This process dissolves battery constituents or alloys in acid to produce metal sulfates. It can be used to recover metals after a mechanical process or from the pyrometallurgy alloys or

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[162] Zhang, Xiaoxiao, Li Li, Ersha Fan, Qing Xue, Yifan Bian, Feng Wu, and Renjie Chen. 2018. "Toward sustainable and systematic recycling of spent rechargeable batteries." *Chemical Society Reviews*, October 7: 7183-7496.

[163] Engel, Jan, and Gretchen A. Macht. 2016. "Comparison of Lithium-Ion Recycling Processes." Conference Proceedings, Kingston, RI: The University of Rhode Island.

slag by-products with high recycling efficiencies.[164] Hydrometallurgy requires less energy, but because of the cost of chemicals and purification, the process is complex and costly. It also generates a lot of wastewater.[165] Hydrometallurgical recovery methods focus on leaching, removal of impurities, and separation. Leaching can occur through both solvent extraction and chemical precipitation to recover lithium, nickel, and cobalt.

Hydro- and pyro- metallurgical recycling are commercially available technologies. Both can recover lithium-containing materials, but further processing is needed to get them to a usable form. This involves refining the constituent material to a sufficiently high quality for use in a new cathode as done with primary mined products, as well as the synthesis of the cathode compound or alloy.

Direct Recycling

The goal of direct recycling is to recover electrode materials in a suitable condition to be used as direct inputs in battery production, without separating each individual material. Direct recycling resynthesizes cathode materials through various chemical processes, yielding an alloy with similar if not identical properties to the new cathode material.

The benefit of recovering usable cathode material is that it preserves the embedded energy and economic investment by avoiding the need to resynthesize cathode materials (e.g., lithium, nickel, cobalt, or manganese) into a cathode compound. Unlike the other two processes, it does not break down the crystalline structure of the cathode into its constituent elements, but instead allows a degraded cathode to be regenerated through a process called cathode relithiation. Typically, direct recycling involves physical separation of the cathode material from other components, washing of the binder, thermal treatment, lithium replenishment of the active material, and a final thermal treatment step. This is the least energy intensive of the processes but does not work with mixed battery chemistries and is furthest from full commercialization.[166]

Additional information on battery reuse and recycling can be found in Appendix E, including details on ongoing state actions and draft battery recycling recommendations for the Legislature as required under Assembly Bill 2832.[167] [168]

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[164] Larouche, François et al. 2020. "Progress and Status of Hydrometallurgical and Direct Recycling of Li-Ion Batteries and Beyond." *Materials* 13, no. 3: 801. https://doi.org/10.3390/ma13030801.
[165] Pavón, Sandra, Doreen Kaiser, Robert Mende, and Martin Bertau. 2021. "The COOL-Process—A Selective Approach for Recycling Lithium Batteries" Metals 11, no. 2: 259. https://doi.org/10.3390/met11020259
[166] ReCell Center, U.S. Department of Energy Office of Science, UChicago Argonne LLC. n.d. Direct Cathode Recycling. Accessed March 1, 2022. https://recellcenter.org/research/direct-cathode-recycling/.
[167] Assembly Bill 2832 (Dahle, 2018) codified in Article 3 (commencing with § 42450.5) of Chapter 8 of Part 3 of Division 30 of the Public Resources Code, required the Secretary of the California Environmental Protection Agency (CalEPA) to convene a Lithium-Ion Car Battery Recycling Advisory Group to review and advise the Legislature on policies pertaining to the recovery and recycling of lithium-ion batteries sold with motor vehicles in the state. The Advisory Group is to submit policy recommendations to the California Legislature, on or before April 1, 2022, aimed at ensuring that as close to 100 percent as possible of lithium-ion vehicle batteries in the State are reused or recycled at end-of-life in a safe and cost-effective manner.
[168] Kendall, Slattery, and Dunn, *Lithium-ion Car Battery Recycling Advisory Group*

IV. Battery Assumptions and Costs

A. BEV and PHEV Efficiencies

Based on battery and energy efficiency trends, CARB staff developed efficiency assumptions used in cost modeling for ACC II. Usable battery energy (UBE) is derived from the assigned range and projected efficiency of the technology package for a vehicle class in a specific model year for BEV and PHEV technologies. Total battery energy (TBE), used to obtain the battery pack cost, is derived from the UBE with the state-of-charge (SoC) utilization percentage. CARB staff used data from ANL's 2021 Light Duty Vehicle Technology report to develop charge depleting energy efficiencies for the BEV and PHEV technologies.[169] The 2021 ANL report contains the most up-to-date modeling information from U.S. DOE and ANL which better represents BEV, PHEV, and FCEV attributes than previous reports and is a consistent comparison of attributes between ZEV types. Staff updated BEV and PHEV charge depleting efficiencies based on the more recent 2021 ANL report for this final analysis. Staff used the data from the report with the following guidelines:

1. Low vs high technology case - The report presented a low technology and a high technology pathway. CARB staff found that 2021 ANL Autonomie report's low technology pathway best matched expected vehicle attributes due to its less aggressive light weighting, aero efficiency gains, and tire rolling resistance reductions over time. CARB staff view this as a more likely scenario in the timeframe of the regulation.
2. Base vs. premium model - The report also presented a "base" version, and a higher performing "premium" version of each vehicle type. Except where towing packages are generated for the medium SUV, large SUV, and pickup, the report's "base" vehicle attributes are used. This is to preserve performance neutrality with the ICEVs in the fleet today that the BEVs are replacing.
3. Lab year - Best in class BEVs available by vehicle manufacturers today were compared to the modeled vehicle attributes from the report. ANL lists their modeled vehicle packages in what they call a "lab year" instead of a model year. Inspection of the ANL report's outputs showed that ANL 2015 "lab year" vehicles align with the initial model year ZEV attributes projected by CARB staff.

Taking this into account, a summary of the modifications to the charge depleting efficiencies used from the 2021 ANL Autonomie report are listed in Table 7. These changes lead to a change in costs for these technology packages.

[169] Islam et al., *A Detailed Vehicle Modeling & Simulation*

Table 7. BEV and PHEV Efficiency Modifications to 2021 ANL Autonomie Report Data for Use in Development of CARB Staff Projected Battery Pack Sizes

<table>
<tr><th>ANL Lab Year</th><th>CARB Model Year</th><th>Vehicle Class</th><th>BEV300/400s</th><th>PHEVs</th></tr>
<tr><td rowspan="5">2015</td><td rowspan="5">2025</td><td>Small Car</td><td>No modification</td><td rowspan="5">EREV PHEV50 Charge Depleting Adjusted Value (Wh/mi)</td></tr>
<tr><td>Medium and Large Car</td><td>105%</td></tr>
<tr><td>Small SUV</td><td>90%</td></tr>
<tr><td>Medium and Large SUV</td><td>95%</td></tr>
<tr><td>Pickup</td><td>No modification</td></tr>
</table>

Both BEV and PHEV efficiencies are improved 0.5 percent year over year from the initial year across the 2026 to 2035 model years (MY) that the proposed regulation covers. The SoC utilization used to calculate total battery energy from usable battery energy is 92.5 percent for BEVs and 80 percent for PHEVs. The modifications to that data and calculations based on SoC utilization percentages result in charge depleting efficiencies and total battery energy for an example vehicle class of small SUVs in Table 8 and Table 9, respectively.

Table 8. Small SUV Charge Depleting Energy Efficiency (Wh/mi)

Technology	2026	2030	2035
BEV300	223	219	214
BEV400	248	243	237
PHEV	323	316	308

Table 9. Small SUV Total Battery Energy (kWh)

Technology	2026	2030	2035
BEV300	72.5	71.0	69.3
BEV400	107.2	105.1	102.5
PHEV	20.2	19.8	19.3

B. BEV and PHEV Battery Assumptions and Costs

Congress, in 2007, requested the National Academies of Sciences, Engineering, Medicine (NAS), a panel of academics, scientists, engineers, and other experts in the field conduct a periodic review of fuel economy standards. More recently, NHTSA contracted the NAS to form the Committee on Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles – Phase 3 to update on requested technologies, consumer behavior, and policy analysis for vehicle efficiency technologies for 2025-2035. The Committee released a report entitled *Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy 2025-2035* in 2021.[170]

Part of the report focuses on battery technology, particularly those that would be used in BEVs. The Committee extensively researched the automotive battery landscape and projected battery costs to fall between $90-$115/kWh by 2025 and further decrease to $65-$80/kWh by 2030. They credit falling prices to improved and simplified battery cell and pack designs, lower raw material input costs, adjustments to cathode technologies, and new manufacturing techniques in addition to increasing production volumes.[171] [172] The Committee also notes that for costs to go below roughly $60/kWh, new advanced lithium-ion battery technologies like silicon anodes, lithium anodes, or lithium-sulfur based chemistry would need to become commercially viable at high production volumes and with the ability to meet the durability requirements of the light-duty automotive sector.

Other recent findings also indicate a continuing trend of declining battery costs. Bloomberg New Energy Finance (BloombergNEF) industry surveys indicate that prices of automotive battery packs were $137/kWh by the end of 2020, representing a nearly 90 percent decline from 2010.[173] Additional analyses from BloombergNEF project that average battery pack costs for the transportation sector may reach as low as $101/kWh by 2023 and $58/kWh by 2030, but those analyses include less energy dense batteries used in the heavy-duty sector, where packaging volume or range may not be some of the primary design criteria as is the case for light-duty vehicles.[174]

Taking all this information into consideration, staff developed battery pack costs for this regulatory analysis of $95.3/kWh in 2026 and $72.5/kWh in 2030 for BEVs using the midpoint presented in the NAS study due to the robustness and transparency of the analysis.[175] CARB staff estimates that cost reduction rates will slow somewhat after 2030 and applied a lower 5 percent year-over-year reduction from 2030 to 2035 to get the resulting pack costs shown in Figure 8. As discussed, future advancements in new battery chemistries are showing promise, but these are not counted on for staff's battery pack cost estimates. If future battery advancements are realized, they could deliver up to a 50 percent reduction in battery pack weight. That potential significant reduction in battery pack weight would further reduce vehicle weight and increase overall efficiency, decreasing the energy required for a targeted range or increasing range while maintaining the same battery energy capacity.

Battery cells and packs for PHEVs have traditionally differed from those used in BEVs. The energy requirements for BEVs and PHEVs dictate different battery pack configurations,

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[170] National Academies of Sciences, Engineering, and Medicine, Assessment of Technologies
[171] BloombergNEF. 2020. Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh. December 16. Accessed March 1, 2022. https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/.
[172] National Academies of Sciences, Engineering, and Medicine, Assessment of Technologies
[173] BloombergNEF, Battery Pack Prices
[174] BloombergNEF, Battery Pack Prices
[175] Battery pack costs are representative of the direct manufacturing costs for each ZEV technology's battery pack for each year of the regulation and are inclusive of everything contained within that pack. The pack includes thermal systems and hook ups, battery management system components contained within the pack, and connectors and wiring internal to the pack.

physical dimensions, and energy contents for the two technologies. There are some common components, like the battery management system, safety disconnects, power wiring, and thermal management systems that could be shared between the two types of vehicles. However, the battery packs between the two vehicle technologies will be different in many ways including the battery cells and the count and configuration of the battery cells due to the electric topology. PHEVs, generally, use different battery cells than BEVs due to the power requirements compared to the battery pack size – BEVs require high specific energy from a battery while PHEVs require a balance of energy and power. Not only are the physical cell designs and energy capacities different, the variation of lithium-ion chemistry for each vehicle technology may also be different. Some vehicle manufacturers may use the same cell in the future if battery manufacturers are able to meet specific targets; however, such solutions appear to be less common, requiring compromise on the optimization of the cell to one or both applications.

For the SRIA, CARB staff used a 40 percent cost markup for battery costs in PHEVs compared to BEVs based on analysis in the 2017 Total Battery Consulting xEV Insider Report. Stakeholders commented the cost premium was too high and not representative of future PHEV battery costs. The proposed regulations require a minimum of 50 miles of all-electric range which necessitates larger energy capacity battery packs than the PHEVs required for the analysis completed in the 2017 xEV Insider Report. CARB staff adjusted the cost markup downward to 30 percent based on the stakeholder feedback. The resulting specific PHEV battery costs are shown with the BEV battery costs in Figure 88. Total battery costs for small SUVs in several example years are shown in Table 10.

Figure 8. Battery Pack Costs for BEVs and PHEVs for Model Years 2026 through 2035

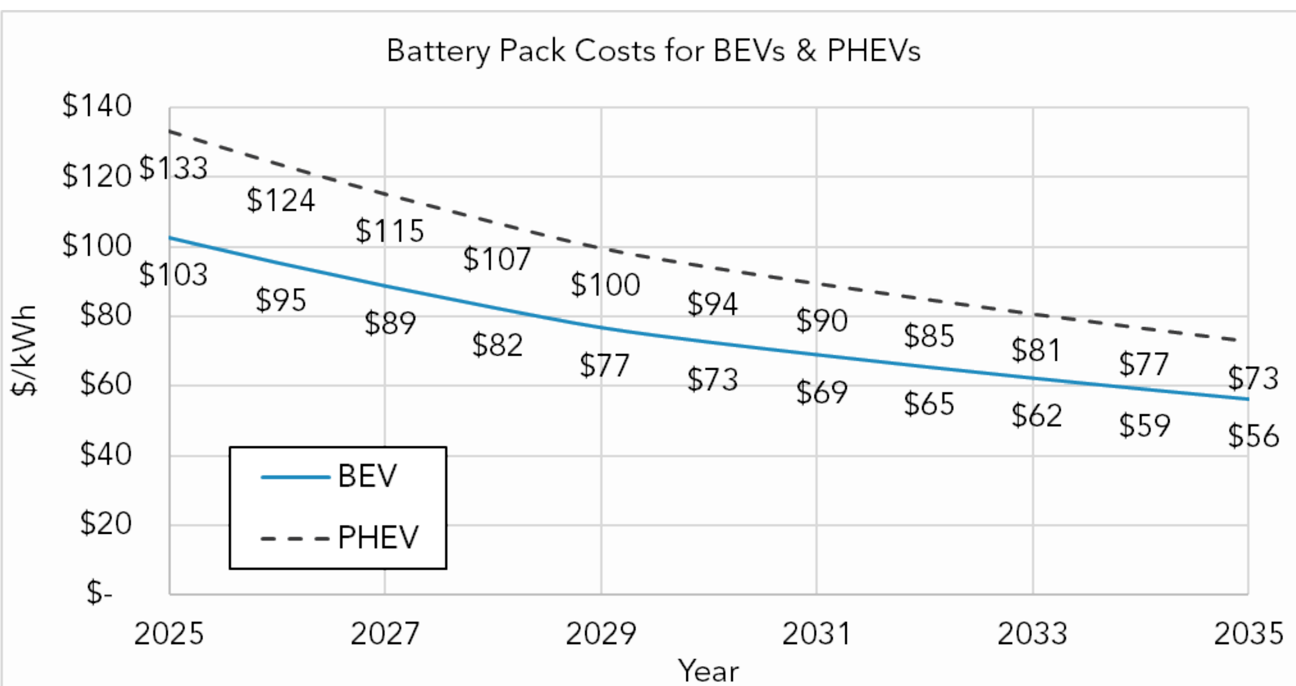


Table 10. Total Battery Pack Costs for Small SUVs

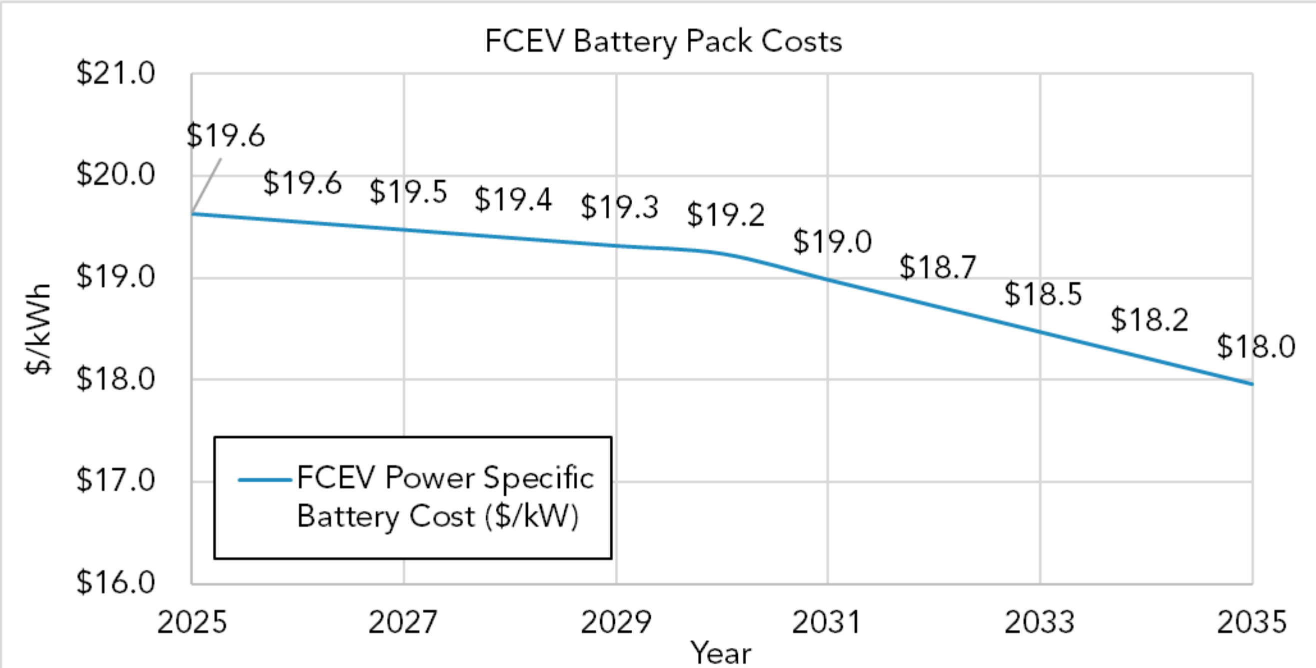
Technology	2026	2030	2035
BEV300	$6,909	$5,151	$3,887
BEV400	$10,222	$7,620	$5,750
PHEV	$2,499	$1,863	$1,406

C. FCEV Battery Assumptions and Costs

The batteries used for the fuel cell vehicle analysis completed by ANL are like conventional ICE based HEV batteries, both in energy capacity and power capability and are like what is currently being used in the industry.[176] For the SRIA, battery costs were derived from ANL's 2020 report and displayed in terms of cost per unit energy. Similar to the fuel cell stack power and hydrogen tank capacity, FCEV battery energy capacities are updated to those from the ANL's 2021 report's Fuel Cell 300 technology packages with a few differences.[177] The battery power and sizes are used in the same way other vehicle attributes are being used such that they are from the low-technology pathway and the base version of the vehicle. Additionally, the model year the technology is applied to is the lab year it is identified in plus ten years. Following the SRIA analysis, the specific costs for FCEV batteries were changed and are now calculated in dollars per kilowatt ($/kW). Staff determined that the cost curves ten years out from the lab year were not as appropriate to use as was done with the vehicle attributes. Subsequently, the staff has used the approach of the model year those specific costs are applied to are the lab year the specific cost is connected to plus five years. For the lab years that the ANL 2021 report does not model, the battery power and specific costs are linearly interpolated.

[176] Ventricular.org. 2015. "It's Electric - 2015 Review: The Toyota Mirai Hydrogen Fuel Cell Sedan." October. Accessed March 4, 2022. https://ventricular.org/ItsElectric/2020/05/07/first-drive-report-2016-toyota-mirai-hydrogen-fuel-cell-sedan/.
[177] Islam, et al., Detailed Vehicle Modeling & Simulation

Figure 9. FCEV Battery Pack Specific Costs



D. Fuel Cell System Assumptions and Costs

Fuel cell and hydrogen storage tank system costs for FCEVs were based on cost studies and methodologies in ANL's 2021 publication[178], which was developed in close collaboration with staff at Strategic Analysis. ANL, in partnership with manufacturers and suppliers, has long been at the forefront of automotive fuel cell vehicle research. Strategic Analysis is a long-standing consultant to the United States Department of Energy on FCEV cost projections and annually publishes authoritative estimates of system costs. Strategic Analysis studies and ANL's Autonomie model are research efforts funded by U.S. DOE to capture accurate pictures of current technology status and vetted methods for projecting future advancements.

FCEVs are very early in their commercial development with significant remaining opportunity for future cost reduction due to economies of scale and technology advancement. Accurate estimates of present and future costs for fuel cell and hydrogen storage systems need to reflect cost reductions that will occur as more FCEVs are produced each year and more advanced manufacturing processes and FCEV technology is developed. Strategic Analysis cost models account for cost reductions due to production volume, while past ANL reports accounted for cost reductions due to technology advancement over time.

In the 2021 analysis, ANL adjusted their cost estimation methodology by integrating the production volume effects of Strategic Analysis' cost models and assuming growth from low production volume in the near-term to high production volume in the long-term. Communications between CARB, ANL, and U.S. DOE staff confirmed that the revised cost

[178] Islam, et al., Detailed Vehicle Modeling & Simulation

estimates assumed annual production rates of 10,000, 50,000, and 100,000 vehicles per year in model years 2025, 2030, and 2035, respectively[179]. This assumed trend in production volume is similar to CARB's estimates published in the draft SRIA.[180] The comprehensiveness of the revised ANL method and agreement with CARB's prior analysis allowed for a simpler process to utilize vehicle specification and cost model results reported by ANL.

ANL's analysis implements the Autonomie vehicle modeling platform and provides estimates of vehicle design, fuel efficiency, and cost of several types of light-duty vehicles in future years. In addition to updated cost models, the analysis for the 2021 report accounts for updated electric motor performance, high-durability fuel cells (8,000-hour useful lifetime), and other advancements made in the past year. The model assumes certain vehicle performance specifications and determines the set of component specifications (such as fuel cell system power, motor power, battery power and energy capacity, etc.) that allow the vehicle to achieve the desired performance. Component weight is a key factor in identifying the set of parameters for each vehicle.

CARB's cost estimation for FCEVs relied heavily on the ANL report data with some minor adjustments. The average ratio between motor power and vehicle curb weight for all vehicle types other than pickups (which did not need this adjustment, considering they are typically designed to have higher power for towing applications), was observed to be roughly 75kW/kg. To maintain performance neutrality between the vehicle types (other than pickups), CARB adjusted motor power for FCEVs to the average between those vehicle types to 75 kW/kg. In the Autonomie evaluation process, the fuel cell stack is sized to provide sufficient power for the motor after accounting for the battery power. The battery is itself sized for performance considerations, such as the time to accelerate from 0 to 60 mph. CARB therefore adjusted the fuel cell system power by the same amount as the motor power such that the delta between the motor power prior to the 75 kW/kg adjustment and after the adjustments was added to the fuel cell stack power. In addition, based on the observed vehicle weight trends in the Autonomie results, CARB assumed all vehicle specifications for a given lab year (the basis of vehicle technology in Autonomie results) should be applied to vehicles of a model year 10 years later. All other component specifications were taken directly from the Autonomie results reported by ANL.

For most vehicle types (small car, medium car, etc.), the vehicle component specifications were based on the Autonomie results for Base model vehicles. The only exceptions were for pickup trucks and medium SUVs that include towing capability. CARB assumed that all pickup trucks would include towing capability, and based FCEV pickup specifications on Autonomie results for Premium pickups. Premium pickups are modeled in Autonomie to have more power than their Base model counterparts, as expected for vehicles with towing capabilities. Similar results are observed for Premium medium SUVs so the same assumption was made for these vehicles**.** Table 11 shows the resulting fuel cell system power by vehicle class and

[179] Rustagi, Neha. 'Assumptions for 2021 Autonomie Energy Consumption Study'. Email, 2022.

[180] California Air Resources Board. 2022. *Advanced Clean Cars II Proposed Amendments to the Low Emission, Zero Emission, and Associated Vehicle Regulations Standardized Regulatory Impact Assessment (SRIA).* January 26. Accessed March 15, 2022. *https://dof.ca.gov/wp-content/uploads/Forecasting/Economics/Documents/ACCII-SRIA.pdf*

model year. Table 12 shows the amount of hydrogen stored in the hydrogen storage system by vehicle class and model year.

Table 11: Fuel Cell System power (kW)

	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Small Car	74	73	72	71	70	70	70	70	70	70
Med Car	81	79	77	74	72	72	72	72	72	73
Small SUV	92	90	88	87	85	84	84	83	83	83
Med SUV	97	95	93	90	88	87	87	87	86	86
Pickup	168	164	160	155	151	151	151	150	150	150

Table 12: Hydrogen Fuel Tank Size (kg)

	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Small Car	3.9	3.8	3.7	3.6	3.6	3.6	3.6	3.6	3.6	3.5
Med Car	4.2	4.1	4.0	3.9	3.8	3.8	3.8	3.8	3.8	3.8
Small SUV	5.1	5.0	4.8	4.7	4.6	4.6	4.6	4.6	4.6	4.5
Med SUV	5.4	5.2	5.1	5.0	4.8	4.8	4.8	4.8	4.8	4.8
Pickup	7.1	6.9	6.7	6.5	6.3	6.3	6.2	6.2	6.2	6.2

To estimate the costs of the fuel cell and hydrogen storage systems, CARB then applied the cost estimates provided by the ANL report's high technology advancement case. CARB assumed that the costs per kilowatt of fuel cell power and per kilogram of hydrogen stored on-board followed the same trajectory recommended in the Autonomie results. That is, a difference of 5 years was assumed between lab and model years in terms of costs. This was necessary in order to maintain the proper growth rate in annual production volumes. For the fuel cell system, this resulted in costs of $111/kW, $66/kW, and $52/kW in model years 2025, 2030, and 2035, respectively. For the hydrogen storage system, the costs are modeled with a constant portion and variable portion that scales with the amount of hydrogen stored. Table 13 shows the variation by model year in the coefficients for each portion of the hydrogen storage system cost model. Linear interpolation was used for all model years 2026-2029 and 2031-2035. Full fuel cell system and hydrogen storage system costs are shown by vehicle class and model year in Table 14 and Table 15, respectively.

Table 13: Hydrogen Storage System Cost Model Coefficients

Model Year	Constant Portion: Hydrogen Storage System Cost ($)	Variable Portion: Hydrogen Storage System Cost ($/kg)
2025	1946	352
2030	1849	236
2035	981	191

Table 14: Fuel Cell System Cost ($/vehicle)

	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035

Small Car	7,543	6,790	6.053	5,334	4,632	4,431	4,231	4,031	3,832	3,633
Med Car	8,241	7,318	6,433	5,586	4,776	4,569	4,362	4,156	3,950	3,744
Small SUV	9,334	8,361	7,417	6,502	5,616	5,340	5,068	4,799	4,533	4,271
Med SUV	9,936	8,832	7,771	6,755	5,783	5,515	5,250	4,987	4,725	4,466
Pickup	17,166	15,254	13,418	11,659	9,977	9,536	9,097	8,659	8,223	7,788

Table 15: Hydrogen Tank Cost ($/vehicle)

	2026	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
Small Car	3,207	3,078	2,949	2,819	2,690	2,484	2,279	2,073	1,867	1,662
Med Car	3,317	3,174	3,032	2,889	2,747	2,539	2,331	2,123	1,915	1,708
Small SUV	3,602	3,435	3,268	3,101	2,945	2,720	2,505	2,290	2,075	1,860
Med SUV	3,699	3,520	3,342	3,163	2,984	2,768	2,551	2,334	2,117	1,900
Pickup	4,264	4,029	3,795	3,560	3,326	3,096	2,866	2,636	2,406	2,176

V. Non-Battery Component Assumptions and Costs

Understanding both battery and non-battery technology is critical to understanding the status of PEVs and where the technology may be headed. Key technologies include battery cells and packs, battery management systems, drive motors, inverters, on-board chargers (OBC), direct current to direct current (DC-DC) converters, PEV specific HVAC components, and high voltage wiring and interconnects. While batteries account for the greatest portion of vehicle cost, non-battery components are essential to the operation of the vehicles.

In understanding economies of scale and applicability of advancements in individual technologies, it is important to note where PHEVs and ZEVs use the same or different components. Additionally, while PHEV and ZEV powertrains use similar components, vehicle integration layouts can be quite different. ZEVs on the market use single speed gear reduction transmissions to transmit electric machine power to the wheels. The designs tend to be relatively simple and compact compared to PHEVs. ZEVs locate the combined electric motor and gearbox at either the front or rear axle, or in the case of the dual-motor ZEVs at both axles. PHEVs, in contrast, come in a variety of different formats and configurations. Some have two electric motors that are packaged in a transaxle assembly designed for a front-wheel drive vehicle, while other PHEV systems being utilized include electric motors located between the engine and transmission, at the axle, or at a combination of these locations. These basic differences in layout influence the types and designs of motors, transaxles, battery cells, and power electronics that are used in each technology. Additionally, PHEVs typically have a lower power on-board charger to support lower energy capacity battery packs.

There are many categories of non-battery costs that contribute to the ZEV and PHEV technology incremental costs. Non-battery component costs are applied to each ZEV and PHEV technology combination either as a dynamic cost based on the motor power or as a fixed cost. The non-battery costs were derived from extensive third- party vehicle teardown studies of many different types of hybrid electric vehicles, PHEVs, and BEVs. Those studies include:

- CARB contracted Ricardo hybrid electric vehicle component teardowns[181]
- Munro Model 3 teardown
- Munro i3, Bolt, and Model 3 comparison
- UBS Chevrolet Bolt teardown[182]
- Munro 12 Electric Motor comparison
- Munro 6 Inverter comparison
- Munro Model Y teardown

Those studies showed that the leading manufacturers on both cost and performance were taking a very integrated approach to designing and manufacturing their non-battery components. This led to three main areas that needed to be accounted for in the CARB staff analysis:

- The electric motor and housing
- A penthouse or housing with heavily integrated power electronics, many of which share the same circuit boards
- The rest of the supporting items like high voltage cabling and cooling components

From that approach, the non-battery components were broken down into specific component sets and cost curves and/or fixed costs were developed using the best-in-class costs from the tear down studies listed above.

Motor Power

The motor of an electric vehicle converts electrical energy into mechanical energy and power on the axle. This mechanical power is typically defined in kilowatts, here referred to as electric motor power.

In most cases, both ZEVs and PHEVs use permanent magnet electric machines. While most electric machines in ZEVs and PHEVs are of the permanent magnet variety, they generally differ in design for many reasons. ZEV electric machines are responsible for providing all of the motive power for the vehicle. PHEV systems can be split into two different groups: blended and non-blended. Blended PHEVs do not have an electric drive powertrain that can meet all the motive power requirements of the vehicle on electric power only. On the other hand, non-blended PHEVs are capable of driving on electric power over the entire range of driving conditions. Non-blended PHEVs require an electric machine(s) that can deliver power levels roughly equal to that of the ICE.

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181 Ricardo Strategic Consulting, Munro & Associates Inc., and ZMassociates Environmental Corp. 2017. Advanced Strong Hybrid and Plug-In Hybrid Engineering Evaluation and Cost Analysis - CARB Agreement 15CAR018. Teardown Cost Analysis, California Air Resources Board. https://ww2.arb.ca.gov/sites/default/files/2020-04/advanced_strong_hybrid_and_plug_in_hybrid_engineering_evaluation_and_cost_analysis_ac.pdf.
182 UBS. 2017. UBS Evidence Lab Electric Car Teardown - Disruption Ahead? Vehicle Teardown Costing, New York: UBS. https://neo.ubs.com/shared/d1wkuDlEbYPjF/.

PHEV electric motors are a little less powerful than their BEV counterparts. They are assumed to be capable of all-electric operation throughout their charge-depleting mode, but do not assume full performance capability while in charge depleting mode relative to charge-sustaining mode.

With current power densities of electric machines and the size of single gear reduction transaxles, ZEV electric machines can be relatively powerful. PHEVs are generally more limited by the space constraints available in a vehicle that also has a gasoline engine and conventional transmission. This leads to differences in sizing and power densities of the motors. Additionally, cooling electric machines in a PHEV when they are packaged in a transaxle that is connected to an ICE can be more complicated due to the heat produced by the ICE.

Electric motor sizing for both ZEVs and PHEVs better reflect what industry is doing. Manufacturers have been able to realize more accelerative performance out of lower power electric motors than what was expected a decade ago. Due to the electric motors ability to make full torque off idle, electric motors with lower nominal power ratings can achieve equivalent vehicle performance.

CARB staff used data from ANL's 2021 Light Duty Vehicle Technology report to develop the motor sizes for the ZEV and PHEV technologies.[183] The 2021 ANL report contains the most up-to-date modeling information from U.S. DOE and ANL which better represents BEV, PHEV, and FCEV attributes than previous reports and is a consistent comparison of attributes between ZEV types. Staff updated BEV, PHEV, and FCEV sizing based on the more recent 2021 ANL report for this final analysis with the guidelines for the cases used described in Section IV.

Taking this into account, a summary of the modifications to the eMotor power used from the 2021 ANL Autonomie report are listed in Table 16. These changes lead to a change in costs for these technology packages.

Table 16. Modifications to Electric Motor Power from 2021 Autonomie Report Data

ANL Lab Year	CARB Model Year	Vehicle Class	eMotor Power Modification		
			BEV300/400s	FCEVs	PHEVs
2015	2025	Small Car	Rescaled to 75W/kg	Rescaled to 75W/kg	Average EREV PHEV50 eMotor Power to Weight (66W/kg) Applied to Par PHEV50 Turbo Vehicle Mass
		Medium and Large Car			
		Small SUV			
		Medium and Large SUV			
		Pickup	No modification	No modification	

[183] Islam, et al., Detailed Vehicle Modeling & Simulation

CARB staff project that technological improvements will result in lower overall vehicle mass, like improved batteries. To account for that projection, BEV and PHEV motor powers are improved 0.5 percent year over year from the initial year across the 2026 to 2035MYs that the proposed regulation covers. FCEV motor powers are taken in the reference model years from the 2021 Autonomie Report (2015, 2020, 2025 lab years for 2025, 2030, and 2035 model years, respectively) with the model years between those points calculated using linear interpolation.

The resultant motor power for Small SUVs in several example years for BEVs, FCEVs, and PHEVs are shown in Table 17.

Table 17. Electric Motor Power for Small SUVs

Technology	2026MY	2030MY	2035MY
BEV300	138	135	132
BEV400	155	152	148
PHEV	136	134	130
FCEV	124	115	112

<u>Non-Battery Cost Categories</u>

The specific component sets are listed here:

- Traction motors, inclusive of the rotor and stator, are the primary motor for all ZEV applications. The traction motor costs consist of both the permanent magnet synchronous machine (PMSM) and the rest of the motor components, such as the case, mounts, and resolver. The PMSM is assumed to be $3.9/kW eMotor Power, whereas the other components are assumed as a 0.1 multiplier based on the traction motor cost such that the total motor cost inclusive of those other components is 1.1 times the $3.9/kW eMotor Power cost. These additional components are only applicable to BEVs and FCEVs since PHEV have transmission-integrated eMotors.

- Induction motors are used for second motors on those vehicles with an electric all-wheel-drive (eAWD) package, except for truck-based PHEVs. Induction motor costs are $2.4/kW eMotor Power, and the rest of the motor components (i.e., case, mounts, and resolver) are assumed as a 1.3 multiplier to the traction motor cost such that the total motor cost inclusive of those other components is 1.3 times the $2.4/kW eMotor Power cost. The induction motor costs are only applicable for eAWD packages on BEVs, FCEVs, and car-based PHEVs.

- Single-speed gearbox costs include the gears and housing and are applicable to all BEVs and FCEVs with a $400/vehicle fixed cost.

- Traction inverters that are integrated in the electric motor housing vary based on the ZEV technology. The power requirements for PHEVs (particularly blended PHEVs) and BEVs will require different drive motor inverters due to the differences in electric power capability of the drivetrains. Designs may be able to be scaled up in power, but the inverters will likely not be the same component. For BEVs and FCEVs, traction inverters are assumed to be silicon carbide (SiC) at a cost of $3.8/kW eMotor Power.

For primary motors on PHEVs and for second motors in eAWD packages the traction inverter is assumed to be a conventional silicon based insulated-gate bipolar transistor (IGBT) type with a cost of $2.5/kW eMotor Power.

- A 32 Amp Level 2 convenience cord set and adapter for BEVs and PHEVs are a $200/vehicle fixed cost.
- The onboard charger is integrated with other power electronics circuit boards and is applicable for BEVs and PHEVs. The integrated onboard AC charger power is ratioed to the useable battery energy of the vehicle such that the vehicle is capable of fully charging in eight hours with the appropriate electric vehicle supply equipment for BEVs. (kilowatts of onboard charger power equals the useable battery energy divided by 8). For PHEVs, the OBC power is based on a four-hour recharge time. The onboard charger is combined with the DC-DC converter circuitry. The integrated DC-DC converter is the high voltage to low voltage DC-DC converter that is integrated with other power electronics. It is based on a three kilo-Watt converter and is the same across all vehicle technologies – BEVs, PHEVs, and FCEVs. PHEVs and BEVs have different battery pack energy capacities and often do not use OBCs with the same power level. Potentially, smaller OBCs could be operated in parallel to provide more power. This could allow an identical lower power level PHEV OBC component to be used in a BEV to provide the power level needed but necessarily results in a less optimized solution. The combined OBC and DCDC power is assumed to be $39.75/kW and where no OBC is required in the case of FCEVs, the $39.75/kW applies only to the three kilo-Watt DC-DC converter.
- The integrated onboard DC fast charge (DCFC) circuitry includes components like contactors, additional controls integrated with other circuitry, and additional parts and wiring that allows for the vehicle to DC fast charge. The DCFC circuitry costs are only applicable to BEVs at a $156.28/vehicle fixed cost.
- The power management and distribution include the rest of the penthouse-like components like the housing and components to connect, integrate, and house the OBC and DCDC converter, and DCFC circuitry. This applies to all BEVs, PHEVs, and FCEVs at a fixed cost of $719.22/vehicle.
- High voltage "orange cables" that that carry power between the motor, inverter, battery, and other components are applicable to all technologies (BEVs, PHEVs, and FCEVs) at a $187.44/vehicle fixed cost.
- Powertrain cooling costs of $302.22 per electric motor, which include conduits, pumps, fans, and other components that cool the powertrain are applicable to BEVs and FCEVs. This cooling is assumed to be integrated PHEVs with existing ICE coolant loops and electric HVAC controls.
- Second motor high-voltage (HV) cables are the additional orange cabling for when a second electric motor is added with an eAWD package. This is applicable to eAWD packages for BEVs, FCEVs, and car-based PHEVs at a $25/vehicle fixed cost.

Non-battery components and their costs are summarized in Table 18Table below.

Table 18. Non-battery Component Costs

Nominal component set	Tech Application				$/x	Fixed cost	Scale by (x)
	BEV	PHEV Car-Based	PHEV Truck-Based	FCEV			
Traction motor (PMSM)	Y	Y	Y	Y	$3.90		Motor kW
Traction motor (Induction)	Y	Y	N	Y	$2.40		Motor kW
Rest of motor (PMSM)	Y	N*	N*	Y		1.10	Multiplier
Rest of motor (Induction)	Y	N*	N	Y		1.30	Multiplier
Single-speed gearbox	Y	AWD	N	Y		$413.44	-
Traction inverter (IGBT)	N	Y	N	N	$2.50		Motor kW
Traction inverter (Si-C)	Y	N	N	Y	$3.80		Motor kW
Charging cord and adapters	Y	Y	Y	N		$200.00	-
OBC and DCDC Circuitry	Y	Y	Y	N	$39.75		OBC_{kW} + $DCDC_{kW}$
DC Fast Charge Circuitry	Y	N	N	N		$156.28	-
Power Management and Distribution	Y	Y	Y	Y		$719.22	-
HV "orange cables"	Y	Y	Y	Y		$187.44	-
Powertrain cooling	Y	Y	Y	Y		$302.22	per motor
Second motor HV cables	Y	Y	N	Y		$25.00	

Total non-battery costs (not inclusive of fuel cell stack and hydrogen storage tank) for the different ZEV and PHEV technologies for a small SUV in the identified model years are shown in Table 19. These are calculated by aggregating the total non-battery costs for each vehicle class and technology type. Staff projects that the non-battery costs will continue to fall over time based on the learnings observed in the teardown reports and expected continued development of relatively young technologies and have applied a 1 percent year-over-year cost reduction/learning value.

Table 19. Small SUV Non-Battery Costs

Technology	2026MY	2030MY	2035MY
BEV300	$3,537	$3,373	$3,171
BEV400	$3,851	$3,671	$3,451
PHEV	$2,504	$2,382	$2,232
FCEV[184]	$2,727	$2,548	$2,393

[184] Not inclusive of fuel cell system and hydrogen storage tank costs

VI. Delete Costs

A. Background and methodology for standard ICEVs to convert to ZEVs

Conventional ICEVs utilize many components that are not included on BEVs or FCEVs. To compare the incremental cost of BEVs and FCEVs, those ICEV component costs must be deleted.

B. ICE and Transmissions Removal Costs

Both BEVs and FCEVs do not have internal combustion engines (ICE). Developing ZEV technology cost packages that are incremental to ICE technologies requires accounting for the ICE cost and removing that from the total ZEV package cost. ICEs remain on PHEV technologies, so this cost is not removed.

The basis for the ICE removal costs is the 2018 NHTSA CAFE Model technology input costs and 2021 EPA costs.[185] [186] For car-based vehicle classes (small car, medium/large car, and base medium SUVs), a base 2015 model year inline 4-cylinder dual overhead cam (DOHC) engine was identified in the 2018 CAFE model technology input file and was used for the removal cost. For the truck-based SUVs and pickups, a base 2015 model year DOHC V8 was chosen to be the base engine. Since the NHTSA costs were expressed as a retail price equivalent (RPE) with a markup of 1.5 to convert from direct manufacturing cost (DMC) to RPE, the engine cost values were converted to DMC by dividing by 1.5. When averaged with the EPA work, those cost values came to $3,500 for the 4-cylinder car-based engines and $5,000 for the truck based 6-cylinder engines. Those costs are meant to be inclusive of all supporting content including components like fuel tanks, lines, calibration costs, etc.

These 2015 engine values do not have any additional technology and their associated costs applied to them. As such, additional costs for compliance with current and future regulations for ICEVs can be layered on.

Multi-speed transmissions are another key component of conventional ICE powertrains. Both car-based and truck-based transmission removal costs were pulled from 2018 NHTSA CAFE Model technology input costs and work released by EPA staff.[187] [188] Similar to the engine removal costs, since the NHTSA costs were expressed as a retail price equivalent with a

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[185] U.S. Department of Transportation National Highway Traffic Safety Administration. 2018. "CAFE Compliance and Effects Modeling System." NHTSA.gov. Accessed March 2, 2022. *https://www.nhtsa.gov/filebrowser/download/119651*. – Specific file: Central Analysis\input\2018_NPRM_technologies_with_BEV_and_FCV_ref.xlsx

[186] Safoutin, Michael. 2017. "Predicting the Future Manufacturing Cost of Batteries for Plug-In Vehicles for the U.S. EPA 2017-2025 Light-Duty Greenhouse Gas Standards." EPA.gov. October. Accessed March 2, 2022. https://www.epa.gov/sites/default/files/2018-10/documents/evs30-intl-symp-exhib-safoutin-2017-10.pdf.

[187] U.S. Department of Transportation National Highway Traffic Safety Administration. 2018.

[188] Safoutin, Michael. 2017.

markup of 1.5 to convert from direct manufacturing cost, the transmission cost values were converted to back to DMC by dividing by 1.5.

For car-based powertrains, the transmission removal is assumed to be $1500 for a base 5-speed automatic transmission. For truck-based powertrains, a cost of $2000 for a similar base 5-speed automatic transmission (that has costs added to handle the higher loads of the bigger and more powerful truck-based powertrains) is assumed. These costs are removed for BEV and FCEV technology combinations where the ICE powertrain is completely removed to convert to that ZEV technology.

C. Criteria pollutant emissions technology removal costs

Estimated Advanced Clean Cars I LEV III criteria pollutant compliance costs are found in the 2012 ISOR for 2025 model year vehicles.[189] The removal of those costs has been applied to BEVs and FCEVs and are assumed to be the same fixed cost from model years 2025 to 2035. The costs were converted to 2021 dollars from 2010 dollars such that the car-based cost is a fixed $68, and the truck-based cost is a fixed $145.

D. GHG reduction equipment technology removal costs

The U.S. EPA's Revised 2023 and Later Model Year Light Duty GHG Emissions Standards: Regulatory Impact Analysis[190] estimates the average cost per vehicle to be $1,000 for the 2026MY. The costs for an average 2020MY vehicle to comply with the 2022MY requirements is estimated to be $455 which comes to $1455 for the average 2020MY vehicle in the fleet to comply with the 2026MY regulation. Without the 1.5 RPE markup, the direct manufacturing cost is $970 which has been rounded up to $1,000 to account for the small improvements in technology to a 2017MY vehicle to get to the 2020MY standards in U.S. EPA's cost estimates.

E. ZEV Assembly Reductions

ZEV assembly cost reductions are cost savings due to a less complex assembly process and lower associated indirect costs for ZEV technologies. BEVs are assigned a $1600 cost reduction, as the International Council on Clean Transportation's work on incremental BEV costs found two $800 cost reductions for BEV manufacturing in 2025 for vehicle assembly and associated indirect costs.[191] FCEVs, while more complex than BEVs, are still simpler than conventional ICEVs and are assigned half the cost reduction that the BEVs get. PHEVs are

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[189] California Air Resources Board. 2011. Staff Report: Initial Statement of Reasons. Staff Report, Sacramento: California Air Resources Board. Accessed March 2, 2022. https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2012/leviiighg2012/levisor.pdf.

[190] U.S. EPA Final Rule to Revise Existing National GHG Emissions Standards for Passenger Cars and Light Trucks Through Model Year 2026. 86 Fed. Reg. 74,434, Dec. 30, 2021. https://www.epa.gov/regulations-emissions-vehicles-and-engines/final-rule-revise-existing-national-ghg-emissions

[191] Lutsey, Nic, and Michael Nicholas. 2019. Update on electric vehicle costs in the United States through 2030. Working Paper, The International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2021/06/EV_cost_2020_2030_20190401.pdf.

generally very similar to conventional hybrids in many ways, albeit with a larger battery and a few extra components. PHEVs are assumed to have very little additional assembly costs comparative to a conventional ICEV and are not assigned extra costs or cost reductions for assembly.

VII. Rolled Up Incremental Technology Costs

A. Add-on Technologies (Cold, eAWD, Towing)

Acknowledging that the base ZEV and PHEV technologies are not fully representative of consumers preferences for certain technology attributes, CARB staff developed additional technology packages that are added on top of the base PHEVs, BEVs, and FCEVs to meet the needs of consumers in higher market penetration ZEV scenarios.

Table 20. Applicability of Additive ZEV Technologies

Additive Technology Package	Required for	Fleet Uptake % in 2035 Model Year
Cold Weather	BEVs in colder climates	8.8%
Towing	Larger BEVs with towing capability	4.7%
AWD/4WD	BEVs, FCEVs, and smaller PHEVs where ICE equivalent had AWD/4WD	32.5%

1. Cold Weather Package

A single vehicle of each ZEV technology in each vehicle size class is not representative of the diversity of the market. Consumers have preferences to operate their vehicles in various ways which require additional technology. Passenger cabin heating and cooling needs as well as battery thermal management systems can have a significant impact on BEV energy efficiency and range. In response, industry has shifted to heat-pump based heating, ventilation, and air conditioning (HVAC) systems in place of the more traditional resistive heating. This method can be more efficient in energy management while satisfying cabin temperature needs. Some manufacturers have also implemented features such as temperature preconditioning of the cabin or battery while the vehicle is still plugged in and more targeted cabin heating systems employing items like heated steering wheels and heated seats to meet driver demands for comfort without expending as much energy to heat the entire cabin.

About 10 percent of California's vehicle fleet resides in areas that experience at least one full 24-hour period with temperatures below 35 degrees Fahrenheit. While FCEVs and PHEVs would not be as adversely affected by the temperature or could quickly refuel if required, BEVs can be affected by the temperature and cannot be as quickly refueled. To address the issue, a cold weather technology package was created for BEVs to assist in colder climates which includes a more efficient heat pump and additional battery heating components. The BEV cold weather package costs were determined for the 2025MY and the same 1 percent year over year cost reduction that also applies to other non-battery component costs. The

BEV cold weather package cost is shown in Table 21 for all vehicle types in several model years.

Table 21. BEV 300 and 400 Cold Weather Costs

Technology	2026MY	2030MY	2035MY
Small Car	$396	$380	$362
Medium and Large Car	$495	$475	$452
Small SUV	$495	$475	$452
Medium and Large SUV	$594	$571	$543
Pickup	$594	$571	$543

2. Towing Package

Consumers also sometimes buy larger SUVs and pickups to meet towing needs. Towing adversely affects range of any vehicle due to the increased mass the powertrain must move, additional tire rolling resistance of the trailer tires, and reductions in aerodynamic efficiency to the vehicle from the trailer. This is not necessarily much of an issue with FCEVs and PHEVs because they can fully refuel as quickly as conventional vehicles and would likely incur no more refueling stops on a trip than a conventional vehicle. For BEVs, however, even charging at a very high rate of 350 kilowatts, recharging times are lengthier and cannot restore the full range quickly. To address consumer's towing needs with towing-capable BEVs, CARB modeled additive towing packages for BEVs that increases battery capacity such that the vehicle can complete a 440-mile one-way trip when towing a load that cuts efficiency in half and only requires one 20-minute charging stop at 350kW.

Towing-capable ZEVs and PHEVs also receive additional power to account for the heavier loads the vehicles may carry. The increase in power comes from the 2021 ANL Autonomie report. While the non-towing versions are derived from the "base" versions of the different vehicles, towing package medium and large SUVs and pickups use the report's "premium" higher powered values for ZEVs and PHEVs. The FCEV towing variants also receive additional power for their batteries and fuel cell stack as described in Section IV.D. The electric motor power for those packages is shown in Table 22 and the additive costs of the towing package are shown in Table 23.

Table 22. eMotor Power for Towing Packages

Vehicle Class	Technology	2026MY	2030MY	2035MY
Medium and Large SUV	BEV300/400	217	212	207
	FCEV	183	166	164
	PHEV	170	166	162
Pickup	BEV300/400	273	267	260
	FCEV	231	208	204
	PHEV	206	202	197

Table 23. Towing Package Costs

Vehicle Class	Technology	2026MY	2030MY	2035MY
Medium and Large SUV	BEV300	$9,519	$7,311	$5,696
	BEV400	$7,362	$5,644	$4,389
	FCEV	$5,763	$3,659	$3,087
	PHEV	$395	$372	$345
Pickup	BEV300	$13,207	$9,997	$7,669
	BEV400	$10,572	$7,952	$6,060
	FCEV	$2,056	$1,380	$1,250
	PHEV	$306	$288	$267

3. Electric All-Wheel-Drive (eAWD)

Lastly, consumers purchase many vehicles with all-wheel or 4-wheel drive. Staff put together a corresponding electric AWD/4WD package for BEVs, FCEVs, and non-truck-based PHEV cars and SUVs which add an additional electric motor at the undriven axle and all the necessary components to go along with it. Larger PHEV SUVs and pickups do not require an additional motor, because it is assumed that many will utilize a P2 style electric drive system that will operate through a conventional truck-based 4-wheel drive system. P2 systems place an electric motor between the ICE and transmission. Because a traditional mechanical transfer cases that are utilized in truck-based 4WD systems are downline of the transmission, the electric motor will operate through the transfer case to provide electric power to all four wheels without the need for an additional electric motor.

ZEVs and PHEVs that require an additional electric motor to provide AWD functionality do not require all the mechanical components that a conventional ICE-based AWD system does. To estimate those costs, staff found two currently available vehicles that offer nearly identical trims in both front-wheel drive (FWD) and AWD variants; the 2021MY Toyota RAV4 and 2021 MY Honda CR-V. Table 24 shows how the MSRP differences between the variants were used to derive an estimate of the additional component costs required for AWD over FWD drivetrains. A $500 removal cost is now applied to eAWD systems based on those vehicles' price differences. Table 24 shows how the DMC for the mechanical AWD components was calculated which is then used for the mechanical AWD component delete cost for eAWD packages. The parenthetical values in Table 24 are to be subtracted from the respective cells above them. The cost for eAWD packages for a small SUV in several example years is shown in Table 25.

Table 24. AWD Mechanical Delete Costs Estimates

Category	2021 Toyota RAV4 LE[192 193]	2022 Honda CR-V LX[194 195]
AWD MSRP	$27,750	$27,900
FWD MSRP	($26,775)	($26,400)
MSRP Delta	$975	$1,500
Without RPE (/1.5)	$650	$1,000
Average	$825	
Estimate of Component Costs Common to AWD and eAWD[196]	($325)	
DMC Mechanical AWD Components	$500	

Table 25. Small SUV eAWD Package Costs

Technology	2026MY	2030MY	2035MY
BEV300	$360	$336	$308
BEV400	$429	$400	$367
PHEV	$355	$331	$303
FCEV[197]	$308	$263	$240

[192] Toyota Motor Sales, U.S.A., Inc. n.d. Toyota RAV4 Configurator - AWD LE. Accessed March 2, 2022. https://www.toyota.com/configurator/build/step/model:engine-drive-transmission/year/2021/series/rav4/model/4432/.
[193] Toyota Motor Sales, U.S.A, Inc. n.d. Toyota RAV4 Configurator - FWD LE. Accessed March 2, 2022. https://www.toyota.com/configurator/build/step/model:engine-drive-transmission/year/2021/series/rav4/model/4430/.
[194] American Honda Motor Co., Inc. n.d. 2022 Honda CR-V 2WD LX. Accessed March 2, 2022. https://automobiles.honda.com/tools/build-and-price-result?modelid=RW1H2NEW&modelseries=cr-v&modelyear=2022&extcolorcode=NH-830M&tw-type=fromvlp%3D1#section=Powertrain&group=Powertrain&view=Exterior&angle=0&state=TTpSVzFIMk5FVyRFQzpOSC04MzBNJEhDOnVuZGVmaW.
[195] American Honda Co., Inc. n.d. 2022 Honda CR-V AWD LX. Accessed March 2, 2022. https://automobiles.honda.com/tools/build-and-price-result?modelid=RW1H2NEW&modelseries=cr-v&modelyear=2022&extcolorcode=NH-830M&tw-type=fromvlp%3D1#section=Powertrain&group=Powertrain&view=Exterior&angle=0&state=TTpSVzJIMk5FVyRFQzpOSC04MzBNJEhDOnVuZGVmaW.
[196] Includes items like half-shafts, different uprights and suspension components to accommodate drive axles, etc.
[197] Not inclusive of fuel cell system and hydrogen storage tank costs.

VIII. Direct Manufacturing Cost Results

The total incremental direct manufacturing cost (DMC) for each vehicle class and PHEV and ZEV type by model year has been calculated in CARB's ZEV Cost Workbook.[198] Those total incremental DMCs reflect the cost of those packages relative to a compliant, conventional ICE vehicle in each model year. The incremental DMC is the sum of the calculated non-battery DMCs, battery DMCs, fuel cell system DMCs for FCEVs, eAWD, towing, or cold weather package DMCs where applicable, minus the delete DMCs for the ICE, compliant emissions systems, and ZEV assembly reductions. The rolled-up DMCs for small SUV ZEV and PHEV packages without the delete DMCs are shown in Table 26. The delete DMCs for those small SUV packages are shown in Table 27, and the incremental DMCs are show in Table 28. Parenthetical values in the following tables are to be considered negative.

Table 26. Small SUV ZEV and PHEV Non-Incremental Technology DMC

Technology	2026MY	2030MY	2035MY
BEV300	$10,447	$8,524	$7,058
BEV400	$14,072	$11,291	$9,201
FCEV	$16,423	$11,797	$9,115
PHEV	$5,002	$4,244	$3,638

Table 27. Small SUV ZEV and PHEV Delete DMC

Technology	2026MY	2030MY	2035MY
BEV300	($7,668)	($7,668)	($7,668)
BEV400	($7,668)	($7,668)	($7,668)
FCEV	($6,868)	($6,868)	($6,868)
PHEV	($1,000)	($1,000)	($1,000)

Table 28. Small SUV Incremental DMC

Technology	2026MY	2030MY	2035MY
BEV300	$2,779	$856	($610)
BEV400	$6,404	$3,623	$1,533
FCEV	$9,555	$4,929	$2,247
PHEV	$4,002	$3,244	$2,638

The BEV300 package on small SUVs reaches cost parity with a conventional ICE vehicle in the 2033 model year and has the lowest incremental DMC. In the early years, the PHEV package has the second lowest incremental DMC, but both the FCEV and BEV400 packages achieve lower incremental DMC than PHEVs in the 2035 and 2032 model years, respectively.

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[198] California Air Resources Board. 2022. *ZEV Cost Modeling Workbook*. March. Accessed March 28, 2022. https://ww2.arb.ca.gov/sites/default/files/2022-03/zev_cost_modeling_workbook_update_march2022_0.xlsx

The following tables summarize the incremental cost incurred by manufacturers to convert gasoline vehicles to PHEV, BEV300, FCEV, and BEV400 vehicles, respectively.

Table 29. PHEV Incremental Cost by MY, Vehicle Class, Type, Drivetrain, and Towing Capability ($)

Vehicle Class	AWD / 4WD Present	Towing Capable	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
SmallCar	No	No	3,121	2,949	2,787	2,636	2,519	2,413	2,312	2,215	2,123	2,034
SmallCar	Yes	No	3,328	3,152	2,987	2,832	2,711	2,601	2,497	2,396	2,300	2,208
MedCar	No	No	3,372	3,189	3,017	2,856	2,731	2,619	2,511	2,408	2,310	2,215
MedCar	Yes	No	3,637	3,449	3,273	3,107	2,978	2,861	2,749	2,642	2,539	2,440
SmallSUV	No	No	4,002	3,785	3,582	3,392	3,244	3,112	2,986	2,865	2,749	2,638
SmallSUV	Yes	No	4,357	4,134	3,925	3,729	3,575	3,437	3,305	3,179	3,057	2,941
MedSUV	No	No	4,305	4,070	3,851	3,646	3,487	3,345	3,209	3,079	2,955	2,836
MedSUV	No	Yes	4,699	4,459	4,234	4,023	3,859	3,711	3,570	3,434	3,305	3,180
MedSUV	Yes	No	4,305	4,070	3,851	3,646	3,487	3,345	3,209	3,079	2,955	2,836
MedSUV	Yes	Yes	4,699	4,459	4,234	4,023	3,859	3,711	3,570	3,434	3,305	3,180
Pickup	No	No	5,340	5,052	4,782	4,530	4,335	4,161	3,995	3,836	3,684	3,539
Pickup	No	Yes	5,646	5,353	5,079	4,823	4,624	4,445	4,275	4,112	3,956	3,806
Pickup	Yes	No	5,340	5,052	4,782	4,530	4,335	4,161	3,995	3,836	3,684	3,539
Pickup	Yes	Yes	5,646	5,353	5,079	4,823	4,624	4,445	4,275	4,112	3,956	3,806

Table 30. BEV300 Incremental Cost by Model Year, Vehicle Class, Type, Drivetrain, and Towing Capability ($)

Vehicle Class	AWD / 4WD Present	Towing Capable	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
SmallCar	No	No	2,028	1,512	1,031	584	246	(53)	(338)	(608)	(866)	(1,112)
SmallCar	Yes	No	2,276	1,755	1,270	819	476	173	(116)	(391)	(652)	(902)
MedCar	No	No	2,358	1,824	1,327	865	515	206	(88)	(368)	(635)	(889)
MedCar	Yes	No	2,660	2,121	1,619	1,151	797	482	183	(102)	(373)	(632)
SmallSUV	No	No	2,779	2,222	1,703	1,221	856	533	226	(66)	(345)	(610)
SmallSUV	Yes	No	3,139	2,576	2,051	1,563	1,192	863	551	253	(31)	(302)
MedSUV	No	No	2,314	1,647	1,027	449	15	(369)	(734)	(1,081)	(1,412)	(1,726)
MedSUV	No	Yes	11,833	10,521	9,302	8,171	7,326	6,583	5,878	5,208	4,573	3,970
MedSUV	Yes	No	2,717	2,043	1,416	832	391	1	(371)	(724)	(1,061)	(1,381)
MedSUV	Yes	Yes	12,236	10,917	9,692	8,554	7,702	6,953	6,241	5,566	4,924	4,315
Pickup	No	No	5,348	4,498	3,708	2,972	2,419	1,931	1,467	1,026	606	207
Pickup	No	Yes	18,554	16,765	15,104	13,563	12,416	11,409	10,455	9,550	8,691	7,876
Pickup	Yes	No	6,042	5,181	4,379	3,634	3,070	2,571	2,097	1,645	1,215	806
Pickup	Yes	Yes	19,249	17,448	15,776	14,224	13,066	12,049	11,084	10,169	9,300	8,475

Table 31. FCEV Incremental Cost by MY, Vehicle Class, Type, Drivetrain, and Towing Capability ($)

Vehicle Class	AWD / 4WD Present	Towing Capable	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
SmallCar	No	No	6,965	6,045	5,143	4,258	3,389	2,949	2,508	2,068	1,629	1,190
SmallCar	Yes	No	7,168	6,244	5,337	4,447	3,574	3,132	2,691	2,250	1,809	1,369
MedCar	No	No	8,003	6,875	5,786	4,735	3,723	3,273	2,823	2,374	1,925	1,477
MedCar	Yes	No	8,261	7,124	6,025	4,964	3,942	3,491	3,041	2,591	2,142	1,693
SmallSUV	No	No	9,555	8,354	7,183	6,041	4,929	4,385	3,845	3,308	2,776	2,247
SmallSUV	Yes	No	9,866	8,657	7,477	6,327	5,205	4,659	4,117	3,578	3,044	2,513
MedSUV	No	No	12,340	10,314	8,354	6,461	4,635	3,851	3,069	2,290	1,514	741
MedSUV	No	Yes	20,985	18,127	15,365	12,697	10,125	9,159	8,212	7,265	6,318	5,372
MedSUV	Yes	No	12,839	10,790	8,808	6,893	5,046	4,255	3,467	2,683	1,901	1,123
MedSUV	Yes	Yes	21,483	18,603	15,819	13,129	10,535	9,564	8,611	7,658	6,705	5,753
Pickup	No	No	25,277	21,922	18,683	15,562	12,557	11,455	10,355	9,258	8,165	7,075
Pickup	No	Yes	28,362	24,751	21,258	17,883	14,627	13,461	12,333	11,205	10,077	8,950
Pickup	Yes	No	26,234	22,841	19,566	16,408	13,368	12,252	11,140	10,031	8,924	7,822
Pickup	Yes	Yes	29,319	25,670	22,140	18,730	15,438	14,259	13,118	11,977	10,837	9,697

Table 32. BEV400 Incremental Cost by MY, Vehicle Class, Type, Drivetrain, and Towing Capability ($)

Vehicle Class	AWD / 4WD Present	Towing Capable	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
SmallCar	No	No	5,387	4,637	3,939	3,291	2,805	2,377	1,970	1,583	1,216	866
SmallCar	Yes	No	5,687	4,932	4,229	3,576	3,084	2,651	2,240	1,848	1,476	1,122
MedCar	No	No	5,837	5,061	4,340	3,669	3,167	2,724	2,303	1,903	1,522	1,161
MedCar	Yes	No	6,193	5,411	4,684	4,008	3,499	3,050	2,624	2,218	1,832	1,465
SmallSUV	No	No	6,404	5,596	4,845	4,147	3,623	3,161	2,723	2,306	1,910	1,533
SmallSUV	Yes	No	6,833	6,017	5,259	4,554	4,023	3,555	3,110	2,686	2,283	1,900
MedSUV	No	No	8,227	6,876	5,569	4,307	3,090	2,567	2,046	1,527	1,009	494
MedSUV	No	Yes	13,990	12,085	10,243	8,465	6,750	6,106	5,475	4,843	4,212	3,581
MedSUV	Yes	No	8,563	7,199	5,881	4,607	3,378	2,854	2,331	1,810	1,292	775
MedSUV	Yes	Yes	14,325	12,409	10,555	8,765	7,038	6,393	5,760	5,127	4,495	3,862
Pickup	No	No	16,851	14,615	12,456	10,375	8,372	7,636	6,903	6,172	5,443	4,716
Pickup	No	Yes	18,908	16,500	14,172	11,922	9,751	8,974	8,222	7,470	6,718	5,967
Pickup	Yes	No	17,496	15,240	13,062	10,962	8,940	8,201	7,465	6,730	5,998	5,267
Pickup	Yes	Yes	19,552	17,126	14,778	12,510	10,320	9,539	8,783	8,028	7,273	6,518

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