Levelized Cost of Charging – A Detailed Assessment of Fuel Costs for Electric Vehicles in the United States

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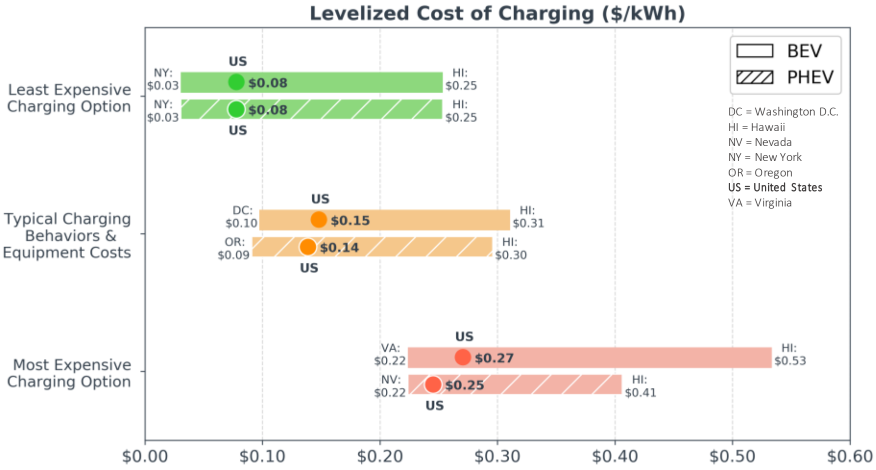
Highlights and eTOC Blurb

- Average cost to charge a battery EV (including equipment) in the U.S. is \$0.15/kWh
- Over a 15-year life, EVs can save thousands of USD in fuel costs compared to gasoline
- Costs vary widely depending on location, use, charging behavior, and equipment costs
- Off-peak charging with residential time of use rates reduces the average cost by 24%

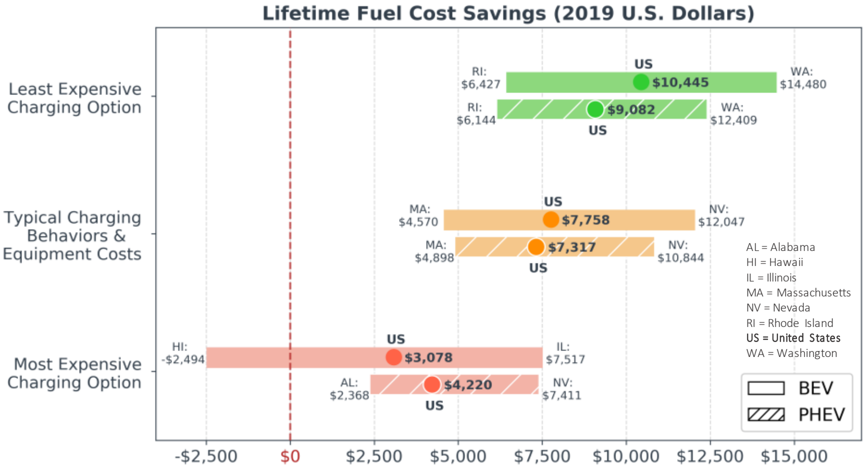
The cost to charge an electric vehicle varies depending on the price of electricity at different charging sites (home, workplace, public), by region and time-of-day, vehicle use, and for different charging power levels and equipment/installation costs. We report state-level charging costs under alternative scenarios, showing major variability due to regional heterogeneity and different charging strategies. We also calculate the lifetime fuel cost savings of an electric vehicle compared to a gasoline vehicle while accounting for regional gasoline price variations.

Graphical Abstract



The **levelized cost of charging** includes costs associated with the purchase and installation of charging equipment and real-world retail electricity prices. The **lifetime fuel cost savings** uses the levelized cost of charging to estimate the total fuel cost savings over a 15-year time horizon for a new (2019) electric vehicle compared to a conventional gasoline vehicle for a set of driving and economic conditions*.

* Lifetime fuel cost savings shown here assumes: 161,729 lifetime VMT, fuel prices in line with 2019 EIA AEO Reference case, and a discount rate of 3.5%.



Context & Scale

Cost is a major driver of vehicle adoption and while much emphasis has been placed on the high purchase price associated with electric vehicles (EVs), it is important to also consider operating costs, including fuel. The cost to charge an EV varies depending on the price of electricity at different charging sites (home, workplace, public), vehicle use, by region and time-of-day, and for different charging power levels and equipment/installation costs. Despite this, most studies assume a single cost for EV charging. This paper provides a detailed assessment of the current levelized cost of charging (LCOC) in the United States, considering when, where, and how EVs are charged. The LCOC includes costs associated with the purchase and installation of charging equipment and retail electricity prices, derived from real-world utility tariffs. To contextualize the LCOC, we estimate lifetime fuel cost savings, comparing refueling costs for EVs to conventional gasoline vehicles over a 15-year time horizon.

Summary

The cost to charge an electric vehicle (EV) varies depending on the price of electricity at different charging sites (home, workplace, public), by region and time-of-day, and for different charging power levels and equipment/installation costs. This paper provides a detailed assessment of the current (2019) levelized cost of light-duty EV charging in the United States, considering the purchase and installation costs of charging equipment and electricity prices from real-world utility tariffs. We find national averages of \$0.15/kWh for battery EVs and \$0.14/kWh for plug-in hybrid EVs in the U.S.. Costs, however, vary considerably (*e.g.*, \$0.08/kWh to \$0.27/kWh for battery EVs) for different charging behaviors and equipment costs, corresponding to a total projected fuel cost savings between \$3,000 and \$10,500 compared to gasoline vehicles (over a 15-year time horizon). Regional heterogeneities and uncertainty on lifetime vehicle use and future fuel prices produce even greater variations.

Keywords

Electric Vehicles; Cost of Electricity; Fuel Costs; Utility Rate Analysis; Demand Charges; Time of Use

Introduction

Electric vehicles (EVs) are increasingly becoming accepted alternatives to light-duty internal combustion engine vehicles (ICEVs) due to their lack of tailpipe emissions, low operating costs, and positive overall driving experience. Supported by national and local regulations, technology advancements (particularly the decline in the cost of lithium-ion battery packs [1][2]), charging infrastructure investments, and increased consumer acceptance, worldwide annual sales of personally owned light-duty EVs surpassed the 2-million mark in 2018, with over 360,000 new EVs sold in 2018 in the United States (U.S.) alone [3][4].

While the rise in EV sales is supported by several factors, cost has been shown to be of significant importance for the large-scale adoption of new vehicle technologies [5][6]. Much emphasis has been placed on the high purchase price associated with EV ownership [7][8]; however, it is important to also consider operating costs, including fuel and maintenance, when assessing the total cost of vehicle ownership.

It is widely believed that EVs are less expensive to maintain than ICEVs, through the reduction of routine scheduled services, decreased brake wear (from regenerative braking), and by result of having fewer fluids and moving parts to monitor [9]. In 2018, New York City's electric fleet vehicles saved an average of 80% per vehicle on maintenance costs vs. equivalent ICEVs [10]. The American Automobile Association (AAA), however, estimates a more moderate 18% savings from their study on operating costs [11]. More reliable lifecycle maintenance data for alternative powertrains are needed to accurately estimate the economic benefits of EV maintenance. Fuel cost savings, on the other hand, are simpler to calculate and can be substantial when considered throughout a vehicle's lifespan. Electricity is often cheaper than gasoline; additionally, EVs have better powertrain efficiencies than ICEVs, consuming less energy per mile [12]. While gasoline costs vary by region, the cost of electricity is characterized by a more diverse set of factors including charging location, time, and power level.

The cost to charge an EV (*i.e.*, the EV "fuel" cost) depends on many factors, including the retail price of electricity, capital cost of charging or electric vehicle supply equipment (EVSE), the cost of installation and maintenance of this equipment, and, for dedicated charging stations, additional business and operational expenses [13][14]. Each factor is further dependent on the type of EVSE used—AC Level 1 (L1), AC Level 2 (L2), or DC Fast Charging (DCFC), charging site—home residence, workplace, or public station, charging profile, and geographic region. This complexity produces a wide range of possible EV charging costs. Despite this, many studies (*e.g.*, [9][15][16][17][18]) assume the cost of EV charging to be equivalent to the average residential cost of electricity (often the price reported by the U.S. Energy Information Administration (EIA) [19]) or the average levelized cost of electricity generation [20][21][22]. These simple assumptions fail to capture important variations in the cost of EV charging associated with the factors described previously.

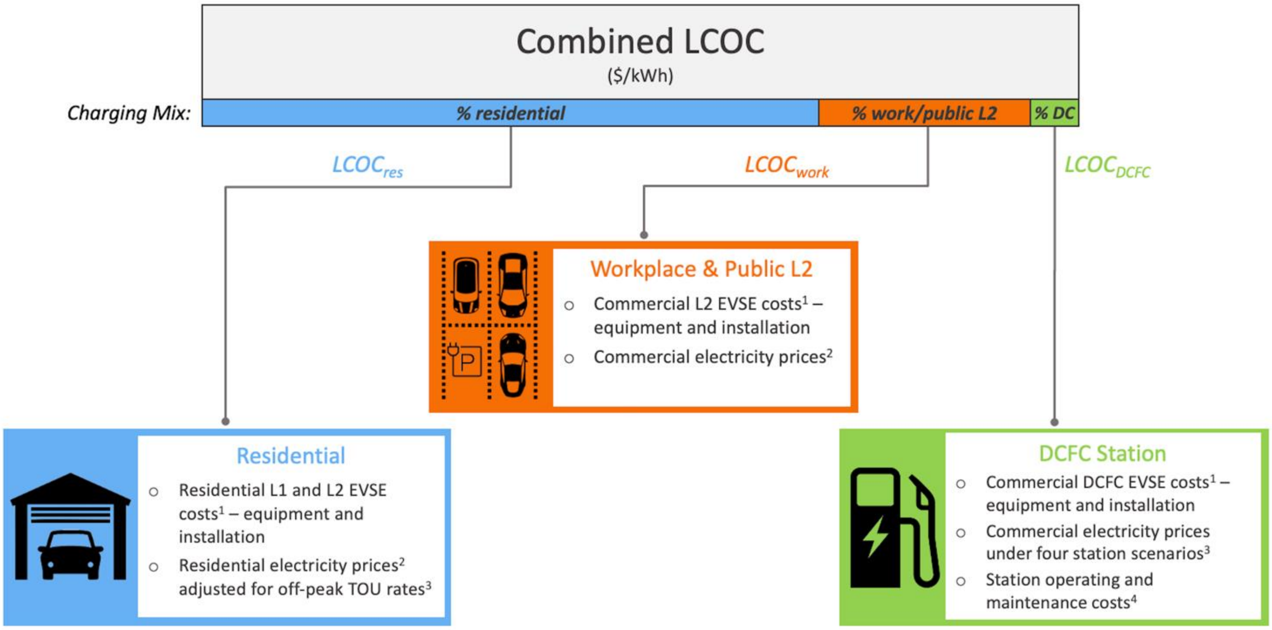
Prior studies have explored the economics of EV charging. Zhang *et al.* [23] assessed the factors that directly and indirectly influence the economics of charging infrastructure, concluding that charging price, as an endogenous factor, should be considered more carefully in modelling. Economic evaluations of public charging stations have been conducted in Germany [24] and China [25], though these studies are conducted from a station operator's perspective rather than a consumer's perspective and do not extend to other charging sites or regions. Zhang *et al.* explored the relationship between charging infrastructure characteristics—including the charging site and tariff type—and EV operating costs [26]. The study, however, focused on a single region (California) and was limited to a small set of electricity rates and L1 or L2 charging. Lee and Clark performed a similar assessment of residential, workplace, and public charging, accounting for the fixed cost of EVSE and the variable price of electricity in their estimates [18]. They did not, however, capture regional differences in electricity prices or attempt to model heterogeneous charging behaviors. Finally, in a recent study from the Union of Concerned Scientists, residential utility rates from the 50 largest U.S. cities were analyzed, finding that in all cases utilities offered an electricity rate that allowed EV owners to save on fuel costs compared to gasoline vehicles [27]. The study, however, only considered the cost of charging at home due to the large cost uncertainties associated with workplace and public charging.

Overall, while regional variability in the cost of electricity is widely understood and accepted, the cost to charge an EV is also affected by other factors, namely the cost of charging equipment and differences in the mix of charging sites (home, workplace, public) and power levels. While previous studies have explored some aspects of the cost to charge an EV and its variability, this study provides an unprecedented assessment of the current (2019) state-level levelized cost of light-duty EV charging (LCOC) in the U.S., derived from real-world electricity rates, including demand charges and time-of-use (TOU) tariffs, while also accounting for variations in how and where EVs are currently refueled. In addition, the lifetime fuel cost savings (LFCS) was estimated for a new BEV and PHEV (compared to a new ICEV) over a 15-year time horizon based on state-level gasoline prices and the LCOC.

Methods

EV owners have multiple options for recharging their vehicles. They can charge at home, in a public or private parking area with installed EVSE (*e.g.*, workplaces, grocery stores, shopping malls, etc.), or at a dedicated public charging station (L2 or DCFC). For this analysis, each site was modeled independently to capture variations in their associated equipment costs, installation costs, and retail electricity prices—the price paid to purchase electricity from a utility. Costs at each charging site were weighted by their share of total energy consumption–the "charging mix" (*CM*)–to produce a combined LCOC value representative of the weighted cost of EV charging for a set of assumptions, represented in Figure 1. The combined LCOC is defined as:

$$LCOC_{comb} = CM_{res} * LCOC_{res} + CM_{work} * LCOC_{work} + CM_{DCFC} * LCOC_{DCFC} \tag{1}$$



[1] Real-world EVSE data *[2] EIA [28]* *[3] Utility Rate Database [29]* *[4] EV station Financial Analysis Scenario Tool*

Figure 1. Approach for estimating the levelized cost of charging (LCOC) for an electric vehicle by independently modeling alternative charging options.

The LCOC at each charging site is dependent on the capital cost of EVSE ($C_{capital}$), including the cost to purchase and install EVSE, the cost to operate and maintain EVSE ($C_{O\&M}$), and the average retail price of electricity (C_{el})[1].

$$LCOC = \frac{C_{capital} + \sum_{i=1}^{life} \frac{C_{O\&M,i}}{(1+dr)^{i}}}{E_{life}} + C_{el} \tag{2}$$

where *life* is the equipment lifespan in years (assumed to be 15, equivalent to the assumed vehicle lifespan[2]); $C_{O\&M,i}$ is the annual maintenance cost in year *i* (estimated at 1% of the capital cost of equipment per year) discounted over the equipment lifespan using a discount rate *dr* (assumed to be 3.5% per year, the social rate of time preference[3] reported in [30]); E_{life} is the total energy supplied throughout the EVSE's lifespan (in kWh); and C_{el} is the average retail electricity price (in $/kWh) that utilities charge their customers (vehicle owners for residential and station operators for public stations). If estimates of future retail electricity prices are available, they can be considered in the LCOC calculation and discounted, similarly to what was done for $C_{O\&M,i}$. This paper, however, reports a snapshot of the 2019 LCOC only.

In the following sections, the methods used to estimate the LCOC at each charging site—residential, workplace/public L2, and DCFC—are detailed.

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[1] All electricity is assumed to have been purchased from a utility provider. Prospects for onsite generation (and associated costs) or distributed stationary energy storage were not considered for this analysis.

[2] We recognize that there is a current lack of data on EVSE lifespans. This is a conservative assumption as it is possible that EVSE will operate well beyond a single vehicle's lifespan, supplying energy for multiple generations of EVs. Additionally, certain installation costs, particularly those associated with home electrical upgrades, may not be required for future upgrades to a home EVSE unit.

[3] The social rate of time preference reflects a "reasonable social aggregation of preferences over intertemporal inequality, giving actual savings behavior and estimates of future growth rates" [30].

Residential LCOC

Most EV charging currently takes place at home where owners can take advantage of low residential electricity prices and convenient overnight charging [31]. For residential charging, the LCOC is calculated from Eq. (2) and E_{life} is:

$$E_{life,res} = VMT_{life} * e_{miles} * FE * CM_{res} \tag{3}$$

where VMT_{life} is 161,729 miles[4] (from the 2017 National Household Travel Survey assuming a vehicle lifespan of 15 years [32]), e_{miles} is the fraction of miles driven in charge-depleting mode (1.0 for BEVs, 0.76 for PHEVs, the utility factor of the vehicle with highest cumulative sales since 2010 at the time of writing)[5] reported in the 2018 EPA Automotive Trends Report [33], with an all-electric range of 53 miles), FE is the vehicle fuel economy in kWh/mile (0.28 based on 119 $\mathrm{MPG_e}$, the production-weighted average fuel economy of model year 2017 BEVs in the U.S. [33] and assuming 1 gasoline gallon equivalent equals 33.70 kWh [34]), and CM_{res} is the fraction of charging occurring at home (0.81, based on the charging behaviors, collected by the Electric Power Research Institute (EPRI), for 45 BEV owners and 25 PHEV owners from 2016-2018 [35]).

Home charging can be accomplished at a slow rate (2 to 5 miles of range per hour [36]) without paying for additional home upgrade costs by using the standard 120V L1 household plug included with the vehicle. Many EV owners in the U.S., however, install a 240V L2 EVSE unit at an added cost for the convenience of faster charging (typically 10 to 20+ miles of range per hour [36]) and additional control over how and when a vehicle is charged enabling higher levels of “smart charging” (*e.g.*, automated start times that align with off-peak electricity prices). L2 charging is especially common for BEV owners, who rely on home charging to meet their daily driving requirements [35][37], however it likely poses a greater burden on the distribution system when compared to L1 charging [38]. The cost of residential L2 EVSE equipment and installation were estimated at ~$1,800 from billing data acquired for over 1,200 residential EVSE installations in the U.S. (see A.4 for more details).

The EIA reports the average residential price of electricity for 2,288 utilities in the U.S. [28]. However, EV owners may have the flexibility to schedule their charging to align with times when variable electricity prices are at their lowest (typically overnight). For TOU tariffs, charging during off-peak times can result in significant cost savings [18][27]. These opportunities are not properly accounted for in EIA’s reporting of the average price of residential electricity because EV owners stand to benefit more than the average consumer by taking advantage of TOU rates since EV charging is more flexible than many other household loads.

To account for the prevalence and potential cost savings to EV owners that TOU tariffs provide, current real-world TOU rates were data mined from the Utility Rate Database (URDB) to determine their off-peak pricing. The URDB provides up-to-date utility tariff information for over 3,700 U.S. utilities in the

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[4] Total vehicle miles traveled (VMT) was estimated from the average annual vehicle miles by age (Table 22 in [32]), applied over a fixed 15-year vehicle lifespan. Note that vehicle lifespan and utilization vary by vehicle type (*e.g.*, pickup truck vs. midsize car), however as an attempt to generalize EVs, these adjustments were not considered.

[5] The Chevrolet Volt. Despite GM ending production of the Volt in February 2019, its specifications, used here, are representative of any PHEV with ~50 miles of range.

residential and commercial sectors [29]. Tariffs are used to estimate annual average retail electricity prices, reflecting the cost to build, finance, maintain, and operate powerplants and the electrical grid (for-profit utilities also include a financial return for its owners and shareholders). In the baseline scenario, it was assumed that consumers would optimize their rate selection and charging behaviors in order to minimize EV fuel costs—fully leveraging off-peak TOU pricing when available and economical. To model this, the EIA's average price of residential electricity (for each utility) was adapted to incorporate off-peak TOU rates, where applicable, from the URDB. For the 277 utilities offering TOU rates to customers, the off-peak TOU price was compared to the utility's average residential price of electricity. For 235 utilities (85%), the off-peak TOU price offered additional cost savings opportunities. In these cases, the lower TOU price was substituted for its EIA-reported counterpart. State-level estimates were calculated by weighting the LCOC for each utility providing service therein by their respective customer share (from [28]). Additional modeling details regarding the LCOC calculation for residential charging are covered in A.1.

Workplace/Public L2 LCOC

Increasingly, more employers and businesses are installing L2 EVSE in their parking areas as an employee benefit or to attract new customers and increase customer dwell-time, in hopes of generating new business [39]. Similar to residential LCOC, workplace/public L2 LCOC is calculated with Eq. (2). To estimate the capital cost of equipment and installation, billing data were analyzed for 119 commercial L2 EVSE installation projects (see A.4 for details). The median reported cost of equipment ($3,500/plug) and installation ($2,500/plug) were used in the baseline scenario. Given the variability in cost data, however, the 5th and 95th percentile cost estimates were chosen as lower and upper bounds in a sensitivity analysis to examine their effects on the LCOC.

The state-level average price of commercial electricity reported by EIA was assumed for the retail electricity price of workplace and public L2 charging [40]. These rates were not modified to account for the additional charging-induced electrical load since it was assumed to be marginal compared to existing commercial loads. The workplace/public L2 LCOC is computed using Eq. (2), where E_{life} is the lifetime energy supplied by workplace and public L2 EVSE assuming they are utilized for approximately 4.5 hours per day (equivalent to 30 kWh/day) over a 15-year lifespan [41].

DCFC LCOC

DCFC stations can help to curb "range anxiety" and enable long-distance BEV travel [42][43]. Additionally, DCFC provides rapid recharging opportunities for BEV owners who cannot reliably charge at home. The LCOC for DCFC was calculated using the National Renewable Energy Laboratory's EV station Financial Analysis Scenario Tool (EFAST). EFAST is a variant of the Hydrogen Financial Analysis Scenario Tool (H2FAST[6]) [44] tailored to DCFC stations, calculating a LCOC value that accounts for capital costs, electricity prices, taxes, and additional operating expenses. EFAST also generates detailed annual finance projections in the form of income statements, cash flow statements, and balance sheets.

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[6] The H2FAST tool is publicly available as a downloadable Excel spreadsheet at: https://www.nrel.gov/hydrogen/h2fast.html

Due to their high power levels—currently 50 to 150 kW per plug is typical—the equipment and installation costs for DCFC were much higher than for L2 EVSE. The median cost of equipment (50 kW – $38,000/plug, 150 kW – $90,000/plug) for nearly 100 DCFC installations through The EV Project and Live Electric (see A.4 for details), informed the estimates for the baseline scenario. Installation costs were found to follow a trend of $0.40/W of total installed power, meaning a 50-kW plug would cost $20,000 to install and a 150-kW plug would cost $60,000. As with workplace and public L2 EVSE, the 5th and 95th percentile cost estimates for DCFC EVSE were used as lower and upper bounds in a sensitivity analysis.

The price of electricity for DCFC varies considerably depending on the utility tariff (especially demand charges), station size/total capacity, and utilization. For example, Muratori *et al.* showed that the price of electricity for DCFC ranges from less than $0.10 to over $2.00 per kWh, depending on station design and utilization [13]. To address this variability, the average electricity prices for four DCFC station sizes and usage profiles (based on scenarios developed in [45] that are illustrative of present and near-future operations) were used. These scenarios are described in detail in A.2 and in [45]. The average annual price of electricity was determined for each load profile over more than 4,000 applicable commercial rates in the URDB including–seasonal variations, demand charges, tiered pricing structures, TOU, and combinations thereof. Additional modeling details regarding the LCOC estimation for DCFC are covered in A.3.

In modeling DCFC station operations, land costs were not considered. Additionally, it was assumed that operators would provide electricity to consumers at a break-even price (*i.e.*, no return on investment). These decisions were made in response to the high variability in local land prices and the many possible business strategies that station operators might adopt. We do, however, explore the impact of higher installation costs due to required upgrades to the electrical distribution system triggered by high-power DCFC. Lastly, subsidies, incentive programs, and other methods for reallocating costs (*e.g.*, car manufacturers or other businesses subsidizing EV charging costs to support/attract consumers) were not considered within this analysis, opting to measure the "true cost" of charging, not necessarily the cost experienced by individual EV owners. Table 1 summarizes equipment and installation costs for different types of EVSE (assuming median values from the range of billing data described in A.4).

Table 1. Median capital costs of electric vehicle supply equipment from collected billing data.

	Equipment	Installation	Total Cost
Residential			
L1	$0	$0	$0
L2	$550/plug	$1,286/plug	$1,836/plug
Public			
L2	$3,500/plug	$2,500/plug	$6,000/plug
Public DCFC			
50 kW	$38,000/plug	$20,000/plug	$58,000/plug
150 kW	$90,000/plug	$60,000/plug	$150,000/plug

Scenarios

A baseline scenario was developed to estimate the average LCOC for current BEV and PHEV owners in the U.S. Additionally, a sensitivity analysis examined the effects of certain selected factors on the LCOC. These scenarios are defined in Table 2. The charging mix for different charging sites and share of residential L1 and L2 EVSE for the baseline scenario are inferred from charging data, collected by EPRI, for 23

Chevrolet Volt, 31 Nissan Leaf, and six Tesla vehicles over a year and a half [35][7]. The PHEV baseline assumes no DCFC since, at present, DCFC is not an option for most PHEVs. Lifetime VMT for the baseline scenario is the average vehicle miles traveled over 15 years reported by the 2017 National Household Survey [32], 161,729 total miles. Additionally, high VMT (200,000 miles) and low VMT (100,000 miles) cases are considered. The residential TOU factor describes the following scenarios: in the "100% TOU" case, all residential charging is assumed to align with off-peak TOU pricing (derived from the URDB [29]); for "Opportunistic TOU", EV owners with access to off-peak TOU that is less expensive than their utility's average residential rate (reported by EIA [28]) use it, while others charge at the average residential rate; finally, under the "Business as Usual" case all EV owners charge at their utility's average residential rate (reported by EIA [28]) and do not leverage TOU pricing. For EVSE costs, the baseline scenario assumes the median equipment and installation cost from collected billing data (see A.4). A sensitivity around residential EVSE costs explores the impact of installing residential L2 EVSE. For commercial EVSE, the 5th and 95th percentile costs from collected billing data (see A.4) are used to bound the sensitivity analysis. Moreover, the impact of an additional $125,000/plug (in excess of capital costs) was considered for 150-kW DCFC EVSE to explore the effect of additional costs related to integrating high-power DCFC into the existing distribution network.

Table 2. Baseline and sensitivity scenarios.

Factor	Lower Bound	BEV-Baseline	PHEV-Baseline	Upper Bound
Charging Mix	100% Residential, 0% Public L2, 0% DCFC	81% Residential, 14% Public L2, 5% DCFC	81% Residential, 19% Public L2, 0% DCFC	0% Residential, 0% Public L2, 100% DCFC
Lifetime VMT	200,000	161,729	161,729	100,000
Residential TOU	100% TOU	Opportunistic TOU	Opportunistic TOU	Business as Usual
Residential EVSE	100% L1	16% L1, 84% L2	50% L1, 50% L2	100% L2
Workplace/Public L2 EVSE cost	5th percentile EVSE costs	Median EVSE costs	Median EVSE costs	95th percentile EVSE costs
DCFC EVSE cost	5th percentile EVSE costs	Median EVSE costs	Median EVSE costs	95th percentile EVSE costs + electricity upgrade ($125k per 150-kW plug)

Lifetime Fuel Cost Savings

While vehicle purchase price is readily accessible and easily interpreted by consumers, fuel cost savings, involving multiple variables and more complicated calculations, are often not considered [46]. In response, the LFCS for a new (2019) BEV and PHEV were calculated. The LFCS describes the total discounted fuel savings for an EV when compared to a similar conventional vehicle over a fixed lifespan and identical operating conditions (*i.e.*, the same annual miles driven). It is an aggregate measure of the discounted cost savings associated with improved efficiencies and lower present day and projected fuel costs for EVs. From a total cost of ownership perspective, the LFCS could partially offset the purchase price premium paid by EV owners. Additional offsets that are not included in the LFCS include savings on maintenance costs, tax credits, and additional purchase incentives. The LFCS is calculated as:

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[7] Values were derived under the assumption that all L1 charging occurs at home.

$$LFCS = LFC_{ICEV} - LFC_{EV} \tag{4}$$

$$LFC = \sum_{i=1}^{life} \frac{VMT_i * FE * C_{fuel,i}}{(1+dr)^i} \tag{5}$$

where *LFC* is the lifetime fuel cost (in 2019 dollars), *life* is the vehicle's lifespan in years (assumed to be 15), *VMT* is the annual vehicle miles traveled (from average annual miles per vehicle by vehicle age in the 2017 National Household Travel Survey [32]), *FE* is the vehicle fuel economy (in gallons/mile or gallon of gasoline equivalent/mile, determined from the production-weighted average fuel economy of model year 2017 vehicles reported by EPA [33]), $C_{fuel,i}$ is the fuel cost in year *i* (in \$/kWh or \$/gallon [47]), and *dr* is the discount rate, assumed to be 3.5% [30]. Future fuel prices are projected using the annual relative cost increase from 2019 to 2034 in EIA's 2019 Annual Energy Outlook (AEO19) "Reference" case projections for residential electricity and gasoline [48]. For PHEVs, it was assumed that 76% of driving occurs in charge-depleting mode, the utility factor for the Cheverolet Volt with an all-electric range of 53 miles, as reported in [33]. Table 3 shows the key assumptions used to calculate LFCS:

Table 3. Baseline assumptions for lifetime fuel cost savings (LFCS) calculation.

Vehicle Assumptions	**ICEV**	**PHEV**	**BEV**
MPG$_e$	29	e: 119, g: 45	119
%e$_{miles}$ / %g$_{miles}$	0/100	76/24	100/0
Lifetime VMT	161,729	161,729	161,729
Vehicle Lifespan	15 years	15 years	15 years
Additional Assumptions			
Gasoline cost	Starting from July 2019 AAA gasoline prices (\$2.73/gal) and assuming escalation in line with AEO19 "Reference" Case		-
Electricity cost	-	Starting from 2019 LCOC and assuming escalation in line with AEO19 "Reference" Case	
Discount rate	3.5%	3.5%	3.5%

AEO19: EIA Annual Energy Outlook 2019 [48]

Results

Under the baseline scenario, the current national average LCOC in the U.S. is \$0.15/kWh for light-duty BEVs and \$0.14/kWh for light-duty PHEVs. For BEVs, this assumes a charging mix of 81% residential, 14% workplace/public L2, and 5% DCFC, and that 84% of residential charging uses L2 EVSE (consistent with [35]). For PHEVs, this assumes a charging mix of 81% residential and 19% workplace/public L2, and that 50% of residential charging uses L2 EVSE (also consistent with [35]). These LCOC values are similar to the average residential cost of electricity reported by EIA (\$0.13/kWh) [19], though estimates diverge extensively when additional factors are considered. In this section we explore the variability of the cost of EV charging and related fuel cost savings. Unless otherwise specified, all values reported in this section refer to the baseline BEV scenario from Table 2.

To assess the possible variability in the national LCOC, a sensitivity analysis was conducted over six factors related to charging behaviors, vehicle use, and EVSE costs (Figure 2). The charging mix (*i.e.*, the share of charging performed at each charging site), lifetime VMT (affecting equipment amortization), the availability and usage of residential TOU rates, and the power level of residential EVSE (L1 vs. L2) all play a major role in determining the LCOC. Charging exclusively at DCFC stations, for example, increases the national LCOC by 26% ($0.19/kWh). Ubiquitous use of L1 EVSE at home reduces the cost by 24% ($0.11/kWh). Utilizing low cost, off-peak TOU rates also has a major impact on the LCOC, ranging from a 14% reduction ($0.13/kWh) in the case where all residential charging leverages off-peak pricing to a 17% increase ($0.17/kWh) in the "business as usual" case. Reducing lifetime VMT to 100,000 miles, increases charging costs by 15% (~$0.17/kWh) assuming residential EVSE costs are amortized over a single vehicle's lifespan, while higher VMT leads to cost reductions (~$0.14/kWh for 200,000 miles).The capital costs of workplace and public EVSE (both L2 and DCFC) have less impact on the LCOC, with effect ranges of -3% to +8% and ~0% to 3%, respectively. This can be largely attributed to the comparatively low share of energy consumed by workplace and DCFC charging (19% of total energy) versus residential charging (81% of total energy) in the baseline scenario.

Each factor may also interact with the others, producing a wide range of possible LCOC values. The combined effects of multiple factors are quantified in the "Compounded" bar at the bottom of Figure 2. In the "best case" scenario, BEVs are charged exclusively at home with L1 EVSE during off-peak TOU pricing periods. This reduces the national LCOC by 48% ($0.08/kWh). Conversely, in the "worst case" scenario, BEVs are charged exclusively at DCFC stations characterized by high EVSE costs and expensive distribution system upgrades. Under these conditions, the national LCOC increases by 83% ($0.27/kWh). In both cases, a shift in charging mix amplified the effects of other factors associated with the LCOC at the primary site, suggesting that prioritizing cost reductions for the primary charging site (*e.g.*, residential in the baseline scenario) would be the most effective way to reduce the LCOC for current EV owners.

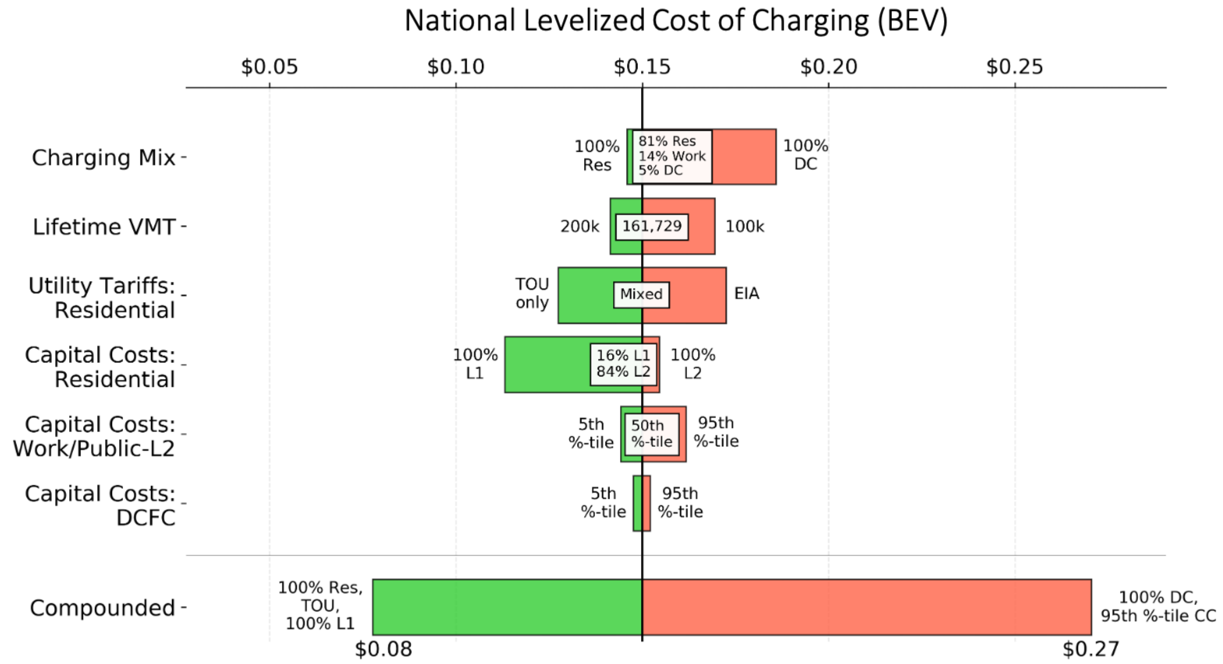

Figure 2. Sensitivity of levelized cost of charging (LCOC) for U.S. battery electric vehicles to charging site mix, vehicle use, utility tariffs, and equipment costs.

An additional sensitivity was conducted to consider free workplace and public L2 charging, a scenario in which employers and businesses provide free charging to employees and customers as either an added benefit or as an incentive to attract business. Assuming no shift in charging mix, this reduces the national LCOC by 14% ($0.13/kWh). However, consumers could change their charging behaviors in response to a free charging opportunity. To assess the impact of changes in charging behavior, we assume that the availability of free workplace and public L2 charging induces a shift in the charging mix away from residential charging. If EV owners leverage free charging for 25% and 50% of their energy needs (resulting in 70% and 45% residential charging, respectively, while DCFC remains constant at 5%), the national LCOC would drop by 25% ($0.11/kWh) and 49% ($0.07/kWh), respectively.

The LCOC also varies significantly by state (Figure 3). This can be attributed to variations in the cost to generate and distribute electricity and the availability of EV-friendly utility tariffs, including residential TOU and commercial rates with low demand charges. The LCOC for the baseline BEV scenario varies from $0.10/kWh in Oregon to $0.31/kWh in Hawaii with most states in the $0.12/kWh to $0.16/kWh range.

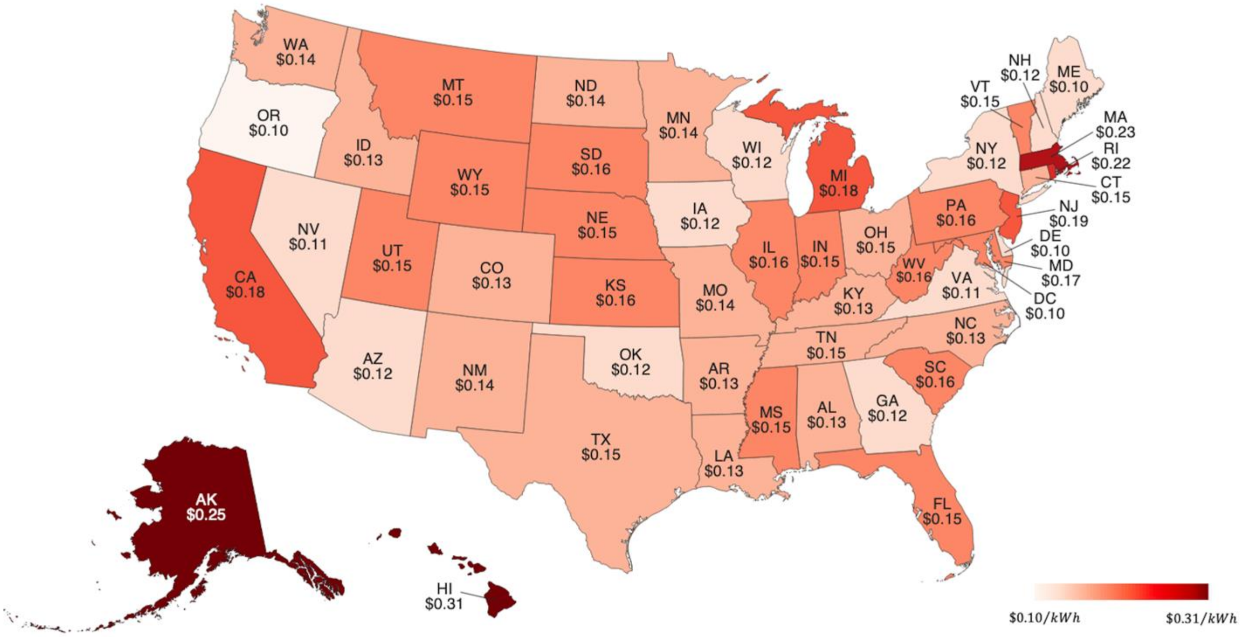

Figure 3. State-level variability in levelized cost of charging (LCOC) for battery electric vehicles (BEVs) in the baseline scenario.

While the LCOC is a key assumption for an economic analysis of EVs, it is not intuitive for understanding the practical impact of the cost of charging on the total cost of EV ownership. The LFCS translates the LCOC into a measure of lifetime cost savings (versus an equivalent ICEV), providing a useful, though non-comprehensive, indicator for expected future savings associated with EV ownership. The LFCS for BEVs in the baseline scenario are shown for all states in Figure 4.

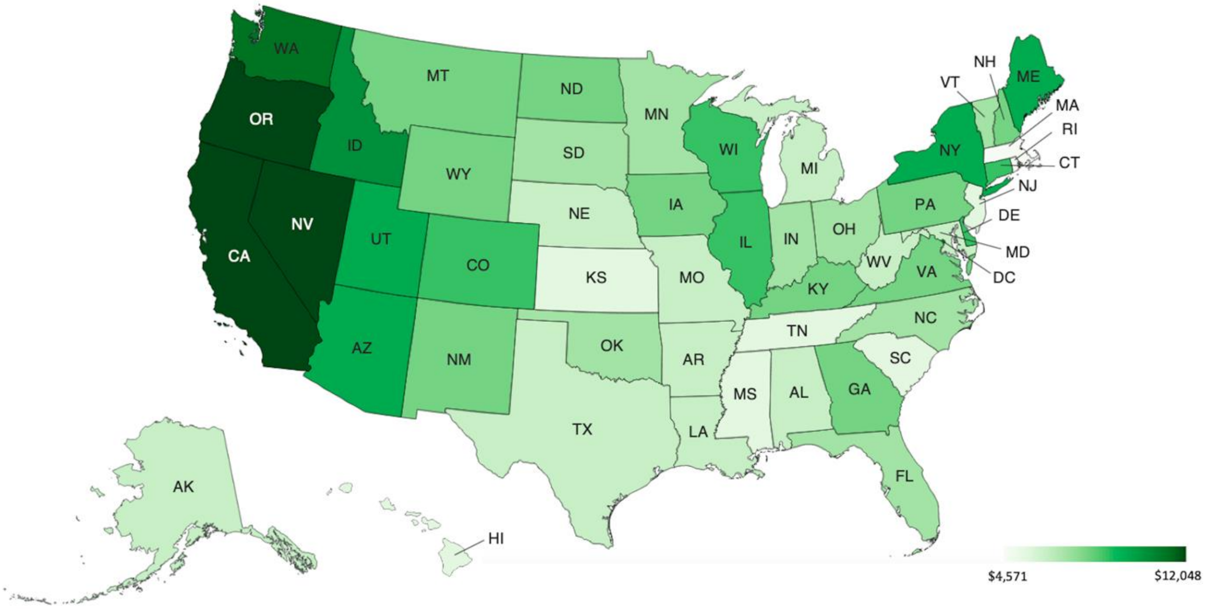

Figure 4. State-level variability in lifetime fuel cost savings (LFCS) for battery electric vehicles (BEVs) in the baseline scenario.

Looking at LFCS, some states with higher gasoline prices, like California ($11,653) and Pennsylvania ($8,059), are more favorable for EVs despite their LCOC being higher than the national average. Conversely, states with lower gasoline prices compared to electricity like Texas ($6,382) and Tennessee ($6,222) are less favorable for EVs. The national average LFCS for light-duty BEVs is $7,758, meaning the average consumer can expect to save nearly $8,000 in fuel costs over a 15-year period by purchasing a new 2019 BEV rather than a new ICEV. For light-duty PHEVs, the national LFCS is very similar ($7,317). This similarity is a result of three main factors:

- BEV owners are more likely to install a residential L2 EVSE unit (84% of home charging with L2 compared to 50% for PHEV owners [35]), sacrificing cost for the convenience of faster and more flexible charging.
- BEV owners get 5% of their electricity from DCFC stations [35], the most expensive of the modeled charging sites. PHEV owners, on the other hand, are unable to charge with DCFC.
- For PHEVs with a ~50 miles all-electric range (historically popular in the U.S.), most driving occurs using electricity (utility factor of 76% [33]). Shorter range PHEVs, like the Toyota Prius Prime with 25-miles of all-electric range and a utility factor of 53% [33], have a more modest LFCS of $6,545 (national average).

Previously, it was shown how variations in charging behavior and EVSE costs have a significant effect on the LCOC. It was also shown how geographic region affects the LCOC and LFCS. Combined, however, these factors produce an even greater range of economic outcomes. Figure 5 presents this variation for LFCS under the three charging cost scenarios. The low-cost scenario represents the "best case" with respect to charging costs (*i.e.*, least expensive charging site with low capital costs). The baseline scenario has already been described in detail and the high-cost scenario represents the "worst case" with respect to charging costs. State-level LCOC and LFCS values were calculated for both BEVs and PHEVs for each of the three charging cost scenarios and are reported in Figures A7 and A8, respectively. The range of possible

LFCS values in all states for each of the three charging cost scenarios are presented in Figure 5. For BEVs, the range of LFCS outcomes varies from $14,480 in Washington's low-cost scenario to -$2,494 in Hawaii's high-cost scenario (meaning that in this scenario a BEV owner would pay $2,494 more in fuel costs over a 15-year lifespan than an ICEV owner). For PHEVs, the range of possible LFCS varies between $12,409 in Washington (low-cost scenario) and $2,368 in Alabama (high-cost scenario).

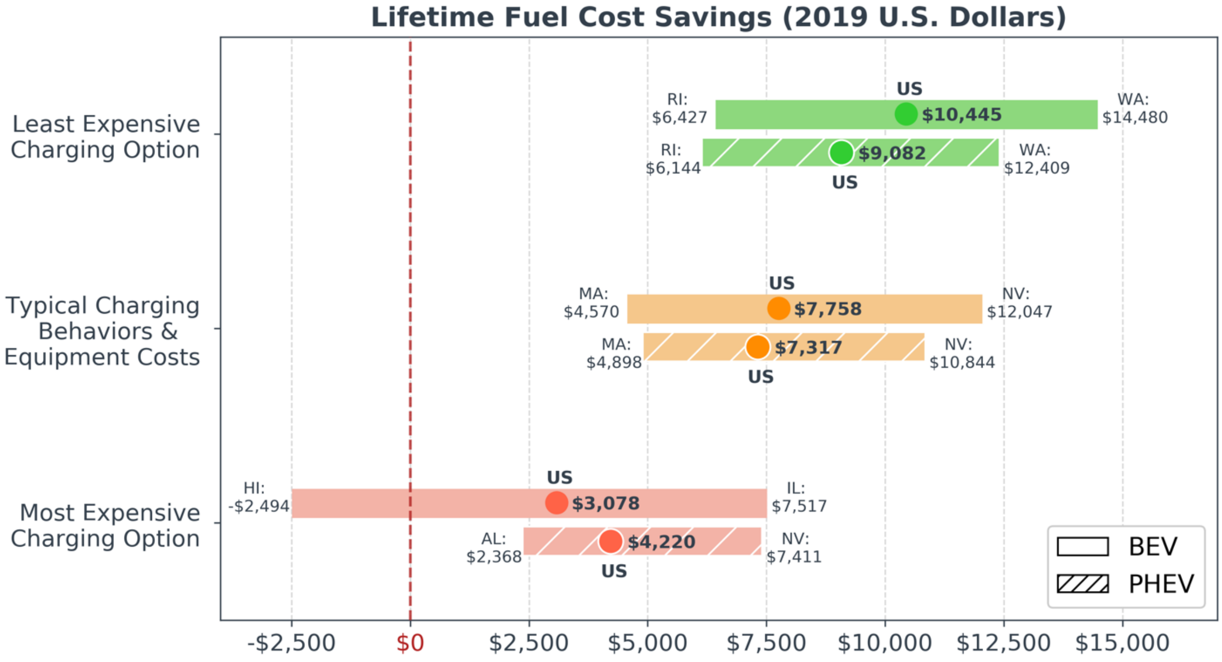

Figure 5. State-level variability in lifetime fuel cost savings (LFCS) for low, baseline, and high charging cost scenarios.

Additionally, there are a number of key assumptions in the LFCS calculation that are affected by large uncertainties, especially vehicle usage (VMT), economic factors, and future fuel price projections. An additional sensitivity analysis is reported in Figure 6 to quantify these uncertainties considering different charging behaviors and equipment costs (represented by the LCOC scenarios), lifetime VMT, fuel price forecasts (considering residential electricity and gasoline price projections from EIA's 2019 Annual Energy Outlook [AEO19] "Low" and "High Oil Price" cases, illustrated in Figure A9), and discount rates.

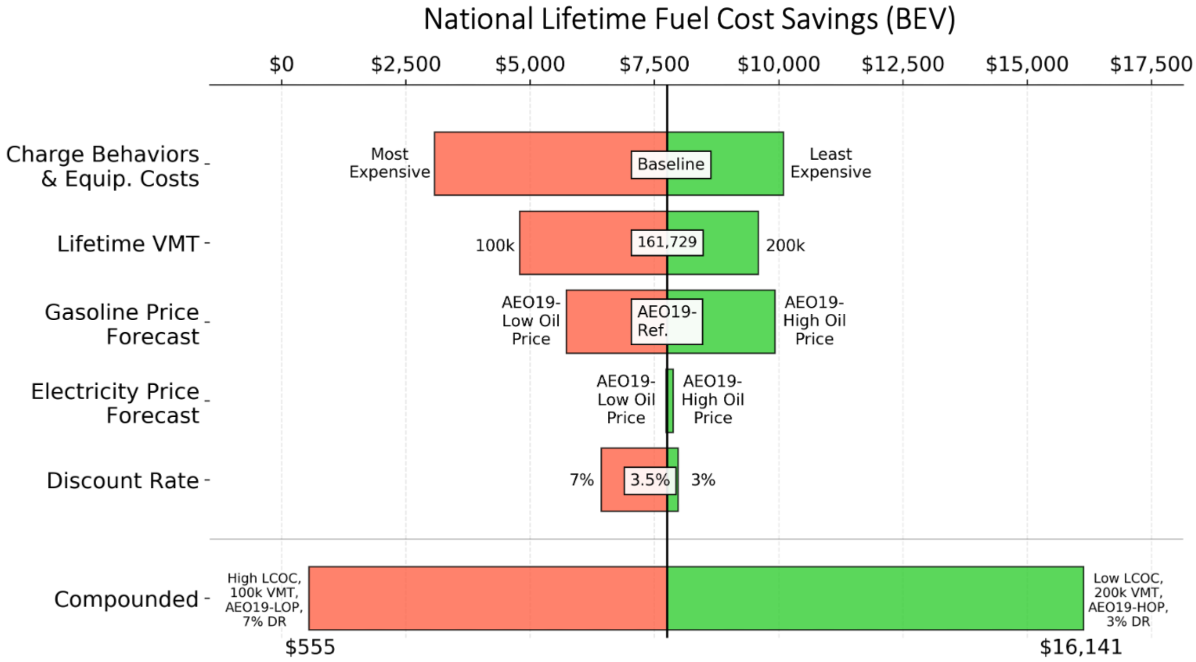

Figure 6. Sensitivity of the national average lifetime fuel cost savings (LFCS) for battery electric vehicles to the levelized cost of charging (different charging behaviors and equipment costs), vehicle use, energy price forecasts, and discount rates.

The LFCS is most sensitive to differences in charging behaviors and equipment costs (the variations in LCOC discussed above), though it is also largely affected by VMT and, unsurprisingly, gasoline price projections (projected 2034 gasoline prices range between $2.49 and $3.82/gallon, leading to a +/-28% change in LFCS). Similar to how the charging mix amplifies the effects of certain factors determining the LCOC, lifetime VMT is a moderating variable for the calculation of LFCS. As VMT increases, the marginal cost savings due to these other factors are magnified. Escalation in electricity prices over time is similar in all three of the EIA scenarios (see Figure A9, with projected 2034 electricity prices ranging between 0.15 and $0.16/kWh), thus its effect on LFCS is minimal. The LFCS is also sensitive to the chosen discount rate, with higher rates devaluing future savings and reducing LFCS, though its effect is comparatively small. The combined effects of multiple factors are quantified in a “Compounded” bar. The national average LFCS is shown to range from just $555 in savings over 15-years to more than $16,000 depending on these assumptions.

All the data generated in this analysis, including the underlying assumptions, are available for public download at XXX. Assumptions are also reported in Section A.6 of the Appendix.

Discussion

This study fills a significant research gap in the areas of EV charging and cost of ownership analyses by providing a detailed assessment of the total cost to charge a light-duty EV in the U.S., capturing variations related to charging sites, equipment types and costs, and geographic regions. In addition to determining the LCOC for three distinct charging sites—residential, workplace/public L2, and DCFC—an average LCOC for BEVs and PHEVs was calculated that is representative of current charging patterns. A sensitivity analysis was performed to better understand the factors that drive the LCOC and bound the cost of EV charging. The LCOC was used to calculate the LFCS, a measure of total fuel savings for operating an EV compared to an ICEV under identical driving conditions. Finally, a sensitivity analysis of LFCS to varying assumptions and the uncertainties regarding future fuel prices was conducted finding it be primarily affected by changes in charging behaviors and equipment costs (i.e., LCOC scenarios), vehicle use (VMT), and future gasoline prices.

Each component of the LCOC is subject to change over time, especially as EV adoption continues to increase and utilities become more experienced with EV-specific rate design. Similarly, equipment and installation costs are expected to continue to fall as the market expands (for reference, from 2010 to 2019 the typical cost for L2 charging equipment decreased by nearly 67% [49]). While useful for present day and near future applications, the LCOC is a snapshot metric that should be recalculated periodically to ensure it represents current EV, EVSE, and energy markets.

The LFCS metric provides a useful extrapolation of the LCOC that can be used in total cost of ownership assessments, including those made by consumers prior to purchasing a new vehicle. It provides an indication of the expected lifetime savings on fuel costs under present-day conditions (current electricity tariffs and charging patterns). While accounting for projected fuel cost increases (electricity and gasoline) over the next 15 years, it does not project fundamental shifts in the design and availability of utility tariffs in response to increased EV adoption or other factors. It also assumes that charging patterns (*i.e.*, where people charge their EVs) do not change over time.

In addition to providing detailed current LCOC and LFCS values for the U.S., this analysis has produced general insights that are globally relevant. First, the cost to charge an EV varies significantly and is dependent not only on variations in regional electricity prices, but also on the charging site, time of charging, power level, infrastructure cost, equipment utilization, and availability of EV-friendly utility tariffs. While specific values will undoubtedly be different for other countries, the methodology presented can be applied to determine LCOC and LFCS outside the U.S. Second, it is currently more economical for EV owners to charge at lower power levels, minimizing the cost of EVSE and mitigating demand charges. For example, an upgrade to L2 EVSE for residential charging adds more than $0.04/kWh to the cost to charge when levelized over a 15-year period (a 37% increase compared to use of L1). Higher vehicle use or equipment lifespan can significantly reduce this cost. Moreover, L2 charging is faster and enables greater flexibility to reshape EV charging loads and leverage TOU electricity pricing. Third, at present, DCFC is the most expensive charging option for BEVs due to high capital costs, low utilization coupled with commercial tariffs with demand charge components, and additional operating expenses (especially with for-profit business models). Additionally, DCFC is less flexible than residential or workplace charging, where vehicles remain plugged-in for extended periods of time enabling “smart charging” that further reduces the cost to charge. Residential charging, on the other hand, is typically the most cost-effective option, especially when leveraging off-peak TOU pricing. Shifting all residential charging to off-peak TOU periods reduces charging costs by 26%. Fourth, free workplace and public L2 charging are predictably effective at reducing EV charging costs for consumers. Finally, high all-electric range PHEVs can offer similar lifetime fuel cost savings to BEVs (94%). This is largely a result of the high share of driving that uses electricity, the lack of DCFC, and the fact that PHEV owners are, at present, less likely to upgrade from L1 to L2 EVSE at home. Shorter all-electric-range PHEVs (e.g., 25 miles) provide 84% of the fuel cost savings compared to BEVs.

The LCOC and LFCS reported here (and their variability), can inform consumers, decision and policy makers, and serve as input for analyses requiring accurate EV charging costs. Given their dependence on underlying assumptions (*e.g.*, charging mix), the values reported herein are not intended to inform any specific individual, whose assumptions will undoubtedly be different. However, access to the full set of LCOC and LFCS values generated in this analysis (publicly available at XXX) enable consumers to estimate the LCOC and LFCS for the region(s) and mix of charging sites that are most appropriate for them.

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Author contributions

Conceptualization, M.M. and B.B.; Methodology, M.M., B.B., and S.S.; Software, Formal Analysis, Visualization, B.B.; Data Curation, B.B., M.G., and S.S.; Writing – Original Draft, B.B., M.M., and S.S.; Writing – Review & Editing, B.B., and M.M.; Funding Acquisition, M.M. and S.S.; Supervision, M.M..

Declaration of Interests

The authors declare no competing interests.

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Supplemental Information

A.1 Residential LCOC Calculation

To calculate the retail price of residential electricity, utility-level residential prices reported by EIA [28] were adapted to account for off-peak TOU pricing (assuming that EV owners schedule their residential EV charging to align with off-peak times). Specifically, the URDB [29] was queried for utilities offering an applicable TOU tariff with off-peak pricing that was less than its corresponding average price reported by EIA. For these cases, the average price of electricity was replaced with the off-peak TOU price. Only applicable TOU rates (*i.e.*, rates not containing one of the special-purpose phrases listed in Table A1) were considered.

Table A1. List of phrases used to disqualify special-purpose residential rates.

- Administrative housing
- Closed rate
- Currently closed
- Electric heat
- Employee
- Heat
- Heating
- Low-income
- Low income
- Retired employee
- Thermal
- Unmetered
- Water

Fixed charges, such as monthly meter charges, were omitted from the residential LCOC calculation since it was assumed that increased electricity demand would have no effect on these costs. Additionally, residential rates with demand charge components were omitted since it would have required access to detailed household load profiles to estimate the cost of charging. This was determined to be beyond the scope of this analysis.

Utility-level residential LCOC was calculated with Eq. (2), assuming the share of total energy required to drive 131,000 miles (81% of 161,729 miles in the baseline scenario). State-level estimates of the residential LCOC were calculated using the customer-weighted average (from [28]) of the utility-level LCOC. This entire procedure is presented in Figure A1.

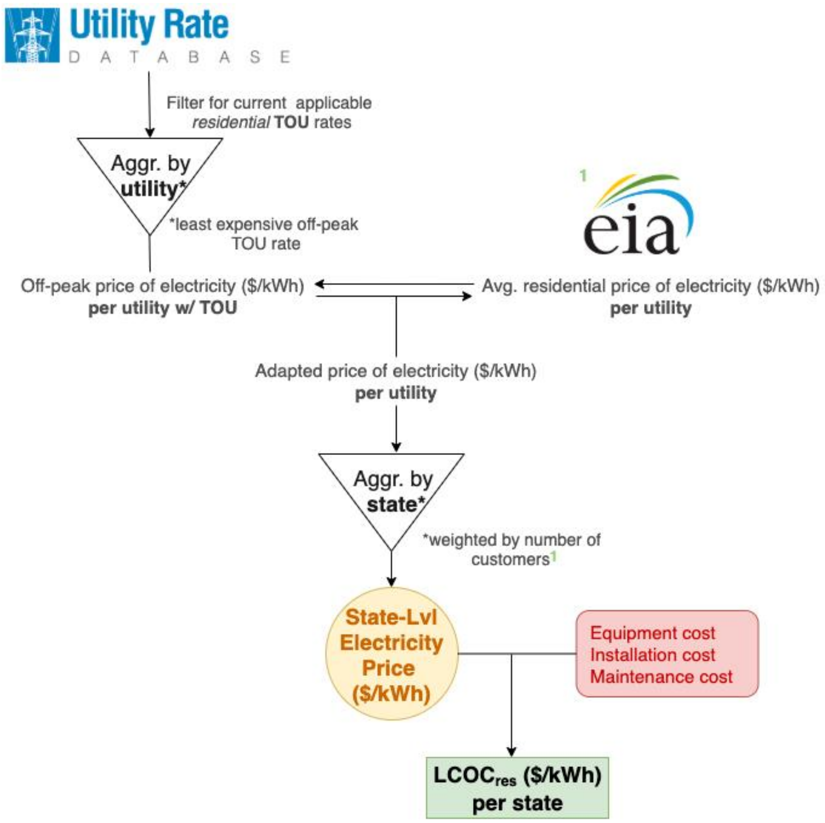

Figure A1. Residential levelized cost of charging (LCOC) calculation process flow.

A.2 DCFC Station Profiles

Commercial utility tariffs typically include fixed ($/month), energy/consumption ($/kWh), and demand ($/kW) charges that may vary by consumer type, region, season, time-of-use, and energy tier [13]. Calculating the average price of electricity, therefore, requires time-resolved electricity consumption profiles to compute all of the associated costs. In this study, four distinct DCFC load profiles, shown in Figure A2 and developed by Muratori et al. [45], were used to explore the variations in current and near-future DCFC station utilization. Profiles consist of the average station load (in kW) over 15-minute intervals for one full year, a resolution that aligns with how monthly demand charges are typically computed in the U.S. Profiles 1 and 2 were derived using real-world power profiles from existing DCFC stations, each with a single 50-kW charger. Profile 1 represents a remotely located charger that is rarely utilized (~1-2 charges per day–1.14% utilization). Profile 2 represents a highly utilized single-plug urban charge station (~17 charges per day–11.72% utilization). Profile 3 represents a near-future, medium-sized station with four 150-kW plugs (13.67% utilization), and Profile 4, another future scenario but much larger, with 20 highly utilized 150-kW plugs designed as a "gasoline station equivalent" for EV charging (20.70% utilization). These profiles are available for download at XXX.

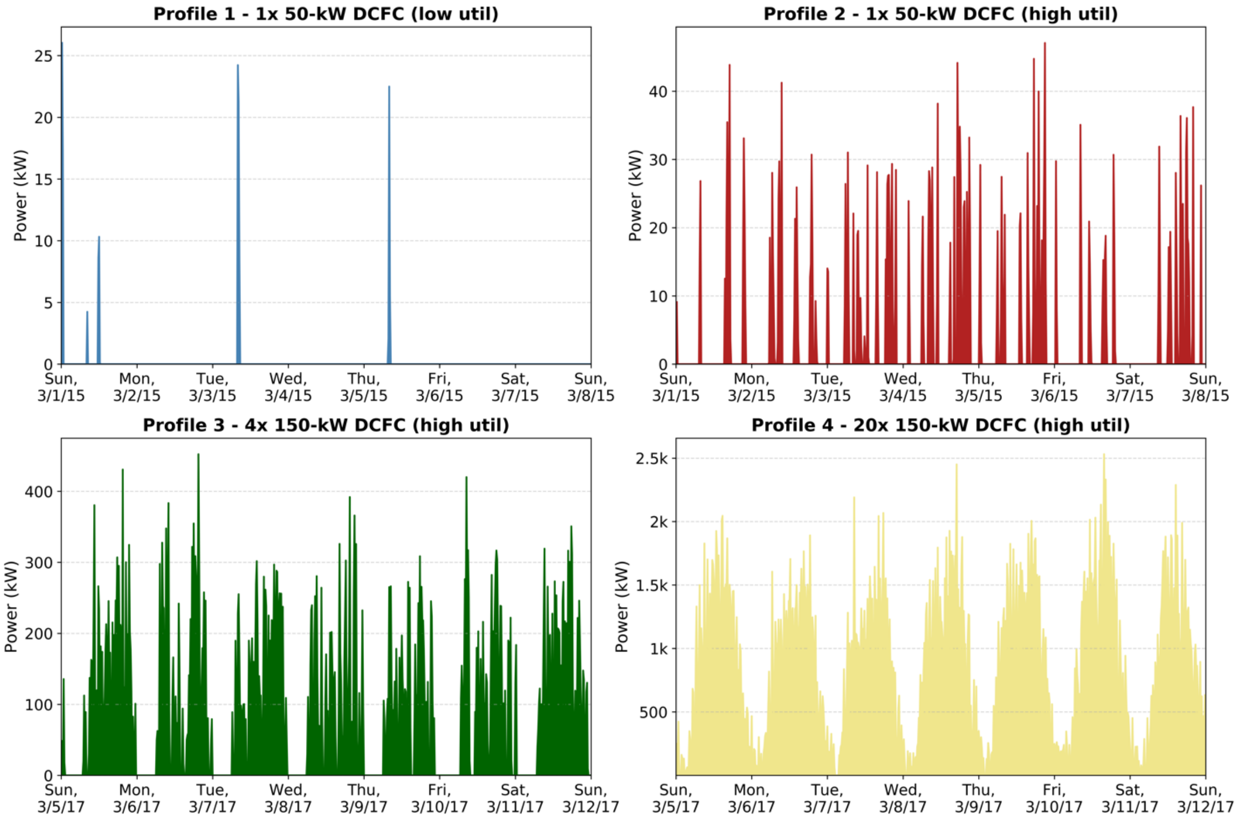

Figure A2. Load profiles for four DCFC station scenarios, from [45].

A.3 DCFC LCOC Calculation

The average annual price of electricity was calculated for each of the four DCFC station profiles using current industrial and commercial rates available through the URDB [29]. Inapplicable rates were filtered by the criteria outlined in [13]. The average annual price of electricity accounts for fixed charges, energy/consumption charges, and demand charges associated with each year-long demand profile, including price tiers, seasonal variations, and TOU pricing. For each combination of electricity rate and demand profile, the average price of electricity was aggregated by utility (assuming that if a utility offers multiple rates, the most cost-effective one would be selected). Utility-level electricity prices were then aggregated by state, taking the average price of electricity from each utility operating therein and weighting by the current number of similarly sized DCFC stations within each utility-county (obtained from the Department of Energy's Alternative Fuel Data Center (AFDC) [50]). The weighted state-average price of electricity for each of the station profiles was fed to the EFAST tool, along with additional cost inputs such as equipment and installation costs, tax rates, and internal rate of return (IRR) to determine the LCOC. The LCOC for each of the four station scenarios was weighted by the size of existing DCFC stations (total number of plugs from the AFDC) and their relative energy requirements. This entire procedure is documented in Figure A3. The state-level LCOC for each of the four station scenarios (as well as the combined DCFC LCOC value) are made available in the supplemental data download.

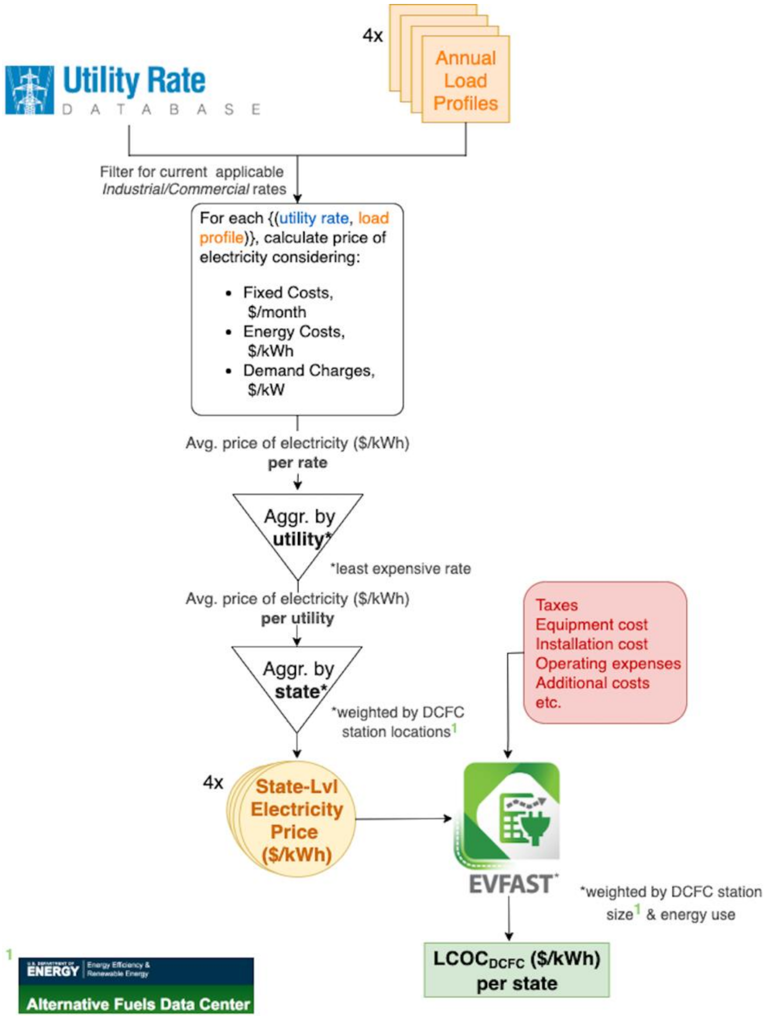

Figure A3. Direct current fast charging (DCFC) levelized cost of charging (LCOC) process flow.

A.4 Equipment and Installation Cost Data

EVSE equipment and installation costs were gathered from a variety of data sources. Billing data from 1,332 L2 EVSE projects, including 1,213 residential sites and 119 public sites, were acquired from Smart Charge America. Reported equipment costs, shown in Figure A4, were largely similar to purchase prices found online, with some variation depending on the equipment’s power level and additional features. Publicly installed L2 EVSE typically had higher equipment costs than residential L2 EVSE due to the increased weatherproofing, added durability, pedestal mounting, inclusion of customer interfaces/payment systems, and added warrantees or service agreements often reported in the billing price.

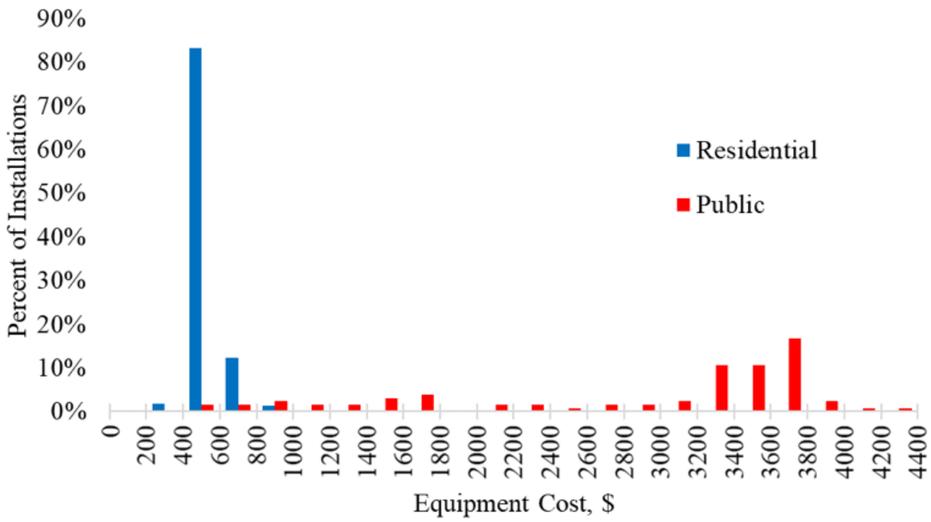

Figure A4. Equipment costs of level 2 electric vehicle supply equipment on a per-plug basis.

The installation costs for L2 EVSE projects (shown in Figure A5) varied significantly on a case-by-case basis. Low-cost residential installations can be relatively straightforward, while high-cost installations might require significant electrical work, including expensive upgrades to the distribution system, to complete. Commercial (*i.e.*, public) L2 installations were found to be both more expensive and more variable (with respect to billing costs) than the residential installations. These EVSE are commonly co-located with parking spaces, requiring extensive construction and electrical work including trenching and repaving to provide power to the necessary location.

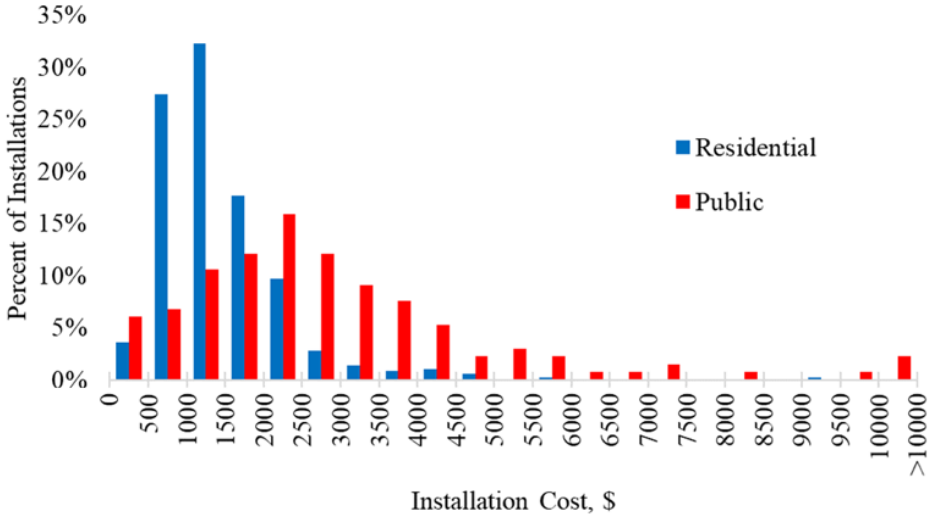

Figure A5. Installation costs of level 2 electric vehicle supply equipment on a per-plug basis.

Despite its confidential nature (there are currently only a handful of companies completing DCFC installation projects), billing data was acquired for nearly 100 DCFC projects from The EV Project and Live Electric. The equipment cost estimates for 50-kW and 150-kW DCFC EVSE that are reported in Table 1 were derived from these data. The equipment cost distribution is not included to preserve confidentiality.

Due to the significant power requirements of DCFC, installation costs can be very high. Construction costs, like trenching, paving, and landscaping are generally required and for larger stations, distribution system-level upgrades may be needed to accommodate the increased load. Figure A6 displays the installation costs for nearly 100 DCFC installation projects in the U.S normalized by the total amount of installed power ($/W). The median ($0.40/W) was used to extrapolate the installation costs for modeling large-scale DCFC stations.

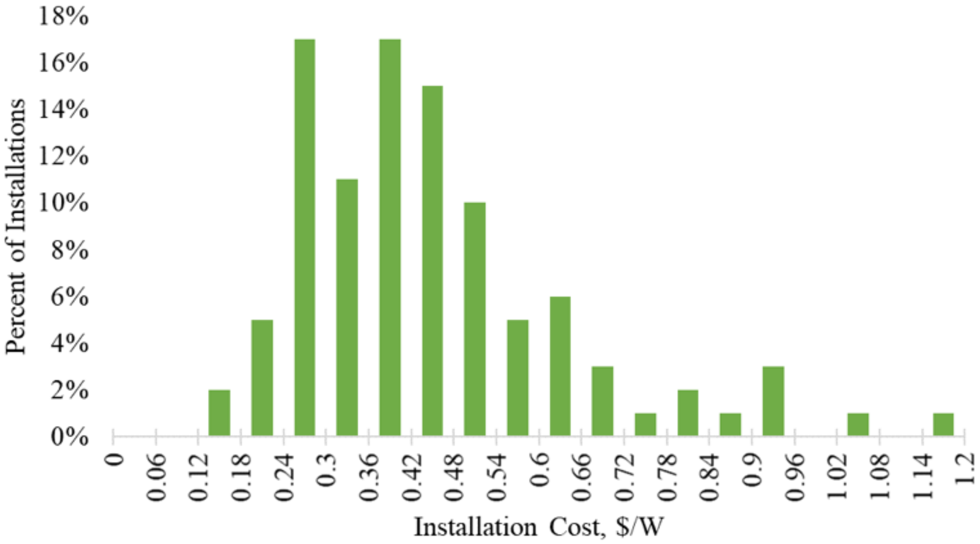

Figure A6. Distribution of installation costs for 50-kW direct current fast chargers (in $/W installed power).

A.5 State-level LCOC and LFCS

Figure A7 reports the baseline LCOC for BEVs (red) and PHEVs (blue) at the state- and national-levels (represented by points in the figure). The range of possible LCOC values for different charging mixes—residential, workplace/public-L2, and DCFC, utility rates, and EVSE capital costs are represented by bars in the figure.

Figure A8 reports the baseline LFCS for BEVs (green) and PHEVs (yellow) at the state- and national-levels (represented by points in the figure). The range of possible LFCS values for different charging mixes—residential, workplace/public-L2, and DCFC, utility rates, and EVSE capital costs are represented by bars in the figure.

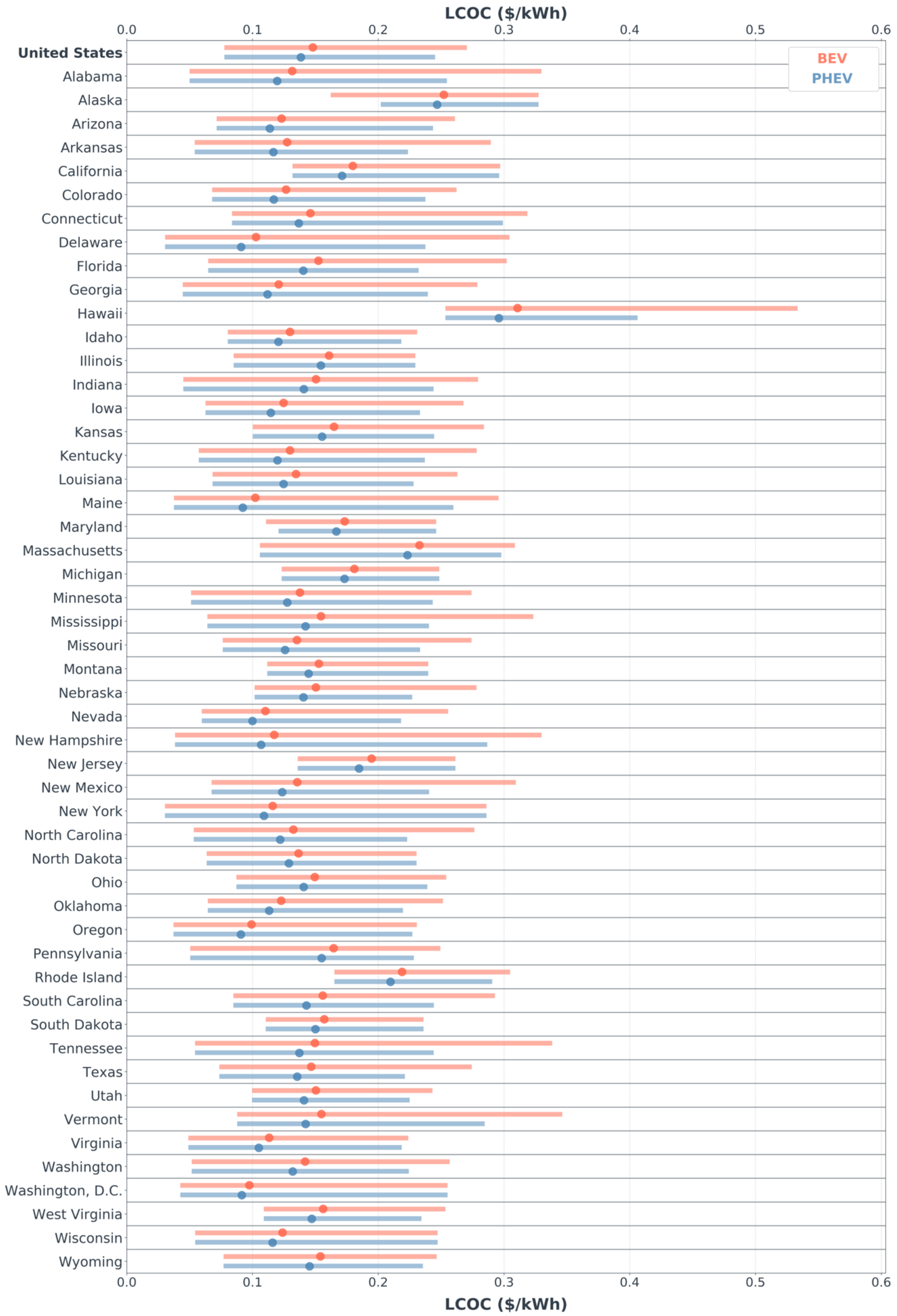

Figure A7. State-level baseline levelized cost of charging (points) and range (bars) for low (left) and high (right) sensitivities.

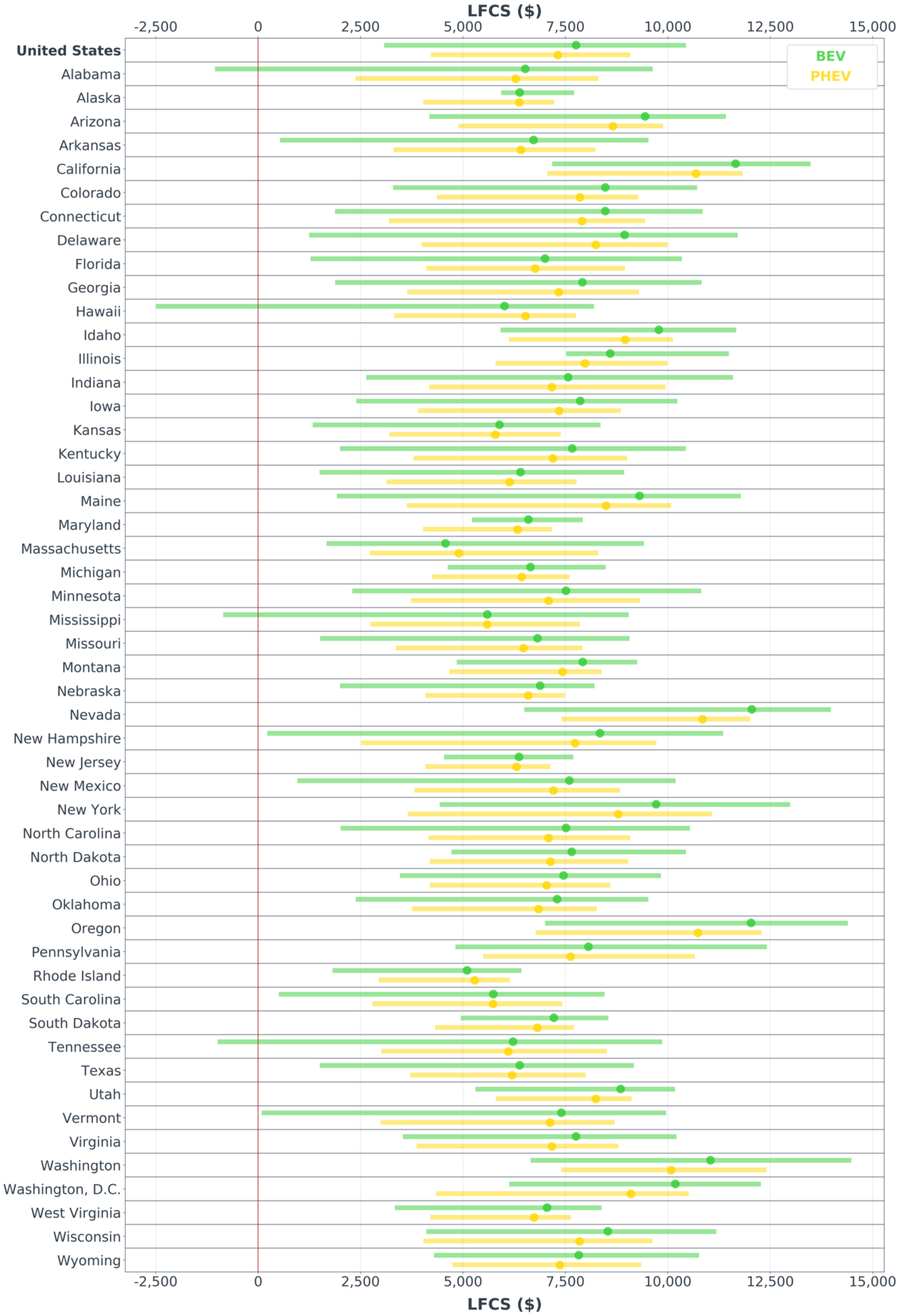

Figure A8. State-level baseline lifetime fuel cost savings (points) and range (bars) for low (right) and high (left) sensitivities.

A.6 Assumptions

LCOC Assumptions

Variable	Value	Units and Source
Vehicle and EVSE lifespan	15	years
EVSE maintenance cost	1	% equip. cost annually
lifetime-VMT (baseline)	161,729	miles [32]
BEV efficiency	119	mpge [33]
PHEV gasoline-efficiency	45	mpg [33]
PHEV electricity-efficiency	119	mpge [33]
PHEV share of e-miles	76	% [33]
Workplace EVSE utilization	30	kWh/day [41]
Discount rate (baseline)	3.5	% annually [30]
Inflation rate	1.9	% annually [44]
Tax rate (DCFC)	21	% [44]
Capital gains tax (DCFC)	15	% [44]
Sales tax (DCFC)	2.25	% of sales [44]
Credit card payment fees (DCFC)	2.5	% of sales [44]
Internet cost (DCFC)	600	$ annually [44]
Property insurance (DCFC)	0.9	% annually [44]
Admin. Expenses (DCFC)	0.5	% of sales [44]
Land rent (DCFC)	0	$/month
IRR (DCFC)	0	% of sales
BEV charge mix (baseline)	81; 14; 5	% Residential; % Public L2; % DCFC [35]
PHEV charge mix (baseline)	81; 19	% Residential; % Public L2 [35]

EVSE Cost Assumptions (units: $/plug)

Type	Median	5th %-tile	95th %-tile
Residential-L1 equip	0	-	-
Residential-L1 install	0	-	-
Residential-L2 equip	550	-	-
Residential-L2 install	1,286	-	-
Public-L2 equip	3,500	812	7,435
Public-L2 install	2,500	510	6,624
DCFC-50 kW equip	38,000	32,449	44,407
DCFC-50 kW install	20,000	10,500	46,500
DCFC-150 kW equip	90,000	76,500	105,300
DCFC-150 kW install	60,000	31,500	264,500

LFCS Assumptions

Assumption	Value	Units and Source
ICEV efficiency	29	mpg [33]
2019 gasoline prices	$2.73/gal national average [47]	
Projected fuel costs (electricity & gasoline)	AEO19 [48], see Figure A9	

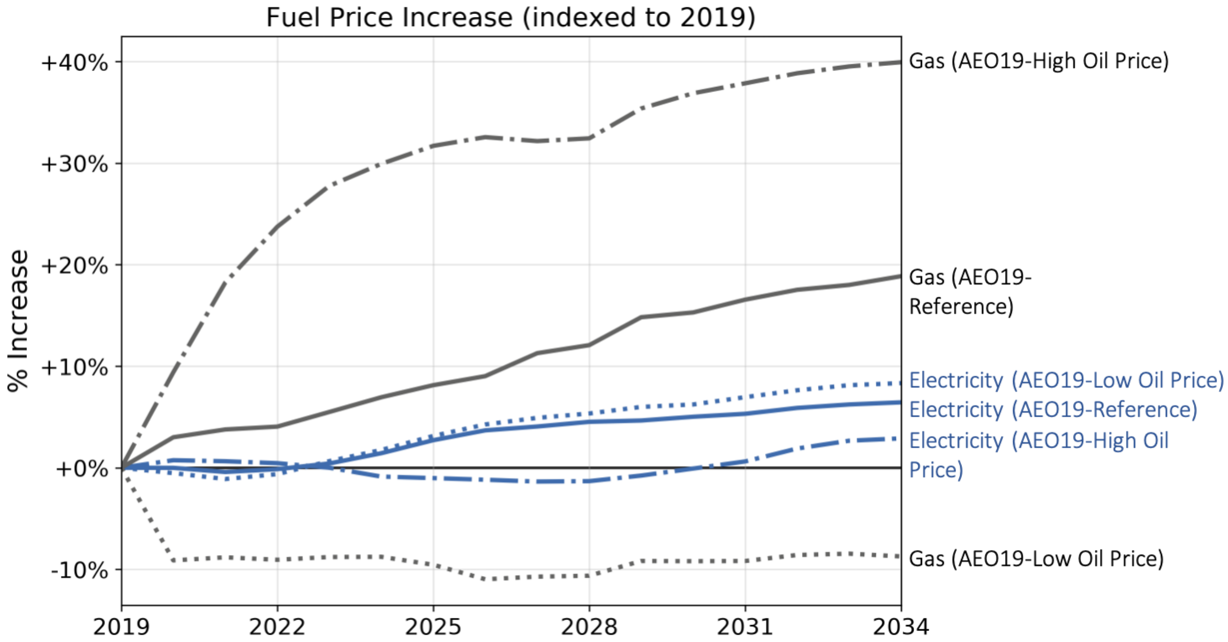

Figure A9. 15-year gasoline and residential electricity price escalation projections from the EIA's 2019 Annual Energy Outlook (AEO19) for three separate cases: "Reference" (baseline), "High Oil Price", and "Low Oil Price" [48].