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ASSESSMENT OF LIGHT-DUTY ELECTRIC VEHICLE COSTS AND CONSUMER BENEFITS IN THE UNITED STATES IN THE 2022–2035 TIME FRAME

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EXECUTIVE SUMMARY

As global electric vehicle production volumes proliferate, their costs decline and the prospects of a transition to electric vehicles increase. Governments around the world are working to accelerate the transition to zero emission transportation to meet air quality, climate, energy security, and industrial development goals. The United States is looking to reverse its laggard position by promoting electric vehicles with actions in the supply chain, regulations on automakers, incentives for consumers, and support to deploy charging infrastructure.

Improvements in battery and electric vehicle technology lead to research questions about how quickly electric vehicle costs will decline and reach price parity with conventional vehicles, and also about the magnitude of the associated fuel-saving benefits. This paper analyzes bottom-up vehicle component-level costs to assess battery electric, plug-in hybrid electric, and conventional vehicle prices across the major classes of the U.S. light-duty vehicle market through 2035. We apply these cost estimates to evaluate vehicle costs and their broader consumer benefits and discuss the implications for vehicle emission regulations in the United States.

Figure ES1 summarizes the findings for average conventional gasoline and electric vehicle prices through 2035 for U.S. cars, crossovers, SUVs, and pickups, which represent all light-duty vehicle sales in the United States. Conventional vehicles in these classes are compared with battery electric vehicles (BEVs) with electric ranges from 150 to 400 miles and plug-in hybrid electric vehicles (PHEVs) with ranges of 20 to 70 miles. Battery electric vehicles have upfront prices that are about $3,000 to $25,000 greater than their gasoline counterparts in 2022. With declining electric vehicle battery and assembly costs, shorter-range BEVs of 150 to 200 miles are projected to reach price parity by 2024–2026, followed by mid-range BEVs with 250 to 300 miles around 2026–2029, and the longest-range BEVs with 350 to 400 miles around 2029–2032. PHEV prices decline at a relatively slower rate due to their relatively smaller battery packs and the additional combustion powertrains; no PHEVs in any class reach price parity with conventional vehicles over the time frame of this analysis.

Figure ES1. Conventional, battery electric, and plug-in hybrid electric vehicle prices of cars, crossovers, sport utility vehicles, and pickups in the United States for 2022–2035.

Table ES1 summarizes the year by which battery electric vehicles reach price parity with conventional vehicles, based on the same data presented in Figure ES1. As shown, for a given electric vehicle range, the expected timing for price parity is similar for cars, crossovers, and SUVs. Price parity for pickup trucks is about one year delayed for BEVs with 300-mile range or less. For the largest and heaviest 350-mile and 400-mile range pickups, price parity is delayed by two to three years, respectively, compared to the other vehicle classes.

Table ES1. Summary of year by which battery electric vehicle price parity is reached

Vehicle class	Range (miles)					
	BEV-150	BEV-200	BEV-250	BEV-300	BEV-350	BEV-400
Car	2024	2025	2027	2028	2029	2030
Crossover	2024	2025	2027	2028	2029	2030
SUV	2024	2025	2027	2028	2029	2030
Pickup	2025	2026	2028	2029	2031	2033

Note: Numbers in table are rounded to the nearest year.

Our analysis leads us to three high-level conclusions:

Battery electric vehicle purchase price parity is coming before 2030 for BEVs with up to 300-miles of range across all light-duty vehicle classes. Continued technological advancements and increased battery production volumes mean that pack-level battery costs are expected to decline to about $105/kWh by 2025 and $74/kWh by 2030. These developments are critical to achieving electric vehicle initial price parity with conventional vehicles, which this analysis finds to occur between 2024 and 2026 for 150- to 200-mile range BEVs, between 2027 and 2029 for 250- to 300-mile range BEVs, and between 2029 and 2033 for 350- to 400-mile range BEVs. These findings apply to electric cars, crossovers, sport utility vehicles (SUVs), and pickup trucks, which cover all light-duty vehicle sales in the United States. Pickups, which represent 15% of new 2020 light-duty vehicle sales, are the slowest to reach price parity. Battery cost sensitivity analyses illustrate the key impact of battery costs on price parity timing. Increasing the annual battery cost reduction from 7% to 9% typically accelerates the timing for parity by about 1 to 2 years, while decreasing the annual battery cost reduction from 7% to 3% typically delays parity by about 1 to 4 years.

Battery electric vehicles provide significant cost savings to drivers several years before purchase price parity. The first-owner six-year cost of ownership analysis, which includes cost savings from using electricity instead of gasoline and reduced maintenance needs, shows how new vehicle buyers will have an attractive new vehicle purchase proposition for battery electric vehicles in the 2022 to 2027 time frame based on economics alone. By 2025, BEVs with up to 300 miles of range have a six-year cost of ownership that is less than comparable gasoline models in every light-duty vehicle class. The longest-range 400-mile range pickups are last to reach ownership parity and do so in 2027. Typical six-year fuel and maintenance cost savings range from $6,600 to $11,000 per vehicle purchased in 2025, with the greatest absolute savings for the pickup and SUV class. These lower annual operating costs greatly offset BEVs' higher initial purchase price and enable ownership parity several years before initial purchase parity. The relative fuel savings of BEVs are greatest in the near term, and moderately decline in later years due to the greater relative efficiency improvement expected of conventional vehicles. PHEVs with 50 miles of electric range approach first-owner cost of ownership parity with conventional vehicles by 2030, but their 2030 six-year ownership costs are $7,500 to $11,300 greater than those of 300-mile range BEVs.

Transitioning to battery electric vehicles unlocks billions of dollars in consumer savings. Although the upfront costs of transitioning to BEVs in the near term are substantial, the benefits quickly outweigh the costs. Following a path to meet President Biden's goal of 50% electric vehicle sales by 2030, we estimate that annual costs are greatest in 2022 at about $4.5 billion, when BEVs' upfront incremental price is the greatest. As annual BEV sales increase and upfront incremental prices are reduced, BEVs begin to reach first-owner cost of ownership parity with conventional vehicles. The net consumer benefits outweigh the costs beginning in 2024, and the net benefits continue to grow as BEV sales increase. By 2027, the annual net present value of consumer benefits surpasses $18 billion and reaches about $70 billion by 2030. Capturing these benefits will require continued BEV market growth to about 2 million annual sales by 2025 and about 8 million annual sales by 2030. On average, the individual first-owner consumer savings for new 300-mile range BEVs purchased in 2030 is about $9,000.

Our findings have direct relevance to policies aiming to promote zero-emission vehicle (ZEV) uptake and reduced greenhouse gas and conventional pollutant emissions from light-duty vehicles. Despite the evidence on electric vehicle purchase and ownership cost parity, the transition is not inevitable and continues to rely on market-driving policies. Regulations and ZEV targets can only be as ambitious as they are feasible, and feasibility relies heavily on costs and benefits. Our findings that new battery electric vehicles with up to 400 miles of range in every light-duty vehicle class will reach purchase price parity with conventional light-duty vehicles by 2033 and ownership parity several years sooner shows that strong ZEV regulations and performance standards in this time frame can be implemented and lead to billions of dollars in cost savings for consumers. Such regulations are critical to ensure that continued industry investments are made and consumer benefits are realized.

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INTRODUCTION

The global transition to zero-emission vehicles continues to accelerate. On an annual basis, global light-duty electric vehicle sales—including both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)—increased from less than 10,000 in 2010, to more than 1 million in 2017, more than 3 million in 2020, and more than 6.5 million in 2021. Globally, nearly 17 million cumulative light-duty electric vehicles were sold through 2021 (EV-Volumes, 2022). BEVs represent about 70% of these sales and PHEVs represent 30%. As shown in Figure 1, the three markets of China, Europe, and the United States, where there are the most supporting policies in place, accounted for 92% of those sales. With this market growth, battery manufacturing and electric vehicle production continue to proliferate, and the development of a global automotive supply chain is underway.

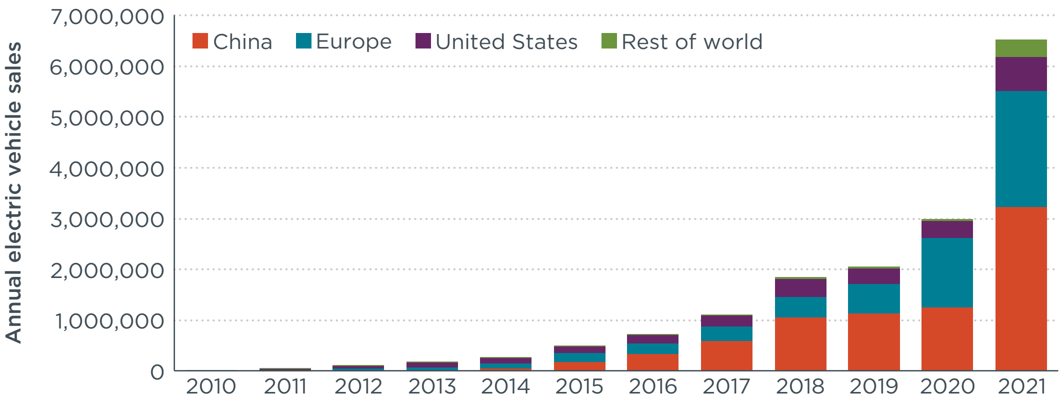

Figure 1. Annual global light-duty electric vehicle sales, 2010–2021 (based on EV-Volumes, 2022).

The United States is the third largest electric vehicle market behind China and Europe, and the gap has widened since 2017 (Bui, Slowik, & Lutsey, 2021). Of the 17 million cumulative electric vehicles sold globally through 2021, about 14% were sold in the United States, compared to 32% in Europe and 47% in China. After stalling at about 330,000 annual electric vehicle sales from 2018 to 2020, the U.S. electric vehicle market has grown to about 670,000 in 2021. Over this same time period, the electric vehicle sales share of new light-duty vehicles in the United States increased from about 2% to 4.5%.

Regulations that require increased electric vehicle production and sales are the foundational driver of electric vehicle model availability and increased volume. Many of the strongest electric vehicle markets globally are in China, driven by the New Energy Vehicle (NEV) regulation coupled with local policies (Cui, 2018; Hall, Cui, & Lutsey, 2020; Liu, Zhao, Liu, & Hao, 2020). Most electric vehicle sales in North America are in regions that adopt California's zero-emission vehicle (ZEV) regulation, which requires electric vehicles to reach 8% to 15% of new vehicle sales by 2025 (California Air Resources Board [CARB], 2017; Lutsey, 2018). Strong vehicle emission regulations can also accelerate uptake, as seen with Europe's jump to a 19% combined BEV and PHEV sales share in 2021, up from 3% in 2019, largely due to the stronger 2020 vehicle CO_2 regulation (Mock, 2019; Mock & Yang, 2022).

Policymakers around the world are considering stronger emission regulations that could require far greater electric vehicle penetration in the 2030–2035 time frame. Many governments have targets for 100% sales of zero-emission new vehicles by

2030–2040, and some have begun to develop enforceable regulations (Cui, Hall, Li, & Lutsey, 2021). The European Union is likely to introduce a light-duty vehicle regulation for 100% zero-emission vehicles by 2035 (Krukowska & Nardelli, 2021). China's proposed NEV regulations include a NEV credit target of 28% by 2024 and 38% by 2025 (MIIT, 2022), which could lead to a NEV sales share of at least 20% for passenger cars by 2025, the official national target (China State Council, 2020). There are also semi-official targets for 40% by 2030 and over 50% by 2035 (Society of Automotive Engineers [SAE] China, 2020). California is developing a regulation for 100% zero-emission vehicles by 2035 (Office of Governor Gavin Newsom, 2020; California Air Resources Board, 2021) and several additional states are likely to adopt California's standards (Northeast States for Coordinated Air Use Management [NESCAUM], 2022). The United States will update its vehicle regulations and has set a target for 50% of all new light-duty sales in 2030 to be battery electric, plug-in hybrid, or fuel cell (White House, 2021).

As governments work to implement these ambitious targets, key questions regarding electric vehicle costs and benefits arise. Questions about whether and how ZEV regulations and performance standards will affect consumer costs, both at the point of vehicle purchase and from a consumer ownership perspective, are critical to their development. More stringent ZEV targets and regulations are increasingly feasible and cost-effective with the continued decline in electric vehicle costs. To that aim, this paper analyzes bottom-up vehicle component-level costs to assess average plug-in electric (BEV and PHEV) and conventional vehicle prices across the major U.S. light-duty vehicle classes (car, crossover, sport utility vehicle, pickup) through 2035. These cost estimates are used to evaluate vehicle costs and broader consumer effects, as well as to discuss the implications for vehicle emission regulations in the United States.

The world has faced numerous major global challenges in the 2020 decade. The ongoing COVID-19 pandemic, the Russia-Ukraine war, supply chain disruptions, trade friction, and inflation have affected every sector of the world economy. These global challenges have already had several clear and immediate effects on the automotive sector in the near term, including higher upfront vehicle prices, more expensive gasoline, and increased battery raw material prices. The extent and duration to which these effects will continue to be felt are highly uncertain and not quantified here. Rather, this study is focused on the long-term outlook for light-duty vehicle technology, costs, and consumer benefits.

VEHICLE COST ANALYSIS

This section analyzes battery and electric vehicle manufacturing costs in the 2022–2035 time frame and compares them with the costs for manufacturing conventional gasoline vehicles. Based on the detailed engineering analysis of electric vehicle component costs, average BEV and PHEV costs for car, crossover, sport utility, and pickup light-duty vehicle classes in the United States are analyzed. The vehicle cost analysis is generally based on the approach of similar previous analyses (Lutsey, Cui, & Yu, 2021; Lutsey & Nicholas, 2019a, 2019b; National Academies of Sciences, Engineering, and Medicine, 2021) with several key improvements. Compared to the previous work, this analysis is updated with new research, data inputs, and U.S. light-duty vehicle technical specifications. The overall methodology and the key analytical differences compared to our previous work are described in more detail in the following sections.

BATTERY PACK COST

This analysis applies the most recent estimates for battery pack production costs and future projections based on detailed bottom-up technical studies of battery cost elements and overall battery pack costs. Projections with explicit technical specifications for battery pack production (e.g., material, cell, and pack costs; cost versus production volume; bottom-up cost engineering approach, etc.) and detailed automaker statements are included. Compared to the analysis of battery pack-level costs shown below, cell-level costs typically make up from 70% to 80% of pack-level costs (Anderman, 2019; Bloomberg New Energy Finance, 2021); unless cell and pack costs are stated within each study, a pack-to-cell cost ratio of 1.33 is assumed for 2020, improving to 1.25 by 2030. Although different studies assess the associated costs differently, this analysis refers to the battery pack cost as seen by a manufacturer of light-duty vehicles, including battery production cost and any associated indirect costs to the supplier. Battery pack costs for heavy-duty vehicles would be somewhat higher than assessed here, due to different battery pack performance requirements, modularization, and relatively lower production volumes (Basma, Saboori, & Rodriguez, 2021).

Recent sources help characterize global 2020–2021 battery costs. Based on industry surveys, volume-weighted average global BEV pack-level prices were approximately $126 per kilowatt-hour (kWh) in 2020 and $118 per kWh in 2021 (Bloomberg New Energy Finance, 2020, 2021). About 45% of global electric vehicle battery production through 2019 occurred in China (Slowik, Lutsey, & Hsu, 2020); China battery pack costs for a given battery chemistry and production volume are typically 20% lower than estimates for the United States and Europe (Lutsey et al., 2021). For this assessment of U.S. electric vehicle costs, the industry-average battery costs are determined based on the sources below.

Figure 2 summarizes the data sources used to inform our projections for battery pack cost reductions through 2035, including expert sources, research literature projections, and automaker announcements. Our battery cost review includes the most recent projections by expert sources including the California Air Resources Board (2022), Roush Industries Inc. (see Saxena, Stone, Nair, & Pillai [forthcoming]), Bloomberg New Energy Finance (2020, 2021), UBS (2020) and technical research studies, including Mauler, Lou, Duffner, and Leker (2022), Nykvist, Sprei, and Nilsson (2019), Penisa et al. (2020), Hsieh, Pan, Chiang, and Green (2019), and Berckmans et al. (2017). The automaker announcements shown include Volkswagen for $135 per kilowatt-hour in

2021–2022 (Witter, 2018), Tesla for $55/kWh in 2025 (Tesla, 2020), and Renault and Ford for $80/kWh in 2030 (Automotive News, 2021a, 2021b; Ford, 2021). Not shown due to uncertainties related to timing, General Motors in 2020 announced continued improvements toward below $100/kWh at the cell level, and Volkswagen in 2021 announced developments toward "significantly below" $100/kWh at the pack-level (General Motors, 2020; Volkswagen, 2021).

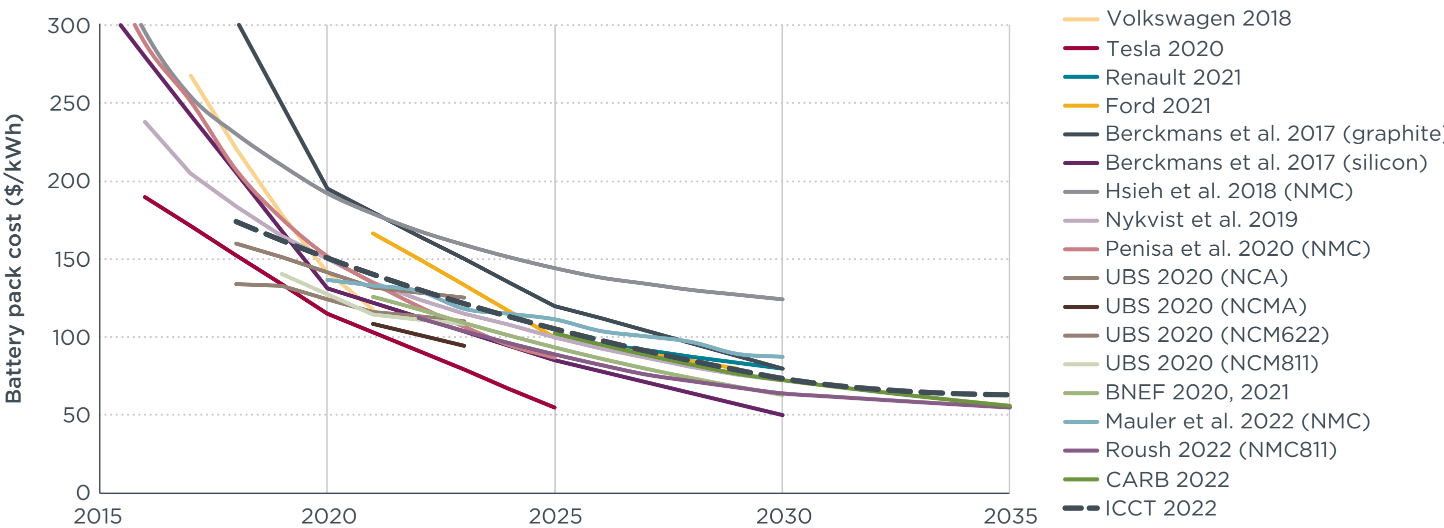

Figure 2. Electric vehicle battery pack costs from technical studies and automaker statements.

The "ICCT 2022" black hashed line shows the U.S. battery pack cost estimate applied in this analysis for a BEV with a nominal 50 kWh battery pack. As shown, pack-level costs decline from $131 per kWh in 2022 to $105/kWh in 2025, $74/kWh in 2030, and $63/kWh in 2035; this represents a 7% annual reduction over the 2022–2030 time frame, which declines to an average annual reduction of 3% over the 2030–2035 time frame. A decreasing pack-to-cell ratio with increasing pack capacity is applied, which means that larger battery packs have lower per-kilowatt-hour costs (Safoutin, McDonald, & Ellies, 2018). Pack-level costs per kWh for PHEVs are 23% higher than those for BEVs throughout the analysis, based on CARB (2022).

The ICCT 2022 curve is the same battery pack cost curve as our previous study (see Lutsey & Nicholas, 2019a); we provide an updated review based on the most recent expert, research literature, and automaker announcements to put that projection into context, and find that it still appropriately represents industry average battery costs. The projected continued decline in battery pack costs represents a continued trend toward lower cost and higher specific energy electrode materials, as well as improvements in cell and pack manufacturing. For battery materials, a continued global trend toward a higher market share of batteries using cobalt- and nickel-free lithium iron phosphate (LFP) cathodes is anticipated, resulting in lower overall material costs. In parallel, depending on the market segment, a continuous trend to nickel-rich nickel-manganese-cobalt (NMC) cathodes (e.g., NMC811) is typically expected. Nickel-rich NMC cathodes have higher specific energy and require less of the expensive cobalt. The addition of silicon to a graphite silicon composite anode can help to increase the specific energy (Berckmans et al., 2017). With continued improvements in battery specific energy, measured in Watt-hours per kilogram (Wh/kg), and volumetric energy density, measured in Watt-hours per liter (Wh/L) (U.S. Department of Energy, 2022a), the mass of materials per unit energy is reduced, and battery pack size is smaller and lighter for a given electric vehicle range, thus reducing total pack costs. Other factors include continued improvements in the cell-to-pack ratio and reduced production costs per unit volume due to an increase in production volume per pack design from about 50,000 to 100,000 battery packs annually in 2020 to about 500,000 and greater from 2025.

The battery cost projections in this analysis are based on improvements and innovations that do not require fundamental technological breakthroughs or nascent next-generation battery technologies such as solid-state batteries or sodium-ion batteries. Such breakthroughs could potentially lead to lower battery costs than quantified here, along with advancements in faster charging speeds and improved safety.

Battery raw materials. Against all these factors contributing to a continued decline in battery cell- and pack-level costs, the cost of battery raw materials—especially cobalt, nickel, and lithium—is an increasing concern in 2022 as many materials are listed at record high prices (Bloomberg New Energy Finance, 2022). This is due to many factors including inflation, the Ukraine-Russia war, and trade friction. The global supply of raw materials appears tight in the years ahead, and there is risk that the rate of battery cost reductions could decline in the near term if raw material prices remain elevated or continue to increase (Bloomberg New Energy Finance, 2022; International Energy Agency, 2022).

At the same time, high raw material prices may also lead to a shift in battery chemistries. High cobalt and nickel costs are expected to reinforce the trend toward cheaper nickel- and cobalt-free LFP cathodes (International Energy Agency, 2022). Sudden cost increases for cobalt and nickel raw material are particularly challenging for batteries with NMC and nickel-cobalt-aluminum oxide (NCA) cathodes because of their high cobalt and nickel content. Although automakers and battery suppliers typically enter long-term battery and raw material contracts, the industry may further respond by shifting to lower-cost LFP cathodes in the mid- to long-term. This trend is already being observed in 2021–2022 for manufacturers including Ford, Tesla, and Volkswagen (Foote, 2022; Volkswagen, 2021; Wayland, 2021).

Several of the battery cost projections from the journal publications shown in Figure 2 are based on batteries with NMC cathodes, and some considered raw material prices in their cost models. The differences between the cost projections generally result from various assumptions on future raw material costs and learning rates. The Hsieh et al. (2019) finding of battery pack costs of $124/kWh in 2030 underscores the key linkage between raw material prices and battery pack costs. Their projections are based on a two-stage learning curve model that incorporates raw material price projections and learning in battery manufacturing. The finding of $124/kWh in 2030 for NMC battery packs is based on an assumed annual cobalt price increase of $13.3/kg, from $25.36/kg in 2016 to about $211/kg in 2030, which the authors call "probably an overestimate." For context, $211/kg is about 2.5 times greater than prices during the cobalt price peaks in March 2018 and March 2022, and about six times greater than the average prices in 2017 and 2019 (Trading Economics, 2022; Wentker, Greenwood, & Leker, 2019). The Hsieh et al. finding of $124/kWh is also based on an increase in nickel and lithium prices by $1.3/kg and $1.9/kg annually, from $9/kg and $40/kg in 2016 to $27/kg and $67/kg in 2030, respectively. Hsieh et al. also analyze an alternative scenario where material prices remain constant and find an NMC-based battery pack price of $93/kWh in 2030.

Other studies also quantified the impact of increasing raw material prices on total battery manufacturing costs. For batteries using NMC cathodes, Penisa et al. (2020) found that learning and innovation have greater influence on battery pack costs than raw material price increases, and the authors quantify that doubling the price of lithium and cobalt increases battery pack prices by 5% to 10%. Similarly, older Bloomberg New Energy Finance research found that doubling lithium prices could increase battery prices by 8%, based on 2017 prices (Bloomberg New Energy Finance, 2017). However, as battery pack prices continue to fall, raw material prices represent a growing share of the total costs, and changes in raw material prices have a greater relative effect on total costs. Mauler et al. (2022) applied future material price expectations and cost reductions based on innovation and found costs of NMC-based battery cells of about \$70/kWh in 2030 based on 2020 raw material prices, which we estimate to be about \$87/kWh at the pack level. When the researchers apply raw material price increases, the cost reductions are decreased; under the "most pessimistic" raw material price expectations, the cost reductions from innovation are fully offset, and cell-level costs are about \$104/kWh in 2030. This is based on an annual price increase of 5.5% for lithium, 9% for nickel, and 12% for cobalt. For context, these annual raw material price increases are similar to those applied in Hsieh et al. (2019), which were 4% for lithium, 8% for nickel, and 16% for cobalt. The researchers did not analyze a scenario where future raw material prices are reduced relative to 2020 prices; doing so would result in further battery cost reductions.

Despite the risk of fluctuating material prices, a 2021 battery cost review finds that many expert studies have long-term confidence and optimism in stable battery market growth, and a continued decline in battery costs regardless of raw material price developments is expected (Mauler, Duffner, Zeier, & Leker, 2021). Experts at Roush Industries (Rogers, Nair, & Pillai, 2021a) argue that projecting battery cell costs based on raw material prices is not a reliable indicator of future cell costs, based on technological improvements in the battery cell, pack, and vehicle integration that allow for greater specific energy and reduced raw materials per kilowatt-hour. As shown in Figure 2, Roush predicts pack-level battery costs of about \$90/kWh in 2025 and \$65/kWh in 2030. Furthermore, automakers and battery suppliers typically enter long-term battery and raw material contracts and thus are less vulnerable to price volatility of raw materials, as evidenced by recent supply deals by Ford, General Motors, Stellantis, Tesla, and Volkswagen (Foldy, 2022; Hull & Stringer, 2022; McLain & Rogers, 2022; Reuters, 2022a, 2022b; Scheyder, 2022). Nevertheless, the price parity findings in this analysis are tested for their sensitivity to annual battery cost reductions further below.

VEHICLE MANUFACTURING COSTS

Electric vehicle manufacturing costs are estimated on a bottom-up vehicle component cost basis. These costs are determined for representative vehicle classes in the U.S. new passenger vehicle market. The steps include initially quantifying the reference conventional vehicles and their technical specifications and then estimating the detailed components for equivalent electric vehicles and their associated costs.

Conventional vehicles. Table 1 summarizes the sales share and average technical specifications for model year (MY) 2020 U.S. conventional vehicle sales across the light-duty vehicle classes as applied in this analysis, based on data from the National Highway Traffic Safety Administration (2022). The market-leading vehicle classes are crossovers (35% of U.S. MY 2020 sales), cars (27%), SUVs (23%), and pickups (15%); detailed information about how the classes are defined is in the notes below

Table 1. The analysis below evaluates costs for those four classes. Average vehicle characteristics, including market share, rated engine power, curb weight, footprint, fuel economy, and price, are used to define reference conventional vehicles. The fuel economy values shown reflect the U.S. Environmental Protection Agency consumer label values. The prices shown reflect the manufacturer suggested retail price (MSRP).

Table 1. Average characteristics for 2020 reference combustion vehicles.

Vehicle class [a]	MY 2020 sales	Sales share	Rated power (kW)	Curb weight (lb)	Footprint (ft^2)	Fuel economy [b] (mpg)	Price [c] (2020 USD)
Car	3,579,198	27%	153	3,288	47	31.3	$29,709
Crossover	4,686,767	35%	146	3,594	46	28.0	$30,919
SUV	3,062,536	23%	227	4,583	54	21.5	$47,380
Pickup	1,943,537	15%	253	4,904	66	19.0	$42,765
Fleet average	**13,272,038**	**100%**	**182**	**3,931**	**51**	**26.1**	**$36,126**

Note: Based on data from NHTSA (2022).
[a] Our car class comprises NHTSA's SmallCar and MedCar "technology classes." Crossovers comprise SmallSUVs, which contains SUV-body style vehicles with curb weight, footprint, and 0-60 acceleration times similar to those of cars. SUVs comprise NHTSA's MedSUV class, which includes minivans, vans, and SUV-body style vehicles with characteristics greater than cars; about 97% of SUVs are categorized as light trucks. Our pickup class matches NHTSA's pickup class; about 96% of new pickups use gasoline fuel and the rest use diesel. Examples of high-selling MY2020 crossover vehicles include Honda CR-V, Ford Escape, and Toyota RAV4.
[b] US consumer label-equivalent fuel consumption (mpg) in miles per gallon of gasoline.
[c] Prices are in 2020 dollars.

The NHTSA baseline dataset for MY 2020 vehicles provides information on vehicle class, engine and transmission technology, and price on a model-by-model basis. We assess 2020 baseline combustion vehicle powertrain total costs (i.e., direct and indirect) by sales-weighting the total costs of these technologies for each vehicle class. A summary of total powertrain costs for each class is shown in Table 2. Estimates of aftertreatment system total costs and all-wheel drive/four-wheel drive (AWD/4WD) total costs were added to the engine and transmission total costs to quantify the full combustion powertrain total costs. Aftertreatment costs were estimated based on sales-weighted engine displacement and the corresponding aftertreatment system cost in Blanco-Rodriguez (2015), adjusted to 2020 dollars by a 1.08 inflator (U.S. Inflation Calculator, 2022) and scaled upward by 10% to account for U.S. emissions standards' increased stringency over Europe's (Blumberg & Posada, 2015). More recent cost estimates of gasoline aftertreatment systems are unavailable.

The total costs for AWD/4WD were approximated as $1,500 for cars, $2,000 for crossovers, $3,000 for SUVs, and $3,500 for pickups. These total costs were estimated by comparing the price premium between four-wheel drive/two-wheel drive models and their AWD/4WD counterparts within the NHTSA database. Although AWD premiums varied widely across vehicle makes and models, the total costs shown in Table 2 reflect lower-end values. Average AWD/4WD costs are calculated from the sales-weighted share of AWD/4WD vehicles from the NHTSA MY 2020 database. Other powertrain total costs associated with nonplugin combustion vehicles include electrical improvements up to and including strong hybridization. The mild and strong hybridization portion of "other" total costs in the table below are small compared to the overall powertrain total costs, due to relatively low market penetration of electrification technologies. In the 2020 combustion vehicle fleet, around 5% of the overall powertrain total costs for cars and crossovers, less than 2% of the costs for SUVs, and less than 0.5% of the costs for pickups are from electrification technology costs up to and including strong hybridization.

Table 2. Sales-weighted average powertrain total costs for 2020 reference combustion vehicles.

	Car	Crossover	SUV	Pickup
Engine	$5,852	$5,826	$6,455	$6,957
Emission control	$359	$351	$509	$648
Transmission	$2,367	$2,281	$2,341	$2,248
AWD/4WD	$294	$1,210	$1,888	$2,662
Other costs	$777	$979	$751	$532
Sum of powertrain costs	$9,649	$10,647	$11,943	$13,048

Note: Other costs comprise all electrification technology total costs up to and including strong hybridization.

This analysis applies an updated approach to quantifying conventional vehicle manufacturing costs compared to our previous work (see Lutsey & Nicholas, 2019a). Previously, conventional vehicle manufacturing costs were assessed based on UBS (2017) estimates of powertrain costs, nonpowertrain direct costs, and indirect costs. This analysis assumes that the average price for each class shown in Table 1 represents a fixed percentage markup over direct manufacturing costs. NHTSA applies a retail price equivalent (RPE) factor of 1.5 in its CAFE standards. This means that the total costs are estimated as 1.5 times direct costs. We apply an RPE factor of 1.5 for all vehicle classes. Thus, we estimate vehicle direct manufacturing costs for combustion vehicle classes as average price divided by 1.5. Dividing the powertrain total costs in Table 2 by 1.5 gives powertrain direct costs. Subtracting powertrain direct costs from vehicle direct costs (calculated from the prices in Table 1) gives the remaining nonpowertrain direct costs (chassis, trim, assembly, etc.). The results of these calculations are shown in Table 3. As a point of reference, the U.S. Environmental Protection Agency (EPA, 2009) dissected RPE into its constituent components. Fleet average automaker profit was found to be around 6% of direct costs (supported by automaker financial reports), and total dealer selling and markup contributors amount to around 16% of direct costs. As discussed further below, these same markups were assumed to apply to electric vehicles on a fleetwide average.

Table 3. Baseline 2020 combustion vehicle direct, indirect, and total price.

		Car	Crossover	SUV	Pickup
Direct	Powertrain	$6,433	$7,098	$7,962	$8,699
	Nonpowertrain	$13,373	$13,514	$23,625	$19,811
	Total direct	$19,806	$20,612	$31,587	$28,510
Indirect	Depreciation, amortization, R&D, administration and expenses, automaker profit, dealer selling and markup	$9,903	$10,306	$15,793	$14,255
Total price		**$29,709**	**$30,919**	**$47,380**	**$42,765**

This analysis assumes that post-2026 U.S. light-duty vehicle regulations will continue to require new conventional vehicle fuel economy to improve annually, regardless of the level of electric vehicle penetration. Conventional vehicle efficiency improvements and the associated increase in manufacturing costs are modeled based on Lutsey, Meszler, Isenstadt, German, and Miller (2017). At the time of Lutsey et al. (2017), the 2015 baseline car and truck fleets considered therein were already respectively 23% and 20% more efficient than the "zero technology" vehicle that represented the start point for technology application. Those 2015 fleets corresponded to the first package of efficiency technologies applied in Lutsey et al. The 2020 fleet, which forms the baseline for the present analysis, is a further 7% to 9% more efficient than the 2015 fleets, according to two-cycle tailpipe compliance values in the EPA's 2021 fuel economy trends report (EPA, 2022).

Improvements beyond the 2020 baseline are estimated based on Lutsey et al. (2017) assuming the baseline 2020 fleet has already had the second technology package cost and effectiveness applied. For an annual average efficiency improvement of 3.5%, corresponding to a total 30% improvement from 2020 to 2030, total cost-effectiveness after adjusting for inflation was estimated as an average of about $39 per percent reduction for cars and crossovers and about $43 per percent reduction for SUVs and pickups. Although the technology packages and costs in Lutsey et al. are outdated, we consider these adjusted cost-effectiveness values to be near recent estimates of promising combustion vehicle technologies (e.g., 48V mild hybrids, high compression ratio Miller and Atkinson engines, high energy ignition) (Dornoff, German, Deo, & Dimaratos, 2022; Rogers, Nair, & Pillai, 2021b).

Beyond 2030, an average cost per percent improvement of about $56 for cars and crossovers and about $61 for SUVs and trucks was applied for the remaining approximately 11.4% improvement through 2035. This level of cost is assumed to represent deeper levels of electrification, further engine improvements, and high levels of mass reduction and aerodynamic improvements (these latter two are also applied to electric vehicles, discussed below). For a 41.4% overall improvement through 2035, total costs are expected to increase by about $1,800 for cars and crossovers and about $2,000 for SUVs and pickups representing increases of about $1,200 and $1,300, respectively, in direct costs. This cost increase is equivalent to about 1% increase in powertrain direct costs per year. Table 4 summarizes the conventional vehicle fuel economy in miles per gallon (mpg) applied in this analysis for 2020, 2022, 2030, and 2035, as well as the associated cost increase relative to 2020.

Table 4. Summary of modeled new combustion vehicle fuel economy (mpg) for 2020, 2022, 2030, and 2035, and cost increase due to improved efficiency.

	Label fuel economy (mpg)				Increase in total costs relative to 2020 vehicle				Increase in direct costs relative to 2020 vehicle			
Vehicle class	2020	2022	2030	2035	2020	2022	2030	2035	2020	2022	2030	2035
Car	31.3	33.6	44.6	53.3	–	$225	$1,180	$1,823	–	$150	$787	$1,215
Crossover	28.0	30.1	40.0	47.8	–	$227	$1,183	$1,823	–	$151	$789	$1,215
SUV	21.5	23.0	30.6	36.6	–	$248	$1,295	$1,994	–	$166	$863	$1,329
Pickup	19.0	20.4	27.2	32.5	–	$250	$1,298	$1,994	–	$167	$865	$1,329
Fleet average	26.1	28.0	37.2	44.5	–	$234	$1,225	$1,887	–	$157	$817	$1,258

Using the SUV class as an example, Table 4 shows how an average new conventional SUV is estimated to improve in efficiency from 21.5 mpg in 2020 to 30.6 mpg in 2030 and 36.6 mpg by 2035. This comes with an average total cost increase of $1,295 by 2030 and $1,994 by 2035, relative to 2020. On average across the four vehicle classes, our U.S. new conventional gasoline vehicle fleet improves from a consumer label efficiency of about 26.1 mpg in 2020 to 37.2 mpg in 2030, while seeing a $1,225 total cost increase. By 2035, the average new gasoline vehicle fuel economy is about 44.5 mpg, which comes with an average total cost increase of $1,887 from 2020. The increase in direct costs shown on the right of Table 4 is the increase in total costs divided by 1.5.

Electric vehicles. Table 5 summarizes the electric vehicle specifications for 2022 and 2030 for six different electric ranges of BEVs and PHEVs. The BEV and PHEV capabilities and rated power (kW) are matched with those of the reference conventional vehicles (see Table 1). The table shows electric vehicle range, electric efficiency, and battery pack size and cost, and gasoline fuel consumption for PHEVs. The technical specifications are based on official electric vehicle range and efficiency values from the U.S. Department of Energy and reflect consumer label efficiency (U.S. Department of Energy, 2022b). Although it is not shown, we apply a charging efficiency factor of 93% for all years. A useable-to-total battery pack size ratio is also applied based on average high-volume MY 2022 electric vehicles such that BEVs can use 92% while PHEVs can use 85% of the kWh, which increases for new vehicles by less than 1% per year through 2030, based on the best available models from 2022. For context, several BEV models including the BMW i4, Chevrolet Bolt EV, Chevy Bolt EUV, Hyundai Ioniq 5, Nissan Leaf, Polestar 2, and Volvo C40 and XC40 have a useable-to-total battery ratio of 96% or greater in 2022. For PHEVs, the lower assumed useable battery fraction is due to the higher-power-to-energy packs having restrictions for thermal management, durability, and safety. Additional details about PHEV motor and engine sizing required to maintain the performance neutrality shown in Table 5 are discussed later.

Table 5. Technical characteristics of electric vehicles for 2022 and 2030.

	Battery electric vehicle (BEV)									Plug-in hybrid electric vehicle (PHEV)									
		Car		Crossover		SUV		Pickup			Car		Crossover		SUV		Pickup	
	Range [a]	2022	2030	2022	2030	2022	2030	2022	2030	Range	2022	2030	2022	2030	2022	2030	2022	2030
Rated power (kW)		153	153	146	146	227	227	253	253		153	153	146	146	227	227	253	253
Fuel economy (mpg)		--	--	--	--	--	--	--	--		37	54	32	45	26	37	23	25
Efficiency (kWh/mile)[b]	BEV-150	0.27	0.19	0.32	0.20	0.37	0.24	0.45	0.31	PHEV-20	0.37	0.27	0.42	0.34	0.54	0.36	0.65	0.45
	BEV-200	0.28	0.20	0.33	0.21	0.38	0.26	0.46	0.33	PHEV-30	0.38	0.27	0.42	0.34	0.54	0.37	0.66	0.45
	BEV-250	0.28	0.21	0.34	0.22	0.39	0.27	0.47	0.35	PHEV-40	0.38	0.27	0.42	0.34	0.54	0.37	0.66	0.46
	BEV-300	0.29	0.22	0.35	0.24	0.40	0.28	0.48	0.36	PHEV-50	0.38	0.27	0.42	0.34	0.55	0.37	0.66	0.46
	BEV-350	0.30	0.23	0.36	0.25	0.40	0.30	0.49	0.38	PHEV-60	0.38	0.27	0.42	0.34	0.55	0.37	0.66	0.46
	BEV-400	0.31	0.25	0.36	0.26	0.41	0.32	0.50	0.40	PHEV-70	0.38	0.27	0.42	0.34	0.55	0.37	0.66	0.46
Battery pack[c] (kWh)	BEV-150	41	27	50	29	57	35	70	45	PHEV-20	8	6	9	7	12	8	14	10
	BEV-200	56	38	67	41	77	49	94	63	PHEV-30	12	8	14	11	18	12	22	14
	BEV-250	72	50	86	53	98	64	119	82	PHEV-40	17	11	18	14	24	16	29	19
	BEV-300	88	64	105	67	119	82	144	104	PHEV-50	21	14	23	18	30	20	36	24
	BEV-350	105	78	125	83	141	100	170	128	PHEV-60	25	17	28	22	36	24	44	29
	BEV-400	123	94	145	100	164	120	197	154	PHEV-70	30	20	33	25	42	28	51	34
Pack cost[d] ($/kWh)	BEV-150	$134	$79	$131	$78	$129	$77	$126	$75	PHEV-20	$165	$97	$165	$97	$165	$97	$165	$97
	BEV-200	$129	$76	$126	$75	$124	$74	$121	$72	PHEV-30	$165	$97	$165	$97	$165	$97	$165	$97
	BEV-250	$125	$74	$122	$73	$120	$71	$117	$69	PHEV-40	$165	$97	$165	$97	$165	$97	$165	$97
	BEV-300	$122	$71	$119	$71	$117	$69	$117	$67	PHEV-50	$165	$97	$165	$97	$165	$97	$165	$97
	BEV-350	$119	$70	$117	$69	$117	$67	$117	$66	PHEV-60	$165	$97	$165	$97	$165	$97	$165	$97
	BEV-400	$117	$68	$117	$67	$117	$66	$117	$66	PHEV-70	$165	$97	$165	$97	$165	$97	$165	$97

Note: Numbers in table are rounded.
[a] BEV-150 = 150-mile range battery electric vehicle; BEV-400 = 400-mile range BEV; PHEV-50 = 50-mile range plug-in hybrid electric vehicle.
[b] Vehicle efficiency and range reflect U.S. consumer label values.
[c] *Battery pack is based on range, electric efficiency, usable fraction of battery pack, and charging efficiency.*
[d] *Larger battery packs have lower per-kWh pack costs, due to a decreasing pack-to-cell ratio (Safoutin, McDonald, & Ellies, 2018).*

The initial 2022 electric vehicle efficiencies in Table 5 are based directly on existing MY 2022 BEV and PHEV models, accounting for increased electricity-per-mile for longer-range electric vehicles. We apply average technical specifications based on several high-volume MY 2022 electric vehicle models within each class. For example, our BEV crossover efficiency is based on the Tesla Model Y, Ford Mach-e, Volkswagen ID 4, Hyundai Kona, Kia Niro, Kia EV6, and Volvo XC40. Electric vehicle efficiency improves annually due to electric component (battery, motor, power electronic) and vehicle-level (mass reduction, aerodynamic, and tire rolling resistance) improvements. The 2030–2035 electric vehicle efficiencies are based on modeling by CARB (2022), accounting for range and adjusting for charging losses. Between 2022 and 2030, we apply an average annual improvement that links the high-volume 2022 average electric vehicle model specifications with the 2030 CARB values. By 2030, the efficiencies are somewhat better than those of the "best in class" models from 2022. For example, our representative 350-mile range battery electric car is 0.23 kWh/mile compared to the 358-mile range 2022 Tesla Model 3 at 0.26 kWh/mile. Our representative 350-mile range crossover in 2030 is 0.25 kWh/mile, compared to the 330-mile range 2022 Tesla Model Y at 0.28 kWh/mile.

The total battery pack costs can be interpreted from the battery pack size (kWh) and cost per kilowatt-hour values shown in Table 5. For example, a 250-mile range battery electric car in 2022 has a 72-kWh battery pack that costs $125/kWh for a total battery pack cost of about $9,000. For a given range, the improved efficiency results in a smaller battery for future models. By 2030, the same 250-mile range battery electric car would require a 50-kWh battery pack at a cost of $74/kWh, for a total battery pack cost of about $3,700.

The other nonbattery manufacturing cost components for electric vehicles are based on several sources. Nonbattery powertrain costs are assessed primarily based on a teardown analysis by UBS (2017) and the National Academies of Sciences Engineering and Medicine fuel economy technology assessment (NASEM, 2021). Virtually all electric vehicles equipped with AWD do so with additional motors, rather than electronic AWD or another AWD system used on combustion vehicles. By matching electric and combustion vehicle power, combined motor power for electric vehicles with multiple motors is the same as the power for single motor vehicles. With additional motors, costs for high voltage cables and motor cooling increase. It is unclear from literature whether motor costs include driveshaft, which would also increase with the number of motors. According to NASEM, future permanent magnet motor costs are expected to decline due to reduced magnetic material requirements. These future costs scale proportionally with motor power, suggesting that certain cost elements that increase with motor number are not included. Further investigation into the true costs of BEV AWD is beyond the scope of this paper. However, manufacturers may opt for induction motors as a second motor in AWD configurations. Absent permanent magnets, induction motors have the potential to decrease AWD costs further, even below the future permanent magnet motor costs shown in NASEM.

Nonpowertrain costs for 2020, including electric vehicle assembly costs, are based on the baseline conventional vehicle nonpowertrain costs for each vehicle class with a 5% decrease due to 30% lower cost of assembly for BEVs, and assembly comprising about 17% of nonpowertrain direct costs (Ford, 2017; König et al., 2021; Vellequette, 2019). From 2020 through 2035, the BEV nonpowertrain components and assembly costs are further reduced by about 5% for several reasons. As automakers expand their BEV model offerings and increase production volumes, there is a shift from modified internal combustion engine (ICE) platforms toward dedicated BEV platforms that enable new areas of cost reductions due to increased economies of scale, cross-segment parts sharing, partnerships among other automakers and suppliers, modified price points on the same vehicle, and better design-to-cost strategies that conventional vehicles have benefitted from for decades (Baik, Hensley, Hertzke, & Knupfer, 2019; Chatelain, Erriquez, Moulière, & Schäfer, 2018; Erriquez, Morel, Moulière, & Schäfer, 2017; Rogers et al., 2021b; Transport and Environment, 2021). To account for electric vehicle mass and aerodynamic drag reduction over time, the full costs of the highest level of mass reduction and aero improvements modeled in Lutsey et al. (2017) are applied incrementally through 2035. Two electric vehicle nonpowertrain cost components were not analyzed due to unavailability of data and presumed small impact: heat pumps, and electric vehicle weight-related modifications to brake rotors/calipers/pads, suspension system, tires, and body structure due to higher mass of electric vehicles.

Table 6 summarizes the direct manufacturing components, costs, and how they are applied in this analysis for an illustrative 250-mile range battery electric vehicle in the car class. Direct manufacturing costs are shown for 2022 and 2030. The direct manufacturing costs are broken down into powertrain (including battery and nonbattery powertrain components) and other direct costs (nonpowertrain and vehicle assembly). The notes column on the right indicates the source and how the costs are applied to other BEV ranges and vehicle classes. The 2017 dollars from the UBS (2017) study are adjusted to 2020 dollars by a 1.06 inflator (U.S. Inflation Calculator, 2022).

Table 6. Battery electric vehicle direct manufacturing costs for a 250-mile range car.

Type	Component	Cost		Notes
		2022	2030 [a]	
Powertrain direct	Battery pack	$9,000	$3,700	See Figure 2 and Table 5.
	Thermal management	$250	$235	Based on UBS (2017), costs scale based on presumed vehicle price class based on range and pack size.
	Power distribution module	$240	$290	Based on UBS (2017), costs scale based on vehicle power in kW.
	Inverter	$630	$380	Costs scale based on power (kW) based on NASEM (2021) Table 5.4 and 5.5 of current and future inverter costs in $/kW.
	Electric drive module	$800	$670	Costs scale based on power (kW) based on NASEM (2021) Table 5.2 and 5.3 of current and future motor costs in $/kW.
	DC converter	$140	$130	Based on UBS (2017), costs are consistent for all BEV ranges and vehicle classes.
	Controller	$50	$45	Based on UBS (2017), costs are consistent for all BEV ranges and vehicle classes.
	Control module	$90	$80	Based on UBS (2017), costs are consistent for all BEV ranges and vehicle classes.
	High voltage cables	$520	$485	Based on UBS (2017), costs scale based on vehicle number of motors and vehicle footprint.
	On-board charger	$510	$400	Based on UBS (2017), costs are consistent for all BEV ranges and vehicle classes.
	Charging cord	$140	$130	Based on UBS (2017), costs are consistent for all BEV ranges and vehicle classes.
Other direct	Nonpowertrain and vehicle assembly	$12,630	$12,330	BEV nonpowertrain and assembly costs are 5% less than comparable combustion vehicle costs for each vehicle class in 2020. A further 5% reduction is applied from 2020 through 2035.
Total direct manufacturing cost		$25,000	$18,950	

Note: Numbers in table are rounded.
[a] UBS (2017) provides component cost estimates out to 2025. For components where UBS cost data are used, we apply an annual cost reduction of about 1% beyond 2025. The average total decline in BEV nonbattery powertrain costs from 2025 to 2030 is about $500.

Consistent with our previous analysis (Lutsey & Nicholas, 2019a), PHEVs are assumed to inherit the costs of both the combustion and battery electric vehicle powertrain. However, several modifications are made to the respective powertrain costs when applied to PHEVs. From the BEV powertrain, PHEV battery pack sizes are reduced relative to BEVs, due to their much shorter all-electric ranges, varying from 20 to 70 miles. Motor and inverter costs on PHEVs are also reduced 25% to 40%, inversely dependent on range (Hyundai, 2022a; Toyota, 2022a, 2022b, 2022c). Longer range PHEV motors have less cost reduction since they are assumed to have higher power. From the combustion powertrain, total powertrain costs are reduced 10% to 15%, with greater reductions for longer-range PHEVs. As PHEV motors can supplement engine power, the engines on PHEVs do not need to be sized to meet maximum power demands in the same way as ICE-only vehicles. This can lead to some small cost savings. More significant savings arise from the switch to a hybrid transmission (eCVT) from a conventional transmission (NASEM, 2021). From 2030 to 2035, it is assumed that a significant share of nonplugin vehicles will be hybrids, leading to lower average ICE powertrain cost savings for PHEVs, as hybrid vehicles in general benefit from the engine and transmission changes. Consistent with industry, the arithmetic sum of engine and motor powers is greater than the combined rated power (Table 1) (Ford, 2022; Hyundai, 2022a; Toyota, 2022b, 2022c). However, the above-described engine and motor cost reductions lead to PHEV combined rated power equivalent to their ICE-only and BEV counterparts (Table 1).

Figure 3 shows the direct vehicle manufacturing costs for electric and conventional vehicles for cars, crossovers, SUVs, and pickups for six BEV ranges (150, 200, 250, 300, 350, and 400) and a 50-mile PHEV. Costs are shown for 2022 and 2030. As indicated on the left half of the figure, direct manufacturing costs for BEVs in 2022 are higher than those of conventional vehicles for the four vehicle classes, ranging from $1,400 for a 150-mile battery electric car to $18,200 for a 400-mile battery electric pickup. The right of Figure 3 shows how, by 2030, direct manufacturing costs for BEVs are less than those of combustion vehicles for all vehicle classes and electric ranges up to 300 miles. In 2030, direct costs for 400-mile range BEVs are between $800 to $1,250 greater than combustion cars, crossovers, and SUVs, and $3,200 greater than conventional pickups. PHEVs experience relatively lower cost reductions; by 2030, PHEV direct manufacturing costs are $3,400 (cars) to $5,000 (pickups) greater than conventional vehicles. The powertrain costs for PHEVs in the figure include the costs of both the combustion and battery electric vehicle powertrain, as discussed above.

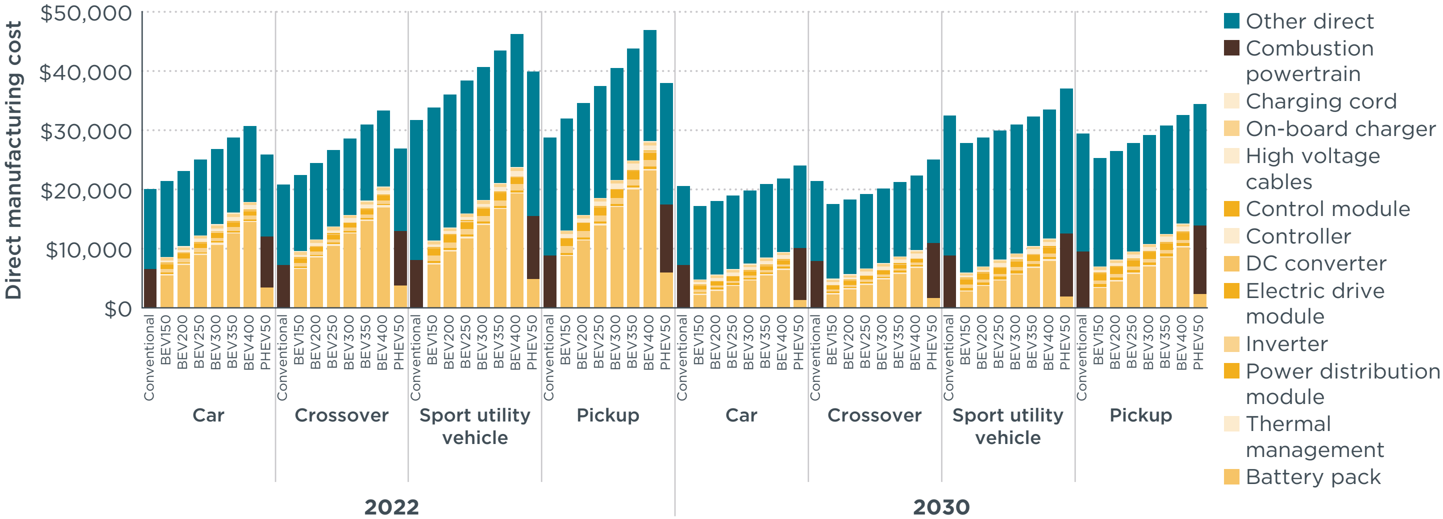

Figure 3. Direct manufacturing costs for conventional and electric vehicles in 2022 and 2030 for cars, crossovers, SUVs, and pickups.

The largest electric vehicle direct cost decreases from 2022 to 2030 are in batteries. For a 300-mile range SUV, for example, reduced battery costs account for about 85% of the total direct manufacturing cost reduction, declining from about $14,000 in 2022 to about $5,650 in 2030. This is the result of reduced per-kilowatt-hour battery cell costs, lower pack-level assembly costs, and improved vehicle efficiency enabling reduced battery size for the same range. Other electric vehicle direct manufacturing cost reductions include nonbattery powertrain costs, which decline by about $500–$800 from 2022 to 2030, and nonpowertrain and vehicle assembly costs, which also decline by about $300–$650 from 2022 to 2030.

VEHICLE PRICES

For electric vehicles, the above direct manufacturing cost analysis is used to estimate electric vehicle prices by technology and electric range. Electric vehicle price is distinguished from the direct manufacturing costs shown in Figure 3 by the addition of indirect costs. Indirect costs include depreciation and amortization (D&A), research and development (R&D), selling and general and administrative expenses (SG&A), automaker profit, and dealer selling and markup. No state or federal tax credits or rebates for electric vehicles are included. In cases where electric vehicles have lower cost than conventional vehicles, the analysis assumes that the vehicles are provided at a lower price to consumers; alternatively, automakers could choose to take additional profits from electric vehicles' manufacturing cost advantage.

Indirect vehicle costs for battery electric vehicles are first assessed based on estimates of D&A, R&D, and SG&A on a per-vehicle basis; automaker profit and dealer selling and markup are assessed separately. Our analysis of D&A, R&D, and SG&A is based automaker financial reporting and how those indirect costs have evolved as their sales volumes have increased. The D&A and SG&A costs for electric vehicles are based on average annual 2017–2021 light-duty indirect cost data for the six largest global automakers in 2021 (Marklines, n.d.) with at least 6 million in annual light-duty sales: Toyota Group (Toyota, 2021a), VW Group (Volkswagen, 2022), Renault-Nissan-Mitsubishi (Mitsubishi, 2022; Nissan, 2022; Renault, 2022), Hyundai-Kia Group (Hyundai, 2022b; Kia, 2022), GM (U.S. Securities and Exchange Commission [SEC], 2022a) and Stellantis (Fiat Chrysler Automobiles, 2020; PSA Groupe, 2020; Stellantis, 2022). Per-vehicle costs are about $1,050 for D&A and about $2,250 for SG&A, and these costs are assumed to remain constant and are applied for all years in the analysis.

The primary driver for declining indirect electric vehicle costs is reduced R&D costs on a per-vehicle basis. For BEVs, R&D costs are based on publicly available data from Tesla, the world's only high-volume all-electric automaker. Specifically, we apply annual R&D costs and annual BEV sales data from Tesla to quantify the R&D costs on a per-vehicle basis for 2017–2021 (U.S. SEC, 2022b). Tesla's annual R&D costs are increased by 50% to account for an expanding product lineup. Future year R&D costs are based on expected U.S. electric vehicle market growth and, thus, greater manufacturing volumes. The Tesla-derived per-vehicle R&D costs are added to D&A and SG&A costs then applied to the broader U.S. automotive market with a three-year lag period to estimate an industry-average BEV indirect cost that declines from about $11,300 per vehicle in 2020, to about $6,450 per vehicle in 2025, and to about $5,400 in 2030. Indirect costs for PHEVs are calculated as the sum product of BEV and ICE indirect costs and the cost share of electric and combustion components of the PHEV powertrain. Average PHEV indirect costs decline from about $9,100 per vehicle in 2020 to about $6,500 per vehicle in 2025 and about $6,200 in 2030.

Electric vehicle automaker profit and dealer selling and markup are calculated based on conventional vehicle markups by applying equivalent per-vehicle D&A, SG&A, and R&D costs to all conventional classes in a manner consistent with electric vehicles. Starting with fleet average conventional vehicle direct costs, a fleet average of 6% automaker profit and a 16% dealer selling and markup are applied to the direct manufacturing costs, based on RPE component breakdown data from EPA (2009). The remaining fleet average indirect costs (D&A, SG&A, R&D) are applied to each class equally. Assuming dealer selling and markup is the same for all classes results in automaker profit margins that vary across vehicle classes: there are lower profits for cars and crossovers and higher mark-ups for SUVs and pickups. Treating electric vehicles with the same adjustments helps to ensure consistent profit margins are built into each vehicle technology. If more automakers shift away from traditional dealerships to online direct-to-consumer sales for electric vehicle sales—as is done by Tesla and is under development by Ford—electric vehicle prices would be reduced.

Figure 4 shows the vehicle prices by technology for 2022 through 2035. From top to bottom are the results for the car, crossover, SUV, and pickup. The black lines represent average conventional gasoline vehicle prices, which rise slightly along with their improved efficiency (see Table 1). BEVs experience substantial cost reductions from 2022 to 2035, as described above. The pink, purple, blue, green, orange, and yellow lines correspond shortest to longest range BEVs. As shown, the BEVs' reduced prices bring price parity with conventional gasoline vehicles as soon as the 2024–2025 time frame, but the timing varies by electric range and vehicle class. Shorter-range BEVs with 150 to 200 miles of range reach price parity around 2024–2026, mid-range BEVs with 250 to 300 miles of range reach price parity around 2026–2029, and the longest-range BEVs with 350 to 400 miles of range reach price parity around 2029–2033. Cars, crossovers, and SUVs reach price parity one to three years earlier than pickups for a given BEV range. PHEVs with 20 to 70 miles of range, shown as the dotted lines, tend to have lower prices than the longest range BEVs in the near term, but are more expensive than any battery electric or combustion vehicle by 2030 for every electric range and vehicle class.

Figure 4. Initial price of conventional and electric vehicles for 2022–2035 for four vehicle classes.

The expected timing for BEV price parity with conventional gasoline vehicles varies slightly among cars, crossovers, and SUVs, across all ranges. However, for heavier and less energy-efficient pickups requiring relatively more kilowatt-hours of battery for each additional mile of electric range, price parity occurs 1 to 3 years later, dependent on range. As previously introduced, the initial conventional vehicle prices in this analysis are based on a sales-weighted assessment of all conventional light-duty vehicles in the United States and, thus, represent average prices. There are, of course, variations in powertrain, performance, luxury features, and other components across conventional and electric vehicles alike. These factors have implications on vehicle price, which means that some models may reach price parity sooner, and others later, than the average values shown here.

Within each vehicle class, longer-range BEVs' larger battery packs add substantial costs over shorter-range BEVs. For example, a car buyer in 2026 can purchase a 200-mile range BEV that is less expensive than a conventional gasoline car. If that car buyer was concerned about range and charging infrastructure, they could pay $3,000 more for a 300-mile range BEV or $6,300 more for a 400-mile range BEV. Similarly, a SUV buyer in 2026 could purchase a 200-mile BEV for less than a comparable gasoline SUV or pay $4,100 more for a 300-mile battery electric SUV or $8,900 more for a 400-mile battery electric SUV. In each situation, vehicle buyers can essentially choose price parity for shorter-range BEVs or pay approximately 10% more for every additional 100 miles of range. These examples demonstrate the trade-off for consumers between lower cost and longer range, and the opportunity for widespread charging infrastructure to enable lower-cost shorter-range vehicle purchases.

Plug-in hybrid electric vehicles with 20 miles to 70 miles of electric range are shown in Figure 4 by the dotted lines. The PHEV price differential versus conventional gasoline vehicles is reduced from 2022 to 2035, but there are no price parity points with conventional vehicles in any class. This is for two primary reasons: PHEVs have the complexity of having both the combustion and electric powertrain components, and the battery pack is a much lower contributor to the PHEV price, so battery cost reductions have a smaller effect on the total price. As an example, the cost differential for a crossover PHEV with a 50-mile electric range is about $8,000 in 2022, which declines to about $3,800 in 2030 and $3,200 in 2035. Overall, by 2035 PHEV prices range from about $2,000 more than their conventional gasoline counterparts for a passenger car PHEV with a 20-mile electric range to $6,200 more for a pickup PHEV with a 70-mile electric range.

The price parity findings were tested for their sensitivity to annual battery cost reductions. Compared to our central case, an annual battery cost reduction of 7% from 2022 through 2030, a lower annual battery cost reduction of 4% (reflecting relatively slower innovation, production volume, and potential raw material price constraints), and a higher annual price reduction of 10% (reflecting greater battery breakthroughs, potentially including solid-state, sodium-ion, or other next-generation battery technologies) are assessed. Toyota, for example, has begun testing solid-state batteries in its electric vehicle concept models, and Nissan aims to sell electric vehicles with solid-state batteries by 2028 (Vijayenthiran, 2022). Nissan estimates solid-state batteries will cost $75/kWh in 2028, which can be reduced to $65/kWh.

Figure 5 illustrates how the year of BEV price parity with conventional vehicles varies with changes to battery cost reductions. The blue triangles reflect the central case findings and are the same as Figure 4 above. The whiskers to the left and right of the blue triangles reflect the price parity findings for the lower and higher battery cost cases, respectively, compared to the central case. The higher battery cost case (4% annual reduction) typically delays price parity by about one year for a 250-mile range BEV and two to four years for a 350-mile range BEV. The lower battery cost case (9% annual reduction) typically accelerates price parity by about one year for a 250-mile range BEV and one to two years for a 350-mile range BEV. The effect of battery cost reduction on the timing for price parity is greater for larger vehicle classes because of their larger battery packs.

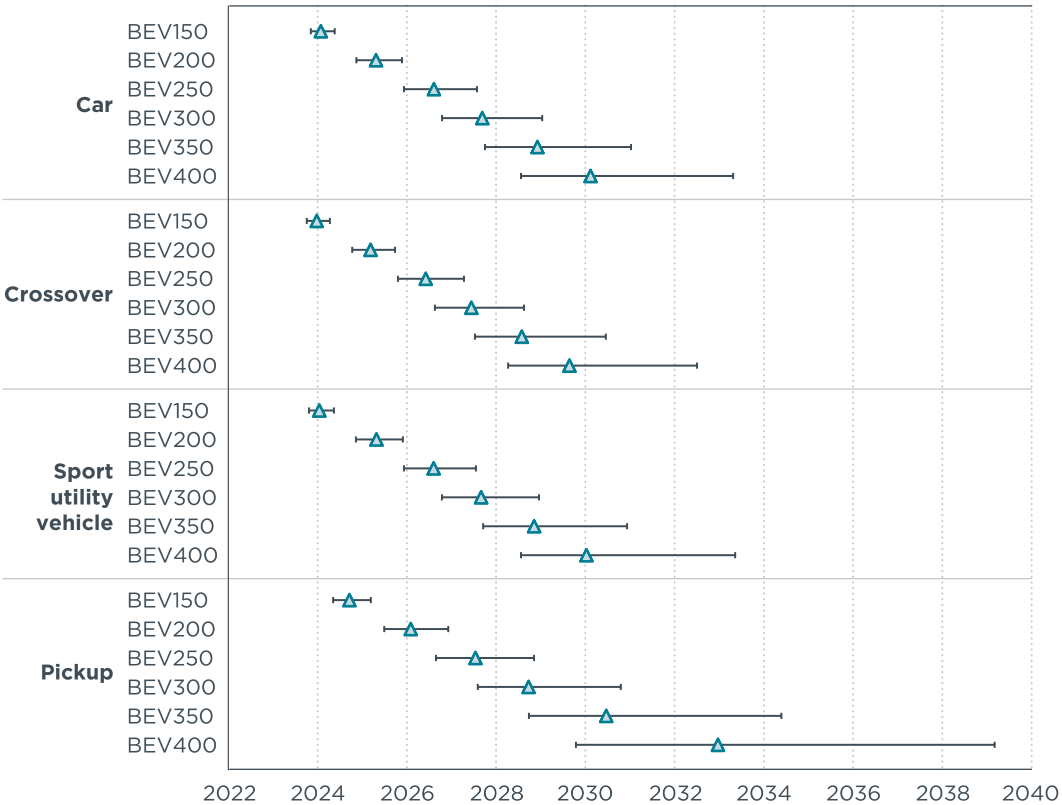

Figure 5. Battery electric vehicle price parity year for varied battery costs.

The Figure 5 results reinforce how price parity in major vehicle classes is expected to be reached in the 2027 to 2028 time frame for 250-mile range BEVs, from 2028 to 2029 for 300-mile range BEVs, and from 2030 to 2033 for the longest-range 400-mile BEVs. The sensitivity demonstrates how relatively higher or lower battery costs lengthen or shorten the expected timing for price parity by a few years, depending on the vehicle range and class. These findings underscore the importance of continued developments regarding battery manufacturing innovation, greater production volumes, and stable raw material prices.

The price parity findings were also tested for their sensitivity to annual electric vehicle energy consumption improvement. Compared to the central case, we reduce the annual BEV improvement by 50% from 2022. Doing so increases the average BEV energy consumption values in Table 5 by 6% in 2025 and 17% in 2030. Increasing BEV energy consumption means that larger, more expensive battery packs are needed for the same all-electric range, and the timing for price parity is delayed. The effect of increased BEV energy consumption on the timing for price parity is greater for larger vehicle classes because of their larger battery packs. We find that reducing annual

BEV efficiency improvement by 50% delays price parity by an average of less than one year for 350-mile range BEVs. Price parity is delayed by an average of about one year for 400-mile range BEVs. These findings illustrate the opportunity for regulatory standards to ensure continued improvements in electric vehicle energy consumption are achieved, such as those under development in the European Union (European Parliament, 2021).

VEHICLE OWNERSHIP COST ASSESSMENT

This section builds on the preceding analysis of manufacturing cost and vehicle price to compare the vehicle technologies on a first-owner cost basis. Analyzing first-owner cost-competitiveness is important to quantifying the value proposition for a prospective electric vehicle buyer. Parameters include vehicle prices from the previous section (manufacturing cost, automaker profit, dealer selling and markup, and other indirect) plus taxes, gasoline and electricity fueling costs, maintenance, and home charging equipment for electric vehicles. Based on evidence that long-range electric vehicles hold their value as well as comparable combustion vehicles, resale value is excluded from the analysis (Harto, 2020).

The first-owner cost of ownership assessment is conducted over a six-year period, based on average vehicle ownership data presented in IHS Markit (2016). The IHS Markit data exclude state, local, and federal subsidies and tax incentives for electric vehicles and their charging infrastructure, providing a technology-neutral comparison. Ownership costs are assessed as a present value, and we apply a discount rate of 5% for all future-year ownership expenditures. The overall methodology generally follows that of Lutsey and Nicholas (2019a), with key updates based on the most recent data and research literature, as discussed below. A 5.6% purchase tax is included, which is approximately the U.S. average.

FUEL AND MAINTENANCE COSTS

Table 7 summarizes the fuel and maintenance cost assumptions and data sources applied in this analysis. Gasoline prices for 2022 are based on data of 2021–2022 U.S. retail gasoline prices by month (U.S. Energy Information Agency [EIA], 2022a), and future years are based on the relative annual projections from the U.S. Energy Information Administration's *Annual Energy Outlook* (U.S. EIA AEO, 2022b). Because the projections in AEO (2022b) were released in early 2022 and thus do not consider the impacts of the Russia-Ukraine war or inflation on gasoline prices, the AEO 2022 "reference case" projections are adjusted upward by about $0.50 based on average monthly 2021–2022 U.S. retail gasoline prices. If average U.S. gasoline prices remain higher than what is reflected in the table, the electric vehicle value proposition would be improved. Electricity prices for home charging are also from the U.S. EIA (2022b), and public DC fast charging electricity prices are from Kelly and Pavlenko (2020). Maintenance costs are from a 2021 U.S. Department of Energy comprehensive quantification of total ownership costs (Burnham et al., 2021). The maintenance costs are adjusted to reflect the maintenance costs for the first owner, based on annual mileage and maintenance service schedules.

Table 7. Summary of gasoline, electricity, and maintenance cost assumptions.

Vehicle technology	Year	Fuel ($/gallon)	Home charging ($/kWh)	DC fast charging ($/kWh)	Maintenance (cents/mile)
Conventional	2022	$3.46	--	--	7.0
	2025	$3.48	--	--	7.0
	2030	$3.52	--	--	7.0
Plug-in hybrid	2022	$3.46	$0.12	--	5.0
	2025	$3.48	$0.13	--	5.0
	2030	$3.52	$0.13	--	5.0
Battery electric	2022	--	$0.12	$0.28	3.6
	2025	--	$0.13	$0.24	3.6
	2030	--	$0.13	$0.20	3.6
Source		EIA AEO (2022)	EIA AEO (2022)	Kelly and Pavlenko (2020)	Burnham et al. (2021)

Annual travel activity is based on data from the National Highway Traffic Safety Administration (2022). For new cars and crossovers, vehicle-miles traveled (VMT) is about 15,900 miles in the first year and declines to about 13,500 in the sixth year. For new SUVs, VMT is about 16,200 in the first year and about 14,200 in the sixth. Pickups have the highest annual VMT at about 19,000 miles in the first year, which declines to about 14,700 in the sixth year. The VMT is identical for electric and conventional vehicles (Chakraborty, Hardman, Karten, & Tal, 2021).

Data on average driving behavior are applied to assess BEV and PHEV consumer annual driving and energy use. For BEVs, a "home charging share" defines the share of VMT that is fueled by a home charger, and all other miles are assumed to be traveled based on energy supplied at a public DC fast charger. The BEV home charging share is informed by an Argonne National Laboratory analysis of "utility factors" and adjusted to account for the likelihood that consumers will seek charging on average about 40 miles before the battery state-of-charge reaches zero (Duoba, 2013). For PHEVs, the "electric driving share" is the fraction of annual miles powered by electricity, and the remaining miles are done on gasoline. Drivers of BEVs and PHEVs are assumed to have access to regular overnight charging. The BEV home charging share and PHEV electric driving share factors applied in this analysis are summarized in Table 8.

Table 8. BEV home charging share and PHEV electric driving share factors.

		Battery electric vehicle		Plug-in hybrid electric vehicle	
		Range	Home charging share	Range	Electric driving share
Electric range	Short	BEV-150	0.84	PHEV-20	0.40
	Short-mid	BEV-200	0.89	PHEV-30	0.52
	Mid	BEV-250	0.93	PHEV-40	0.62
	Mid-long	BEV-300	0.95	PHEV-50	0.69
	Long	BEV-350	0.96	PHEV-60	0.74
	Long-plus	BEV-400	0.97	PHEV-70	0.79
Source		Duoba (2013)		Bradley and Quinn (2010)	

Table 8 shows how a 250-mile range BEV, for example, has a home charging share of 0.93. This means that electricity from a home charger supplies the energy for 93% of annual miles traveled, and public DC fast chargers supply the remaining 7% of miles. Based on the data on annual VMT from above, DC fast charging supplies the energy for about 1,000 miles (cars and crossovers) to 1,200 miles (SUVs and pickups) of annual mileage in the first year. To provide context to these ratios of home to public DC fast charging, a 2020 *Consumer Reports* analysis found that electric vehicles with 250 miles of range require six stops at a DC fast charger each year, which accounts for about 1,200 miles (Harto, 2020).

There are additional ownership costs for BEVs and PHEVs due to their charging needs. The type of home charger and the associated costs are determined based on electric vehicle technology and range, such that BEVs with 150- and 200-mile range and all PHEVs have Level 1 home chargers, whereas BEVs with 250-mile range or greater have Level 2 home chargers. Based on data from Nicholas (2019), average 2020 home charger costs of $540 for Level 1 and $1,350 for Level 2 are included to enable more convenient and lower cost residential charging. These average costs reflect how some home charging situations will require charger upgrades (new wiring and a charger), outlet upgrades (new wiring and a 120-volt wall or a 240-volt dryer-type outlet with no additional charger hardware), or no upgrade. The average home charging costs applied here were corroborated with Bartlett and Shenhar (2020). Costs include hardware and installation, and a 3% decline in per-charger hardware costs per year is applied (Nicholas, 2019).

This analysis incorporates estimated efficiency and operational cost impacts of towing. As introduced previously (see Table 1 and Table 5), the capabilities and power (kW) of electric and conventional vehicles are identical in this analysis and reflect the sales-weighted average specifications of U.S. model year 2020 light-duty vehicle sales. For the pickup class, the average rated engine power is 253 kW, and about 75% of model year 2020 pickup sales are capable of heavy towing. The analysis of direct manufacturing costs is based on these specifications and performance requirements. In terms of operational costs, data on towing frequency and total load while towing or hauling are limited. This analysis assumes that on average vehicle owners would tow or haul about 300–380 miles per year for pickups and about 60 miles per year for SUVs. This corresponds to about 2% and 0.4% of annual VMT, respectively. Towing miles are assumed to correspond with longer-distance trips, so BEV refueling is assumed to be done at DC fast chargers.

All vehicles experience significant efficiency losses when towing. Combustion vehicles are assumed to experience a 45% increase in fuel consumption (31% drop in fuel economy), whereas BEVs double their energy consumption and reduce range by 50%. While towing, PHEVs are assumed to operate entirely on charge-sustaining mode. To provide context to these numbers, anecdotal evidence of conventional pickup truck towing tests indicates 20% to 75% reduction in fuel economy (Butler, 2019; Smirnov, 2022; Smith, 2019). Testing of the battery electric Rivian R1T pickup show a range decrease of 40% to 50% (Evans, 2021).

The combined towing effects of efficiency loss and additional refueling at higher-cost DC fast chargers increase the average six-year fuel costs for electric pickups by about 5%. For combustion pickups, towing adds about 1% to the six-year fuel costs. Of course, some consumers may tow less and others more than the average case assessed here. Because towing comes with a significant drop in electric driving range, some consumers with especially high towing frequency and load may choose to pay more upfront for a larger battery and longer electric range. Doing so would increase the upfront vehicle price.

FIRST-OWNER COST OF OWNERSHIP

This section quantifies the first-owner cost of ownership for electric vehicles and compares them with conventional counterparts. Figure 6 shows the six-year ownership costs for new conventional, battery-electric, and plug-in hybrid electric vehicles for cars and crossovers (top) and SUVs and pickups (bottom). The costs are shown for new vehicles in 2022 and 2030, and include vehicle price, charging equipment, fuel and electricity, maintenance, and purchase tax. In 2022, the 150- and 200-mile range BEVs have a lower six-year ownership cost than conventional vehicles for all vehicle classes. By 2028, all ranges of BEVs (i.e., up to 400 miles) in all vehicle classes have a lower six-year ownership cost relative to gasoline vehicles, and many reach ownership parity several years sooner than that. For example, although not shown, first-owner cost of ownership parity year for 300-mile range BEVs is about 2024–2025. The first-owner cost of ownership for PHEVs with 50 miles of electric range is about the same as conventional vehicles by 2030, and about $7,500 to $11,300 greater than the first-owner cost of ownership of 300-mile range BEVs.

Figure 6. First-owner six-year vehicle ownership costs for cars and crossovers (top) and SUVs and pickups (bottom) for 2022 and 2030.

The biggest change from 2022 to 2030 is in vehicle direct manufacturing costs, as discussed in previous sections. Shifts in operating costs from 2022 to 2030 are comparatively limited. For an example gasoline vehicle of the car class, the discounted six-year fuel costs decline from about $7,700 to $5,900 for new vehicles purchased in 2022 and 2030, respectively, due to the improvements in fuel economy (Table 4). Relative to new gasoline vehicles, new 300-mile range BEVs in 2022 spend $4,800 to $8,400 less on fuel than gasoline cars and pickups, respectively, over a six-year ownership period. By 2030, the relative six-year fuel savings are reduced to about $3,700 to $6,700 for cars and pickups, respectively, due to conventional vehicles' relatively greater annual efficiency improvement and the projected minimal increase in gasoline prices applied in this analysis. About 10% of BEVs' six-year fuel costs are from public DC fast charging, and the rest is from charging at home. The share of DC fast charging costs of total fuel costs is relatively greater for shorter-range BEVs and relatively lower for longer-range BEVs. Six-year maintenance costs are about $2,650 lower for BEVs than gasoline vehicles.

Table 9 provides a different perspective on the consumer value proposition for purchasing a new electric vehicle in the United States in 2030. The table shows, for a new BEV purchased in 2030 or 2035, the number of years of owning and operating a BEV until cost parity is reached. "Immediate" is shown in the cases where the initial upfront price at the time of purchase is already lower than gasoline alternatives. As shown, cost parity is "immediate" for 150- to 350-mile range BEVs purchased in 2030 for every vehicle class shown. For 400-mile range car and pickup BEVs, it takes up to two years of ownership for BEVs' lower operating costs to reach ownership cost parity. By 2035, BEVs of all classes and all ranges immediately have lower ownership costs from the time of purchase. These findings indicate how first-owner six-year cost parity is expected for all electric vehicle ranges in all vehicle classes by 2030, based on the conditions outlined above.

Table 9. Number of years of operation to reach ownership parity.

Vehicle class	Range	Number of years of operation to reach ownership cost parity if purchased in 2030	Number of years of operation to reach ownership cost parity if purchased in 2035
Car	BEV-150	Immediate	Immediate
	BEV-200	Immediate	Immediate
	BEV-250	Immediate	Immediate
	BEV-300	Immediate	Immediate
	BEV-350	Immediate	Immediate
	BEV-400	1	Immediate
Crossover	BEV-150	Immediate	Immediate
	BEV-200	Immediate	Immediate
	BEV-250	Immediate	Immediate
	BEV-300	Immediate	Immediate
	BEV-350	Immediate	Immediate
	BEV-400	Immediate	Immediate
SUV	BEV-150	Immediate	Immediate
	BEV-200	Immediate	Immediate
	BEV-250	Immediate	Immediate
	BEV-300	Immediate	Immediate
	BEV-350	Immediate	Immediate
	BEV-400	Immediate	Immediate
Pickup	BEV-150	Immediate	Immediate
	BEV-200	Immediate	Immediate
	BEV-250	Immediate	Immediate
	BEV-300	Immediate	Immediate
	BEV-350	Immediate	Immediate
	BEV-400	2	Immediate

The cost of ownership analysis does not consider battery replacement, as the available evidence to date suggest relatively little concern about battery failure or extreme degradation. Long-range electric vehicles have not had significant problems to date; Tesla models in the United States with about 150,000 to 200,000 miles have experienced about 10% to 15% range degradation and few battery replacements (Lambert, 2018, 2020: Loveday, 2022). Importantly, these are the electric vehicles with relatively high lifetime driving and DC fast charging usage (frequent DC fast charging can lead to faster battery degradation). Furthermore, industry developments toward 1-million-mile batteries are underway, as evidenced by battery maker CATL, General Motors, and Tesla (Baldwin, 2020; Lienert, 2020). Research shows how NMC-532 graphite cells with exceptional lifetimes have already been developed that are capable of powering an electric vehicle for over 1 million miles, and such performance metrics are being proposed as benchmarks for new battery technologies (Harlow et al., 2019). Although Toyota has sold fewer than 500 BEVs in the United States as of mid-2021, the company claims its new bZ4X will have a 90% battery retention rate over 10 years (Toyota, 2021b).

FLEETWIDE BENEFITS AND COSTS

Building on the above analysis of vehicle prices and first-owner ownership costs, we assess the net present value of the direct consumer costs and benefits from transitioning the U.S. light-duty vehicle fleet to 50% battery electric vehicles by 2030. The net present value analysis includes all of the consumer cost components from the preceding analyses of initial vehicle price and first-owner cost of ownership, which are broadly categorized into three components: (a) upfront incremental price, in which BEV purchase price is greater than their combustion counterparts; (b) upfront reduced price, in which BEV purchase price is lower than combustion counterparts; and (c) six-year operational costs, which include everything except vehicle price from the first-owner cost of ownership analysis above (i.e., home charging equipment, fuel/electricity, maintenance, tax). The analysis does not include additional private or public costs of public charging or social costs associated with upstream petroleum extraction or raw material mining, nor does it include additional benefits of greenhouse gas mitigation, air pollution reduction, reduction in petroleum use and imports, or fuel diversification.

The fleet transition analysis is based on a hypothetical scenario in which annual U.S. BEV sales increase from about 500,000 in 2021 to 2 million by 2025 and about 7.8 million by 2030. This growth corresponds to a BEV share of new light-duty vehicle sales of about 3% in 2021 to 13% in 2025 and 50% by 2030. An average BEV range of 300 miles is assumed for all vehicle classes, and the number of annual BEV sales for each vehicle class is derived from the share of new U.S. light-duty vehicle sales in each class from the model year 2020 NHTSA data in Table 1 (i.e., cars are 27%, crossovers are 35%, SUVs are 23%, and pickups are 15%). The analysis of BEV stock for the assessment of six-year operational costs applies vehicle survival rates by age and class based on NHTSA (2022).

Figure 7 shows the estimated net present value of the costs and benefits of achieving a 50% BEV sales share by 2030 in the United States. Annual costs are greatest in 2022 at about $4.5 billion, when BEVs' upfront incremental price is the greatest. From 2022, annual BEV sales increase and upfront incremental prices are reduced. As 300-mile range BEVs reach price parity in 2028–2029 for cars, crossovers, SUVs, and pickups, the upfront incremental price becomes an upfront reduced price. This is shown by the gray (through 2028) and brown (after 2028) wedges. The large blue wedge includes each of the six-year operational costs previously noted except for vehicle price; it includes home charging equipment, fuel/electricity, maintenance, and tax. Due to significant fuel and maintenance savings, BEVs have lower six-year operational costs compared to gasoline vehicles for all years in this analysis. In 2022, the six-year BEV operational cost is $5,400 (car) to $9,400 (pickup) less than those of gasoline vehicles.

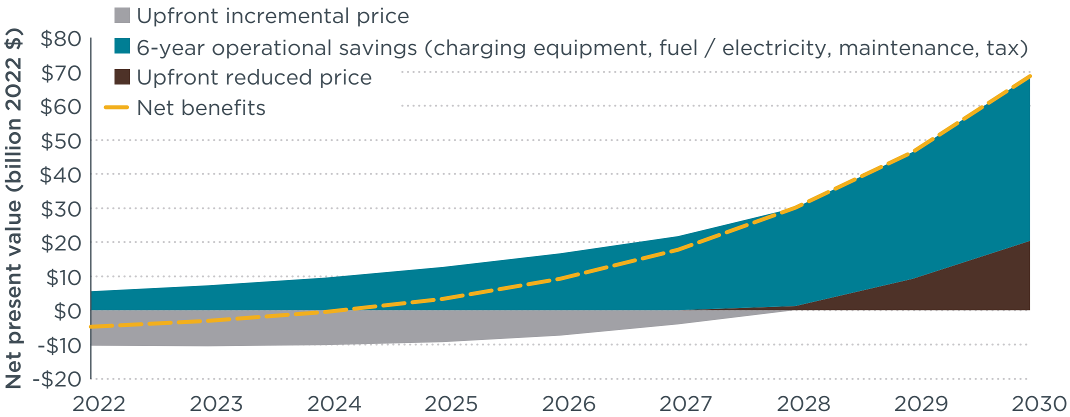

Figure 7. Net present value of the consumer costs and benefits of transitioning to 300-mile range BEVs in the United States: 2022 through 2030.

As shown by the hashed yellow line, the consumer net benefits outweigh the costs beginning in 2024. The net benefits continue to grow as BEV sales increase and price parity approaches. By 2027 the annual net present value benefits surpass $18 billion and reach about $70 billion by 2030. These findings underscore the opportunity to deliver substantial benefits to American consumers by transitioning to BEVs. Achieving the level of benefits quantified here is contingent upon continued market growth to 1 million to 2 million annual BEV sales from 2022–2025, to over 4 million by 2028, and about 8 million by 2030.

DISCUSSION

Governments around the world are setting ever-bolder commitments to zero-emission mobility. Many have targets for 100% ZEV sales by 2030–2040, and some are developing enforceable regulations to meet their targets. In the United States, the Biden administration has set a national target for 50% of new light-duty vehicle sales to be electric by 2030 (White House, 2021). At the state level, California is developing a regulation for 100% zero-emission new light-duty vehicle sales by 2035, and nine additional states have announced their goals for 100% ZEVs as quickly as possible, and no later than 2050 (International ZEV Alliance, 2021).

The preceding analysis quantifies the timing for when electric vehicles make economic sense in the United States, both from a consumer ownership and an initial purchase price perspective. Based on the six-year cost of ownership analysis, nearly every new vehicle buyer in the United States could cost-effectively choose electric over gasoline vehicles by 2030 (see Table 9). Shorter-ranged BEVs reach ownership cost parity the soonest, which is by 2022 to 2023 for 150- and 200-mile range BEVs in all vehicle classes. In terms of upfront purchase price, shorter-range BEVs again reach price parity the soonest, which is by 2024 to 2027 for 150- and 200-mile range BEVs in all vehicle classes. By 2033, initial electric vehicle price parity is anticipated for all classes and ranges (i.e., up to 400 miles).

These findings suggest that achieving the aforementioned national and state-level ZEV targets can be accomplished in a cost-effective manner and deliver substantial economic benefits to consumers. In particular, our study indicates that robust regulations that drive a high ZEV sales share in the 2025–2035 time frame can lead to substantial consumer benefits in terms of vehicle purchase and ownership costs. In other words, electric vehicles' higher upfront cost in 2022 is not a compelling reason to slow the pace of ZEV targets and vehicle efficiency regulations. On the contrary, regulations that drive industry investments and greater production volumes are critical to achieving the pace and scale of battery and electric vehicle cost reductions quantified in this report and the associated timing for price parity. The faster regulations and other policies can drive a transition to electric vehicles, the more consumers will benefit more quickly from lower costs.

Complementary policies and government actions are needed to support the transition to electric vehicles. Electric vehicles' promising economics are contingent on continued battery cost reductions on the order of $105/kWh in 2025 to $74/kWh in 2030, and $63/kWh in 2035. Such developments will rely on continued technological innovation and learning, economies of scale from increased production volumes, and meeting battery and raw material supply demands. New 2021 literature and market research have shown that tightening raw material supply and the associated near-term rise in prices could slow the rate of battery cost reduction (Bloomberg New Energy Finance, 2021; Mauler et al., 2022). As of early 2022, the prices for key metals and raw materials are at record highs, driven by factors including inflation, the Ukraine-Russia war, and trade friction (Bloomberg New Energy Finance, 2022). The extent to which automakers and battery suppliers are already paying more for raw materials and how it will affect near-term battery costs is not yet clear.

The scale of raw material mining and refining will need to keep pace with the demand for battery cells, packs, and vehicle manufacturing, and potential concerns about raw material supply need to be addressed and planned for years in advance (Bloomberg New Energy Finance, 2022; Slowik, Lutsey, & Hsu, 2020). In May 2022, the Biden administration announced new federal funding to boost domestic battery manufacturing and supply chains. The $3.61 billion commitment will support new, retrofitted, and expanded facilities and demonstrations for battery production and recycling, and is part of a larger $7 billion package (U.S. Department of Energy, 2022c). In August 2022, the Administration launched a $675 million program to expand and accelerate critical materials research, development, demonstration, and commercialization for electric vehicles, battery packs, and renewable energy (U.S. Department of Energy, 2022d).

New federal electric vehicle incentives under The Inflation Reduction Act of 2022 link eligibility to the sourcing of raw material and components domestically or from free-trade agreement partners (Taylor, 2022). Several companies are increasing their investments in raw material mining and refining as of mid-2022. In August, BHP announced the company will increase nickel exploration spending due to the surge of electric vehicles (Reuters, 2022c). In July, battery maker Redwood Materials announced a $3.5 billion investment on a battery-materials factory in Nevada (Reuters, 2022d). Tesla is assessing the feasibility of constructing a lithium refinery in Texas (Kharpal, 2022). Continued and greatly expanded efforts to bolster battery production, recycling, and upstream raw material mining and refining will be needed.

The expected timing for first-owner cost parity identified in this analysis is also contingent on consumer access to home charging. For BEVs with at least 250-mile range, the ownership assessment incorporated an average Level 2 home charging cost of $1,350 in 2020, which is quickly paid off by electric vehicles' fuel and maintenance savings. Although the vast majority of early electric vehicle adopters through 2021 have home charging, as the market expands more electric vehicle drivers may not have access to home charging. Drivers that rely on relatively more expensive public DC fast charging do not accrue the same economic benefits as quickly as drivers with home charging, and the timing for ownership parity is delayed. Although not shown in the preceding analysis, we also assessed a "no home charging" case where electric vehicle drivers do not pay for a home charger and charge exclusively at DC fast chargers. Without home charging, the 2025 six-year electric vehicle fuel costs are increased by about $1,360 for a 150-mile car to about $3,200 for a 400-mile pickup.

Without home charging, the timing for ownership cost parity is somewhat delayed. When electric vehicles charge exclusively at DC fast chargers and home charger costs are excluded, the first-owner cost of ownership parity is delayed by an average of about eight months across all of the electric vehicle ranges and classes in the analysis. The higher per-kilowatt-hour electricity costs of DC fast charging over the six-year ownership period are largely offset by the avoided cost of purchasing and installing a home charger. Without home charging, first-owner cost parity is reached before 2028 for all the electric vehicle ranges and classes analyzed. Beyond the six-year ownership period, however, the cost penalty from exclusively DC fast charging increases. This demonstrates the opportunity for widespread access to overnight residential charging options to maximize the economic benefits of electric vehicles. It also indicates the opportunity for continued R&D and greater DC fast charger utilization to enable lower cost fast charging and improve the electric vehicle value proposition.

Different levels of government can help support different aspects of charging deployment. At the federal level, stimulus and clean energy investments, along with tax credits or grants can help broaden home charging access and support broader economic and climate goals. State infrastructure support policies include setting utility rates favorably for EV charging, issuing grants, streamlining permitting, and direct deployment. Local governments can develop EV-ready building and parking codes to accelerate home and near-home charging installation, facilitate curbside charging in residential areas, and streamline local permitting. For Americans where home charging is not possible, governments can help deploy lower-cost near-home public Level 2 charging or provide discounted electricity at DC fast chargers.

This analysis does not consider the effect of any available state, local, or federal subsidies and tax incentives for electric vehicles and their charging infrastructure. In 2022, several U.S. states provide rebates worth about $2,500 for BEVs. At the federal level, there is an electric vehicle income tax credit worth up to $7,500 that is limited to 200,000 electric vehicles sold per manufacturer, and this threshold has been met by Tesla, General Motors, and Toyota (Linkov, 2022). The Inflation Reduction Act of 2022 budget reconciliation bill eliminates the 200,000-vehicle limit and extends tax incentives of up to $7,500 through 2032 (Senate Democrats, 2022). The availability of any federal or state-level incentives for electric vehicles would further reduce electric vehicle prices and greatly accelerate the timing for price parity. The act also provides incentives for domestic production of battery components at up to $45/kWh, which has potential to significantly reduce pack costs and accelerate the timing for electric vehicle price parity (Phillips, Hemmersbaugh, Larson, and Loud, 2022).

CONCLUSIONS

This paper analyzes key questions about the expected timing for electric vehicle parity in the United States based on available technical data and research literature. Electric vehicle manufacturing costs and upfront vehicle prices are quantified across the major light-duty vehicle classes and compared with their conventional gasoline counterparts, illustrating the potential value proposition that many consumers will consider over the next decade. The first-owner cost of ownership assessment further reveals the economic benefits that are accrued from fuel and maintenance savings after vehicle purchase. Our analysis leads us to three key conclusions.

Battery electric vehicle purchase price parity is coming before 2030 for BEVs with up to 300 miles of range across all light-duty vehicle classes. Continued technological advancements and increased battery production volumes mean that pack-level battery costs are expected to decline to about $105/kWh by 2025 and $74/kWh by 2030. These developments are critical to achieving electric vehicle initial price parity with conventional vehicles, which this analysis finds to occur between 2024 and 2026 for 150- to 200-mile range BEVs, between 2027 and 2029 for 250- to 300-mile range BEVs, and between 2029 and 2033 for 350- to 400-mile range BEVs. These findings apply to electric cars, crossovers, SUVs, and pickup trucks, which cover all light-duty vehicle sales in the United States. Pickups, which represent 15% of new 2020 light-duty vehicle sales, are the slowest to reach price parity. Battery cost sensitivity analyses illustrate the key impact of battery costs on price parity timing. Increasing the annual battery cost reduction from 7% to 9% typically accelerates the timing for parity by about 1–2 years, while decreasing the annual battery cost reduction from 7% to 3% typically delays parity by about 1–4 years.

Battery electric vehicles provide significant cost savings to drivers several years before purchase price parity. The first-owner six-year cost of ownership analysis, which includes cost savings from using electricity instead of gasoline and reduced maintenance needs, shows how new vehicle buyers will have an attractive new vehicle purchase proposition for battery electric vehicles in the 2022 to 2027 time frame based on economics alone. By 2025, BEVs with up to 300 miles of range have a six-year cost of ownership that is less than comparable gasoline models in every light-duty vehicle class. The longest-range 400-mile pickups are last to reach ownership parity and do so in 2027. Typical six-year fuel and maintenance cost savings range from $6,600 to $11,000 per vehicle purchased in 2025, with the greatest absolute savings for the pickup and SUV class. These lower annual operating costs greatly offset BEVs' higher initial purchase price and enable ownership parity several years before initial purchase parity. The relative fuel savings of BEVs are greatest in the near term, and moderately decline in later years due to the greater relative efficiency improvement expected of conventional vehicles. PHEVs with 50 miles of electric range approach first-owner cost of ownership parity with conventional vehicles by 2030, but their 2030 six-year ownership costs are $7,500 to $11,300 greater than those of 300-mile range BEVs.

Transitioning to battery electric vehicles unlocks billions of dollars in consumer savings. Although the upfront costs of transitioning to BEVs in the near term are substantial, the benefits quickly outweigh the costs. Following a path to meet the Biden administration's goal of 50% EV sales by 2030, we estimate that annual costs are greatest in 2022 at about $4.5 billion, when BEVs' upfront incremental price is the greatest. As annual BEV sales increase and upfront incremental prices are reduced, BEVs begin to reach first-owner cost of ownership parity with conventional vehicles. The net consumer benefits outweigh the costs beginning in 2024, and the net benefits continue to grow as BEV sales increase. By 2027, the annual net present value of consumer benefits surpasses $18 billion and reaches about $70 billion in 2030. Capturing these benefits will require continued BEV market growth to about 2 million annual sales by 2025 and about 8 million by 2030.

The analysis presented here shows that cost is unlikely to be a direct barrier to battery electric vehicle uptake in the United States after the next several years. Still, the transition is not inevitable and sustained policy support is needed, including ZEV and performance regulations along with complementary infrastructure and supply chain support policies. Our study suggests that ambitious ZEV targets and other policies driving electrification are achievable and can lead to billions of dollars in cost savings for consumers. In fact, a more rapid transition to electric vehicles would provide a greater number of consumers cost savings sooner.

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