Retail Infrastructure Costs Comparison for Hydrogen and Electricity for Light-Duty Vehicles

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Retail Infrastructure Costs Comparison for Hydrogen and Electricity for Light-duty Vehicles

Abstract

Both hydrogen and plug-in electric vehicles offer significant social and environmental benefits to enhance energy security and reduce criteria and greenhouse gas emissions from the transportation sector. However, the rollout of electric vehicle supply equipment (EVSE) and hydrogen retail stations (HRS) requires substantial investments with high risks due to many uncertainties. We compare retail infrastructure costs on a common basis – cost per mile, assuming fueling service to 10% of all light-duty vehicles in a typical 1.5 million person city in 2025. Our analysis considers three HRS sizes, four distinct types of EVSE and two distinct EVSE scenarios. EVSE station costs, including equipment and installation, are assumed to be 15% less than today's costs. We find that levelized retail capital costs per mile are essentially indistinguishable given the uncertainty and variability around input assumptions. Total fuel costs per mile for battery electric vehicle (BEV) and plug-in hybrid vehicle (PHEV) are, respectively, 21% lower and 13% lower than that for hydrogen fuel cell electric vehicle (FCEV) under the home-dominant scenario. Including fuel economies and vehicle costs makes FCEVs and BEVs comparable in terms of costs per mile, and PHEVs are about 10% less than FCEVs and BEVs. To account for geographic variability in energy prices and hydrogen delivery costs, we use the Scenario Evaluation, Regionalization and Analysis (SERA) model and confirm the aforementioned estimate of cost per mile, nationally averaged, and estimate a 15% variability in regional costs of FCEVs and a 5% variability in regional costs for BEVs.

Introduction

Research efforts on electrification of the transportation sector have been driven by growing environmental concerns and interest in energy security. Both hydrogen and electric vehicles have the potential to "remove the vehicle from the environmental equation."[1] Urban areas benefit from zero tailpipe emissions from hydrogen fuel cell electric vehicles (FCEVs) and plug-in vehicles (PEVs) with electric miles. PEVs include both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Hydrogen and electricity increase the diversity of low-carbon energy resources that can be relied upon to meet long-term greenhouse gas reduction goals. Hydrogen and electricity supply pathways require very low volumes of petroleum-based fuels, offering a long-term and domestic alternative to gasoline and diesel fuels.

Both government agencies and the auto industry have promoted EV and FCEV deployments for a more sustainable transportation future. In 2011, President Obama set an ambitious goal of putting one million EVs on the road by 2015 and proposed incentive programs to accelerate EV deployment [2]. According to the December 2010 OEM survey by California Energy Commission [3], OEMs committed to supply over 50,000 FCEVs in California by 2015-2017, an 11% increase over the number in the 2009 survey. However, high initial vehicle costs (full performance BEVs can cost more than $40,000) and lack of consumer acceptance, partly due to limited retail stations, could prove to be major market barriers. Many insightful studies have compared vehicle costs, fuel costs and ownership costs [4-6], while few have focused on retail infrastructure costs [7].

While deploying HRS and EVSE retail stations involves substantial and high-risk investments, as of the end of 2011, there were 215 HRS in operation around the world with a further 122 in the final planning stage [8]. According to Navigant Research [9], there are more than 48,000 publicly accessible EVSE stations installed globally as of the first quarter this year. Increasing volumes have been seen for both HRS and EVSE systems, and additional data is starting to become available for more reliable "current" cost estimates. Considering the uncertainty associated with future cost estimates, we apply broad ranges for our cost estimates based on recent publicly available data. We do not estimate upstream electricity distribution system costs (e.g., transformers) and therefore underestimate full EVSE costs to some degree.

Hydrogen and electricity supply pathways have highly variable costs and social and environmental benefits. This paper focuses on retail infrastructure, which has a lesser degree of variability than full pathway comparisons. We adopt a common transportation energy service basis – per vehicle mile traveled – to compare retail infrastructure, fuel, and vehicle costs for hydrogen and electricity in 2025. A generic 1.5 million person city is assumed for our analysis. We focus on light-duty vehicles (LDVs) only, assuming 10% of LDVs in the city are PEVs or FCEVs with fuel economy estimates from DOE [9] and HRS costs from the Hydrogen Station Cost Calculator (HSCC) [10]. This level of market adoption is relatively aggressive for 2025, and is chosen to avoid many of the transitional costs and dynamics associated with very early infrastructure development and vehicle rollout, which have been examined elsewhere. The HSCC incorporates expert stakeholders' estimates and a select number of other cost estimates. In general, the HSCC results reflect cost reduction trends that could be achieved over the next 5 to 10 years. To estimate EVSE station costs, we compile EVSE cost data based on a variety of sources and assume a moderate cost reduction for 2025, due to learning and experience. For total capital cost estimates per city, we make further assumptions regarding station size, capacity and PEVs mix under home and robust PEV charging scenarios. Our results indicate that city-wide capital costs per mile are within ten percentage points between FCEVs, BEVs and PHEVs, though EVSE level 2 home (L2H) chargers carry a relatively high capital costs (and faster charging times) compared to level 1 home (L1H) chargers. The difference in total costs between the home and robust scenarios is not substantial. When one considers fuel economies and vehicle costs, FCEV and BEV costs per mile are comparable and PHEVs are about 10% less on a cost per mile basis.

Methods

We assume a generic 1.5 million person city in 2025 as our comparison basis, which corresponds to a typical large urban area according to data from U.S. Census, and adopt assumptions about the city and financing shown in Table 1. The PEV mix is 20% BEV and 80% PHEV. We levelize station capital and operating costs on a gallon gasoline equivalent (gge) basis and then calculated costs per mile:

$$CPM = \frac{\frac{C \cdot CRF + OM}{Q} + F}{FE} \quad , (1)$$

where *CPM* refers to total fuel cost per mile in \$/mi, *C* to station capital cost, *CRF* to capital recovery factor, *OM* to annual station operating cost, *Q* to annual fuel demand in gge, *F* to fuel cost in \$/gge, and *FE* to fuel economy in miles/gge. City service cost in \$/city was calculated as a secondary cost metric, based on percentage share of LDVs and miles per LDV:

$$CS = N \cdot S \cdot VMT \cdot CCM \quad , \qquad (2)$$

where *CS* refers to city-wide service or total capital cost (sum of *C* over all stations), *N* to total number of LDVs in the city, *S* to market share of FCEVs or PEVs (10% in this analysis), *VMT* to annual miles per LDV (miles per vehicle-year) and *CCM* to the station capital cost per mile.

Table 1. General assumption for the comparison basis

	Description	Value	Unit
City parameters	Population	1.5	million
	Population density	2900	Persons/mi^2
	Vehicle ownership	0.8	LDVs/person
	Market share of PEVs/FCEVs	10%	-
Financial parameters	Interest rate	10%	-
	Capital lifetime	12	Years
	Fuel costs in 2025	National average	\$/gge

Note: this is a quasi-steady state analysis. It is assumed that many early market growth risks have been overcome by the time 10% of the on-road vehicle is FCEVs or BEVs and PHEVs.

To estimate capital costs per mile traveled, we made input assumptions regarding vehicle efficiency, vehicle miles traveled (VMT), vehicles per station and total station capacity, shown in Table 2. The battery charging efficiency was assumed to be 85% [9]. Other parameters are explained in sections below. Figure 1 shows average daily miles driven for FCEV, BEV and PHEV under two scenarios, and conventional ICE (internal combustion engine)/hybrid electric vehicles. For PHEVs, the percent of VMT on electricity (46.4%) is computed by using the Fleet Utility Factor equation from SAE J2841 [11]. The J2841 daily distance utility factor is the fraction of miles travelled in charge depletion mode at a fleet level. In the Robust Scenario, it is assumed PHEVs have greater access to public charging and therefore drive a greater number of e-miles, on average; this is a back-of-the-envelope input assumption. For BEV miles, we estimate a daily average of 31.6 e-miles. This is consistent with the 2007 Traffic Choices Study [13] in the Seattle urban area, which suggests that 2% of conventional vehicle driving could achieve this level of average daily travel without exceeding the BEV's limited range, especially given the high public EVSE availability in the Robust Public scenario. This suggests that the BEVs are purchased into select households able to achieve high annual electric miles despite limited battery size or range. Moreover, we assume that hydrogen refueling is available outside the city to allow for infrequent, long-distance trips along interstates and to distant urban areas.

Table 2. Input assumptions for cost-per-mile calculation

	FCEV	PHEV	BEV	Note
Fuel economy (mpgge)	59	46/114 (g/e[a])	104 (321 Wh/mi)	See ref.6
Battery size (CD[b] range)	-	25	100	Unit: miles
Average Daily VMT (robust)	33.2	33.2	26.6 (31.6)	VISION model [12]
Station size (kg/day for hydrogen stations)	1500 (L) 500 (M) 250 (S)	L1H: 1.4kW L2H: 3.3kW L2W: 7.7kW DCFC: 50kW		Annual average 75% utilization rate for HRS
Vehicles per station	L: 1989 M: 663 S: 331	Two scenarios. (see Table 3)		FCEVs use 0.57 kg H2 per day

Notes: a. g/e=gasoline/electricity; b. CD=charge-depleting (EV mode); L=large; M=medium; S=small; L1H=level 1home, L2H=level 2 home, L2W=level 2 work, DCFC=direct current fast charge

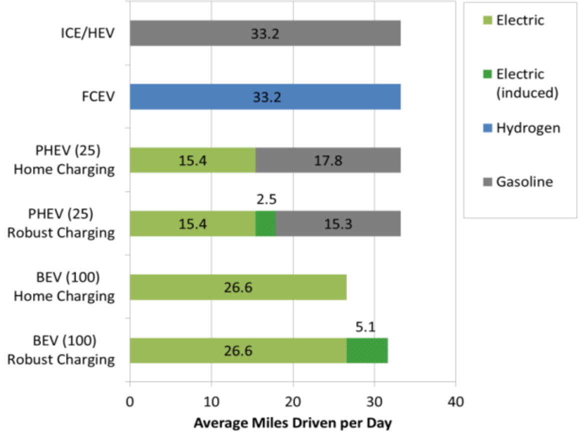

Figure 1. Average miles driven per day for each vehicle

Number of hydrogen stations by size

The three HRS sizes considered in the analysis, 250, 500, and 1,500 kg/day, are intended to capture economies of scale while maintaining sufficient station availability. For estimating the number of HRS for each size, we employ the distribution of gasoline station sizes described in a 2006 study [14], where relative station sizes in a given urban area follow a fixed gamma distribution. The study [14] concludes that normalized station size distribution is largely uniform across U.S. cities, varying only slightly with size or population density. Based on this general distribution, we estimate 33 large, 56 medium and 51 small HRS serving the generic city.

Number of EVSE stations by type

For PEVs, we consider four types of EVSE charging under two distinct EVSE scenarios, as shown in Table 3. Both L1H and L2H are for residential use, with L2H providing a faster charge than L1H. L1H usually provides up to 1.44 kW (120 VAC, 12 amp), and L2H up to 3.3 kW (240 VAC, 15 amp). L2W provides charging at work with a maximum power of 7.7 kW. DCFC is for commercial and public applications with a charging rate as high as 50 kW.

All PEVs have home chargers (one per PEV). Under the Home Dominant scenario, 76% of PHEVs rely on L1H EVSE and the rest are charged by L2H. Some 43% of BEVs rely primarily upon L1H and the rest by L2H. Each home charger has one port. Under the Robust Public scenario, L1H chargers serve 80% of PHEVs and 65% of BEVs. In sum, for the Home Dominant and Robust Public scenarios, respectively, there are 83,280 and 92,400 L1H chargers, and 36,720 and 27,600 L2H chargers.

Table 3. Primary chargers in each EVSE scenario

EVSE type	Home Dominant	Robust Public
Level 1 – home (L1H)	76% PHEVs/43% BEVs	80% PHEVs/65% BEVs
Level 2 – home (L2H)	24% PHEVs/57% BEVs	20% PHEVs/35% BEVs
Level 2 – work (L2W)	120 PHEVs or 74 BEVs/L2-W	84 PHEVs or 46 BEVs/L2-W
Fast charge (DCFC)	600 PHEVs[a] or 320 BEVs/DCFC	400 PHEVs or 220 BEVs/DCFC

a. Future PHEV batteries may not be able to accept fast charging

For L2W and DCFC, we simulated charging demand profiles for a typical workday derived from two vehicle-charging scenarios in a 2007 NREL study [15]. For each charging scenario, we assume the demand distributions among all EVSE types for PHEVs and BEVs shown in Table 4. The vehicle-to-EVSE ratios for L2W and DCFC are estimated based upon peak hourly demand constraints where we assume a 50% margin for both L2W and DCFC. As shown in Figure 2, each EVSE capacity satisfies average daily fluctuations in the two PEV charging scenarios, with some capacity buffer for variability in hourly demand. Given our assumptions, under the Home Dominant scenario, home charging provides 92% of all demand from PEVs, the vehicle-to-L2W ratio is 120 for PHEVs and 74 for BEVs, and there are 1,124 L2W and 235 DCFC stations. Under the Robust Public scenario, L2W and DCFC provide 10% of all demand from PEVs with 84 PHEVs/46 BEVs per L2W and 400 PHEVs/220 BEVs per DCFC, and there are 1,665 L2W and 349 DCFC stations.

Table 4. Demand (kWh) distribution among all EVSE for PHEVs and BEVs

Type	Home Dominant		Robust Public	
	PHEV	BEV	PHEV	BEV
L1H	70%	33%	68%	55%
L2H	22%	58%	22%	33.5%
L2W	5%	5.7%	6.3%	8.5%
DCFC	3%	3.3%	3.7%	3%

Hydrogen station costs

Small, medium and large HRS costs are estimated based upon the Hydrogen Station Cost Calculator [10] (HSCC). The HSCC was developed with inputs from expert stakeholders through the Hydrogen Infrastructure Market Readiness project [16]. These costs are comparable to other cost estimate sources [10]. The results from the HSCC convey station cost reduction potential over the next 5-10 years, accounting for reductions due to experience and the economies of scale of larger stations. Four types of HRS are defined within the HSCC to represent different stages of station technology development over time. A general cost function estimates station capital cost with station size and cumulative installed station capacity (an indicator for industry experience) as inputs, shown in eq.3.

$$CC = CC^0 \left(\frac{Q'}{Q^0}\right)^{\alpha} \left(\frac{V'}{V^0}\right)^{\beta} \qquad (3)$$

where *CC* refers to Station Capital Cost in $ per station, CC^0 to base station capital cost ($2.8M), *Q'* to station capacity in kg per day, Q^0 to base station capacity (450 kg/d), *V'* to cumulative capacity, V^0 to cumulative capacity (25,000 kg/d) corresponding to the base station, and *α* (0.707) and *β* (-0.106) are scaling and learning factors respectively, estimated by fitting HSCC aggregated station costs.

EVSE station costs

For each type of EVSE, current cost estimate ranges are based on a variety of sources (see appendix). No attempt was made to differentiate costs for specific EVSE attributes within each type category. We assume a 15% reduction from today's EVSE costs due to mass production, streamlined installation, and learning. This is a relatively conservative assumption, which could be interpreted as an experience curve with a progress ratio of 98.5% (assuming, for the sake of example, approximately 40 MW of installed EVSE capacity by 2013, and 53,000 MW cumulative installed nationally by the analysis year, 2025. See [10] for a discussion of the HRS progress ratios.).

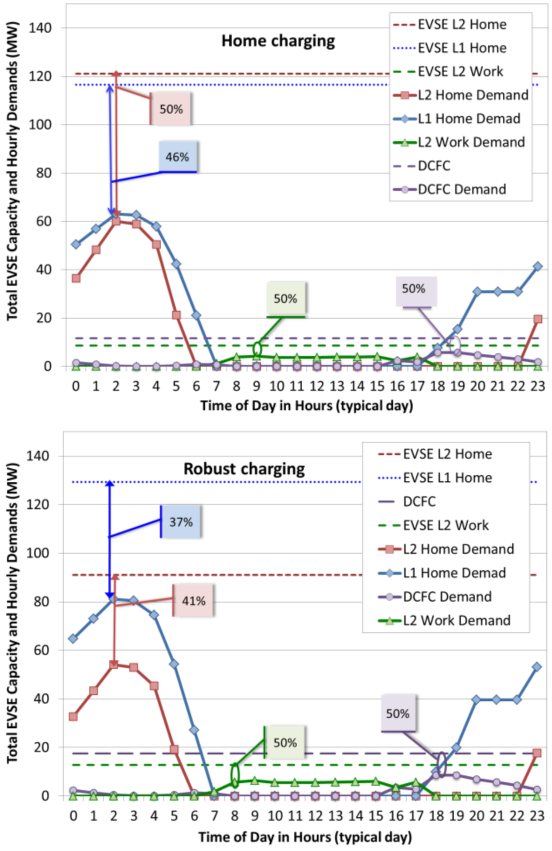

Figure 2. Total EVSE capacity and typical hourly demands under home charging and robust charging scenarios

For each EVSE type, we aggregated data for equipment and installation costs, and estimate the median of both costs as our central, or medium cost case, as indicated in Figure 3. Installation costs vary greatly. The central installation cost is handled in a slightly different way, which could be average or adjusted average depending on data sources (see appendix for details). High and low costs were the central value plus and minus 33% of the difference between the central value and the highest and lowest values for equipment and installation (approximating standard deviations), except for DCFC. High and low cost values for DCFC were the highest and lowest values of both equipment and installation costs resulting in a broad range of variability (see details in Appendix A4). Figure 3 presents the estimated total capital cost (equipment plus installation) per unit for each type of EVSE. We do not include upstream electricity system distribution costs (e.g., transformers) and therefore underestimate full EVSE costs to some degree.

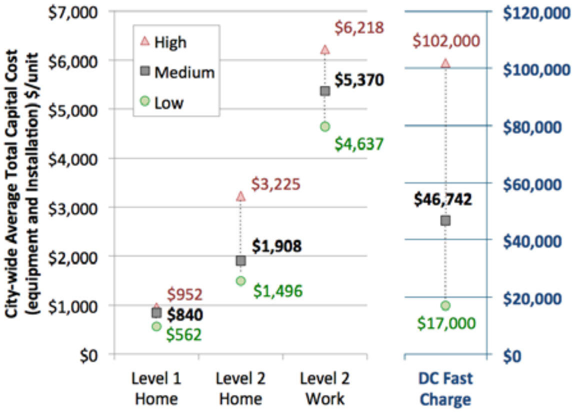

Figure 3. Total capital cost by EVSE type

Results

Total capital costs per city and capital costs per mile traveled

With the estimated number of HRS for each station size and station capital costs from the HSCC within the city, we calculate the total capital costs for HRS to meet hydrogen fuel demand for the 10% market penetration in the generic city. Similarly, we calculate the citywide total EVSE capital cost for each charging scenario. HRS capital costs are about twice EVSE capital costs, on a citywide basis, largely due to limited economies of scale for HRS. There is a small difference in citywide capital costs between the Home and Robust scenarios, as shown in Figure 4 (top). The bottom of Figure 4 indicates total VMT fueled by hydrogen in FCEVs, electricity in BEVs and PHEVs, and gasoline in PHEVs (bars, left-hand vertical axis). The figure also shows total capital costs per mile for HRS and EVSE (lines and marks, right-hand vertical axis). The gasoline cost of 7.5 cents per mile is shown for reference. Capital costs per mile are essentially indistinguishable between the HRS (3.1 c/mi) and EVSE (3.0 c/mi) in the Home Dominant scenario, especially when considering the uncertainty and variability around input assumptions. The Robust Public scenario has a 19% lower capital cost per mile (2.5 c/mi) due to more L1H and less L2H relative to the Home Dominant scenario; the greater number of L2W and DCFC stations does not exceed the capital cost savings from this shift to more L1H charging.

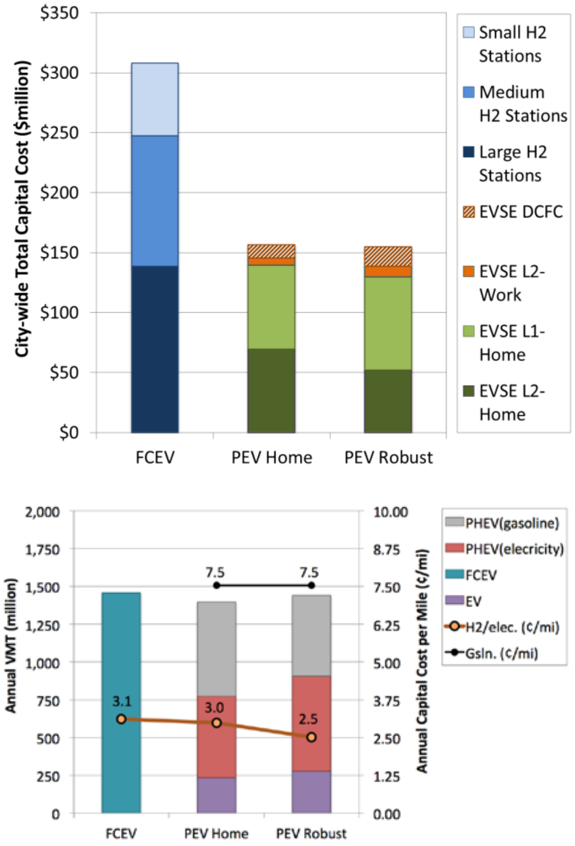

Figure 4. Citywide total capital costs (top) and total VMT by fuel type and capital costs per mile traveled (bottom)

These cost results are sensitive to a number of key input assumptions, some of which are highly speculative and simple "back-of-the-envelope" assumptions. Additional empirical cost data, more explicit station logistics and rollout dynamics, various sensitivity analyses, and an optimization routine (see the SERA model discussion below) would all improve this analytic approach. In particular, the relative EVSE cost result between the Home Dominant and Robust Public scenarios is very dependent upon our input assumptions. It is not based upon a thorough evaluation of the tradeoffs between public and home charging, which is beyond the scope of this analysis.

The levelized cost per mile is shown as a function of the distribution of e-miles supported by EVSE type in Figure 5 for the two charging scenarios. Electricity use per week under the two scenarios is shown in Figure 6. Levelized capital cost per mile analysis suggest that to reduce overall costs, increased public EVSE infrastructure must be accompanied by a shift from Level 2 to Level 1 Home charging. This is consistent with an assumption of rational economic behavior and preference or convenience tradeoffs on the part of consumers. However, consumer preferences, responsiveness to price signals, charging patterns, and induced electric VMT will all play an important role in determining the future mix of EVSE types. The total electricity use per week under the robust scenario is just above 1M kWh.

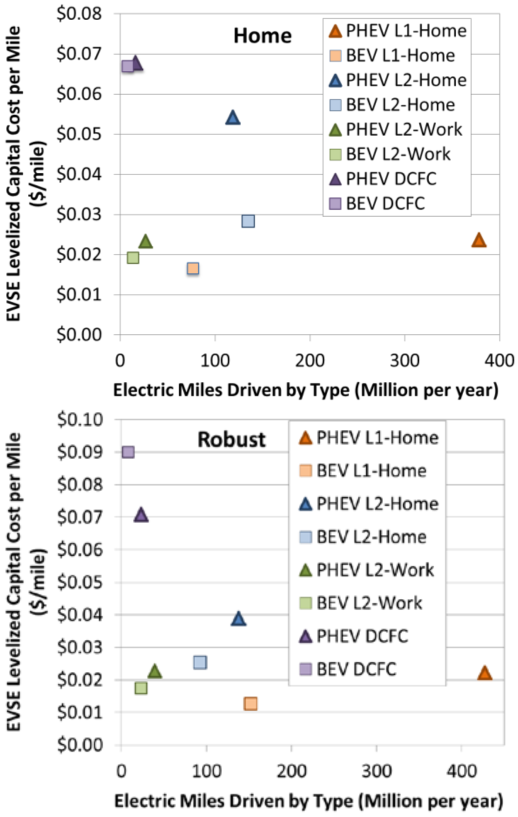

Figure 5. Distribution of VMT by EVSE type (Top: Home Dominant scenario. Bottom: Robust Public scenario)

Our capital cost estimates involve significant variability and uncertainty, but of different types for HRS and EVSE. We assume high and low capital costs for sensitivity analysis of capital cost per mile. As shown in Figure 7, the result is a large range, on the order of 2-3 cents per mile. For HRS, the cost range is primarily due to assumptions about reductions achieved through experience and learning. EVSE cost ranges are primarily due to uncertainty and variability in equipment and installation costs. Given our assumptions, a Robust EVSE infrastructure reduces capital cost per mile for BEVs by 22% and for PHEV by 13% (medium case) due to increased L1H charging. This relative cost result was not the focus of the present study, but rather indicates the degree to which EVSE costs vary based upon assumptions.

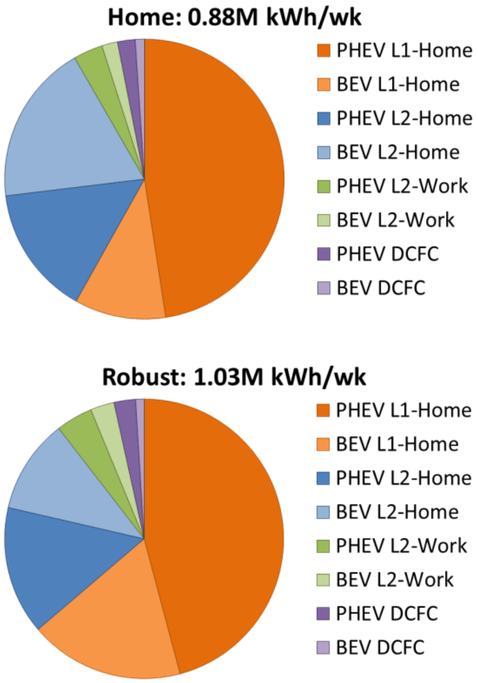

Figure 6. Electricity use per week by PEV/EVSE type

Total fuel costs per vehicle mile

Based on the assumptions shown in Table 5, we calculate the total fuel costs per mile for each vehicle type, shown for the Home Dominant scenario in Figure 8. FCEVs, BEVs and PHEVs all have advantages over conventional ICE vehicle fuel costs, and PEV fuel costs are comparable to HEV fuel costs. Central values for total fuel costs under the Home Dominant scenario suggest BEV and PHEV costs 21-13% lower than FCEV costs. Sensitivities on capital costs show that FCEVs generally have higher total fuel cost than BEVs and PHEVs, and total fuel cost for BEVs has a greater uncertainty range than that for PHEVs because PHEVs operate with about 46% e-miles. For the Robust Public scenario (not shown in Figure 8), the total fuel cost relative to the Home Dominant costs for BEVs is 9% lower, and only slightly lower for PHEVs.

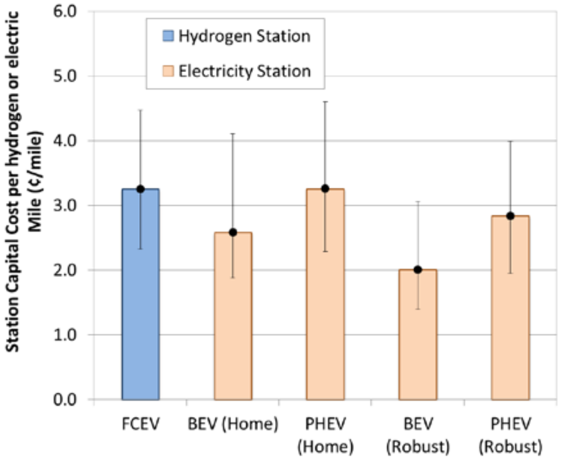

Figure 7. Sensitivity of capital cost per mile

With vehicle fuel economy and vehicle cost ranges from DOE (2012) [6], we determine the sensitivity to fuel economy and corresponding vehicle cost as shown in Figure 9. Including fuel economies and vehicle costs, FCEV and BEV costs per mile are comparable, and PHEVs are about 10% less per mile. We assume average electricity costs in 2025 from AEO (2013), hydrogen from central natural gas, and conventional gasoline. Including a $150/tonne CO_2eq carbon price signal tends to level out cost comparisons, as indicated by the orange diamonds in Figure 9.

Table 5. Assumptions for hydrogen fuel cost, electricity cost, gasoline fuel cost and fuel economies

	Value	Reference/note
Hydrogen fuel cost	$3/kg	This is intended to be generic, with $2/kg for production at a central natural gas SMR unit and $1/kg for multiple delivery modes.
Electricity cost	$0.116/kWh for home scenario $0.097/kWh for robust scenario	EIA AEO 2013 reference case [17] Use residential rate for home scenario and commercial rate for robust scenario
Gasoline fuel cost	$3.50/gal	EIA AEO 2013 reference case [17]
Fuel economy	FCEV: 58.75 mpgge BEV: 104.07 mpgge PHEV: 46.35/113.91 mpgge (g/e) HEV: 49.30 mpg ICE: 33.20 mpg	mpgge= miles per gallon of gasoline equivalent US DOE RFI [9] Average values from 2020 and 2030 Values for PHEV shown here are for gasoline and electric fuel efficiencies

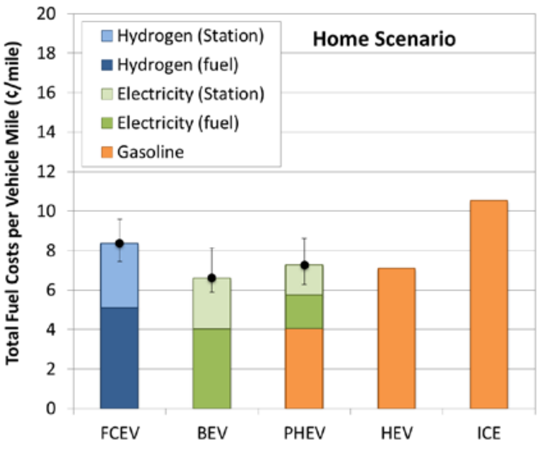

Figure 8. Total fuel costs per vehicle mile, Home Scenario results only (¢/mile)

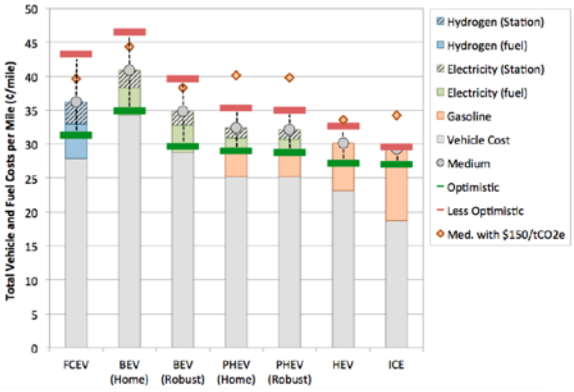

Figure 9. Sensitivity to fuel economy and corresponding vehicles cost

Discussion: variability of results

Substantial spatial variability exists in energy prices and infrastructure costs, and these can result in significant differences in levelized costs per distance traveled, depending on the vehicle and fuel type. To explore the magnitude of these variations, we use a regional infrastructure build-out scenario for hydrogen-production infrastructure and HRS constructed using the SERA model [18]. The SERA scenario estimates the cost of hydrogen delivered to FCEV refueling stations, the number of such stations in each urban area in the continental United States, and the capacity distribution of those stations. Note, however, that many alternative scenarios for the build-out of regional hydrogen production and delivery infrastructure components are possible and that the scenario presented here is solely chosen to illustrate the magnitude of geographic variability that might be exhibited. The fundamental sources of regional differences in the cost of hydrogen are the geographic unevenness in hydrogen demand, different urban characteristics (e.g., population density), the significant cost of transporting hydrogen long distances, local niches for the use of particular feedstocks and production technologies, and varied opportunities for economies of scale [18]. Also note that the regional hydrogen prices used in the analysis represent local levelized costs (e.g., not averaged over large multi-state regions or the service territories of hydrogen production and delivery companies) and may not be realistic depictions of plausible regional hydrogen prices, since it is likely that market forces would regularize prices geographically. We supplement this information on regional hydrogen prices with price estimates for gasoline and electricity from the "reference case" in the U.S. Energy Information Administration's 2013 Annual Energy Outlook [17]. EVSE and vehicle costs, VMT assumptions, fuel economies, and vehicle usage/charging/refueling patterns remain the same as in the results discussed in the previous section of this paper.

Figure 10 shows the resulting nationally weighted average cost-per-mile for different vehicle types and charging assumptions using this scenario, which involves alternative vehicle introductions in the 55 largest urban areas [19] by the year 2025. The bar chart illustrates that station, fuel, and vehicle costs are roughly commensurate for the different vehicles, but that alternative-fuel vehicles (FCEV, EV, PHEV) have higher average cost than conventionally fueled vehicles (HEV, ICE). In all cases, vehicle costs are much larger than fuel and station costs, and station costs are smaller than fuel costs.

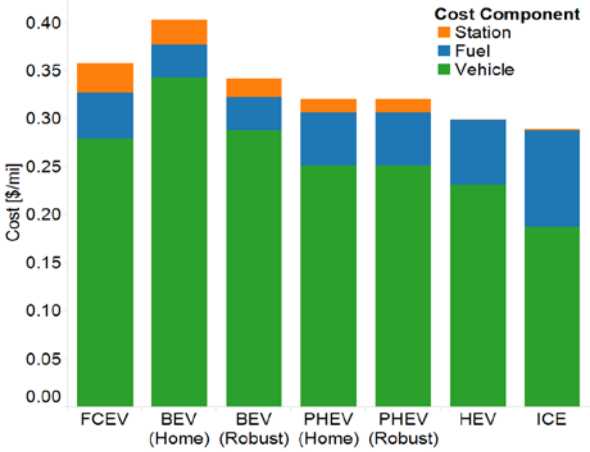

Figure 10. Nationally weighted average cost-per-mile for vehicle types and charging patterns using regional energy prices and FCEV-related infrastructure costs.

We also examine variations in vehicle costs (low, medium, and high), fuel economy (pessimistic, neutral, and optimistic), and refueling station costs (low, medium, high) on a regional basis. The top panel of Figure 11 shows that the $0.05-0.15/mile variability in overall cost per mile tends to be greater for FCEVs and BEVs and that there is a substantial overlap between the overall costs when this variability is considered. Vehicle costs tend to make the largest contributions to the variability, followed by approximately equal variability contributions from fuel economy and station costs.

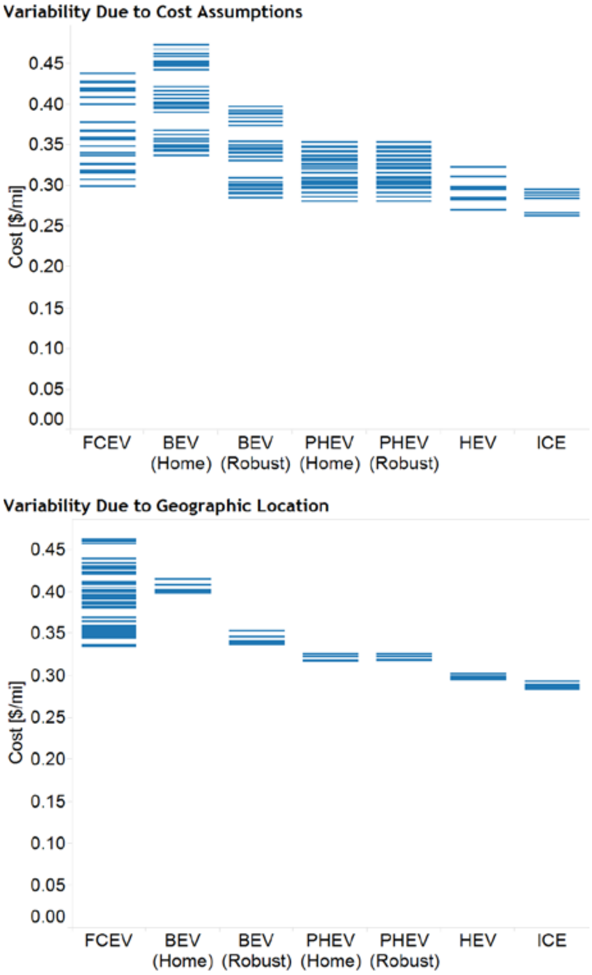

Figure 11. Variability due to cost assumptions (top) and geographic location (bottom) for the weighted average cost-per-mile for vehicle types and charging patterns using regional energy prices and FCEV-related infrastructure costs, and a variety of cost and fuel economy scenarios.

The bottom of Figure 11 illustrates the geographic variability (among the 55 largest urban areas) in overall cost per mile: for FCEVs this is due to differing fuel supply and station costs, whereas for the other vehicle types this is only due to differing fuel costs. In future analyses we will extend our models of EVSE costs to include geographic influences, but those are not included in the analyses presented here: we expect their geographic variation to be much smaller than the geographic variation in HRS costs because supplying hydrogen to large numbers of FCEVs requires the substantial development of new production facilities and delivery infrastructure, whereas in the case of EVs the existing electrical power generation infrastructure supplies the fuel. Comparing the top and bottom of Figure 11, one sees that the largest variability lies in the geographic influence on FCEV cost per mile, but that cost assumptions also imply substantial uncertainty. In sum, ranges in total costs per mile overlap significantly due to variability in cost input assumptions and geographic location.

Conclusion

Retail infrastructure costs for FCEVs and PEVs are compared on a cost-per-mile basis for a generic urban city in 2025. Using recently collected cost data and projection estimates, we analyze two distinct EVSE scenarios and consider three HRS sizes. Given our input assumptions, analysis results suggest that levelized retail EVSE and HRS capital costs per mile are essentially indistinguishable between FCEVs and BEVs in the Home Dominant scenario. Total fuel costs per mile, including levelized retail capital and fuel costs, are about 13-21% lower for PEVs than for FCEVs. Including vehicle costs and fuel economy, FCEV and BEV central costs per mile are comparable, and PHEVs are about 10% less per mile. In an examination of variability across all major U.S. cities, the national weighted average cost-per-mile is generally consistent with the simple generic city comparison, though HRS costs are slightly lower on a national average basis due to economies of scale achieved in large cities.

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Appendix. EVSE station cost

A1. Cost estimates for Level 1 Residential EVSE

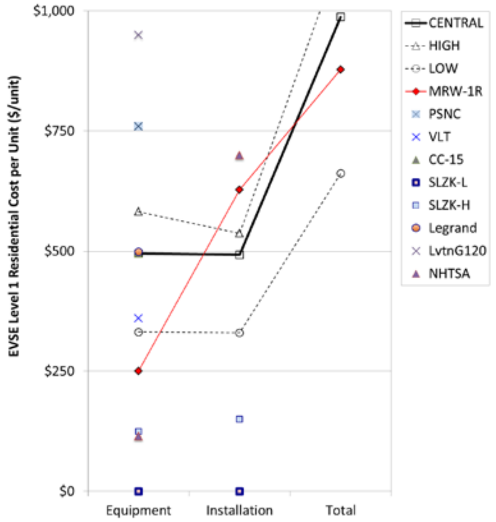

Figure A1 Costs for Level 1 Residential EVSE

Table A1 Summary of Level 1 Residential EVSE costs

Value Type	Equipment	Installation	Total
Central	$495	$493	$988
Low	$332	$330	$662
High	$582	$537	$1,120

Table A2 Level 1 Residential EVSE cost data sources

Symbol	Reference	Notes
LEVEL 1 - Residential		
SLZK	DOE 2011	L: Low; H: High.
MRW	Morrow 2008	1R: Level 1 Residential
PSNC	PIA 2013	Panasonic; Standard for Leaf
CC-15	PIA 2013	Clipper Creek; 15 A
VLT	PIA 2013	Standard with Volt
LvtnG120	PIA 2013	Comes wit carrying case.
Legrand	PIA 2013	Legrand. Selects rate charge.
CC-ACS20	PIA 2013	Wall-mountable cordset.
NHTSA	NHTSA 2010	Cost range for equipment and intallation

Central equipment costs are the median of all equipment types shown in Figure A1 and central installation costs are the average of MRW, SLZK-H and NHTSA. High and low costs are equal to the central value plus and minus 33% of the difference between the central value and the highest and lowest values for equipment and installation.

A2. Cost estimates for Level 2 Residential EVSE

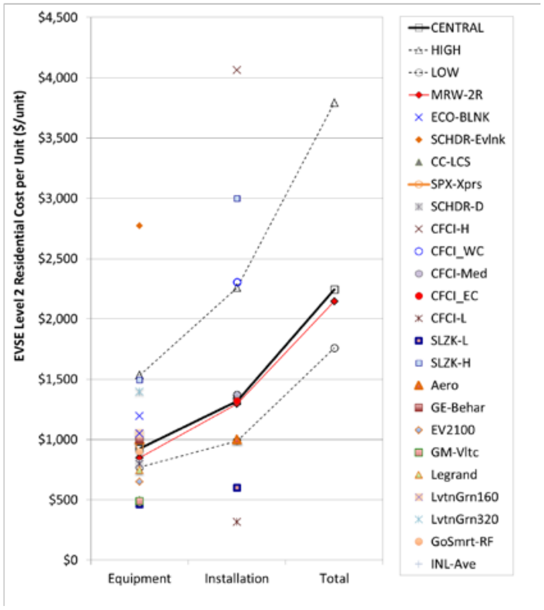

Figure A2 Costs for Level 2 Residential EVSE

Table A3 Summary of Level 1 Residential EVSE costs

Value Type	Equipment	Installation	Total
Central	$925	$1,320	$2,245
Low	$771	$989	$1,760
High	$1,534	$2,260	$3,794

Table A4 Level 2 Residential EVSE cost data sources

Symbol	Reference	Notes
LEVEL 2 - Residential		
MRW	Morrow 2008	2R: Level 2 Residential
CC-LCS	PIA 2013	Clipper Creek; LCS: model
ECO-BLNK	PIA 2013	Ecotality Blink
GE-Behar	PIA 2013	General Electric WattStation. Designed by Yves Behar.
SCHDR-Evlnk	PIA 2013	Schneider Electric EVlink Outdoor model
SPX-Xprs	PIA 2013	SPX Power Xpress. Plugs into 240V outlet
CFCI	Joffe 2010	Clean Fuels Connection; L: Low; H: High; Med: Median; EC: East Coast; WC: West Coast
LvtnGrn160	PIA 2013	Leviton Evr-Green 160
LvtnGrn320	PIA 2013	Leviton Evr-Green 320
GM-Vltc	PIA 2013	SPX and GM, made for Volt.
GoSmrt-RF	PIA 2013	Go Smart ChargeSpot RF
Aero	PIA 2013	Estimated value (not official).
Smns Versi	PIA 2013	Siemens VersiCharge
EV2100	PIA 2013	EV-Charge America, EV2100
SLZK	DOE 2011	L: Low; H: High.
INL-Ave	Francfort 2013	Average US residential installations

Central equipment costs are the median of all values shown in Figure A2. Central installation costs are derived from estimates of median values from CFCI's average East/West coast historical costs, assuming median values are 13% less than average values. High and low costs are equal to the central value plus and minus 33% of the difference between the central value and the highest and lowest values for equipment and installation.

A3. Cost estimates for Level 2 Commercial

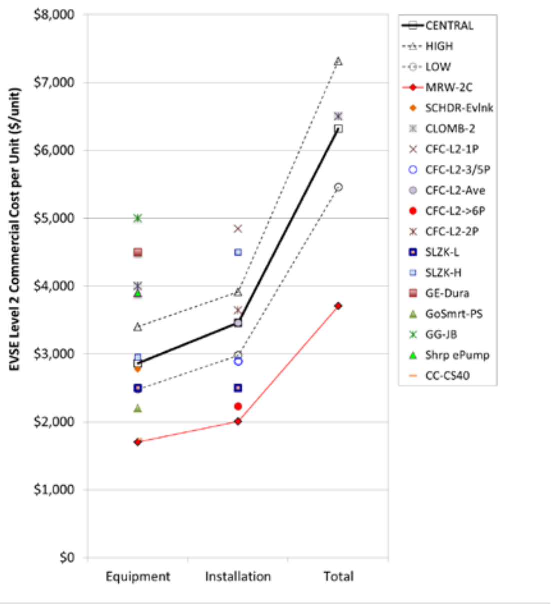

Figure A3 Costs for Level 2 Commercial

Table A5 Summary of Level 2 Commercial EVSE costs

Value Type	Equipment	Installation	Total
Central	$2,861	$3,457	$6,318
Low	$2,478	$2,977	$5,455
High	$3,402	$3,914	$7,316

Table A6 Level 2 Commercial EVSE cost data sources

Symbol	Reference	Notes
LEVEL 2 - Commercial		
MRW-2C	Morrow 2008	2R: Level 2 Residential
SLZK	DOE 2011	L: Low; H: High.
CLOMB-2	Stewart 2010	Coulomb
Shrp ePump	PIA 2012	Shorepower, multi-head
SCHDR-Evlnk	PIA 2013	Schneider Electric EVlink Outdoor model
GG-JB	PIA 2012	Green Garage Assoc. Juice Bar. BMW Group.
GE-Dura	PIA 2013	General Electric DuraStation. 100 yrs experience.
GoSmrt-PS	PIA 2013	Go Smart ChargeSpot. Can set fee collection.
CC-CS40	ClipperCreek 2013	ClipperCreek CS-40 Public Infrastructure
CFCI	Joffe 2011	Clean Fuels Connection; L: Low; H: High; Med: Median; EC: East Coast; WC: West Coast

Central equipment costs are the median of all values shown in Figure A3. Central installation costs are equal to CFCI-L2-Ave, which is the average for L2 public installations. High and low costs are the central value plus and minus 33% of the difference between the central value and the highest and lowest values for equipment and installation.

A4. Cost estimates for DC Fast Charge (DCFC)

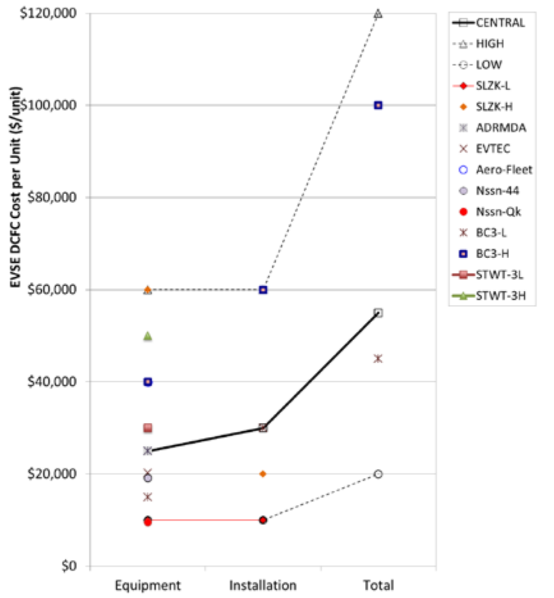

Figure A4 Costs for DCFC

Table A7 Summary of DCFC costs

Value Type	Equipment	Installation	Total
Central	$24,990	$30,000	$54,990
Low	$10,000	$10,000	$20,000
High	$60,000	$60,000	$120,000

Table A8 DCFC cost data sources

Symbol	Reference	Notes
DC FAST CHARGE		
SLZK	DOE 2011	L: Low; H: High.
ADRMDA	PIA 2013	Andromeda Power ORCA-Mobile
EVTEC	PIA 2013	EVTEC MobileFastCharger. 20kW portable charger
Aero-Fleet	PIA 2013	Aerovironment Fleet Fast Charging Station Line
Nssn-44	PIA 2013	Nissan NSQC-44. Quick charger for Nissan dealers
Nssn-Qk	PIA 2012	Smaller, lower-cost. Nissan.
BC3	Business Council on Climate Change 2011	L: Low; H: High.
STWT-3	Stewart 2010	L: Low; H: High. Coulomb reference. 20 min charge

Central equipment costs are the median of values shown in Figure A4. Central installation costs are the average of SLZK and BC3. High and low costs are the highest and lowest values of both equipment and installation costs.