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Update on electric vehicle costs in the United States through 2030

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This working paper assesses battery electric vehicle costs in the 2020–2030 time frame, collecting the best battery pack and electric vehicle component cost data available through 2018. The assessment also analyzes the anticipated timing for price parity for representative electric cars, crossovers, and sport utility vehicles compared to their conventional gasoline counterparts in the U.S. light-duty vehicle market.

INTRODUCTION

The early launch of electric mobility is underway in many parts of the world. Plug-in electric vehicle sales amounted to more than 2% of new light-duty vehicles in 2018 and experienced more than 70% sales growth from 2017 to 2018, culminating in a worldwide total of 5 million plug-in electric vehicles at the end of 2018. Figure 1 illustrates the distribution of electric vehicle sales through 2018 among 10 countries that make up 92% of these sales, showing how the major markets in Asia, Europe, and North America have led the market development to date. Electric vehicle uptake is especially concentrated where targeted electric vehicle policies proactively address electric vehicle barriers related to model availability, cost, convenience, and consumer awareness through incentives and regulations.

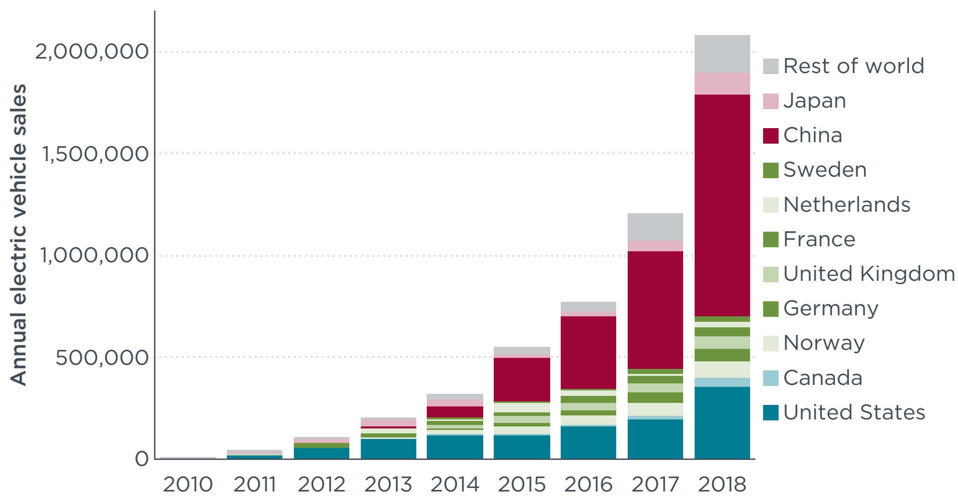

Figure 1. Global light-duty electric vehicle sales, 2010–2018.

Several automakers have stated their intentions to sell more than 15 million electric vehicles per year by 2025, up from 1.2 million in 2017 and 2 million in 2018.[1] This order of magnitude increase in electric vehicle deployment is directly related to the expected decline in battery pack cost over the 2017–2025 period. The increased production volume could further induce market competition and innovation in the battery supply chain, creating greater economies of scale and further cost reductions.

This paper analyzes projected electric vehicle costs from 2018 through 2030. The primary focus is on fully battery electric vehicles, with associated evaluation of plug-in hybrid electric vehicles, based on bottom-up cost analyses of lithium-ion battery packs and other electric components. An assessment is made of the time frame

1 Nic Lutsey, Modernizing vehicle regulations for electrification (ICCT: Washington DC, 2018), https://www.theicct.org/publications/modernizing-regulations-electrification

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expected for achieving upfront vehicle cost parity, which is based on initial costs, and first-owner cost comparisons for electric vehicles versus conventional gasoline vehicles. Questions about electric vehicle cost parity are broadly important to help inform the types of regulatory policy and incentives that would be most effective for the transition to a mainstream electric vehicle market.

BATTERY COSTS

This assessment summarizes several rigorous, detailed, and transparent technical studies published in 2017–2018 that quantify battery pack and overall electric vehicle costs. Forecasts, literature reviewed, and projections without explicit technical specifications for battery pack production (e.g., material, cell, pack costs; cost versus production volume; bottom-up cost engineering approach, etc.) are excluded, but applicable automaker statements are included.

Table 1 shows electric vehicle battery costs projections for 2020–2030 determined by select technical studies of battery production. The studies include a variety of different technologies, production volumes, and cost elements. Although there are differences in the methods described in each technical study, the methods generally include in some variation in material, process, overhead, depreciation, warranty, and profit; an exception is that the Ahmed et al. (2018), cited in the Table 1 notes, study excludes profit. The various studies find somewhat different battery cell- and pack-level costs, with typical cell-level costs making up from 70% to 76% of pack-level cost.

The studies in Table 1 also describe several key details about the basis for the battery pack cost. Such details commonly related to cost reduction include improved cathode chemistry to reduce the amount of higher-cost

Table 1. Electric vehicle battery pack cost ($/kWh) for 2020–2030, from technical reports and industry announcements.

Type	Report	2020	2022	2025	2030	Notes
Technical reports	Ahmed et al., 2018[a]	143	134	122		Pouch NMC 6,2,2-graphite, production volume-based; includes total cost to automaker for material, process, overhead, depreciation, warranty
	Anderman, 2017[b]		142			Cylindrical 21700, NCA 83,13,4, production volume-based; includes cost of material, capital, pack integration, labor, overhead, depreciation, R&D, administration, warranty, profit
	Anderman, 2018[c]	160		128		Pouch NMC 8,1,1-graphite, production volume-based; includes cost of materials, capital, pack integration, labor, overhead, depreciation, R&D, administration, warranty, profit
	Berckmans et al., 2017[d]	191	165	120	80	Pouch NMC 6,2,2-graphite anode, production volume-based; includes material, process, labor, overhead, depreciation, profit
		317	131	85	50	Pouch NMC 6,2,2-silicon alloy anode, production volume-based; includes material, process, labor, overhead, depreciation, profit
	UBS, 2017[e]	184		133		Pouch NMC 6,2,2-graphite, production volume-based; includes material, process, labor, overhead, depreciation, profit
Automaker statements	Davies, 2017[f]	152				Volkswagen statement. Associated with planned production volume of 100,000 per year by 2020 for I.D. series
	Lienert & White, 2018[g]	160	133			General Motors statement related to Chevrolet Bolt (NMC 6,2,2), associated 2020–2022 production volume has not been stated
	Tesla, 2018[h]	130	100			Tesla statement related to Model 3 production volume of 500,000 with Panasonic battery production in Nevada by 2020

Note: NMC = nickel manganese cobalt oxide; NCA = nickel cobalt aluminum (numbers refer to the proportion of each element); Unless cell and pack costs are provided within the study, a pack-to-cell cost ratio of 1.33 is assumed. Unless stated otherwise within the study, matching production volumes to year assumes 100,000 units/year in 2020 and 500,000 units/year for 2025. See studies for additional details, sensitivity analysis, differing chemistries, etc.

[a] Shabbir Ahmed, Paul Nelson, Naresh Susarla, and Dennis Dees, "Automotive Battery Cost Using BatPac" (2018), https://www.iea.org/media/Workshops/2018/Session2ShabbirAhmedANL.pdf

[b] Menahem Anderman, "The Tesla battery report: Tesla Motors: Battery technology, analysis of the Gigafactory and Model 3, and the automakers' perspectives" (2017), http://www.totalbatteryconsulting.com/industry-reports/Tesla-report/Extract-from-the-Tesla- Battery-Report.pdf

[c] Menahem Anderman, "The xEV Industry Insider Report" (2018), https://totalbatteryconsulting.com/industry-reports/xEV-report/Extract-from-the-2018-xEV-Industry-Report.pdf

[d] Gert Berckmans, Maarten Messagie, Jelle Smekens, Noshin Omar, Lieselot Vanhaverbeke, and Joeri Van Mierlo, "Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030," *Energies* 10, no. 9 (September 2017): 1314, https://doi.org/10.3390/en10091314

[e] UBS, "UBS evidence lab electric car teardown: Disruption ahead?" (2017), https://neo.ubs.com/shared/d1ZTxnvF2k/

[f] Chris Davies, "VW I.D. EV boast: We'll hugely undercut Tesla's Model 3 says exec," SlashGear, July 17, 2017, https://www.slashgear.com/vw-i-d-ev-boast-well-hugely-undercut-teslas-model-3-says-exec-17491688/

[g] Paul Lienert and Joseph White, "GM races to build a formula for profitable electric cars" (January 8, 2018), https://www.reuters.com/article/us-gm-electric-insight/gm-races-to-build-a-formula-for-profitable-electric-cars-idUSKBN1EY0GG

[h] Tesla, "2018 Annual Shareholder Meeting" (June 5, 2018), https://www.tesla.com/shareholdermeeting

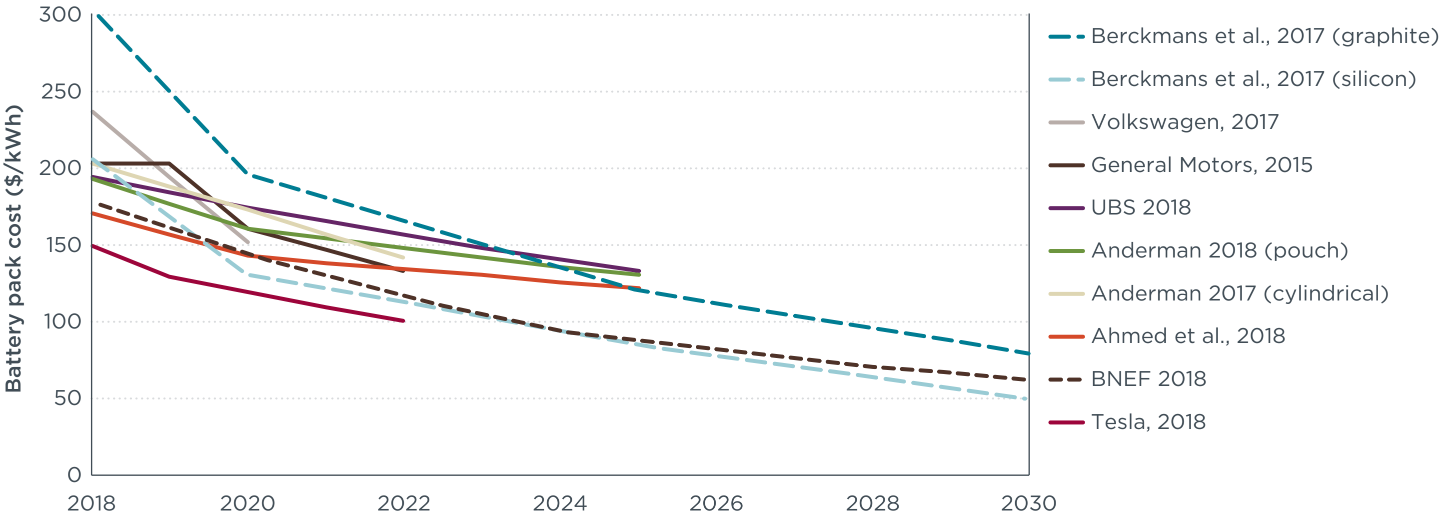

Figure 2. Electric vehicle battery pack costs from technical studies and automaker statements.

cell materials like cobalt, battery cell design to achieve greater energy density, battery pack improvements designed for further density improvements, and lower assembly costs that are the result of learning and much greater production volume. In addition to the automaker statements by Volkswagen, General Motors, and Tesla noted in Table 1, the near-term technical report results are corroborated by a survey of dozens of industry stakeholders conducted by Bloomberg New Energy Finance (BNEF),[2] as well as direct public statements from automakers. Nickel cobalt aluminum oxide (NCA) batteries in 2018 tended to be $100–$150 per kilowatt-hour (kWh), compared to nickel manganese cobalt oxide (NMC) batteries that are typical of other automakers and generally produced at lower volumes for $150–$200/kWh.

Figure 2 shows findings from the studies cited in the Table 1 notes to illustrate the likely range of battery pack costs for 2020–2030. Several estimates indicate that battery pack costs will decline to $130–$160/kWh by 2020–2022, and then to $120–$135/kWh by 2025. However, Tesla states it will reach $100/kWh by 2022, associated with its NCA-based battery pack technology and based on its earlier high-production volume. Berckmans et al. (2017) finds that even greater battery cost declines can be achieved with NMC cathode batteries, if the anode can transition from the 2018-dominant graphite to a silicon alloy while overcoming cycle-life issues. BNEF's industry survey indicates the volume-weighted average battery pack cost is $176/kWh and indicates pack-level costs will decline to $62/kWh in 2030.

In order to determine average battery cost for our assessment, industry average battery costs of $128/kWh at the cell level and $176/kWh at the pack level, which are assumed to be for a representative 45 kWh battery pack, are applied to costs for 2018. Matching battery costs to the middle of the trends in Table 1 sources, and reducing these costs by 7% per year, results in the battery pack-level costs—which vary by vehicle pack size—that are shown for various vehicles analyzed below. These battery cost estimates, often reassessed by the same groups with similar methods one or two years later, have trended lower each year. Also, leading high-volume companies will continue to have lower costs than the industry average values that are applied in this analysis. Assessing the speed of the cost reduction with such dynamics, as the technology matures, is difficult and uncertain. Therefore, a lower-cost battery pack assumption that matches the lowest estimates in the figure is applied for an additional sensitivity case.

VEHICLE COST ANALYSIS

This vehicle cost analysis assesses three light-duty passenger vehicles that are defined to be representative of three broad vehicle classes. The vehicles' initial cost and their total cost of ownership for the first owners of the vehicles are analyzed. The three vehicle classes are cars, crossovers, and sport utility vehicles (SUVs), which are based on the sales-weighted technical attributes from U.S. market model year 2016 data, the latest complete dataset for these vehicle classes' price, rated engine power, efficiency, and

2 Bloomberg New Energy Finance, "A Behind the Scenes Take on Lithium-ion Battery Prices" (March 5, 2019), https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

Table 2. Technical specifications for three analyzed vehicle classes.

		Conventional						Electric						Plug-in hybrid					
		Car		Crossover		SUV		Car		Crossover		SUV		Car		Crossover		SUV	
		2018	2030	2018	2030	2018	2030	2018	2030	2018	2030	2018	2030	2018	2030	2018	2030	2018	2030
Power (kW)		150	150	150	150	220	220	150	150	150	150	220	220	150	150	150	150	220	220
Fuel economy (mpg)		30	37	26	33	20	25							47	56	41	49	27	32
Range[a] (miles)	**Short**							150	150	150	150	150	150						
	Mid							200	200	200	200	200	200	50	50	50	50	50	50
	Long							250	250	250	250	250	250						
Electric efficiency (kWh/mile)	**Short**							0.28	0.26	0.34	0.31	0.48	0.44						
	Mid							0.29	0.27	0.35	0.32	0.50	0.46	0.31	0.29	0.37	0.34	0.53	0.49
	Long							0.30	0.28	0.36	0.33	0.51	0.47						
Battery pack (kWh)	**Short**							42	39	50	46	72	66						
	Mid							58	54	69	64	99	92	15	14	19	17	27	25
	Long							75	69	90	83	128	119						
Utility factor	**Short**							0.93	0.93	0.93	0.93	0.93	0.93						
	Mid							0.95	0.95	0.95	0.95	0.95	0.95	0.69	0.69	0.69	0.69	0.69	0.69
	Long							0.97	0.97	0.97	0.97	0.97	0.97						
Pack cost ($/kWh)	**Short**							$177	$74	$175	$74	$175	$73						
	Mid							$175	$73	$175	$73	$167	$72	$210	$88	$210	$88	$200	$86
	Long							$175	$73	$172	$73	$154	$64						

Note. kW = kilowatt; mpg = miles per gallon gasoline; kWh = kilowatt-hour. Numbers are rounded. Vehicle efficiency and range are based on U.S. consumer label values. [a]For range designations, short = BEV150, mid = BEV200 and PHEV50, long = BEV250.

vehicle size.[3] The crossovers include station wagons and small SUVs,of which approximately half are classified as passenger cars and half as light trucks for regulatory purposes. Based on the 2016 data, the three vehicle classes represent 41%, 26%, and 22%, respectively, of new U.S. light-duty vehicle sales. The remaining 11% of the U.S. light-duty vehicle market is pickup trucks, which are not analyzed in this report because of the lack of information about applicable electric vehicle components and specifications. The comparable average conventional gasoline vehicle prices were about $29,000 for cars and crossovers and $41,000 for SUVs.

The primary focus of the study is on fully battery electric vehicles (BEVs), although several equivalent calculations for plug-in hybrid electric vehicles (PHEVs) with gasoline engines also are included in the evaluation. Because the electric vehicle market is expected to continue to include lower-cost, lower-range options and higher-cost, higher-range options, this analysis includes 150-mile (BEV150), 200-mile (BEV200), and 250-mile (BEV250) BEVs and a 50-mile PHEV (PHEV50).

Table 2 shows the technical vehicle specifications for the conventional gasoline, electric, and plug-in hybrid vehicles for three vehicle classes in 2018 and 2030. The technical specifications include rated power in kilowatts (kW), fuel economy in miles per gallon (mpg), electric range in miles, electric efficiency in kilowatt-hours per mile (kWh/mile), and battery pack size in kilowatt-hours (kWh). Also applicable for electric and plug-in hybrids is the utility factor, which is the fraction of daily miles that could be powered electrically by the vehicles of the given electric range. These utility factors range from 0.69 for 50-mile plug-in electric hybrids up to 0.97 for 250-mile electric vehicles,[4] which is described and applied in the evaluation of vehicle ownership costs below.

The initial 2018 electric vehicle efficiencies of these vehicles are based directly on existing model year 2018 electric vehicle models, accounting for increased electricity-per-mile for longer-range electric vehicles due to larger, heavier battery packs.[5] In addition, the crossover vehicle efficiency accounts for the general difference in efficiency from cars to crossovers and the crossover having all-wheel drive. For the SUV, the electric efficiency accounts for the vehicle being a larger, heavier

3 Dataset from National Highway Traffic Safety Administration, "Compliance and Effects Modeling System" (2018), https://www.nhtsa.gov/corporate-average-fuel-economy/compliance-and-effects-modeling-system. Examples of representative models for cars are Ford Fusion, Honda Accord, Nissan Altima; for crossovers, Ford Escape, Honda CR-V, Toyota RAV4; and for SUVs, Ford Explorer, Honda Pilot, and Toyota Highlander.

4 For further information, see SAE International. *Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data*, (J2841 2010-09), https://www.sae.org/standards/content/j2841_201009/

5 U.S. Department of Energy, "Download fuel economy data" (2019), https://www.fueleconomy.gov/feg/download.shtml

Table 3. Electric vehicle component costs from various studies.

Type	Component	UBS (2017) costs			How UBS costs are adapted to determine electric vehicle costs for this analysis
		Gasoline	2017 electric	2025 electric	
Electric vehicle powertrain	Battery pack	-	$11,500	$8,000	The UBS estimate shown here is for $133/kWh in 2025. This is updated to $104/kWh in 2025 and $72/kWh in 2030 for this analysis this by applying pack-level cost reduction of 7% per year based on research noted in the text.[a]
	Thermal management	-	$250	$225	Electric powertrain costs are based on UBS component costs for cars and crossover vehicles (150 kW) and scaled up by 47% (220 kW versus 150 kW) for SUVs.[b]
	Power distribution module	-	$250	$295	
	Inverter/converter	-	$697	$523	
	Electric drive module	-	$1,200	$1,080	
	DC converter	-	$150	$134	
	Controller	-	$51	$46	
	Control module	-	$93	$84	
	High voltage cables	-	$335	$302	
	On-board charger	-	$273	$205	
	Charging cord	-	$150	$135	
Conventional powertrain	Powertrain (engine, transmission, exhaust, etc.)	$6,800	-	-	UBS costs are scaled up to reflect the higher power of U.S. average cars and crossover vehicles by 18% (150 kW versus 127 kW) and SUVs by 74% (220 kW versus 127 kW)[b]
Other direct	Vehicle assembly	$12,700	$12,600	$11,900	For vehicle assembly, UBS costs are scaled up to account for the larger footprint of average U.S. vehicles: 6% for cars, 5% for crossovers, and 21% for SUVs.[b] This also includes the incremental costs of vehicle improvements needed to meet efficiency standards.
Indirect cost	Includes depreciation, amortization, research and development (R&D), and administration expenses	$4,000	$10,584	$3,200	Based on UBS, combustion vehicle indirect costs are fixed at 20.5% of direct costs. For electric vehicles, the same proportional R&D indirect cost reduction over time that UBS used for cars is assumed for all three vehicle classes.

[a] See Table 1 and Figure 2. Average $/kWh values shown, precise value by vehicle class and year differ by battery capacity

[b] Average car and crossover (150 kW) and SUV (220 kW) power based on sales-weighted averages from U.S. model year 2016 data. See NHTSA: https://www.nhtsa.gov/corporate-average-fuel-economy/compliance-and-effects-modeling-system

vehicle and having all-wheel drive and towing capacity.

The bottom three rows of Table 2 show the battery pack costs per kWh for 2018 and 2030. The resulting battery cell-level costs, averaged across the three BEV cases, are $78/kWh in 2025 and $56/kWh in 2030. A decreasing pack-to-cell ratio with increasing pack capacity is assumed,[6] meaning larger battery packs (e.g., for 250-mile range SUV) have lower per-kilowatt-hour pack costs. The resulting average pack-level costs across these BEV cases decline to $104/kWh in 2025, and to $72/kWh in 2030. The SUV with the largest pack size in 2030 has the lowest per-kilowatt-hour cost among these cases at $64/kWh. PHEV pack-level costs are assumed to remain 20% higher than those for BEVs throughout the time frame of the analysis.

Table 3 summarizes electric vehicle component and vehicle-level costs from UBS,[7] which are based on a vehicle teardown study of the

6 The pack-to-cell ratios considered here range from 1.54 for a 16 kWh pack down to 1.2 for 112 kWh and larger packs. See Michael Safoutin, Joe McDonald, and Ben Ellies, "Predicting the Future Manufacturing Cost of Batteries for Plug-In Vehicles for the U.S. Environmental Protection Agency (EPA) 2017–2025 Light-Duty Greenhouse Gas Standards," World Electric Vehicle Journal, 2018, 9 (3): 42, https://doi.org/10.3390/wevj9030042

7 UBS, "UBS evidence lab electric car teardown: Disruption ahead?" (2017), https://neo.ubs.com/shared/d1ZTxnvF2k/

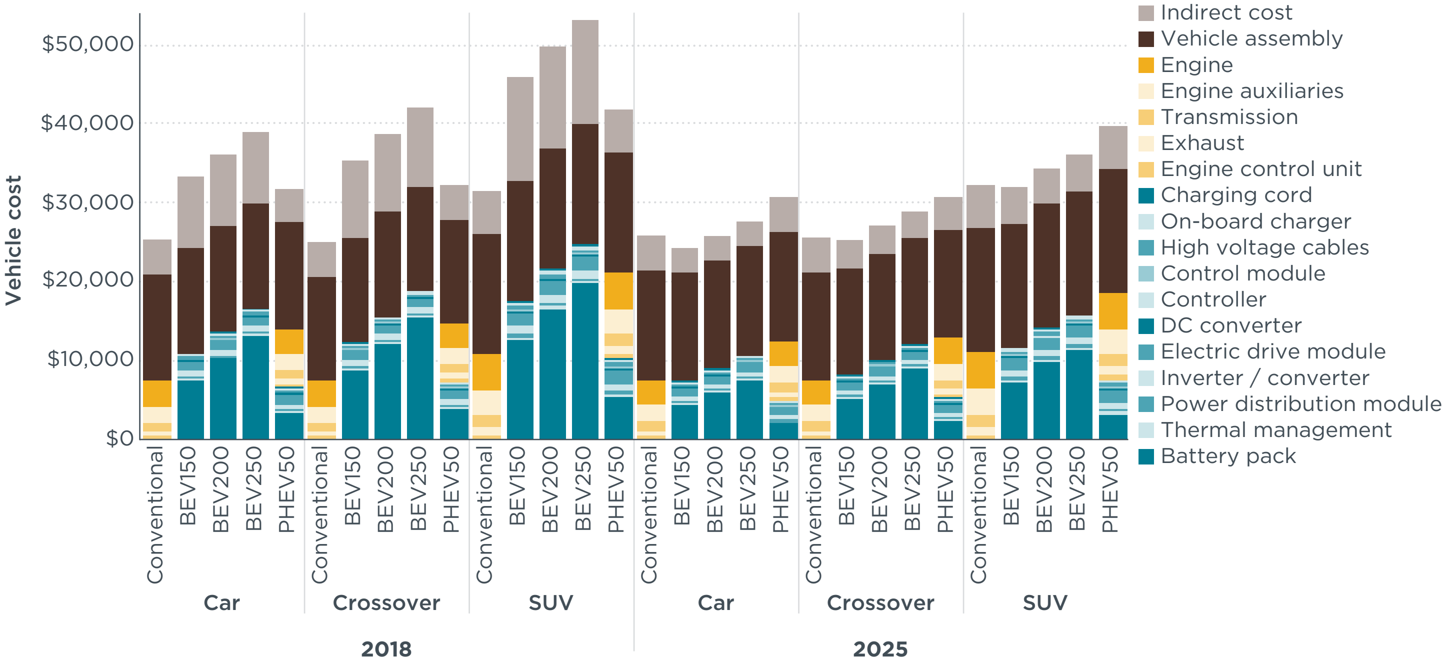

Figure 3. Vehicle technology costs for conventional and electric vehicles in 2018 and 2025 for cars, crossovers, and SUVs.

Chevrolet Bolt with a 60 kWh battery pack and electric power output of 145 kW. The highest-cost electric vehicle component is the battery pack, which declines from $11,500 to $8,000, based on UBS' estimate that the pack cost reaches $133/kWh by 2025. This analysis relies on the UBS teardown data, making several updates to incorporate the latest battery cost data and to adapt the UBS values for the crossover and SUV vehicle classes. The key change to the UBS numbers is updating the battery pack cost to reflect the latest previously mentioned research, leading to an average pack cost in this analysis of $104/kWh in 2025. Explanations of how the UBS data are updated and adapted for this analysis are included in the rightmost column. For example, powertrain components are scaled to vehicle power, vehicle-level manufacturing costs are scaled to the vehicle footprint, and indirect costs are treated as a percentage of direct costs.

As indicated in Table 3, a major cost reduction comes from the reduced indirect costs. UBS' indirect cost reductions for electric vehicles amount to a reduction from 66% of direct non-battery vehicle costs in 2017 down to 21% in 2025. These electric vehicle indirect costs—which include research and development, depreciation, and amortized costs from electric vehicle investments—see substantial declines of about 70% from 2017 to 2025 because those costs are spread across greatly increased electric vehicle production.

Several additional assumptions are included to incorporate other factors in the vehicle cost analysis. Increased fuel economy improvements for conventional gasoline vehicles and associated incremental price increases—$700 for cars, $800 for crossovers, and $1,000 for SUVs—are applied to meet expected vehicle efficiency regulations through 2025.[8] To incorporate these incremental cost increases for each year from 2018 through 2030, the upfront vehicle price increases by approximately 0.35% annually.

The applicable vehicle costs, including conventional and electric vehicle technology components, are illustrated in Figure 3. As indicated, electric vehicle costs in 2018 are substantially higher than conventional vehicle costs for the three vehicle classes, by $8,000 for a short-range car to $21,000 for a long-range SUV. By 2025, BEV costs approach the cost of a conventional vehicle that year, ranging from somewhat lower for a BEV150 car, crossover, and SUV up to about $3,700 higher for a BEV250 SUV. Although there are reductions in PHEV50 costs by 2025, their overall cost is $4,900–$7,500 higher than their conventional gasoline counterparts in 2025.

As shown in Figure 3, declining battery costs account for much of the decline in electric vehicle costs. For example, the 200-mile electric crossover battery pack drops by more than 42% from more than $12,000 in 2018 to less than $7,000 in 2025, because of the

8 Nic Lutsey, Dan Meszler, Aaron Isenstadt, John German, and Josh Miller, Efficiency technology and cost assessment for U.S. 2025–2030 light-duty vehicles (ICCT: Washington DC, 2017), http://www.theicct.org/US-2030-technology-cost-assessment

reduced battery cell cost, lower pack-level assembly cost, and increased vehicle efficiency allowing for less battery capacity. Indirect costs contribute an even larger amount of the overall reduction in cost for electric vehicles. Electric vehicles' indirect costs per vehicle—$9,000 for cars and crossovers, and $13,000 for SUVs—are much higher than those of conventional vehicles—$4,200 for cars, $4,300 for crossovers, and $5,400 for SUVs—in 2018. These electric vehicle indirect costs drop largely because of the reduced R&D per vehicle over time. Many electric vehicle components—especially the high-cost battery cells—are developed by a competitive supplier base, rather than directly by automakers, so this continues a long-time trend toward more supplier content in vehicles.

Several other assumptions link the vehicle costs in Table 3 to the price of the vehicle based on applicable industry-average dealer and profit markups. Based on UBS,[9] cars maintain a 15% dealer markup and have a 5% profit. For the other two vehicle classes and across all technologies, the same 15% markup for dealer incentives and marketing is assumed over time. The analysis applies a 15% profit for SUVs and a 10% profit for crossovers, the midpoint between the car and SUV. This is done for consistency and to ensure electric vehicles have the same profit built in as the profit assumed for conventional vehicles. In addition, an 8.5% purchase tax is included for all vehicles, approximately matching the U.S. average. These assumptions do not affect the timing of initial cost parity attainment for electric vehicles because they are taken as constant for all the technology types.

9 UBS, "UBS evidence lab electric car teardown: Disruption ahead?" (2017), https://neo.ubs.com/shared/d1ZTxnvF2k/

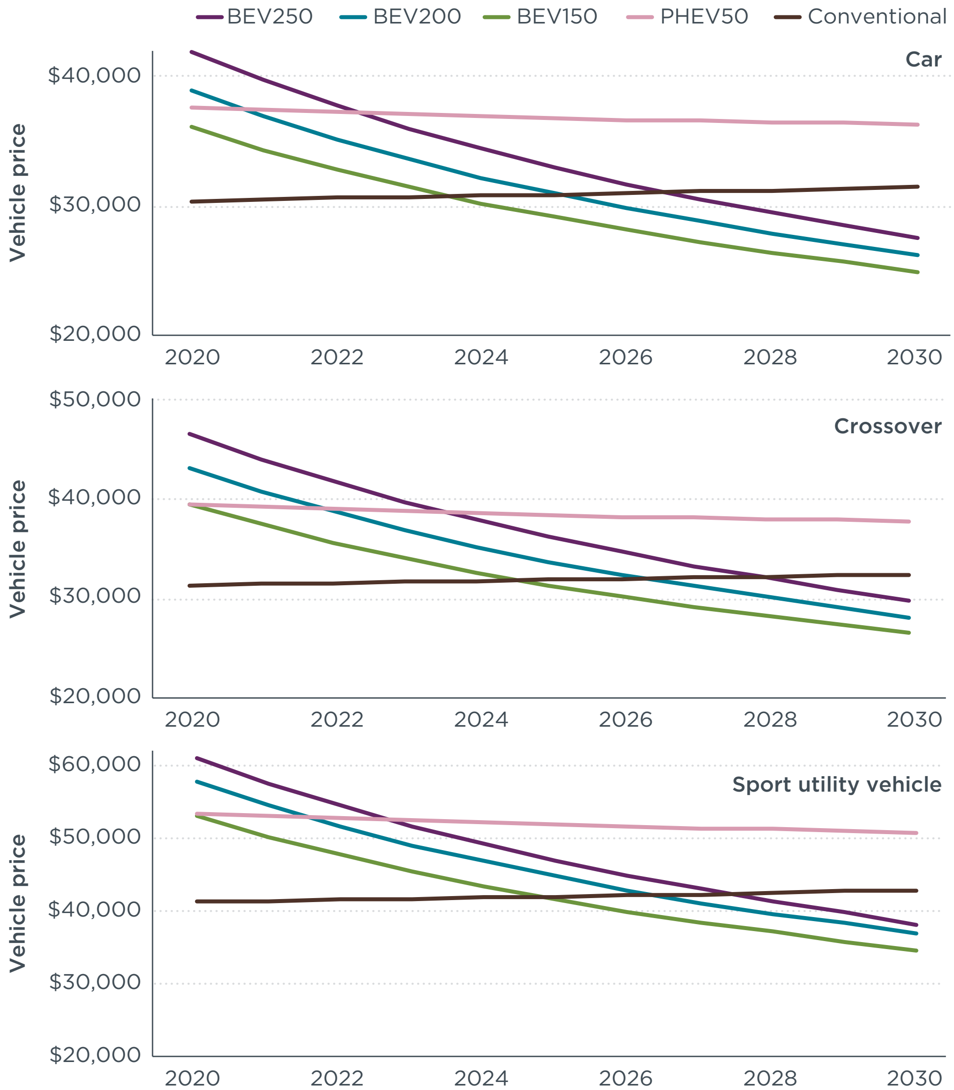

Figure 4. Initial purchase price of conventional vehicles and electric vehicles for cars, crossovers, and SUVs for 2020–2030.

ELECTRIC VEHICLE PRICE PARITY

From the preceeding technical specifications of the vehicle technologies for the three vehicle classes, changing vehicle prices are assessed through 2030. As described, the evaluation matches the technical specifications of average U.S. market car, crossover, and SUV categories. Figure 4 shows the vehicle technology prices for the car (top segment), crossover (middle), and SUV (bottom). Each segment includes the average conventional gasoline vehicle (gray line), increasing incrementally as the average vehicle gets more efficient by adding powertrain and road-load efficiency improvements. Each segment of the figure reflects the changing technology costs for electric vehicles of different ranges (i.e., BEV150, BEV200, BEV250, PHEV50).

Figure 4 shows that electric vehicles will see substantial cost reductions resulting from battery technology, scale improvements, and reduced indirect costs from lower automaker research and development costs over the 2020–2030 time frame. The 150-mile electric vehicles achieve cost parity, crossing the conventional vehicle line, sooner than the longer-range electric vehicles. For the BEV150 vehicles, cost parity is met for the electric car in 2024, and in 2025 for the crossover and SUV. The longer-range electric vehicles achieve parity later—in 2025 for the BEV200 car, 2026 for the BEV200 crossover and SUV, 2027 for the BEV250 car and SUV, and 2028 for the BEV250 crossover. These later years for cost parity are because the BEV200 and BEV250 vehicles' larger battery packs add costs of $1,600–$3,300 for cars, $1,900–$3,900 for crossovers, and $2,400–$4,100 for SUVs above the battery costs of the BEV150 by 2025.

PHEV50s are also shown in Figure 4. PHEVs see a reduction in cost differential versus conventional gasoline vehicles by 2030, but there is no foreseeable initial cost parity point with conventional vehicles. The PHEV50 car price differential compared to conventional vehicles declines from $7,300 in 2020 to $4,900 in 2030. The PHEV50 SUV price differential drops from $12,000 in 2020 to $8,000 in 2030. There are two major reasons that PHEVs, unlike BEVs, do not have a point of cost parity. First, the battery pack is a much lower contributor to the PHEV price, so even dramatic battery cost reductions have less effect. Second, the PHEV retains the powertrain parts of the combustion vehicle while also adding new electric components. As shown, PHEVs with significant electric range (in this case 50 miles) will remain more expensive than conventional vehicles, and the price advantage of BEVs over PHEVs will grow substantially from about 2024 on.

CONSUMER COST COMPETITIVENESS

In addition to the question of initial purchase price parity is the question of when cost-competitiveness is experienced by an electric vehicle consumer who owns and operates the vehicle for several years. The prospective electric vehicle driver's cost-of-ownership parity is analyzed by applying several additional average U.S. new vehicle driver assumptions. The first owner of the vehicle is assumed to operate the vehicle for 5 years, which is typical of vehicle ownership and vehicle leasing terms in the United States.

For analyzing vehicle energy expenditures, fuel and electricity prices are taken from the U.S. Energy Information Administration, where gasoline increases from $2.90 to $3.48 per gallon from 2018 to 2035 and electricity increases from $0.12/kWh to $0.13/kWh from 2018 to 2035.[10] To assess future-year fuel costs, a discount rate of 5% for each year beyond the purchase year is included in net present value accounting. For the annual travel activity, data are applied from the Transportation Energy Data Book.[11] The new vehicle miles traveled for cars start at 13,800 in the first year and decrease to 12,700 by the fifth year; for the SUVs, annual driving drops from 16,000 in the first year to 14,500 in the fifth year. For crossovers, the average of these two trends is applied. Conventional vehicle maintenance costs are assumed to be $0.061, $0.065, and $0.094 per mile for the car, crossover, and SUV, respectively, as well as BEV maintenance costs of $0.026, $0.029, and $0.39 per mile.[12]

Several additional factors are applied to the ownership costs for electric vehicles. First, a home charger cost of $1,300 for BEVs and $300 for PHEVs is included to enable more convenient residential charging. A utility factor is applied to incorporate how BEVs and PHEVs typically are driven for fewer annual electric miles than typical new vehicle annual driving averages. The utility factor estimates the average fraction of daily miles covered by electric vehicles of the given electric range (e.g., 0.69 for the PHEV50, 0.93 for the BEV150, and 0.97 for the BEV250).[13] The remaining miles (31% for the PHEV50, 7% for the BEV150, 3% for the BEV250) are therefore expected to be covered by nonelectric driving. PHEVs are simply driven in gasoline-powered charge-sustaining hybrid mode for the remaining miles. For BEVs, the nonelectric driving would be by a "replacement" vehicle, for example a separate vehicle in that household, a rental, or a ride-hailing vehicle. For consistency for BEV replacement miles, the total cost of ownership values from combustion vehicles from within this analysis are applied (per-mile costs of $0.63 for the car, $0.66 for the crossover, and $0.75 for the SUV in 2018).

10 U.S. Energy Information Administration, Annual Energy Outlook 2019 (U.S. Department of Energy, January 24, 2018), https://www.eia.gov/outlooks/aeo/index.php

11 Oak Ridge National Laboratory, Transportation Energy Data Book (Edition 36. August 31, 2018), https://cta.ornl.gov/data/editions/Edition36_Full_Doc.pdf

12 Car values from UBS, "UBS evidence lab electric car teardown: Disruption ahead?" (2017), https://neo.ubs.com/shared/d1ZTxnvF2k/. Crossover and SUV values are scaled up from cars, proportional to manufacturing cost. PHEV per-mile maintenance assumed to be the average of conventional and BEV costs.

13 For further information, see SAE International, *Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data*, (J2841 2010-09), https://www.sae.org/standards/content/j2841_201009/

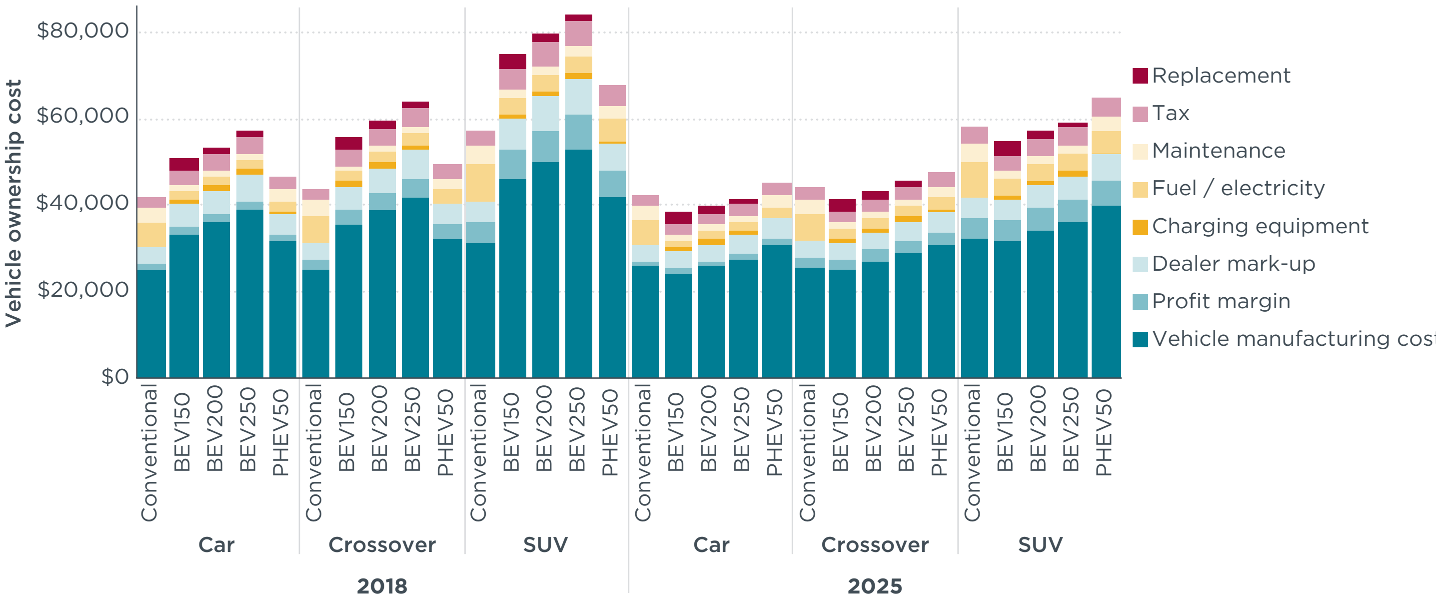

Figure 5. Total vehicle ownership costs for conventional and electric vehicles in 2018 and 2025 for cars, crossovers, and SUVs.

Figure 5 illustrates manufacturing, markup, charging, fueling, maintenance, tax, and vehicle replacement costs. The figure shows the 5-year ownership costs for the three vehicle classes, for conventional and electric vehicles, in 2018 and 2025. The vehicle manufacturing costs match those in Figure 3, but the addition of the other factors in the figure make overall BEV ownership costs lower than the conventional vehicle in seven of the nine BEV cases in 2025. After vehicle costs, the most important factor affecting the relative costs of the technologies is fuel savings. In 2025, the first-owner fuel cost for an average new car buyer is $5,400 for gasoline, compared to about $1,800–$2,000 in electricity for the electric vehicles using our net present value assumptions. For the SUV, the average conventional vehicle consumes $8,100 in gasoline versus $3,600–$4,000 in electricity in 2025. BEVs also accrue relative maintenance cost savings, but have the additional costs of charging equipment and a replacement vehicle with which to make up the forgone miles from its shorter range.

Figure 6 shows the total 5-year vehicle ownership costs for the car (top segment), crossover (middle), and SUV (bottom). Each of the segments includes the average conventional gasoline vehicle (gray line), and the ownership costs for the BEV150, BEV200, BEV250, and PHEV50 vehicles for 2020–2030. As shown in Figure 4 for vehicle cost, the dominant feature is that the BEVs see substantial cost reductions from battery technology and scale improvements. In addition, the BEVs see significant fuel savings, which in turn make their ownership cost parity year with the conventional vehicle occur from 1.4 to 2.2 years sooner than their initial cost parity year across the nine BEV cases.

A comparison of Figure 6 and Figure 4 shows that from a consumer ownership perspective, electric vehicles are an attractive proposition several years before initial price parity. A major factor is the fuel savings associated with electric vehicles, specifically the conventional vehicle fuel costs minus the electricity costs for BEVs. For example, the fuel cost savings for the first vehicle owner of the BEV200 electric vehicle in 2025 are approximately $3,500 for cars, $3,900 for crossovers, and $4,200 for SUVs compared to the average conventional vehicle of that class. The shorter-range BEV150s reach first-owner parity about 1.5 years before the BEV200 and about three years before the BEV250. PHEVs see a substantially reduced ownership cost differential with conventional vehicles, by about half from 2020 to 2030, but they do not see cost parity within that time frame.

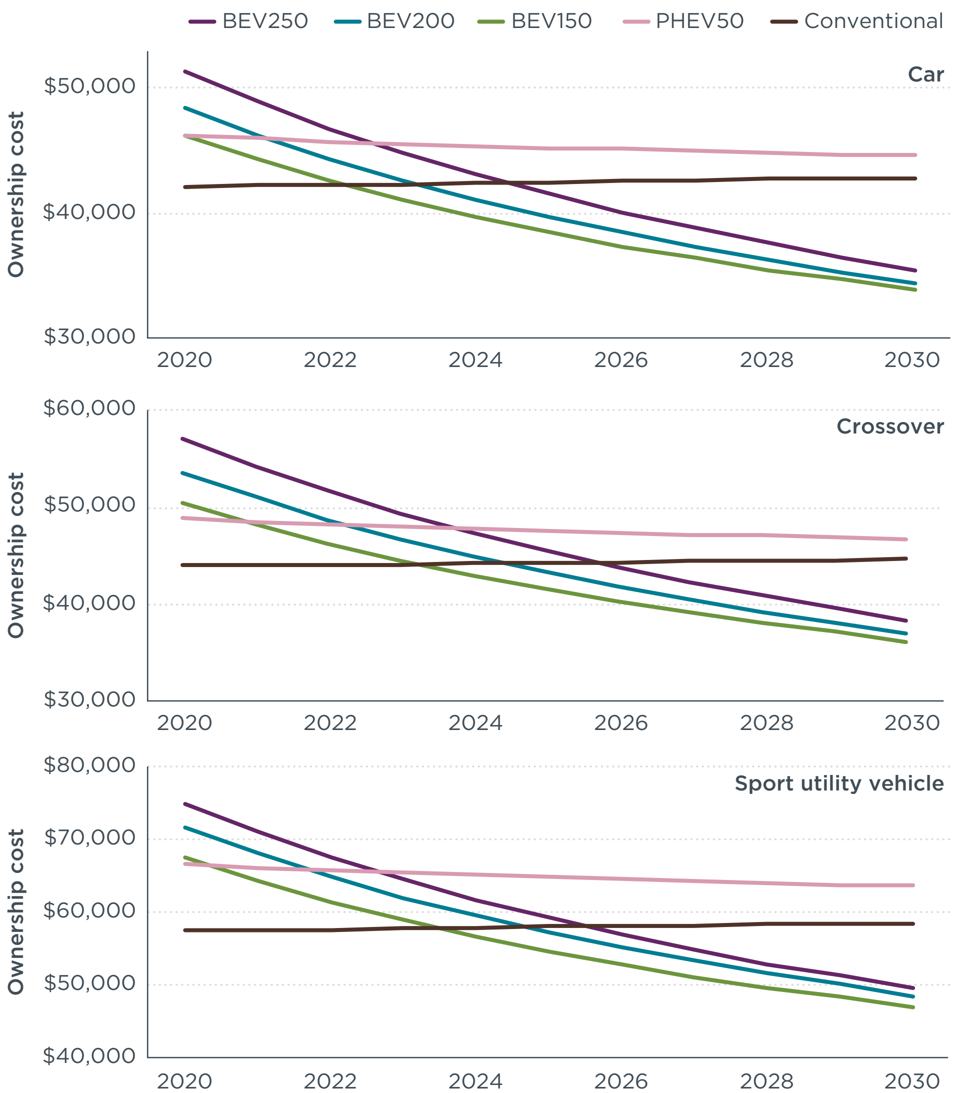

Figure 6. Ownership cost of conventional vehicles and electric vehicles for cars, crossovers, and SUVs for 2020–2030.

CONSIDERATION OF LOWER BATTERY COST

Acknowledging that nearly every study, including studies by the referenced authors and by the ICCT's own previous analysis, have underpredicted battery cost reductions, a lower-cost sensitivity case is included as part of this analysis. This low-cost case helps in examining how further reductions in battery costs would affect this assessment regarding electric vehicle cost parity. For the lower-cost case, a 9% annual cost decline is applied instead of the central assumption above for a 7% per year battery cell cost reduction. This lower-cost case results in average battery pack-level costs of $89/kWh in 2025 and $56/kWh in 2030, compared to $104/kWh in 2025 and $72/kWh in 2030 in the primary analysis in the preceding sections. The costs determined in the lower-cost case more closely match those of Bloomberg New Energy Finance (see footnote 2) and the Berckmans et al. (2017) silicon alloy anode case cited in the notes to Table 1.

Figure 7 shows the year of cost parity based on initial vehicle cost and first-owner total ownership costs for the primary and low-cost cases. The years for the lower-cost electric vehicle cases are shown as lighter color data points in the figure. The lower battery cost generally moves the parity point with conventional combustion vehicles approximately one year earlier, although the effect differs by vehicle class and BEV range. The effect of battery cost reduction on shortening the time required to reach cost parity is greater for longer-range crossovers and SUVs because of their larger battery sizes. For initial cost parity, the lower-cost scenario brings parity forward 1.2 years for the BEV250 crossover and just 0.4 years for the BEV150 car. For first-owner total ownership costs, the lower-cost case brings cost parity forward to a lesser extent; the average decrease in the time needed to reach cost parity across the nine vehicle types is 0.6-years, ranging from 0.9 years for the BEV250 crossover to 0.2 years for the BEV150 car.

CONCLUSIONS

This working paper synthesizes available technical data to analyze electric vehicle costs for cars, crossovers, and SUVs through 2030. The work assesses the time frame for upfront vehicle cost parity (based on initial costs) and first-owner cost competitiveness (based on a first owner's use with fuel savings)

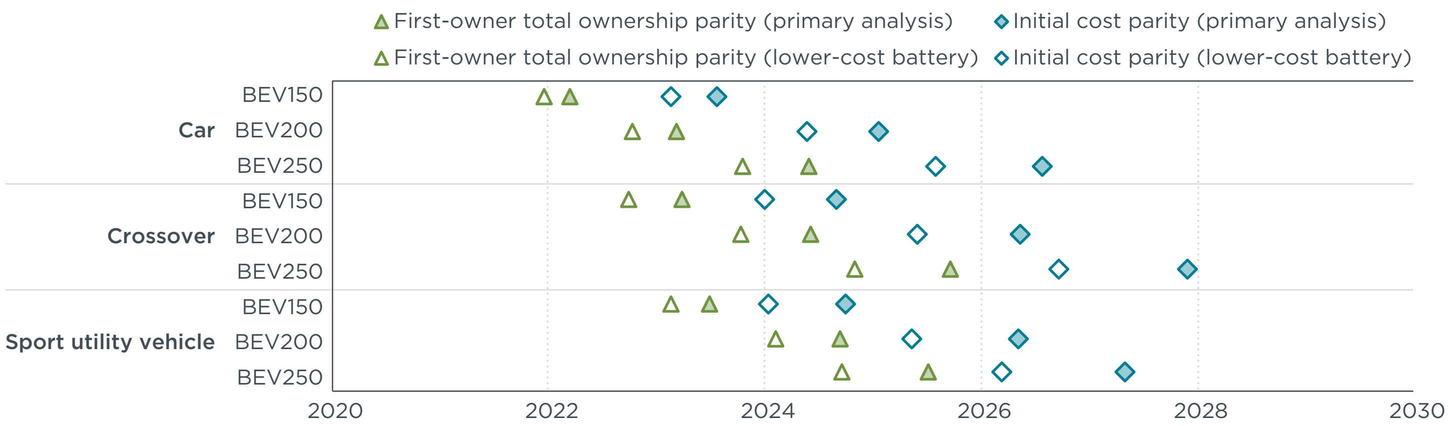

Figure 7. Year of cost parity based on first-owner total cost of ownership and initial vehicle cost, shown for the primary analysis and a lower-cost battery scenario.

for electric vehicles versus conventional gasoline vehicles. The analysis reveals two high-level findings.

Electric vehicle initial cost parity is coming within 5–10 years. As battery pack costs drop to approximately $104/kWh in 2025 and $72/kWh in 2030, electric vehicle cost parity with conventional vehicles is likely to occur between 2024–2025 for shorter-range and 2026–2028 for longer-range electric vehicles. This applies to typical electric cars, crossovers, and SUVs. If faster battery cost breakthroughs lead to a further reduction in battery costs, for example to $89/kWh in 2025 and $56/kWh in 2030, this will bring electric vehicle initial cost parity forward by approximately one year.

Cost-competitiveness for consumers approaches even faster than initial cost parity based on fuel savings. Analysis of first-owner 5-year ownership costs indicates that an average new vehicle buyer will see an attractive proposition to choose electric vehicles in the 2022–2026 time frame. The consumer ownership parity point for each vehicle application is one to two years sooner than initial cost parity, due to the high fuel savings of electric vehicles. For example, the first owners of 200-mile electric vehicles realize fuel savings of $3,500 for cars, $3,900 for crossovers, and $4,200 for SUVs, based on electricity costs typically being much lower than conventional vehicle gasoline expenses.

Despite these positive findings, electric vehicles achieving cost parity does not ensure a complete transition to electric mobility. Norway, for example, provides incentives to make electric vehicles cost less than conventional vehicles.[14] This has increased all-electric vehicle sales from nearly zero in 2012 to 30% of new vehicles in 2018. The relative progress in Norway underscores the importance of incentives. But it also underscores the insufficiency of cost parity to transition to an all-electric market; if cost parity was the only critical barrier, markets with such compelling incentives would more rapidly approach 100% electric. To comprehensively address the barriers to adoption, policies can encourage or require more electric models,[15] a robust charging infrastructure ecosystem to ensure convenience,[16] and programs to inform consumers.[17]

This analysis has several limitations. The work is focused on average cars, crossovers, and SUVs without acknowledging heterogenous household vehicle needs. Technologies like plug-in electric hybrids may still be attractive for particular households, such as those with short commutes, frequent long-distance travel, and available home and workplace charging. Also, this analysis does not address pickups, which represent 11% of the U.S. light-duty vehicle market. Electric technology now has migrated from cars to crossovers and larger SUV models (e.g., Audi e-tron, Hyundai Kona, Tesla Model X, and

14 Sandra Wappelhorst, Peter Mock, and Zifei Yang, Using vehicle taxation policy to lower transport emissions: An overview for passenger cars in Europe (ICCT: Washington DC, 2018), https://www.theicct.org/publications/using-vehicle-taxation-policy-lower-transport-emissions

15 Peter Slowik and Nic Lutsey, The continued transition to electric vehicles in U.S. cities (ICCT: Washington DC, 2018), https://www.theicct.org/publications/continued-EV-transition-us-cities-2018

16 Michael Nicholas, Dale Hall, and Nic Lutsey, Quantifying the electric vehicle charging infrastructure gap across U.S. markets (ICCT: Washington DC, 2019), https://www.theicct.org/publications/charging-gap-US

17 Kenneth Kurani, Nicolette Caperello, and Jennifer TyreeHageman, New Car Buyers' Valuation of Zero-Emission Vehicles: California (Institute of Transportation Studies, University of California Davis, 2016), https://its.ucdavis.edu/research/publications/

many plug-in electric hybrids). Further migration into pickups with greater towing requirements has been slower, but electric pickup announcements continue from companies like Tesla, Ford, Rivian, and Workhorse. Improved cost analysis of charging infrastructure is also important, and cost savings depend on policies that ensure electricity prices remain relatively low.

The findings in this paper lead to several policy implications. Battery costs, electric vehicle volume, and policy move in unison. The electric vehicle cost projections in this analysis are predicated upon sustained policy that drives increased electric vehicle battery volume. Nearly all of the electric vehicles in the world—more than 5 million through 2018—are in markets with regulations that require low-emission vehicles, offer incentives of thousands of dollars per vehicle, provide charging infrastructure, and have complementary awareness campaigns. Automaker announcements of plans to increase electric vehicle production by an order of magnitude by 2025 are largely consistent with this. Setbacks with regulations and incentives would slow progress, whereas stronger regulatory policy in more markets around the world would expedite the cost parity time frame presented here.

Regulatory agencies have failed to acknowledge how quickly electric vehicles will reach cost parity with conventional vehicles. U.S. regulatory analysis, based on outdated data, indicates that electric vehicle costs remain dramatically higher than conventional vehicle costs through 2025.[18] Based on the analysis provided herein, this is not the case. Similar analysis focused on markets around the world could, similarly, reveal that the most up-to-date electric vehicle cost data could justify much stronger regulations. As the cost parity point is reached, governments can dramatically accelerate the shift to clean mobility with regulations that spur electric vehicle deployment.

18 The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021–2026 Passenger Cars and Light Trucks; Notice of Proposed Rulemaking, 49 Code of Federal Regulations (Vol 83, August 24, 2018).