WHITE PAPER

JUNE 2018

ELECTRIC VEHICLE COSTS AND CONSUMER BENEFITS IN COLORADO IN THE 2020–2030 TIME FRAME

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ACKNOWLEDGMENTS

This work has been prepared for the Colorado Energy Office and Colorado Department of Public Health & Environment.

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EXECUTIVE SUMMARY

As electric vehicles are produced and sold in greater numbers around the world, their costs continue to decrease, opening up greater potential for a broader electric vehicle market. Many governments are accelerating this trend by promoting electric vehicles to meet pollution reduction, consumer fuel saving, and industrial development goals. Through 2018, 10 U.S. states, the Canadian province of Québec, and China have direct requirements for electric vehicle deployment. Several jurisdictions across North America are considering similar policies.

In adopting zero-emission vehicle (ZEV) regulations, questions remain regarding how quickly electric vehicle costs are declining and the magnitude of consumer benefits compared to conventional vehicles. This paper analyzes these two questions in the context of Colorado's potential adoption of a ZEV regulation. The paper analyzes electric vehicle prices and consumer benefits for the Colorado light-duty vehicle market from 2023 through 2030. We apply state-of-the-art battery projections to evaluate the implications of increased deployment of electric vehicles to comply with a ZEV regulation.

Figure ES-1 summarizes the average electric vehicle price difference associated with meeting increasingly stringent ZEV regulations, along with the associated first-owner and secondary owner benefits for Colorado drivers from 2023 through 2030. Electric vehicles' additional costs to consumers decline from $4,200 in 2023 to $500 in 2026, before providing a cost improvement to consumers from $500 in 2027 to more than $3,000 in 2030. After the vehicle purchase, the average first-owner benefits over 5 years are between $2,700 and $3,200 per vehicle, including costs related to a home charger and the fuel and maintenance savings. After the first vehicle owner, the secondary effects over the life of the vehicle are even greater, from $5,900 to $6,300 per vehicle, largely due to the substantial fuel and maintenance savings. Total net lifetime effects increase from approximately $4,800 to $12,000 per vehicle from 2023 to 2030.

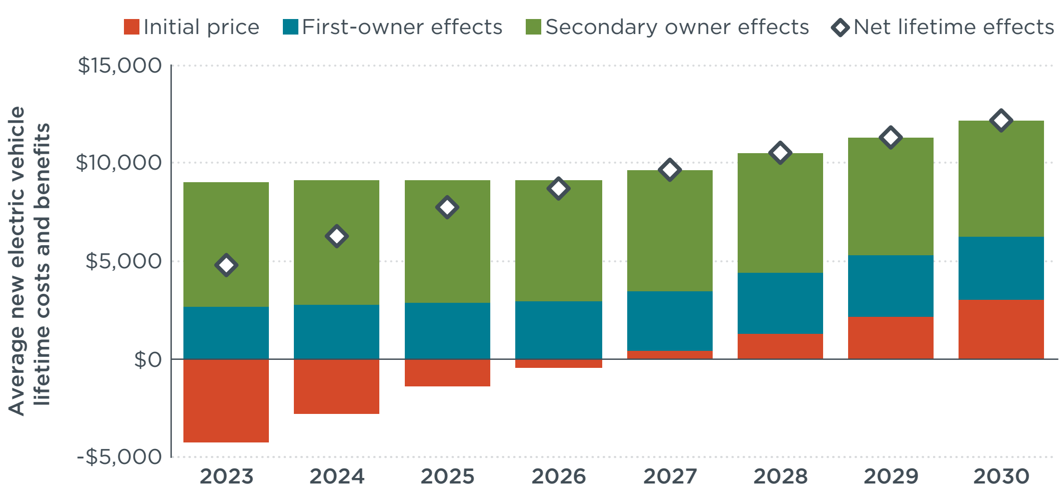

Figure ES-1. Average electric vehicle price and first-owner and secondary owner effects of increased electric vehicle penetration from 2023 through 2030.

Our analysis leads us to three high-level conclusions.

Declining battery costs will make electric vehicles less expensive than conventional vehicles. In terms of upfront vehicle purchasing, shorter-range battery electric vehicles up to 200 miles of range reach price parity with conventional gasoline vehicles by 2024–2026, followed by longer-range electric vehicles from 2027–2029. Including first-owner fuel and maintenance savings, battery electric vehicle price parity occurs 2 years sooner, from 2022–2027 across cars, crossovers, and sport-utility vehicles (SUVs).

Electric vehicle benefits greatly exceed costs for the consumer. Including lifetime costs, battery electric cars, crossovers, and SUVs with up to 300 miles of range deliver net benefits, ranging from $3,200 to $12,000 per vehicle to drivers in Colorado by 2025. Although plug-in hybrid electric vehicles do not reach price parity for first owners of the vehicles, these vehicles deliver lifetime benefits exceeding upfront costs for cars and crossovers by $1,400 to $2,700 per vehicle.

Electric vehicle requirements pass a cost-benefit analysis. By incorporating a mix of electric vehicle technologies across vehicle classes, a Colorado ZEV regulation can be met with a strongly positive cost-to-benefit balance. For a 2023–2025 ZEV regulation, vehicle price increases of $155 million to $223 million would result in $589 million to $669 million in benefits—over 3 times greater benefits than costs. The benefits of a ZEV regulation, if extended through new 2030 vehicles, would be much greater, delivering up to $3 billion for Colorado drivers.

The implications of this evaluation of a potential Colorado ZEV regulation are much broader. Due to steady electric vehicle improvements and declining costs, ZEV regulations will now definitively pass standard regulatory cost-benefit evaluations. This means that in the 2022–2026 period, governments can shift from incentives to regulations to steer the transition to electric vehicles. Beyond the basic economics, considering the environmental and social benefits of reducing emissions makes the case even stronger. Much greater electric vehicle penetration, moving toward full electrification, will be necessary for the transport sector to meet climate stabilization and air quality goals. This makes it clear that electric vehicles can simultaneously deliver on environmental and economic goals.

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INTRODUCTION

Since the launch of modern electric vehicles in 2010, the market has grown substantially. Figure 1 illustrates the growth in annual new electric vehicle sales in the United States (EV-Volumes, 2019). The electric vehicle market has grown to more than 350,000 per year in 2018, growing 79% over 2017. Cumulative electric vehicle sales in the United States through the end of 2018 were around 1.2 million. In a global context, these cumulative U.S. sales are approximately equal to all of Europe's, and roughly half of China's, electric vehicle market. Figure 1 also shows the electric vehicle sales share of new U.S. vehicles growing from 1.2% in 2017 to 2.1% in 2018.

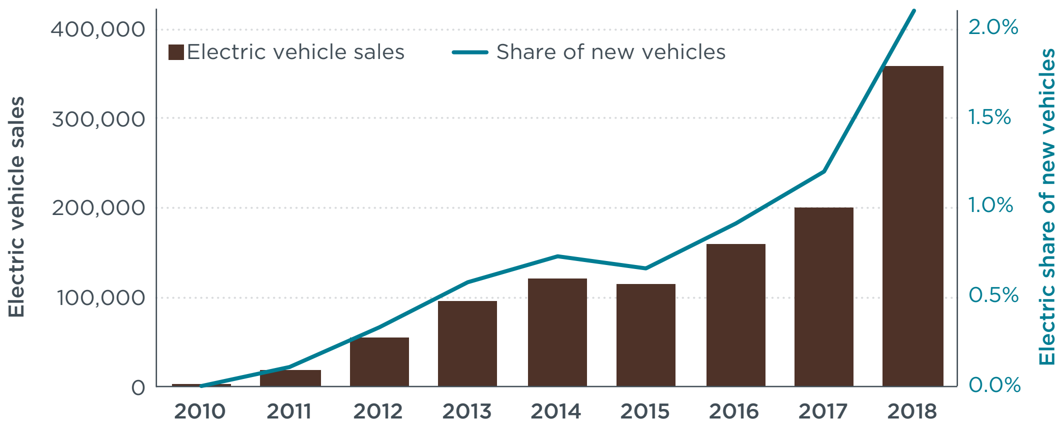

Figure 1. Annual light-duty electric vehicle sales in the United States, 2010–2018.

Electric vehicle uptake is concentrated where there are targeted policies that address the barriers of model availability, cost, convenience, and consumer awareness. Most electric vehicle sales have been in states that adopt the zero-emission vehicle (ZEV) regulation, which requires increasing electric vehicle deployment to approximately 10% of new vehicle sales by 2025. These states include California and nine others, which together represent two thirds of the electric market (Slowik & Lutsey, 2018). In addition to the 10 states with existing ZEV regulations, Colorado, New Mexico, and Washington state are considering similar policies (Colorado Department of Public Health & Environment, 2019; State of New Mexico, 2019; Washington State Legislature, 2019a, 2019b). In Canada, Québec also has adopted, and British Columbia is working to adopt, a similar ZEV regulation (British Columbia Office of the Premier, 2019; Gouvernement du Québec, 2019). The basis for such regulations is that the emission reductions are necessary for environmental goals, and the associated costs and fuel-saving benefits are also central considerations.

This paper analyzes how declining electric vehicle costs impact the compliance costs and benefits of a ZEV regulation in Colorado (Colorado Department of Public Health & Environment, 2019). We assess the technology costs and associated benefits (e.g., fuel and maintenance savings) from the deployment of plug-in hybrid electric vehicles (PHEVs) and all-electric battery electric vehicles (BEVs) in sedan, crossover, and sport-utility vehicle (SUV) market segments in the 2020–2030 time frame.

ELECTRIC VEHICLE COST ANALYSIS

This section analyzes how battery price reductions impact electric vehicle prices, as compared with conventional gasoline vehicles, in the 2020–2030 time frame. Based on the detailed engineering analysis of electric vehicle component costs, we evaluate overall PHEV and BEV costs in average car, crossover, and SUV classes over time. The vehicle cost analysis is based on our working paper (Lutsey & Nicholas, 2019), but with additional electric vehicle types with different ranges for use in the later fuel saving and ZEV compliance sections.

BATTERY PACK STUDIES

To analyze the future cost of electric vehicles, the most critical technology element is the battery pack cost, due to its declining trend and high fraction of the electric vehicle cost. Average automotive battery pack prices have declined by 85%, from $1,160 to $176 per kilowatt-hour (kWh), from 2010 to 2018 (Goldie-Scot, 2019). The associated progress includes cell chemistry, cell design, pack design, and manufacturing improvements that simultaneously result in higher energy density and lower cost.

A variety of technical studies evaluate the trend for continued technical improvements and cost reductions over the 2020–2030 time frame. Table 1 summarizes applicable technical studies from 2017 and 2018 that quantify battery pack costs for continued advances in battery technology and volume. These studies are state-of-the-art in terms of offering transparent bottom-up engineering analysis with specificity on lithium ion battery chemistries and production volume and include details on battery pack production (e.g., material, cell, and pack costs; cost versus production volume; bottom-up cost engineering approach, etc.). The table also includes automaker statements from Volkswagen, General Motors, and Tesla.

Table 1. Studies and announcements on electric vehicle battery pack cost

Type	Report	Battery specifications and cost elements included
Technical reports	Ahmed et al., 2018	Pouch NMC 6,2,2-graphite, production volume-based; includes total cost to automaker for material, process, overhead, depreciation, warranty
	Anderman, 2017	Cylindrical 21700, NCA 83,13,4, production volume-based; includes cost of material, capital, pack integration, labor, overhead, depreciation, R&D, administration, warranty, profit
	Anderman, 2018	Pouch NMC 8,1,1-graphite, production volume-based; includes cost of materials, capital, pack integration, labor, overhead, depreciation, R&D, administration, warranty, profit
	Berckmans et al., 2017	Pouch NMC 6,2,2-graphite anode, production volume-based; includes material, process, labor, overhead, depreciation, profit
		Pouch NMC 6,2,2-silicon alloy anode, production volume-based; includes material, process, labor, overhead, depreciation, profit
	UBS, 2017	Pouch NMC 6,2,2-graphite, production volume-based; includes material, process, labor, overhead, depreciation, profit
Automaker statements	Davies, 2017	Volkswagen statement. Associated with planned production volume of 100,000 per year by 2020 for I.D. series
	Lienert & White, 2018	General Motors statement related to Chevrolet Bolt (NMC 6,2,2); associated time frame for production volume has not been stated
	Tesla, 2018	Tesla statement related to Model 3 production volume of 500,000 with Panasonic battery production (cylindrical 21700, NCA 83,13,4) in Nevada by 2020

Note: NMC = nickel manganese cobalt oxide; NCA = nickel cobalt aluminum (numbers refer to the proportion of each element)

The battery pack costs from these studies and automaker announcements pertain to 2018 through 2030. They generally assume production volumes of 100,000 electric vehicle battery packs per year for 2020 and 500,000 units per year for 2025. Several of the estimates indicate that costs will decline to $120 to $135 per kilowatt-hour by 2025. Tesla (2018), reaching higher volume more quickly than others, indicates it will reach $100/kWh much sooner, and Berckmans et al. (2017) find that even greater battery cost declines will occur. The research studies provide a technical basis and are corroborated by industry statements. An industry survey by Bloomberg New Energy Finance indicates a reduction from $176/kWh in 2018 to $62/kWh in 2030 (Goldie-Scot, 2019). Based on these references, we apply an average battery cost of $128/kWh at the cell level, and $176/kWh at the pack level, for 2018 for a representative 45 kWh battery pack, and we reduce the costs at 7% per year for future years.

To apply battery cost estimates for the vehicle-level costs below, we apply a decreasing pack-to-cell cost ratio with increasing pack capacity. Our pack-to-cell cost ratio ranges from 1.54 for a 16 kWh pack down to 1.20 for 112 kWh and larger packs, based on Safoutin, McDonald, and Ellies (2018). This means larger battery packs (e.g., for a 300-mile range SUV) have lower per-kilowatt-hour pack costs, compared to smaller packs. Our resulting average pack-level costs across the 12 different BEV cases decline to $102/kWh in 2025, and to $71/kWh in 2030.

ELECTRIC VEHICLE COSTS

For our vehicle cost analysis, we assess vehicles that broadly represent the three major classes for light-duty vehicles. We evaluate each vehicle on its initial cost, cost of ownership for the first owner of the vehicle, and lifetime vehicle ownership costs. We analyze three vehicle classes—cars, crossovers, and SUVs—based on the latest available complete dataset for model year 2016 sales-weighted U.S. technical attributes for price, rated engine power, efficiency, and vehicle size (National Highway Traffic Safety Administration [NHTSA], 2018). The crossover class includes car-based SUVs and station wagons which are, from a regulatory perspective, approximately half cars and half light trucks. The comparable average conventional gasoline vehicle prices were about $29,000 for cars and crossovers and $41,000 for SUVs.

Table 2 shows the technical vehicle specifications for the BEVs and PHEVs for three vehicle classes in 2018, 2025, and 2030. The analysis includes lower-cost, shorter-range options and higher-cost, longer-range options. We analyze 150-mile (BEV150), 200-mile (BEV200), 250-mile (BEV250), and 300-mile (BEV300) BEVs and also 20-mile (PHEV20), 40-mile (PHEV40), and 60-mile (PHEV60) PHEVs. Technical specifications that are applicable for the analysis include rated kilowatt (kW) power, miles per gallon (mpg) fuel economy, electric range in miles, kilowatt-hours per mile (kWh/mile) electric efficiency, and kilowatt-hours (kWh) battery pack size.

Table 2. Technical specifications for four electric vehicles in three analyzed vehicle classes

		Electric									Plug-in hybrid								
		Car			Crossover			SUV			Car			Crossover			SUV		
		2018	2025	2030	2018	2025	2030	2018	2025	2030	2018	2025	2030	2018	2025	2030	2018	2025	2030
Power (kW)		150	150	150	150	150	150	220	220	220	150	150	150	150	150	150	220	220	220
Fuel economy (mpg)											47	54	60	41	47	52	27	31	34
Range (miles)	**Short**	150	150	150	150	150	150	150	150	150									
	Mid 1	200	200	200	200	200	200	200	200	200	20	20	20	20	20	20	20	20	20
	Mid 2	250	250	250	250	250	250	250	250	250	40	40	40	40	40	40	40	40	40
	Long	300	300	300	300	300	300	300	300	300	60	60	60	60	60	60	60	60	60
Electric efficiency (kWh/mile)	**Short**	0.28	0.27	0.26	0.34	0.32	0.31	0.48	0.46	0.44									
	Mid 1	0.29	0.28	0.27	0.35	0.33	0.32	0.50	0.47	0.46	0.30	0.29	0.28	0.36	0.34	0.33	0.51	0.49	0.47
	Mid 2	0.30	0.29	0.28	0.36	0.34	0.33	0.51	0.49	0.47	0.31	0.30	0.29	0.37	0.35	0.34	0.53	0.51	0.49
	Long	0.30	0.29	0.28	0.36	0.36	0.34	0.52	0.50	0.48	0.32	0.31	0.30	0.38	0.37	0.35	0.55	0.52	0.51
Battery pack (kWh)	**Short**	42	40	39	50	48	46	72	69	66									
	Mid 1	58	55	54	69	66	64	99	95	92	6	6	6	7	7	7	10	10	9
	Mid 2	75	72	69	90	86	83	128	123	119	12	12	11	15	14	14	21	20	20
	Long	91	87	84	109	104	101	156	149	144	19	18	18	23	22	21	33	31	30

Note: Numbers are rounded. Efficiency and ranges are based on U.S. consumer label values.

The initial 2018 electric vehicle efficiencies of these vehicles are based on existing model year 2018 models (U.S. Department of Energy, 2019). These efficiency values account for increased electricity use per mile for longer-range electric vehicles due to larger, heavier battery packs, as well as other attributes regarding the utility of vehicles (e.g., more crossovers have all-wheel drive, SUVs have four-wheel-drive and higher towing capacity). Based on SAE International (2010), we apply a utility factor to estimate the fraction of daily miles that could be powered electrically based on the vehicles' electric range, ranging from 0.40 for 20-mile PHEVs up to 0.98 for 300-mile BEVs, which is applied in the evaluation of vehicle ownership costs below.

The basis for the electric vehicle component costs is a vehicle engineering teardown study of a Chevrolet Bolt with a 60 kWh battery pack, electric power output of 145 kW, and consumer label range of 238 miles (UBS, 2017). We update to battery cost data shown above, and also to adapt the UBS values for the crossover and SUV vehicle classes' attributes. For the various representative vehicles, powertrain components are scaled to vehicle power, vehicle-level manufacturing costs are scaled to the vehicle footprint, and indirect conventional vehicle costs are treated as a percentage of direct manufacturing costs.

We also apply vehicle cost increases for increased efficiency improvements for conventional gasoline vehicles. We include 2% per year fuel economy improvements—starting from 30 mpg car, 26 mpg crossover, and 20 mpg SUV in 2018—to meet expected future efficiency regulations. The associated incremental price increases of $1,100 for cars, $1,300 for crossovers, and $1,800 for SUVs are applied to meet expected vehicle efficiency regulations through 2030 (Lutsey, Meszler, Isenstadt, German, & Miller, 2017). These incremental vehicle cost increases are incorporated with a 0.35% annual increase from 2018 through 2030.

Figure 2 illustrates vehicle costs, including conventional and BEV technology components. As indicated, BEV costs in 2018 are substantially higher than conventional vehicle costs for each of the three classes. The incremental cost for BEVs ranges from about $8,000 for the short-range car (i.e., $33,000 BEV150 versus $25,000 conventional) to about $26,000 for the long-range SUV (i.e., $57,000 BEV300 versus $31,000 conventional). Across the 12 BEVs, the incremental BEV-versus-conventional vehicle cost is reduced by 27% to 33% from 2018 to 2025. Electric vehicle costs approach the conventional vehicle costs by 2025, with the difference ranging from the BEV150 car being $1,500 less expensive to the BEV300 SUV being $6,200 more expensive than their conventional counterparts.

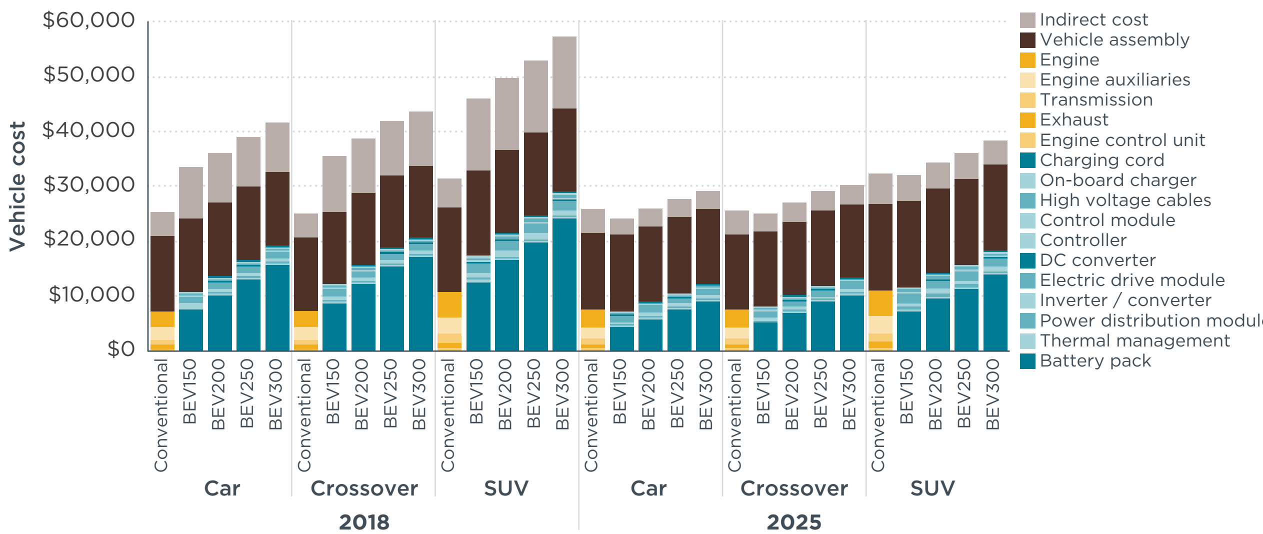

Figure 2. Vehicle technology costs for conventional and battery electric vehicles (BEVs) for 2017 and 2025 for car, crossover, and SUV.

As shown in Figure 2, battery and indirect costs for BEVs are the two largest areas for cost reduction. Declining battery costs account for much of the decline in BEV costs. For example, the 200-mile electric crossover battery pack cost drops by 42% from more than $12,000 in 2018 to about $7,000 in 2025, due to reduced battery cell and pack-level assembly cost, as well as increased vehicle efficiency allowing for less battery capacity. Indirect costs include depreciation, amortization, research and development, administration, and warranty. Indirect costs also contribute to a large fraction of the BEV cost reduction, as their research and development, depreciation, and amortized costs are spread across greatly increased production. BEV indirect costs per vehicle ($9,000–$13,000) are much higher than those of conventional vehicles ($4,200–$6,100 for SUVs) in 2018. By 2025, the BEV indirect costs drop to $3,200–$4,600, such that they are lower than conventional vehicles for each vehicle class.

Figure 3 illustrates vehicle costs, including conventional and PHEV technology components. As indicated, PHEV costs in 2018 are substantially higher than conventional vehicle costs. The incremental cost for PHEVs ranges from $4,700 for a PHEV20 car to $11,000 for a PHEV60 SUV. By 2025, the incremental PHEV costs compared to conventional vehicles are reduced by between 19% and 28% across the nine technology types. The incremental PHEV-versus-conventional incremental costs in 2025 range from $3,700 for a PHEV20 car to $8,000 for a PHEV60 SUV. Comparing Figure 2 results to those in Figure 3, PHEV costs are lower than comparable BEVs in 2018, but well above comparable BEVs in 2025 as the battery cost reductions have a much greater effect on the BEVs.

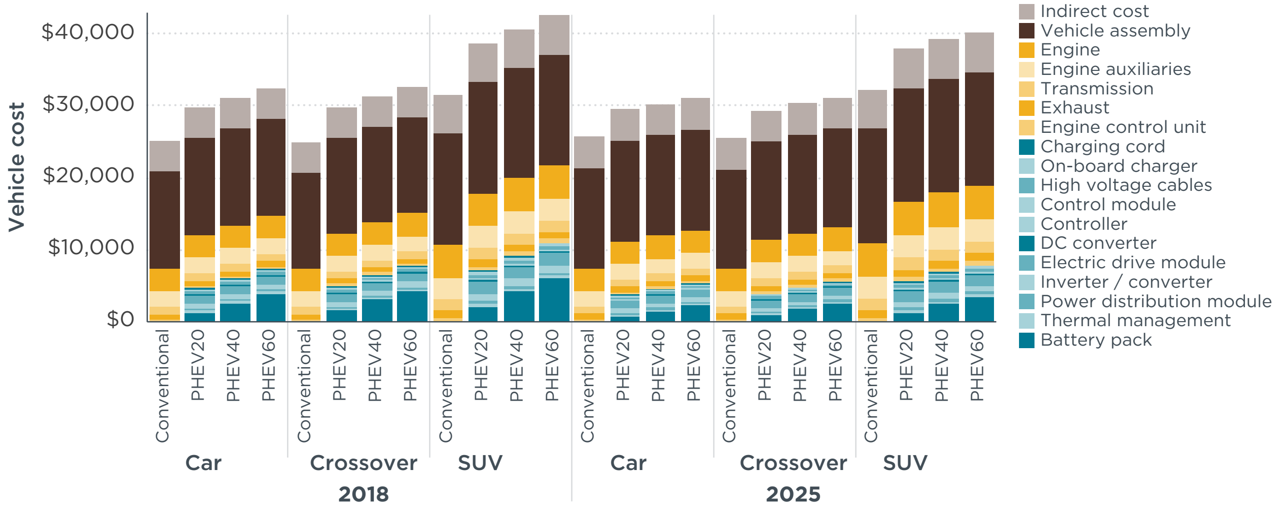

Figure 3. Vehicle technology costs for conventional and plug-in hybrid electric vehicles (PHEVs) for 2018 and 2025 for car, crossover, and SUV.

We apply several assumptions for industry markups to link the vehicle costs from above to the vehicle price. First, we assume that all vehicles maintain a 15% dealer markup for dealer incentives and marketing for all years. Second, we assume a profit margin that scales up for the larger vehicle classes: 5% for cars, 10% for crossovers, and 15% for SUVs. This ensures electric vehicles have the same profit built in as assumed for conventional vehicles. In addition, we include a 7.6% sales tax (including state and average local taxes) for all vehicles sold in Colorado (Tax Foundation, 2019). These assumptions do not impact the time of initial cost parity for electric vehicles, as they are taken as constant for all the technology types.

RESULTS FOR ELECTRIC VEHICLE PRICES THROUGH 2030

Figure 4 shows the changing vehicle technology prices through 2030 for the car (top segment), crossover (middle), and SUV (bottom). Each segment includes the average conventional gasoline vehicle (gray line) with incrementally increasing prices for efficiency improvements. The figure shows the decreasing prices for the electric vehicles of various ranges from the 20-mile PHEV (PHEV20) to the 300-mile BEV (BEV300).

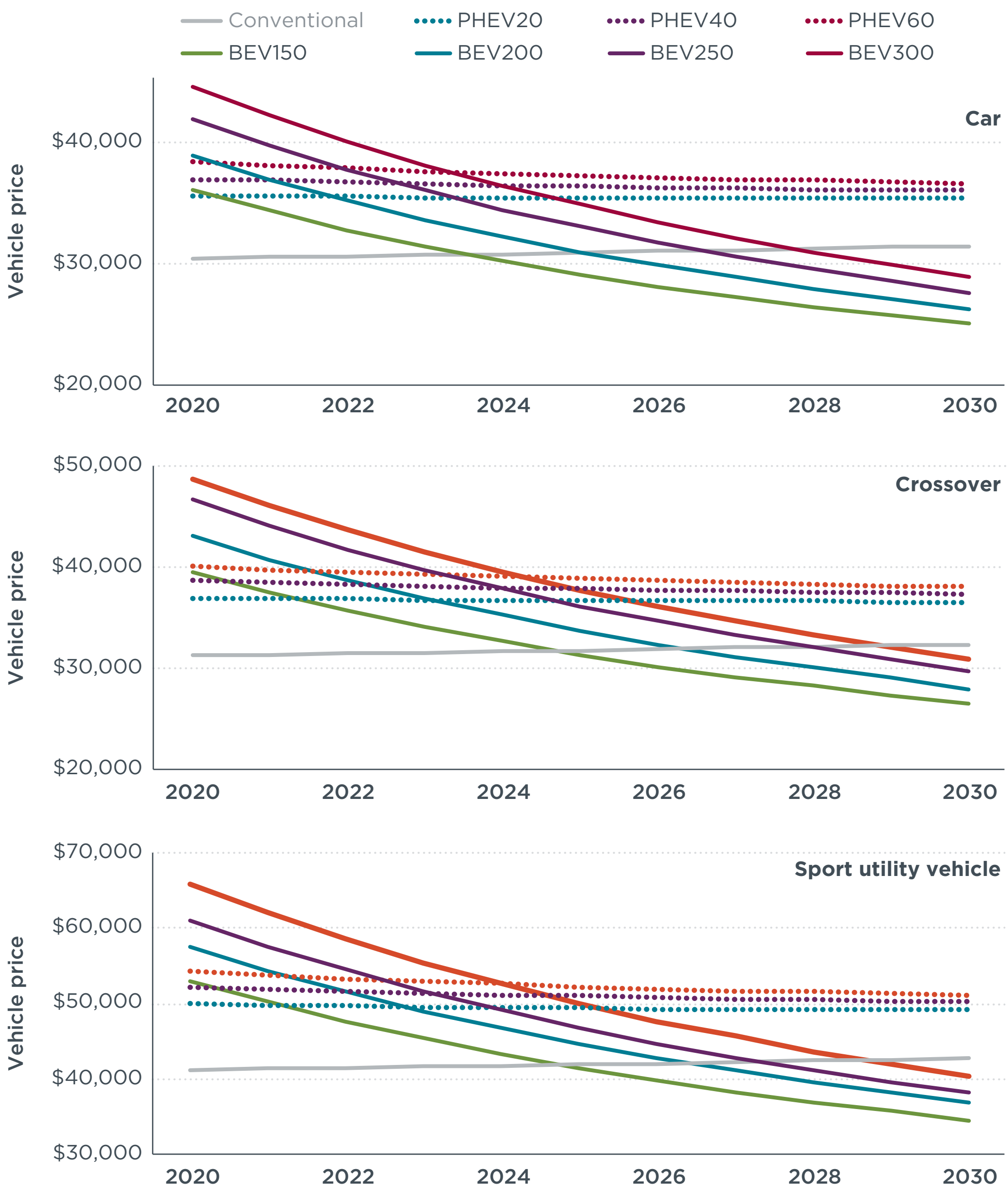

Figure 4. Initial purchase price of conventional and electric cars, crossovers, and SUVs for 2020–2030.

As illustrated in Figure 4, the greatly reduced prices of the BEVs result in their reaching price parity with conventional vehicles through the 2024–2029 time frame. The BEV150 vehicles achieve price parity soonest, crossing the conventional vehicle line by 2024 for cars, and by 2025 for crossovers and SUVs. The longer-range BEVs achieve price parity later. The BEV200 car, crossover, and SUV reach price parity in 2025–2026, followed by BEV250s in 2027–2028 and BEV300 in 2028–2029. This is due to these longer-range BEVs' larger battery packs adding substantial costs over the shorter-range versions of the same vehicle type. To give a sense of this price difference for a prospective vehicle buyer in 2025, compared to the shorter-range BEV150 car, a BEV200 will cost $1,900 more and a BEV300 will cost $5,700 more. Similarly, longer-range crossovers cost

$2,400 to $6,400 more, and longer-range SUVs will cost $3,200 to $8,500 more than the BEV150 versions by 2025.

Plug-in hybrid electric vehicles with 20 miles (PHEV20) to 60 miles (PHEV60) of electric range are also shown in Figure 4. The PHEV price differential versus conventional gasoline vehicles is reduced by 2030, but there are no price parity points with conventional vehicles. The PHEV20 car price differential with conventional vehicles declines from $5,200 in 2020 to $4,500 in 2025. For an example of a larger vehicle class and larger pack, the PHEV40 SUV cost differential drops from $10,900 in 2020 to $9,000 in 2025. PHEVs do not have a price parity point like the BEVs because the battery pack—where there are large price reductions—is a much lower contributor to the PHEV price and because the PHEV retains the combustion powertrain.

CONSUMER IMPACT ASSESSMENT

Building from the vehicle technology differences previously presented, we analytically compare the technologies by their first-owner cost-competitiveness and their projected lifetime net benefits. The first-owner cost-competitiveness, including the relative fuel and maintenance costs of owning and operating electric vehicles for several years, provides an important comparison from a car buyer perspective. The consumer effects over the full expected vehicle life include secondary effects in the used car market and provide an important input from a public policy perspective. After describing the applicable assumptions for average Colorado new vehicle drivers, we analyze these two consumer perspectives.

FUEL AND VEHICLE USE ASSUMPTIONS

We make a series of fuel and vehicle use assumptions for the consumer cost and benefit analysis. For the incorporation of the vehicle energy expenditures, fuel and electricity prices are from the U.S. Energy Information Administration (2019), using the Mountain region data for Colorado-specific prices. The retail gasoline price increases from $2.90 in 2018 to $3.31 per gallon from 2018 to 2035, and electricity remains roughly the same at $0.12/kWh through 2018 to 2035. To assess future-year fuel costs, we assume a discount rate of 5% in net present value accounting. We assume 5 years of ownership for the first owner of the vehicle, based on general trends for vehicle leasing and financing terms that typically are 4 to 6 years.

To include maintenance costs, we assume per-mile costs of $0.061, $0.061, and $0.076 for the car, crossover, and SUV for conventional vehicles, and $0.026, $0.028, and $0.036 for the respective BEV200s based on UBS (2017). These maintenance cost estimations are generally supported by the data collection of fleet operating costs of hundreds of electric vehicles, and thousands of conventional vehicles, in New York City fleet operations (New York City, 2019). Crossover and SUV values are scaled up, proportional to relative vehicle manufacturing cost, from the UBS (2017) estimation for cars. PHEV per-mile maintenance costs are assumed to be the average of conventional and BEV costs for each vehicle class.

For the annual travel activity over the vehicle life, we apply data from the Transportation Energy Data Book (Davis & Boundy, 2019) as follows. For the vehicle lifetimes, we assume 15 years for cars and crossovers and 16 years for SUVs, based on the median vehicle lifetime. For cars and crossovers, the new vehicle miles traveled decrease from approximately 13,800 in the first year to 12,700 by the fifth year, and 8,600 in the 15th year. For SUVs, annual driving declines from 16,000 in the first year, to 14,500 in the fifth, to 8,800 in the 16th.

Electric vehicles have several additional factors in their ownership costs. Home charger costs of $1,300 for BEVs and $300 for PHEVs are included to enable more convenient residential charging. The BEV home charging cost is assumed to decrease at 3% per year as capital equipment and installation business is expected to scale over time. A utility factor incorporates how BEVs and PHEVs are typically driven fewer annual electric miles than typical new vehicle annual driving averages. The utility factor estimates the average fraction of daily miles covered by an electric vehicle for a given electric range (e.g., 0.40 for the PHEV20, 0.93 for the BEV150, and 0.98 for the BEV300) based on SAE International (2010). The remaining miles (i.e., 60% for the PHEV20, 7% for BEV150, 2%

for the BEV300) would therefore be covered by non-electric driving. PHEVs are driven in gasoline-powered charge-sustaining hybrid mode for the remaining non-grid-powered miles. The non-electric BEV driving would be by a "replacement" vehicle (e.g., a separate household vehicle, rental, or ride-hailing vehicle). The BEV replacement miles are based on the total cost of ownership values from combustion vehicles from within this analysis. For example, the per-mile costs for the conventional car are $0.63 for the car, $0.66 for the crossover, and $0.75 for the SUV in 2025.

FIRST-OWNER ELECTRIC VEHICLE COST OF OWNERSHIP

Figure 5 shows the manufacturing, markup, charging, fueling, maintenance, tax, and vehicle replacement costs for the first owner of the BEVs and conventional vehicles. The figure shows the 5-year ownership costs for the three vehicle classes, for conventional and electric vehicles, in 2018 and 2025. The vehicle costs, matching those from Figure 2, are the largest differences across the technologies within each vehicle class. But the addition of the other factors in the figure make overall BEV ownership costs lower than the conventional vehicle counterparts in seven of the 12 BEV cases in 2025. After vehicle costs, the most important factor that impacts the relative costs of the technologies is fuel savings. In 2025, the first-owner fuel costs for an average new car buyer come to $5,200 for gasoline, compared to about $1,600 to $1,900 in electricity for the electric vehicles. For the SUV, the average conventional vehicle consumes $7,700 in gasoline versus $3,100 to $3,700 in electricity in 2025. BEVs also accrue relative maintenance cost savings, but have additional costs from charging equipment and the replacement vehicle to make up the forgone miles.

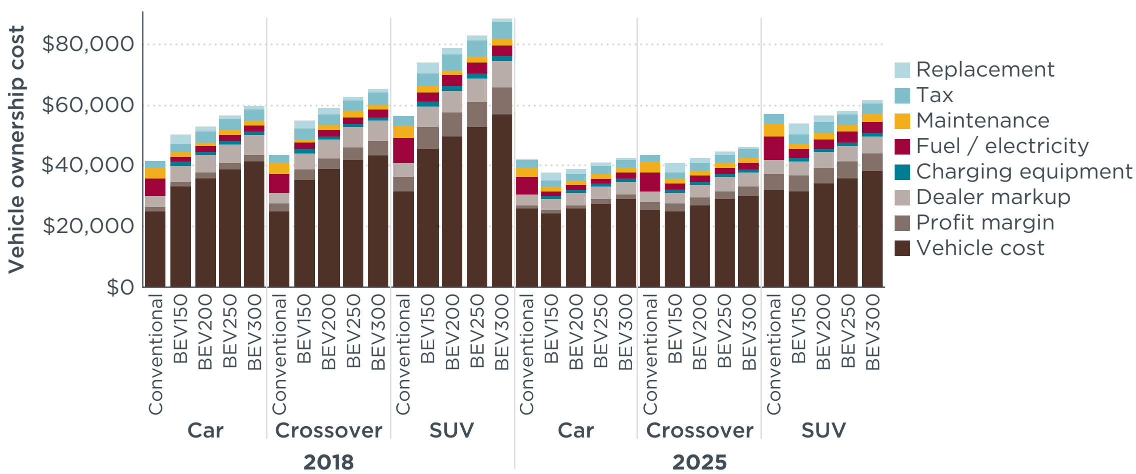

Figure 5. First-owner costs for conventional and electric cars, crossovers, and SUVs for 2018 and 2025.

Figure 6 shows the 5-year ownership costs for the conventional and PHEV technologies for the three vehicle classes in 2018 and 2025. The addition of the other factors in the figure make overall PHEV ownership costs closer to the conventional vehicle by 2025 than in the initial vehicle price case shown in Figure 3, due largely to the $2,300 to $3,200 fuel savings from the PHEV compared to conventional vehicle across the cases. As in the initial cost case, there is still no cost parity point between PHEV and conventional vehicles in this first-owner analysis.

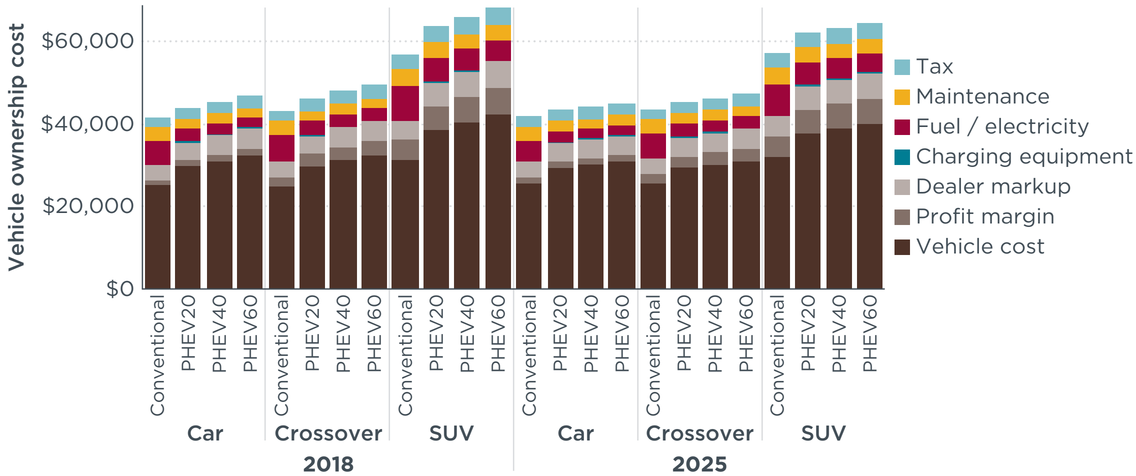

Figure 6. First owner costs for conventional and plug-in hybrid electric cars, crossovers, and SUVs for 2018 and 2025.

Figure 7 shows the total 5-year vehicle ownership cost differences between the electric and conventional vehicles for the four BEVs and the three PHEVs in 2025 across the car, crossover, and SUV classes. The difference is shown as a positive number when the electric vehicle provides a benefit to the vehicle owner, and a negative if the electric vehicle results in a net additional cost to the owner. As an example, in Figure 7, the BEV150 car (the leftmost vertical bar) shows about $2,200 in maintenance benefit (yellow bar), $3,600 in fuel savings (green), an initial price benefit of $1,800 (dark gray), and $3,600 (light gray) in additional other differences (home charger, replacement vehicle, tax). The net change from all these factors is that the BEV150 car offers a $4,000 benefit for the owner, as shown with the white diamond.

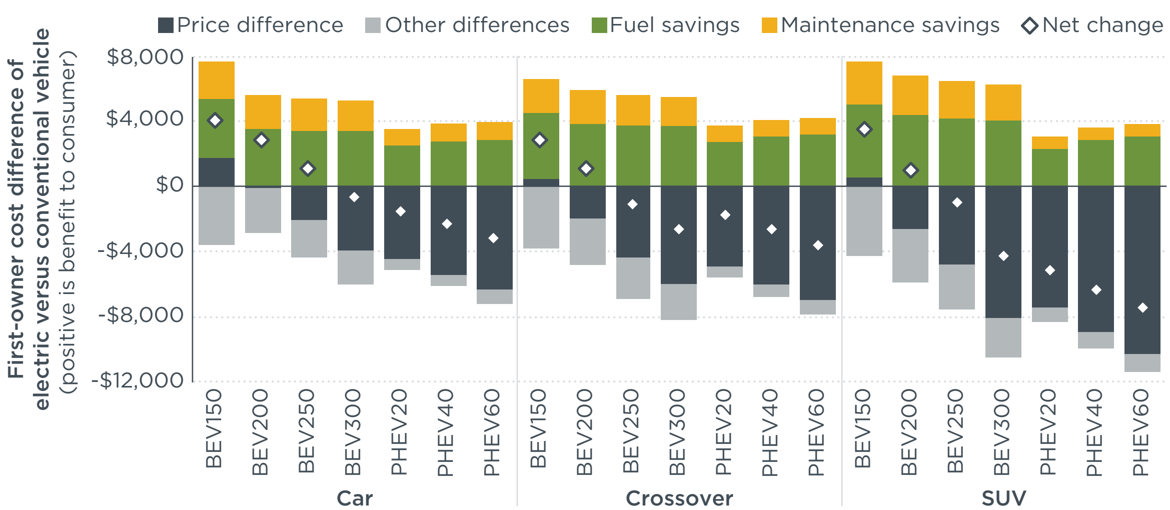

Figure 7. First-owner difference in ownership cost for electric versus conventional cars, crossovers, and SUVs in 2025 (positive is benefit to the consumer, negative is a cost).

Across the 21 different electric vehicle cases in Figure 7, there are seven that have net first-owner benefits that are positive (all three BEV150s, all three BEV200s, and the car BEV250). The 12 BEVs each have average fuel plus maintenance savings between $5,200 and $7,200 per vehicle over 5 years of ownership. Within each vehicle class, the largest distinguishing factor for the electric vehicles' operating cost difference versus the conventional vehicles is the electric vehicle price difference, which is largely driven by the battery pack cost. Figure 7 helps to demonstrate the consumer proposition for buyers considering electric vehicles once ownership cost parity is reached for shorter-range BEVs, but not for longer-range BEVs. A prospective crossover driver in 2025 could pay $2,800 less to own a BEV150, or $2,600 more for the BEV300, as compared to owning a conventional gasoline crossover.

ELECTRIC VEHICLE LIFETIME COST OF OWNERSHIP

To analyze the total ownership costs, we consider the total net present value of all the above costs for cars, crossovers, and SUVs driven over their full vehicle lifetime. The initial vehicle cost differences (i.e., for purchase price, home charging, vehicle purchase tax) are unchanged from the first-owner cost analysis shown in the section above. Including lifetime ownership cost accounting includes the greater effect from annual cost differences (i.e., for fuel, maintenance, replacement costs) between electric and conventional vehicles for 15 years for cars and crossovers and 16 years for SUVs. Although the effect is approximately tripling the lifetime from the 5-year ownership, the monetary effect is to multiply the recurring annual differences by 2.2 to 2.3 due to the net present value accounting that discounts future-year effects.

Figure 8 shows the lifetime vehicle ownership cost differences between the electric and conventional vehicles in 2025 across the car, crossover, and SUV classes. The overall electric-versus-gasoline lifetime ownership difference—shown by the white diamonds in the figure—is shown as a positive number when the electric vehicle provides a net benefit, and a negative number if the electric vehicle results in a net additional consumer cost. To take an example, in Figure 8 the BEV150 car (the leftmost vertical bar), shows about $4,700 in maintenance benefit (yellow bar), $7,900 in fuel savings (green), an initial price benefit of $1,800 (dark gray), and $3,600 (light gray) in additional other differences (home charger, replacement vehicle, tax). The net change from all these factors is that the BEV150 car offers a $10,800 benefit over the conventional gasoline vehicle.

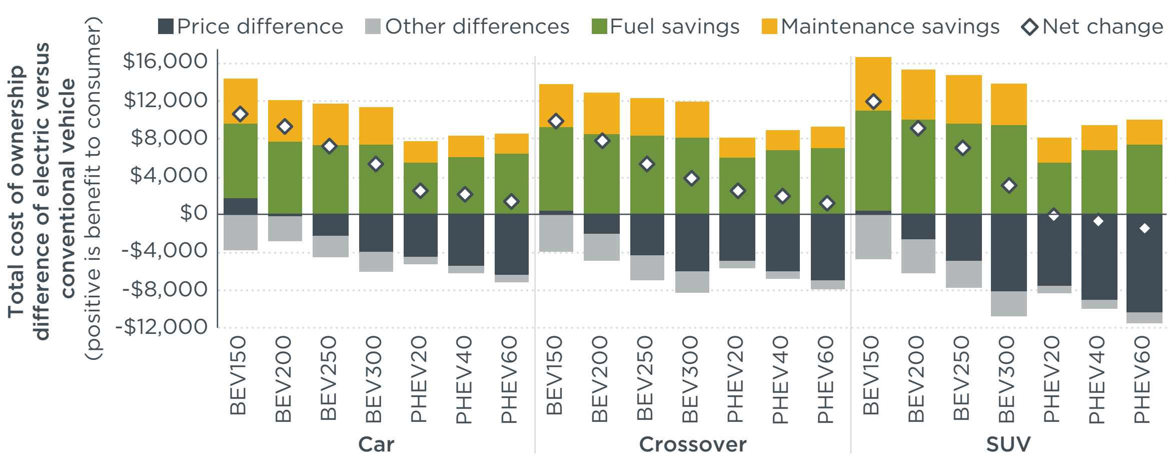

Figure 8. Lifetime difference in ownership cost for electric versus conventional cars, crossovers, and SUVs in 2025 (positive is benefit to the consumer, negative is a cost).

Across the 21 different vehicle classes in Figure 8, each of the 12 BEVs have positive net benefits, ranging from about $3,200 to $12,000. The 12 BEVs have average fuel plus maintenance savings between $11,000 and $16,000 per vehicle over their lifetimes. The average lifetime net benefit for the 12 BEVs is $7,600. To take a representative vehicle class and technology type, the crossover 200-mile BEV has a net benefit of approximately $7,900. Also shown, the PHEVs in the car and crossover classes result in net-positive lifetime vehicle impacts of $1,400 to $2,700, but the PHEV SUVs have lifetime costs that are roughly the same or somewhat higher than conventional SUVs.

Also, considering the typical speculation that a significant fraction of BEVs may eventually need battery replacements, we evaluate the potential impact. We note that from limited evidence to date, the electric vehicles with the longest electric range have not had such issues; Tesla models with 160,000 miles have seen only approximately 10% range degradation and few battery replacements (e.g., see Lambert, 2018). This is especially important because these are BEVs that have accumulated relatively high lifetime driving, and they also likely have the greatest use of fast charging—through Tesla's free rapid charging—and battery degradation fears have been largely associated with higher fast charging use over time.

Even factoring in a speculative and conservatively high assumption of 10% battery pack replacement rate for each vehicle, the results would not change the fundamental findings shown in Figure 8. Including this rate of battery replacements for the 2025 vehicle cases analyzed above results in an average lifetime battery replacement cost of $300 (i.e., approximately $3,000 for 10% of vehicles) for the BEV150 car up to $1,000 for the BEV300 SUV. Comparing these costs to the data shown in Figure 8, the lifetime benefits in each BEV case are much greater—4 to 9 times for BEV300s and 24 to 36 times for BEV150s—than the average potential battery pack replacement cost. This side analysis is speculative, and we do not have comparable estimates for lifetime engine and transmission replacements for conventional vehicles, so we do not include it in the primary analysis.

POTENTIAL ZEV COMPLIANCE SCENARIOS

As a final analytical step to the analysis, we assess the implications of the above technology cost findings for the potential ZEV regulation scenarios. We apply the above benefit and cost data for the various vehicle technology cases to a projected fleet of new vehicles in Colorado in the 2023–2030 time frame. The analysis of the 2023–2025 period reflects the effect of Colorado adopting a ZEV regulation to match that of California and nine other states. We also quantify how benefits and costs accrue assuming a continuation of the ZEV regulation for model years 2026 through 2030 due to further technology innovation and market development.

To assess the potential ZEV standards, three scenarios are developed that reflect a range of plausible industry-wide compliance approaches for the Colorado light-duty vehicle market. The Colorado market has a higher percentage of light truck sales than the U.S. average. Based on the 2016 data, the car, crossover, SUV, and pickup classes represent 41%, 26%, 22%, and 11%, respectively, of new U.S. sales (NHTSA, 2018). After comparing U.S. and Colorado registration data including IHS Markit data from the Colorado Automobile Dealers Association (2019) and California New Car Dealers Association (2019) with the official U.S. regulatory data (U.S. Environmental Protection Agency, 2019), we estimate a Colorado breakdown of 24% cars, 32% crossovers, 28% SUVs, and 16% pickups for model year 2018 and later vehicles.

The primary assumptions for the ZEV compliance scenarios are the expected breakdown of BEVs versus PHEVs and the mix of electric ranges for those two technologies. For the trend in the BEV share of electric vehicles, our central assumption is that the recent trend continues. The recent trend in Colorado's new electric vehicles that are BEVs is from 58% in 2016, to 64% in 2017, and to 70% in 2018. Our central scenario continues the recent trend to reach 80% BEVs by 2025 and 85% by 2030. Two additional scenarios are included. One has an increasing BEV trend that reaches BEV shares of 90% by 2025 and 95% in 2030; the other remains at the same BEV share of 70% through 2030. The breakdown of BEVs and PHEVs includes a mix of all the ranges analyzed above, with approximate averages of 200 miles for BEVs and 25 miles for PHEVs.

To assess ZEV compliance, we set our scenarios to minimally comply with California ZEV regulatory requirements through 2025, in the event that the standards were to be implemented for the Colorado market. The existing California regulations require that automakers increasingly deploy eligible zero-emission vehicles to meet ZEV credit requirements that increase from 5% in 2018 to 22% in 2025 (California Air Resources Board, 2016). Because ZEV credits increase with electric range, and most BEVs receive two to four credits per vehicle, the actual required electric vehicle deployment is approximately 8% in 2025 (California Air Resources Board, 2017). For a hypothetical continuation of the trend through 2030, we analyze scenarios that reflect the cost parity results and increase electric vehicle penetration to 35% by 2030.

We illustrate two results for our central analysis of ZEV scenarios. The first shows the improving average price differential of electric versus conventional vehicles along with the increasing electric vehicle penetration. This applies the price analysis shown in Figure 4 to the ZEV scenario defined here. The second illustration summarizes the average electric vehicle price differential with gasoline vehicles and the total vehicle ownership benefits within each model year. This applies the above first owner (see

Figures 5, 6, and 7) and lifetime cost of ownership analysis (see Figure 8) to the ZEV compliance scenario.

Figure 9 shows the average electric vehicle price difference (i.e., for the sales-weighted average price difference for electric vehicles sold in Colorado versus their conventional counterparts) and increased electric vehicle penetration from 2020 through 2030 for our central ZEV compliance scenario. The figure shows that minimum ZEV compliance electric vehicle penetration reaches 7.4% in 2023, 8.4% in 2024, and 9.4% in 2025. This electric vehicle penetration, including a mix of BEVs and PHEVs across the three vehicle classes (car, crossover, and SUV) and across electric ranges (from 20–300 miles). As shown by the blue line in the figure, the average electric vehicle price differential decreases from $4,300 in 2023 to $500 in 2026, and then delivers a price benefit to consumers—before considering any fuel and maintenance benefits—that increases from $500 in 2027 to surpass $3,000 in 2030. This indicates average price parity around 2026–2027. Shorter-range BEVs reach parity sooner, longer-range BEVs later, and PHEVs do not reach price parity.

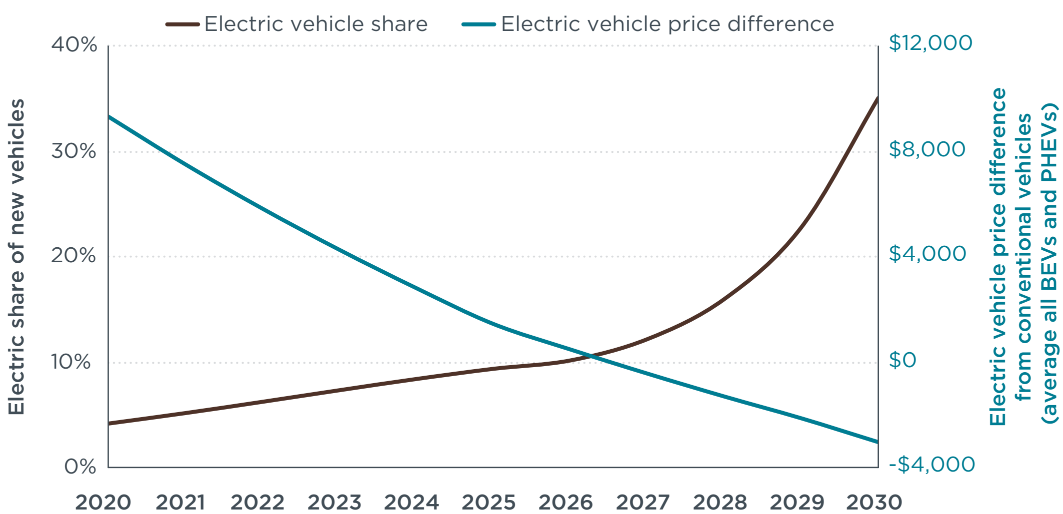

Figure 9. Increased electric vehicle penetration and average electric vehicle price difference from 2020 through 2030.

Figure 10 shows the average electric vehicle price difference along with the first-owner and secondary owner effects associated with our analysis of increased electric vehicle penetration from 2023 through 2030 in Colorado. As indicated, the average electric vehicle price represents an additional cost to consumers (from $4,300 to $500) from 2023 to 2026, before representing a cost improvement to consumers (from $500 to more than $3,000) from 2027 to 2030. After the vehicle purchase, the average first-owner benefits over 5 years are between $2,700 and $3,200 per vehicle, including costs from the charger, fuel, electricity, and maintenance. After the first vehicle owner, the additional secondary effects over the lifetime of the vehicle are even greater, ranging from $5,900 to $6,300 per vehicle, largely due to the substantial fuel and maintenance savings. Total net lifetime effects, including initial price, first-owner, and secondary owner effects, are shown. Overall the average electric vehicle delivers a net benefit that increases from approximately $4,800 to $12,000 per vehicle from 2023 to 2030.

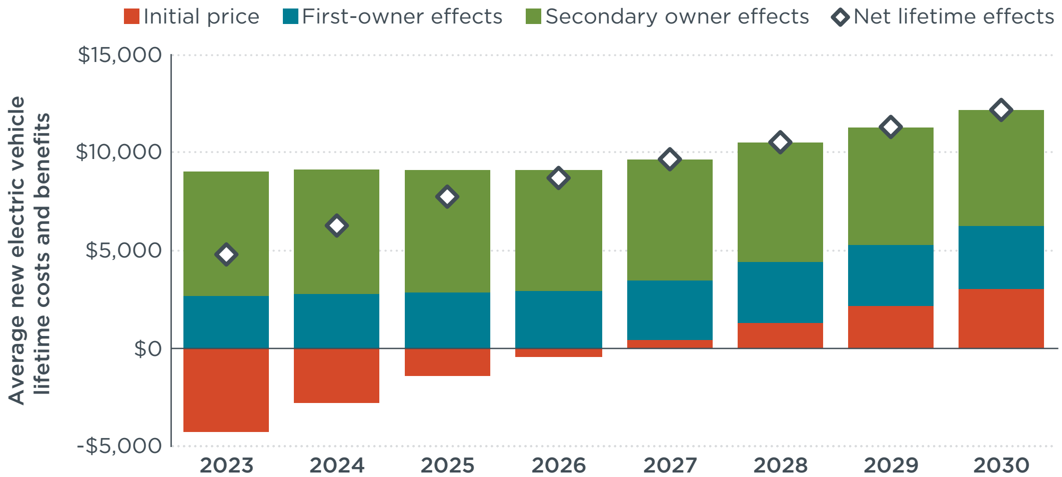

Figure 10. Average electric vehicle price and first-owner and secondary owner effects of increased electric vehicle penetration from 2023 through 2030.

In addition to the central scenario, additional electric vehicle penetration scenarios with a constant BEV share over time (at 70% through 2030) and an increasing BEV share (increasing to 95% by 2030) are also analyzed. Table 3 summarizes the costs and benefits for each model year from 2023 through 2030 for the three ZEV compliance scenarios. The table includes the number of new electric vehicles sold each year, the average vehicle price differential, first-owner effects, and secondary effects. As indicated, the higher BEV case has lower overall cost and fewer electric vehicles through 2025 due to the BEVs having greater ZEV credit per vehicle than PHEVs. For the central scenario and the two additional scenarios, the key details—including electric vehicle sales, average price differences, and average fuel savings—are shown in tables in the Appendix.

Table 3. Summary of electric vehicle scenario cost and benefit effects by model year

	Central scenario (Continued BEV share trend to 85%)				Constant BEV share scenario (BEV share remains constant at 70%)				Higher BEV share scenario (BEV share increases to 95%)			
Model year	Electric vehicles	Electric vehicle initial price[a]	First-owner effect	Secondary effect	Electric vehicles	Electric vehicle initial price[a]	First-owner effect	Secondary effect	Electric vehicles	Electric vehicle initial price[a]	First-owner effect	Secondary effect
2023	20,000	-$4,300	$2,700	$6,300	21,000	-$4,300	$2,700	$6,200	19,000	-$4,200	$2,700	$6,500
2024	23,000	-$2,800	$2,800	$6,300	25,000	-$3,000	$2,800	$6,100	21,000	-$2,500	$2,700	$6,500
2025	26,000	-$1,400	$2,800	$6,300	29,000	-$1,900	$2,800	$6,000	24,000	-$1,000	$2,800	$6,500
2026	28,000	-$500	$2,900	$6,200	32,000	-$1,000	$2,900	$6,000	25,000	$100	$2,900	$6,500
2027	34,000	$500	$3,000	$6,100	38,000	-$300	$3,000	$5,900	31,000	$1,100	$3,000	$6,400
2028	46,000	$1,300	$3,100	$6,100	50,000	$400	$3,100	$5,800	42,000	$2,100	$3,100	$6,300
2029	66,000	$2,200	$3,100	$6,000	69,000	$1,000	$3,100	$5,700	63,000	$3,000	$3,200	$6,200
2030	102,000	$3,100	$3,200	$5,900	102,000	$1,700	$3,200	$5,600	102,000	$4,000	$3,200	$6,100
Combined over each period (dollars are in millions)												
2023–2025	69,000	-$187	$191	$436	75,000	-$223	$210	$459	64,000	-$155	$174	$415
2026–2030	276,000	$515	$859	$1,658	291,000	$225	$897	$1,665	263,000	$717	$825	$1,639

Notes: Values are rounded.
[a] Costs to consumers are shown as negative, benefits to consumers are shown as positive

The primary benefit-cost proposition from the ZEV regulation is shown in Table 3. In the central scenario, the vehicle costs in the 2023–2025 time period of $187 million are greatly outweighed by the associated $627 million in vehicle lifetime benefits. This amounts to $440 million in net benefits, and vehicle lifetime benefits that are 3.3 times the initial vehicle costs. When looking at 2026–2030, the effects are more overwhelmingly positive because most BEV models reach cost parity and become less expensive than gasoline vehicles. The costs and benefits differ somewhat for the two other scenarios: For model years 2023 through 2025, the increased vehicle cost of $155 million to $223 million would result in $589 million to $669 million in lifetime vehicle benefits. Considering the two alternative scenarios, the 2025 ZEV regulation results in 3.0 to 3.8 times greater benefits than costs. Even considering only first-owner effects over 5 years of ownership, the benefits are roughly equivalent to costs (e.g., $191 million versus $187 million in the central case).

The results indicate that continuing the ZEV regulation for model years 2026 through 2030 would have much more substantial benefits. As shown in the bottom row of Table 3, the average vehicle costs would be positive, and therefore vehicles in Colorado would, on average, become less expensive if a ZEV regulation required electric vehicle penetration that increases to 35% of new vehicle sales by 2030. From 2026 through 2030, a hypothetical next phase of a ZEV regulation would result in $2.8 billion to $3.2 billion in net direct economic benefits in Colorado. The central scenario includes $515 million in vehicle price savings resulting from the lower cost of electric vehicles, $859 million in consumer savings to the first owners of those vehicles, and $1.66 billion for subsequent vehicle owners of the model year 2026–2030 electric vehicles.

Although the ZEV regulation works on the basis of a percentage of new vehicles deployed, absolute vehicle numbers are shown for context in Table 3. Our initial market assumptions are that new light-duty vehicle sales start at 258,000 in 2018 and grow at 1% per year, and the electric share of those sales in 2018 was 2.8%. To meet a ZEV regulation, our scenarios see increased electric shares to 8.5% to 10.4% of new vehicles by 2025. After 2025, the electric share increases to 35% by 2030 as a hypothetical continuation of ZEV standards that capitalizes on the Colorado market developments and decreased electric vehicle prices. The scenarios result in more than 100,000 electric vehicles sold annually in the state by 2030. The resulting cumulative electric vehicle sales are 140,000 (133,000 to 148,000 in the alternative cases) for 2010 through 2025, and 416,000 (395,000 to 439,000 in the alternative cases) for 2010 through 2030.

CONCLUSIONS

The assessment responds to two ZEV regulation questions: How quickly are electric vehicle costs declining and what are the resulting consumer benefits compared to gasoline vehicles? This paper analyzes these two questions in the context of Colorado's potential adoption of a zero-emission vehicle regulation for new light-duty vehicles from 2023 through 2030. Our assessment of PHEV and BEV technologies of varying electric range offers the ability to quantify the direct costs and benefits of a ZEV regulation that increasingly requires a growing electric vehicle market over time. The findings lead to several conclusions about cost parity timing, per-vehicle benefits, and overall effects from a ZEV regulation.

Declining battery costs will make electric vehicles less expensive than conventional vehicles. Depending on how price parity is measured (i.e., in initial price or first-owner costs), electric vehicles will reach parity with comparable gasoline vehicles between 2022 and 2029. In terms of upfront vehicle purchasing, BEVs up to 200 miles in electric range reach price parity with conventional gasoline vehicles between 2024 and 2026. Longer-range 250–300 mile electric range BEVs reach price parity between 2027 and 2029. Including first-owner fuel and maintenance savings, BEVs achieve parity for vehicle buyers two years sooner—between 2022 and 2027 across cars, crossovers, and SUVs.

Based on the analysis, by 2025 consumer benefits of electric vehicles greatly exceed the associated incremental vehicle costs for the technology. For shorter-range BEVs, first-owner savings are greater than their associated technology costs by 2025. Including lifetime benefits, BEVs with up to 300 miles of electric range in cars, crossovers, and SUVs deliver net consumer benefits, ranging from $3,200 to $12,000 per vehicle. Although parity is not reached for the first owners of PHEVs, the PHEVs deliver lifetime benefits that exceed upfront costs for cars and crossovers by $1,400 to $2,700 per vehicle; however, lifetime PHEV SUV costs are roughly the same or somewhat higher than conventional SUVs.

For new vehicles in Colorado to meet a ZEV regulation that is aligned with the other 10 ZEV regulation states, this would mean increasing the electric vehicle shares in the state from 2.8% in 2018 to 8.5% to 10.4% by 2025. This would bring the cumulative number of electric vehicles sold in the state from approximately 20,000 at the end of 2018 to 120,000 at the end of 2025. The extension of the ZEV program to reach 35% electric share of new vehicles by 2030 would increase electric vehicle deployment in the state to 400,000, or approximately 20 times the number at the end of 2018.

Electric vehicle requirements at these levels, as assessed in this paper, overwhelmingly pass a cost-benefit analysis. We find that, incorporating a mix of electric vehicle technologies across vehicle classes, a Colorado ZEV regulation can be met with a decidedly positive cost-to-benefit balance. For 2023–2025 model years, vehicle price increases of $155 million to $223 million would result in $589 million to $669 million in lifetime vehicle benefits—approximately 3.3 times greater benefits than costs. Under our central analysis, we find that the net benefits to Colorado drivers from such a 2023–2025 regulation are $440 million. The 2023–2025 ZEV regulation not only has strong net benefits, but also could reap much larger benefits in subsequent years. With the continuation of the ZEV program for new vehicles in 2026–2030, a potential next phase of the ZEV regulation would amount to $3 billion in direct economic benefits to Colorado vehicle owners.

The implications of this evaluation of a potential Colorado ZEV regulation are much broader. Due to steady electric vehicle improvements and declining costs, ZEV regulations will now definitively pass standard regulatory cost-benefit evaluations. This means that in the 2022–2026 period, governments can shift from incentives to regulations to steer the transition to electric vehicles. Beyond the basic economics, considering the environmental and social benefits of reducing emissions, the case is even stronger. Much higher electric vehicle penetration, moving toward full electrification, will be necessary for the transport sector to contribute to climate stabilization and air quality goals. This makes it clear that electric vehicles can simultaneously deliver on environmental and economic goals.

REFERENCES

Ahmed, S., Nelson, P., Susarla, N., & Dees, D. (2018). *Automotive battery cost using BatPaC*. Presented at the IEA Workshop on Batteries for Electric Mobility, March 7, 2018, Paris. Retrieved from https://www.iea.org/media/Workshops/2018/Session2ShabbirAhmedANL.pdf

Anderman, M. (2017). *The Tesla battery report: Tesla Motors: Battery technology, analysis of the Gigafactory and Model 3, and the automakers' perspectives*. Retrieved from the Total Battery Consulting website: http://www.totalbatteryconsulting.com/industry-reports/Tesla-report/Extract-from-the-Tesla-Battery-Report.pdf

Anderman, M., (2018, June). *The xEV industry insider report*. Retrieved from the Total Battery Consulting website: https://totalbatteryconsulting.com/industry-reports/xEV-report/Extract-from-the-2018-xEV-Industry-Report.pdf

Berckmans, G., Messagie, M., Smekens, J., Omar, N., Vanhaverbeke, L., & Van Mierlo, J. (2017). Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030. *Energies 2017,* 10(9), 1314. Retrieved from http://www.mdpi.com/1996-1073/10/9/1314

British Columbia Office of the Premier. (2018). *Provincial government puts B.C. on path to 100% zero-emission vehicle sales by 2040*. Retrieved from https://news.gov.bc.ca/releases/2018PREM0082-002226

California Air Resources Board. (2016). Regulation 1962.2, Zero-emission vehicle standards for 2018 and subsequent model year passenger cars, light-duty trucks, and medium-duty vehicles (Effective date: January 1, 2016). Retrieved from https://www.arb.ca.gov/msprog/zevprog/zevregs/1962.2_Clean.pdf

California Air Resources Board. (2017). *California's advanced clean cars midterm review: Summary report for the technical analysis of the light duty vehicle standards*. Retrieved from https://ww2.arb.ca.gov/resources/documents/2017-midterm-review-report

California New Car Dealers Association. (2019). *California auto outlook* (Volume 15, No. 1). Retrieved from https://www.cncda.org/wp-content/uploads/Cal-Covering-4Q-18.pdf

Colorado Automobile Dealers Association. (2019). *Colorado auto outlook* (Covering data thru December 2018). Retrieved from https://www.colorado.auto/sites/default/files/CO%20Dec%2018.pdf

Colorado Department of Public Health & Environment. (2019). Zero emission vehicle mandate proposal. Retrieved from https://www.colorado.gov/pacific/cdphe/zero-emission-vehicle-mandate-proposal

Davies, C. (2017). VW I.D. EV boast: We'll hugely undercut Tesla's Model 3 says exec. Retrieved from https://www.slashgear.com/vw-i-d-ev-boast-well-hugely-undercut-teslas-model-3-says-exec-17491688/

Davis, S., & Boundy, R. (2019). *Transportation energy data book, edition 37*. Retrieved from Oak Ridge National Laboratory website: https://cta.ornl.gov/data/index.shtml

EV-Volumes (2019). EV Data Center. Retrieved from http://www.ev-volumes.com/datacenter/.

Goldie-Scot, L. (2019, March 5). A behind the scenes take on lithium-ion battery prices. *Bloomberg New Energy Finance*. https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

Gouvernement du Québec. (2019). The zero-emission vehicle (ZEV) standard. Retrieved from http://www.environnement.gouv.qc.ca/changementsclimatiques/vze/index-en.htm

Lambert, F. (2018, April 14). Tesla battery degradation at less than 10% after over 160,000 miles, according to latest data. Retrieved from https://electrek.co/2018/04/14/tesla-battery-degradation-data/

Lienert, P., & White, J. (2018). GM races to build a formula for profitable electric cars. Retrieved from https://www.reuters.com/article/us-gm-electric-insight/gm-races-to-build-a-formula-for-profitable-electric-cars-idUSKBN1EY0GG

Lutsey, N., Meszler, D., Isenstadt, A., German, J., & Miller, J. *Efficiency technology and cost assessment for U.S. 2025–2030 light-duty vehicles*. Retrieved from the International Council on Clean Transportation, http://www.theicct.org/US-2030-technology-cost-assessment

Lutsey, N. & Nicholas, M. (2019). *Update on electric vehicle costs in the United States through 2030*. Retrieved from the International Council on Clean Transportation, https://www.theicct.org/publications/update-US-2030-electric-vehicle-cost

National Highway Traffic Safety Administration. (2018). Compliance and effects modeling system. Retrieved from https://www.nhtsa.gov/corporate-average-fuel-economy/compliance-and-effects-modeling-system

New York City. (2019, March 8). Reducing maintenance costs with electric vehicles. *NYC Fleet Newsletter,* Issue 255. Retrieved from https://www1.nyc.gov/assets/dcas/downloads/pdf/fleet/NYC-Fleet-Newsletter-255-March-8-2019-Reducing-Maintenance-Costs-With-Electric-Vehicles.pdf

SAE International. (2010). Utility factor definitions for plug-in hybrid electric vehicles using travel survey data [J2841_201009]. Retrieved from https://www.sae.org/standards/content/j2841_201009/

Safoutin, M., McDonald, J., & Ellies, B. (2018). Predicting the future manufacturing cost of batteries for plug-in vehicles for the U.S. Environmental Protection Agency (EPA) 2017–2025 light-duty greenhouse gas standards. *World Electric Vehicle Journal,* 9(3), 42. Retrieved from https://www.mdpi.com/2032-6653/9/3/42

Slowik, P., & Lutsey, N. (2018). *The continued transition to electric vehicles in U.S. cities* [White paper]. Retrieved from The International Council on Clean Transportation, https://www.theicct.org/publications/continued-EV-transition-us-cities-2018

State of New Mexico. (2019). Executive order 2019-003: Executive order on addressing climate change and energy waste prevention. Retrieved from https://www.governor.state.nm.us/wp-content/uploads/2019/01/EO_2019-003.pdf

Tax Foundation. (2019). State and local sales tax rates, 2019. Retrieved from https://taxfoundation.org/sales-tax-rates-2019/

Tesla. (2018, June 5). Tesla 2018 shareholder meeting [Online video]. Retrieved from https://youtu.be/OIdjv6oHzio

UBS. (2017). UBS evidence lab electric car teardown: Disruption ahead? [Q-Series newsletter]. Retrieved from https://neo.ubs.com/shared/d1ZTxnvF2k/

U.S. Department of Energy. (2019). Fuel economy dataset. Retrieved from https://www.fueleconomy.gov/feg/download.shtml

U.S. Energy Information Administration. (2019). *Annual energy outlook 2019*. Retrieved from https://www.eia.gov/outlooks/aeo/index.php

U.S. Environmental Protection Agency. (2019, March). *The 2018 EPA automotive trends report: Greenhouse gas emissions, fuel economy, and technology since 1975* (EPA-420-R-19-002). Retrieved from https://www.epa.gov/automotive-trends

Washington State Legislature. (2019a). An act relating to advancing electric transportation, House Bill 1664, 2019, 66th Legislature. Retrieved from http://search.leg.wa.gov/search.aspx#document

Washington State Legislature. (2019b). An act relating to advancing electric transportation, Senate Bill 5336, 2019, 66th Legislature. Retrieved from http://search.leg.wa.gov/search.aspx#document

APPENDIX

Table A1. Electric vehicle sales by technology type and model year for ZEV scenarios

Scenario	Class	Technology type	2023	2024	2025	2026	2027	2028	2029	2030
Constant BEV share	Car	BEV150	2,808	3,294	3,763	3,914	4,385	5,257	6,705	9,047
		BEV200	3,715	4,995	6,433	6,749	7,633	9,254	11,953	16,369
		BEV250	2,356	2,230	1,941	2,429	3,248	4,626	6,997	11,199
		BEV300	182	107	0	406	974	1,892	3,498	6,462
	Crossover	BEV150	1,341	1,510	1,653	1,678	1,827	2,117	2,589	3,316
		BEV200	2,843	3,775	4,814	5,034	5,673	6,848	8,802	11,987
		BEV250	859	818	719	1,039	1,539	2,366	3,797	6,376
		BEV300	322	189	0	240	577	1,121	2,071	3,826
	SUV	BEV150	131	172	217	226	253	304	387	523
		BEV200	183	246	316	328	366	437	556	747
		BEV250	131	123	105	133	178	255	387	622
		BEV300	79	74	63	94	141	219	354	597
	Car	PHEV20	3,144	3,595	4,001	4,215	4,791	5,839	7,588	10,465
		PHEV40	786	1,014	1,264	1,639	2,255	3,284	5,059	8,222
		PHEV60	0	0	0	0	0	0	0	0
	Crossover	PHEV20	2,327	2,729	3,117	3,328	3,838	4,753	6,289	8,851
		PHEV40	0	0	0	139	334	648	1,198	2,213
		PHEV60	0	0	0	0	0	0	0	0
	SUV	PHEV20	227	266	304	325	374	464	614	864
		PHEV40	0	0	0	14	33	63	117	216
		PHEV60	0	0	0	0	0	0	0	0
Continued BEV trend (central scenario)	Car	BEV150	2,886	3,394	3,887	4,035	4,601	5,711	7,650	10,978
		BEV200	3,817	5,148	6,647	6,955	8,010	10,050	13,639	19,865
		BEV250	2,420	2,301	2,007	2,505	3,408	5,026	7,983	13,592
		BEV300	187	109	0	418	1,023	2,055	3,991	7,842
	Crossover	BEV150	1,378	1,556	1,708	1,730	1,917	2,299	2,954	4,024
		BEV200	2,920	3,890	4,974	5,189	5,952	7,439	10,044	14,547
		BEV250	882	843	742	1,071	1,615	2,569	4,332	7,738
		BEV300	331	194	0	247	606	1,217	2,363	4,643
	SUV	BEV150	134	177	225	233	266	330	442	634
		BEV200	188	253	326	338	384	475	634	906
		BEV250	134	127	109	137	187	277	442	755
		BEV300	81	76	65	96	148	238	404	725
	Car	PHEV20	2,257	2,388	2,451	2,412	2,604	3,059	3,875	5,250
		PHEV40	564	673	775	938	1,227	1,720	2,582	4,125
		PHEV60	0	0	0	0	0	0	0	0
	Crossover	PHEV20	1,670	1,813	1,909	1,904	2,087	2,490	3,211	4,440
		PHEV40	0	0	0	79	181	339	611	1,110
		PHEV60	0	0	0	0	0	0	0	0
	SUV	PHEV20	163	177	186	186	204	243	313	433
		PHEV40	0	0	0	8	18	33	60	108
		PHEV60	0	0	0	0	0	0	0	0
Increasing BEV trend	Car	BEV150	2,961	3,489	3,996	4,079	4,672	5,923	8,221	12,366
		BEV200	3,916	5,289	6,831	7,033	8,134	10,424	14,654	22,375
		BEV250	2,483	2,364	2,063	2,531	3,462	5,213	8,578	15,310
		BEV300	192	112	0	423	1,037	2,133	4,288	8,833
	Crossover	BEV150	1,414	1,599	1,756	1,749	1,946	2,385	3,174	4,532
		BEV200	2,997	3,997	5,113	5,246	6,044	7,715	10,792	16,386
		BEV250	904	866	764	1,083	1,639	2,665	4,656	8,716
		BEV300	339	199	0	250	614	1,263	2,539	5,229
	SUV	BEV150	138	182	231	236	270	342	475	714
		BEV200	193	260	335	341	390	493	681	1,021
		BEV250	138	130	112	138	190	287	475	851
		BEV300	83	78	67	98	150	246	434	817
	Car	PHEV20	1,428	1,295	1,084	986	996	1,096	1,288	1,586
		PHEV40	357	364	343	384	469	617	858	1,246
		PHEV60	0	0	0	0	0	0	0	0
	Crossover	PHEV20	1,058	982	844	780	799	892	1,067	1,342
		PHEV40	0	0	0	32	69	122	204	335
		PHEV60	0	0	0	0	0	0	0	0
	SUV	PHEV20	103	96	82	76	78	87	104	131
		PHEV40	0	0	0	3	7	12	20	33
		PHEV60	0	0	0	0	0	0	0	0

Table A2. Electric vehicles and average per-vehicle effects by model year for ZEV scenarios

	Scenario	2023	2024	2025	2026	2027	2028	2029	2030
Electric vehicle sales	Constant BEV share	21,434	25,137	28,710	31,930	38,419	49,747	68,961	101,902
	Continued BEV trend (central)	20,012	23,119	26,011	28,481	34,438	45,570	65,530	101,715
	Increasing BEV share	18,704	21,302	23,621	25,468	30,966	41,915	62,508	101,823
Average electric vehicle price difference	Constant BEV share	-$4,340	-$3,036	-$1,859	-$1,045	-$294	$402	$1,047	$1,742
	Continued BEV trend (central)	-$4,256	-$2,797	-$1,436	-$466	$452	$1,324	$2,152	$3,059
	Increasing BEV share	-$4,168	-$2,541	-$981	$97	$1,113	$2,075	$2,989	$3,988
Lifetime effects									
Fuel savings	Constant BEV share	$7,628	$7,528	$7,431	$7,313	$7,192	$7,057	$6,917	$6,768
	Continued BEV trend (central)	$7,798	$7,729	$7,661	$7,558	$7,450	$7,325	$7,194	$7,050
	Increasing BEV share	$7,980	$7,944	$7,908	$7,795	$7,678	$7,543	$7,403	$7,249
Maintenance savings	Constant BEV share	$3,746	$3,759	$3,773	$3,755	$3,737	$3,718	$3,700	$3,682
	Continued BEV trend (central)	$3,899	$3,944	$3,990	$3,993	$3,995	$3,996	$3,997	$3,997
	Increasing BEV share	$4,062	$4,143	$4,224	$4,224	$4,224	$4,223	$4,221	$4,219
Other cost differences [a]	Constant BEV share	-$2,492	-$2,399	-$2,317	-$2,186	-$2,060	-$1,939	-$1,822	-$1,701
	Continued BEV trend (central)	-$2,672	-$2,606	-$2,548	-$2,423	-$2,300	-$2,179	-$2,059	-$1,932
	Increasing BEV share	-$2,866	-$2,828	-$2,796	-$2,653	-$2,512	-$2,374	-$2,239	-$2,095
Total lifetime effects	Constant BEV share	$4,542	$5,852	$7,027	$7,837	$8,575	$9,239	$9,843	$10,491
	Continued BEV trend (central)	$4,768	$6,270	$7,667	$8,662	$9,597	$10,466	$11,284	$12,174
	Increasing BEV share	$5,009	$6,717	$8,354	$9,463	$10,503	$11,467	$12,374	$13,361
First-owner effects									
Fuel savings	Constant BEV share	$3,433	$3,397	$3,369	$3,330	$3,292	$3,240	$3,183	$3,117
	Continued BEV trend (central)	$3,508	$3,487	$3,473	$3,442	$3,410	$3,363	$3,310	$3,248
	Increasing BEV share	$3,590	$3,583	$3,585	$3,550	$3,514	$3,464	$3,406	$3,340
Maintenance savings	Constant BEV share	$1,761	$1,768	$1,774	$1,765	$1,757	$1,749	$1,740	$1,732
	Continued BEV trend (central)	$1,835	$1,856	$1,878	$1,880	$1,881	$1,882	$1,882	$1,883
	Increasing BEV share	$1,913	$1,951	$1,990	$1,990	$1,991	$1,990	$1,990	$1,989
Other cost differences [a]	Constant BEV share	-$2,467	-$2,376	-$2,296	-$2,168	-$2,045	-$1,927	-$1,813	-$1,695
	Continued BEV trend (central)	-$2,645	-$2,580	-$2,524	-$2,402	-$2,282	-$2,165	-$2,048	-$1,925
	Increasing BEV share	-$2,836	-$2,799	-$2,769	-$2,629	-$2,493	-$2,359	-$2,227	-$2,087
Total first owner effects	Constant BEV share	-$1,613	-$248	$988	$1,883	$2,710	$3,463	$4,157	$4,896
	Continued BEV trend (central)	-$1,558	-$34	$1,391	$2,454	$3,460	$4,404	$5,296	$6,265
	Increasing BEV share	-$1,500	$194	$1,824	$3,008	$4,126	$5,171	$6,158	$7,230

Notes: Costs to consumer are negative, benefits to consumers are positive
[a] Other cost differences include home charger, replacement vehicle, tax