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Estimating electric vehicle charging infrastructure costs across major U.S. metropolitan areas

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The rollout of electric vehicles is aided and enabled by a concurrent rollout of infrastructure at home and in public locations. Home charging provides most of the charging needed for most drivers, whereas public infrastructure improves the electric vehicle proposition for prospective buyers, increases the potential electric miles from electric vehicles, and provides charging for those without home charging. Exactly how much charging infrastructure will be needed and what it will cost are top questions for prospective electric vehicle owners, automakers, policymakers, and electric utilities alike.

The need for much more electric vehicle charging infrastructure across the United States through 2025 is well established by a recent charging gap analysis.[1] Based on that analysis, about 4 times more public charging infrastructure than was in place in 2017 is needed by 2025 to match expected electric vehicle market growth. The analysis finds that at least 100,000 public and workplace chargers will be needed across the 100 most populous U.S. metropolitan areas over 2019–2025. These chargers would help serve the 2.6 million new plug-in hybrid electric vehicle (PHEV) sales and battery electric vehicle (BEV) sales expected by 2025 in those 100 areas.

This paper analyzes the capital costs of the electric vehicle charging infrastructure needed for public, workplace, and home charging for the most populous 100 metropolitan areas in the United States from 2019 through 2025. We review charging equipment cost data, including installation and hardware, for chargers of various charging types and locations. These equipment costs are then applied to our recent estimation of public and workplace charging needs, along with home charging needs that are newly assessed here. Ultimately we quantify the infrastructure costs on a metropolitan-area basis. Excluded from this scope are charging costs outside the 100 largest markets, which is to say in smaller cities and fast-charging corridors linking the cities.

Charging cost by type and location

This section describes the types of electric vehicle charging infrastructure related to the charging location. Cost estimates and research studies were used to estimate installation and hardware-related costs for home and nonhome charging to obtain average hardware and installation costs. These installation and hardware costs are used to construct estimates by metropolitan area in the following section.

Three main categories of electric vehicle chargers are assessed in this paper: Level 1, Level 2, and direct current (DC) fast. Basic information regarding the different levels of chargers evaluated in this report is summarized Table 1. The voltage (V) column shows the voltage at which electricity is delivered to the electric vehicle, and the typical power in kilowatts (kW) is the rate of energy transfer. The associated electric vehicle miles of range per hour of charging and the typical charging locations are also shown. Generally, Level 1 is used in home charging, whereas Level 2 is used in a variety of charging conditions, and DC fast

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

Table 1. Electric vehicle charging infrastructure specifications in the United States.

Charging level	Voltage	Typical power	Electric vehicle miles of range per charging hour	Location
Level 1	120 V AC	1.2–1.4 kW AC	3–4 miles	Primarily home and some workplace
Level 2	208 V–240 V AC	3.3–6.6 kW AC	10–20 miles	Home, workplace, and public
DC fast	400 V–1,000 V DC	50 kW or more	150–1,000 miles	Public, frequently intercity

Note: AC = alternating current; DC = direct current; kW = kilowatt; V = volt

charging is most commonly used at public charging stations.

For this paper's estimation of charging equipment costs across U.S. metropolitan areas through 2025, several simplifying assumptions are made regarding charger power requirements. Chargers are assumed to be 1.4 kW for Level 1, 6.6 kW for Level 2, and DC fast chargers include a combination of 50 kW, 150 kW, and 350 kW. We define chargers by these listed power levels rather than the number of outlets. For example, two outlets on the same pedestal providing 3.3 kW per outlet when two vehicles are connected are counted as one Level 2 charger, and a 13.2-kW Level 2 charger pedestal with two outlets is counted as two chargers.

Table 2. Per charger public and workplace charger hardware cost.

Level	Type	Chargers per pedestal	Per-charger cost
Level 1	Non-networked	One	$813
Level 1	Non-networked	Two	$596
Level 2	Non-networked	One	$1,182
Level 2	Non-networked	Two	$938
Level 2	Networked	One	$3,127
Level 2	Networked	Two	$2,793
DC fast	Networked 50 kW	One	$28,401
DC fast	Networked 150 kW	One	$75,000
DC fast	Networked 350 kW	One	$140,000

PUBLIC AND WORKPLACE CHARGER HARDWARE COSTS

Public and workplace charging infrastructure hardware costs include the charger and its pedestal. The main cost drivers are the power of the unit, in kW; whether it requires a pedestal; and whether it is networked with communication or payment gathering capability. Table 2 summarizes the costs applied in this analysis, based on the average hardware costs from several studies[2] and manufacturer price quotes.[3] For calculations, we determine an average cost per charger by level and type including mounting pedestal across all quotes and studies. As shown, Level 2 per-charger costs are lower when there are dual chargers, rather than one charger, per pedestal. Adding networking to a charger more than doubles the cost of hardware. For DC fast charging, we use the single charger cost for all calculations. Costs are reported in 2019 dollars, and future-year hardware costs are assumed to decline over time at the rate of 3% per year.

Based on existing trends from our charging gap analysis, future workplace charging is assumed to be 15% Level 1 and 85% Level 2. Networking enables chargers to communicate by WiFi or cellular signal to report usage, charge customers, and collect payment information. These cost estimates are based on workplace Level 1 not being networked and 62% of workplace Level 2 being networked, corresponding to the percentage of workplace charging that is paid.[4] Public charging is assumed to be 80%

2 Avista Utility, "Docket No. UE-160082 – Avista Utilities Semi-Annual Report on Electric Vehicle Supply Equipment Pilot Program" (2018), https://www.utc.wa.gov/_layouts/15/CasesPublicWebsite/CaseItem.aspx?item=document&id=00044&year=2016&docketNumber=160082&resultSource=&page=&query=&refiners=&isModal=&omItem=false&doItem=false; Department of Energy, "Transportation Energy Futures Series, Alternative Fuel Infrastructure Expansion: Costs, Resources, Production Capacity and Retail Availability for Low-Carbon Scenarios" (2013), https://www.osti.gov/biblio/1079728-transportation-energy-futures-series-alternative-fuel-infrastructure-expansion-costs-resources-production-capacity-retail-availability-low-carbon-scenarios ; Pierre Ducharme and Catherine Kargas. *Feasibility of a Pan-Canadian Network of DC Fast Charging Stations for EVs,* (Electric Vehicle Symposium 29: Montréal, Québec, Canada, June 19–22, 2016), https://www.mdpi.com/2032-6653/8/1/1/pdf; Josh Agenbroad, "Pulling back the veil on EV charging station costs," Rocky Mountain Institute, accessed Jan 5, 2019, https://rmi.org/pulling-back-veil-ev-charging-station-costs/

3 "Commercial EVSE: Public, Fleet, Workplace Charging," ClipperCreek, accessed February 1, 2019, https://store.clippercreek.com/commercial ; "Smart charging stations," Chargepoint, accessed February, 1 2019, https://www.chargepoint.com/products/commercial/

4 Gil Tal, Jae Hyun Lee, and Michael Nicholas, Observed charging rates in California, (Research Report – UCD-ITS-WP-18-02, Institute of Transportation Studies: University of California, Davis, 2018), https://itspubs.ucdavis.edu/index.php/research/publications/publication-detail/?pub_id=2993

networked, and all fast charging is assumed to be networked, as these are typical practices. For Level 1 workplace chargers we assume 80% will be simply a wall outlet, but average costs presented above are for the 20% of dedicated Level 1 chargers.

PUBLIC AND WORKPLACE CHARGING INSTALLATION COSTS

Installation costs are composed of labor, materials, permits, taxes, and utility upgrades, as shown in Table 3. These are based on the most recent and detailed cost estimates among the various investigations into costs for nonresidential infrastructure.[5] Notably, the Electric Power Research Institute (EPRI) studied 637 sites with 1,294 Level 2 charging units, including disaggregated costs for labor, materials, permits, and taxes. The EPRI study also shows how per-charger costs decline as more chargers are installed per site (i.e., sites with 3-5 chargers, and those with over 6 chargers). Costs are further disaggregated by sites within California versus those in the rest of the country and are applied as such in this analysis. For our analysis, based on the EPRI study, we assume workplace charging costs are 10% below, and public Level 2 are 11% higher, than the average numbers shown in Table 3. Utility upgrades are included in the materials cost, based on upgrades incurred in southern California.[6] In practice, part of these utility upgrade costs may be covered by the utility company. Typically, a utility provides the customer an upgrade allowance, above which the customer pays for the remainder of the upgrade cost.

Table 3. Installation costs for Level 2 public and workplace charger, by chargers per site.

		1 charger per site	2 chargers per site	3-5 chargers per site	6+ chargers per site
California	**Labor**	$2,471	$1,786	$1,491	$1,747
	Materials	$1,235	$958	$1,014	$908
	Permit	$283	$172	$110	$65
	Tax	$156	$121	$128	$115
	Total	**$4,148**	**$3,039**	**$2,745**	**$2,837**
Outside California	**Labor**	$1,544	$1,827	$1,647	$1,316
	Materials	$1,112	$1,039	$1,272	$874
	Permit	$82	$62	$59	$38
	Tax	$96	$89	$110	$75
	Total	**$2,836**	**$3,020**	**$3,090**	**$2,305**

Our DC fast charger installation costs, shown in Table 4, are based two sources.[7] Data from the Rocky Mountain Institute study are used to estimate costs for 50-kW chargers, and data from Ribberink et al. are used to project how costs scale for multiple chargers per site and for higher power stations. Similar to Level 2 charging, installation costs per charger fall as more chargers are installed per site. Also, costs do not rise proportionally with power so a charger with triple the power does not result in triple the cost. Hence, installation costs are mainly a function of the number of chargers per site.

Table 4 highlights the role power and multi-charger sites play in determining per-charger installation costs. For example, at a site with one 50-kW charger, installation costs are approximately $45,000. Increasing the power by 7 times to 350 kW results in an installation cost of approximately $65,000, reflecting higher material cost and the probability that switchgear and distribution lines may need to be upgraded. Although we show an approximately $20,000 increase, this is highly variable and certain sites with 350 kW require very expensive upgrades whereas other sites require modest upgrades depending on factors related to charging site

5 Idaho National Laboratory, U.S. Department of Energy, Plug-in electric vehicle and infrastructure analysis (INL/EXT-15-35708), 2015, https://inldigitallibrary.inl.gov/sites/sti/sti/6799570.pdf; NC PEV Taskforce, “Plug-in electric vehicle (PEV) roadmap for North Carolina” (2013), http://www.pluginnc.com/wp-content/uploads/2016/06/7-NCPEVRoadmap_April2014_v2.pdf; Ducharme and Kargas, “Feasibility of a Pan-Canadian Network”; Avista, Semi-Annual Report on Electric Vehicle Supply Equipment Pilot Program; Electric Power Research Institute, “Electric Vehicle Supply Equipment Installed Cost Analysis” (December 2013), http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002000577

6 Based on upgrades incurred in the Southern California Edison territory, $36.99 is added to each Level 2 charging installation. See J.R. DeShazo, Overcoming Barriers to Electric Vehicle Charging in Multi-unit Dwellings: A Westside Cities Case Study, (2017), http://innovation.luskin.ucla.edu/sites/default/files/Overcoming%20Barriers%20to%20EV%20Charging%20in%20Multi-unit%20Dwellings%20-%20A%20Westside%20Cities%20Case%20Study.pdf

7 Hajo Ribberink, Larry Wilkens, Raed Abdullah, Matthew McGrath, and Mark Wojdan, “Impact of Clusters of DC Fast Charging Stations on the Electricity Distribution Grid in Ottawa, Canada,” (Electric Vehicle Symposium 30: Stuttgart, Germany, October 9–11, 2017); Agenbroad, “Pulling back the veil on EV charging station costs”, Rocky Mountain Institute, accessed Jan 5, 2019, https://rmi.org/pulling-back-veil-ev-charging-station-costs/

Table 4. Installation costs per DC fast charger by power level and chargers per site.

	50 kW				150 kW				350 kW			
	1 charger per site	2 chargers per site	3-5 charger per site	6-50 chargers per site	1 charger per site	2 chargers per site	3-5 chargers per site	6-20 chargers per site	1 charger per site	2 chargers per site	3-5 chargers per site	6-10 chargers per site
Labor	$19,200	$15,200	$11,200	$7,200	$20,160	$15,960	$11,760	$7,560	$27,840	$22,040	$16,240	$10,440
Materials	$26,000	$20,800	$15,600	$10,400	$27,300	$21,840	$16,380	$10,920	$37,700	$30,160	$22,620	$15,080
Permit	$200	$150	$100	$50	$210	$158	$105	$53	$290	$218	$145	$73
Taxes	$106	$85	$64	$42	$111	$89	$67	$45	$154	$123	$92	$62
Total	$45,506	$36,235	$26,964	$17,692	$47,781	$38,047	$28,312	$18,577	$65,984	$52,541	$39,097	$25,654

readiness and electrical equipment. Location flexibility is paramount in reducing these costs. There is generally a site limit of 2.5 megawatts of power before a step change in costs. Therefore, the maximum number of chargers per site is 50, 20, and 10 for 50-, 150-, and 350-kW chargers, respectively. Finally, we note that there are some costs that may not be included in the installation costs above including signage, striping, lighting, and security cameras.

Trends in the number of chargers per site allow us to estimate overall future charging developments based on the preceding per-charger cost examples. Recent data on chargers per site from U.S. metropolitan areas with greater electric vehicle uptake serve as a guide for smaller markets. To determine the relationship between electric vehicle market development and chargers per site, markets are first categorized and binned by the status of the electric vehicle market development by metropolitan area at the end of each year from 2014 through 2018. The market development bins are defined by the electric vehicles per million population, ranging from 6,000 (in low electric uptake markets) up to 40,000 (high uptake). Then the associated charger locations and number of chargers per site were analyzed by metropolitan area.[8] These sites are grouped into four categories—one, two, three to five, and six or more chargers per site—to match the categories analyzed above. In areas with low numbers of electric vehicles per million population, sites with six outlets or more are rare but can still account for a large portion of a metropolitan area's chargers.

Figure 1 shows a trend toward more chargers per site in markets with greater electric vehicle uptake. The horizontal axis shows the relative electric vehicle market development in vehicles per million resident population in bins. The vertical axis shows the percentage of chargers per site size category, based on the charger data for all the metropolitan areas in each bin. For example, the lowest level of market development analyzed is 6,000 electric vehicles per million population, where approximately 30% of charging outlets are at sites with two chargers, 30% are with 3–5 chargers, 30% are with 6 or more chargers, and the remaining 10% are at sites with just one charger. Most metropolitan areas fall in the lower bins and the 40,000 electric vehicles-per-million bin is represented by just one metropolitan area, San Jose, in 2018.

The implication of the trend shown in Figure 1, based on Table 3, is that as electric vehicle markets grow, the number of outlets per site increases, and the per-outlet cost drops. Cumulative sales in San Jose by the end of 2018 are what define the highest market penetration category, where there are 40,000 electric vehicles per million population, and 60% of total outlets are located at sites with six or more chargers. The lines in Figure 1 represent the natural log fit of these points (e.g., $y = 0.21 * \ln(x) - 1.57$ for six or more chargers per site), and the equations shown are applied to the infrastructure buildout cost analysis that follows in the cost scenario section.

Compared to Level 2 chargers, DC fast chargers do not show such a clear trend for chargers per site versus electric vehicles per capita. However, overall site size for new installations is growing year by year. To reflect a general increase in the number of chargers per site, we extrapolate the trend from 2014–2018 into the future. In 2018, the percentages of chargers at one, two, three to five, and six or more chargers per site were 11%, 20%, 17%, and 52%, respectively. The corresponding percentages for 2025 are 5%, 13%, 15% and 67%. These percentages are

8 Downloaded from Alternative Fuel Data Center (Alternative fuel stations - electric, Accessed Sept. 1, 2014; Jan 1, 2016; Jan 1, 2017; Jan 1, 2018; and Jan 1, 2019), https://afdc.energy.gov/data_download/

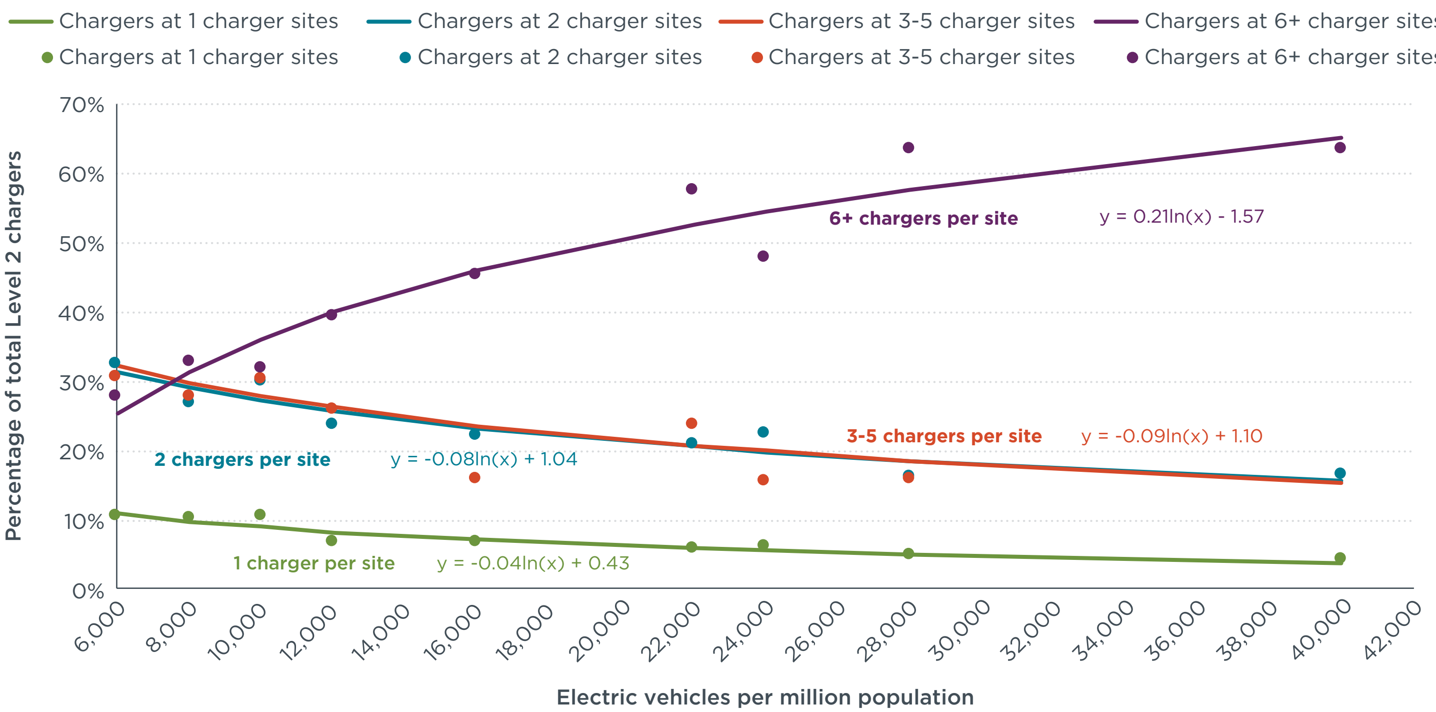

Figure 1. Percentage of public Level 2 chargers by site size as a function of electric vehicles per million population.

not applied as a function of market development, but rather by year across all metropolitan areas. We also assume the breakdown for the distribution of charger power is 44.4% for 50 kW, 44.4% for 150 kW, and 11.1% for 350 kW through our future year scenarios. This breakdown of DC fast chargers of varying power levels reflects our expectation of a continuing tradeoff between electric vehicle range and charger installation cost.[9]

HOME CHARGING HARDWARE AND INSTALLATION COSTS

Our charger cost analysis for home charging is similar to the previous discussion of public and home charging but accounts for varying cost by housing types. Home charging hardware and installation is typically less expensive than for public chargers. We separate the cost of home charging into charger level (Level 1 or Level 2) and housing type (detached house, attached house, and apartment). Hardware and installation costs are included, and installation is composed of labor, materials, taxes, utility upgrades, and permits. Some studies provide only installation cost, but not hardware costs, whereas others provide only hardware and installation costs combined.[10] We therefore represent the costs as combined costs for home charging estimates and average these across studies.

Average charger hardware plus installation costs applied to our analysis for 2019 are shown in Table 5. As

9 Wei Ji, Michael Nicholas, and Gil Tal, "Electric Vehicle Fast Charger Planning for Metropolitan Planning Organizations: Adapting to Changing Markets and Vehicle Technology," Transportation Research Record, 2015, 2502 (1): 134–143, https://doi.org/10.3141/2502-16; Michael Nicholas and Dale Hall, Lessons learned on early electric vehicle fast-charging deployments, (ICCT: Washington DC, 2018), https://www.theicct.org/publications/fast-charging-lessons-learned

10 Idaho National Laboratory, U.S. Department of Energy, Plug-in electric vehicle and infrastructure analysis; Electric Power Research Institute, "Electric Vehicle Supply Equipment Installed Cost Analysis"; NC PEV Taskforce, "Plug-in electric vehicle (PEV) roadmap for North Carolina"; California Air Resources Board, "California's advanced clean cars midterm review: Appendix B: Zero emission vehicles and plug-in hybrid electric vehicles" (California Environmental Protection Agency, Air Resources Board, 2017), https://www.arb.ca.gov/msprog/acc/acc-mtr.htm; California Air Resources Board, "California's advanced clean cars midterm review: Appendix D: Zero emission vehicle infrastructure status in California and Section 177 ZEV states" (California Environmental Protection Agency, Air Resources Board, 2017), https://www.arb.ca.gov/msprog/acc/acc-mtr.htm; DeShazo, Overcoming Barriers; Agenbroad, "Pulling back the veil on EV charging station costs."

shown, the costs vary depending on the electric vehicle home charging situation and the housing type. For the housing types, detached house signifies a house not connected to any others; attached house signifies a house with a shared wall of up to three housing units; and apartments are structures with more than 3 units. We use an average cost across all studies and apply a 3% per year reduction in hardware cost. To give examples of some of the underlying studies, the total installed costs ranged from $650 in the Rocky Mountain Institute study to $2,423 for a networked charger as assessed by Avista Utility. Higher costs for home charging upgrades generally correspond to a greater number of wall and floor penetrations, total circuit distance, or service upgrades. As indicated, attached homes and apartments typically are associated with higher cost upgrades.

Two types of upgrades are shown in Table 5: charger upgrades and outlet upgrades. Charger upgrades refer to new wiring and a charger, whereas outlet upgrades refer to only new wiring and a 120-volt wall outlet (Level 1) or a 240-volt dryer-type outlet (Level 2) with no additional charger. Most vehicle purchases come with a convenience charger that can be plugged into one or both of these outlet types and the convenience charger is not considered an additional infrastructure cost for this analysis. Categories of electric vehicle-owning households that have no additional home cost are also shown for context, as these are discussed in our overall average cost calculations.

The 3% per year hardware reduction is not shown, but as an example, total installed costs for a hardwired Level 2 unit in a detached house drop from $1,445 in 2019 to $1,317 by 2025 and from $4,061 to $3,933 in an apartment over the same period. Outlet upgrades do not decrease in cost over the analysis period. Average outlet upgrade and Level 2 charger installation costs in attached houses are not detailed in any study and are therefore assumed to be the average of apartment costs and costs in detached houses. The Table 5 costs by home charging category and housing type are applied across the U.S. metropolitan area data in the cost assessment that follows.

Table 5. Installation and hardware costs for home chargers by housing type.

Home charging category	Detached house	Attached house	Apartment
Level 1 outlet upgrade	$400	$500	$600
Level 1 charger upgrade	$700	$800	$900
Level 2 outlet upgrade	$680	$2,000	$3,300
Level 2 charger upgrade	$1,400	$2,800	$4,100

Cost scenarios

Costs are estimated for home, public, and workplace charging for approximately 2.6 million new electric vehicle sales in the 100 most populous U.S. metropolitan areas over the 2019–2025 period. In modeling the overall vehicle fleet, which accounts for vehicle retirement, this amounts to a stock increase of 2.3 million vehicles, and a total stock of 3.2 million electric vehicles in 2025 in the top 100 metropolitan areas. This represents 88% of the estimated 3.6 million electric vehicles on the road in the United States in 2025. The cost scenarios presented below are shown in terms of the aggregated costs for all the metropolitan areas combined and on a per-electric-vehicle-sold per year basis.

HOME CHARGING

Home charging is an important part of the charging ecosystem. Its associated cost to support new electric vehicle sales in the top 100 most populous metropolitan areas for the years 2019–2025 is analyzed here. We apply electric vehicle charging dynamics and sales across the metropolitan areas and the areas' housing stock as in our previous analysis[11] to provide a breakdown of electric vehicles by home charging category and housing type.

Our overall U.S. estimates for the number of electric vehicle sales from 2019–2025 in each type of home charging situation, and across housing types, are summarized in Table 6. There are seven home charging categories, two vehicle types (BEV and PHEV), and three housing types. The first row shows drivers who do not use home charging, primarily relying on workplace and public charging. Level 1 users are divided into those who have an existing outlet with no upgrades needed, those who install a new upgraded 120-volt household outlet for their electric vehicle, and those who install a dedicated Level 1 charger (charger upgrade). Level 2 home charging has categories similar to Level 1, but includes those with existing 240-volt dryer-type outlets and upgrades for new outlets and new dedicated chargers (charger upgrade). Ratios for determining the outlets and upgrades by charging level were determined from the results of a California Air Resources Board survey.[12]

The categories in Table 6 have two broad classifications—those that

11 Nicholas, Hall, and Lutsey, Quantifying the electric vehicle charging infrastructure gap.

12 California Air Resources Board, "California's advanced clean cars midterm review: Appendix B."

Table 6. California electric vehicle drivers by home charging category and housing type for 2019–2025.

Home charging category	Detached house PHEV	Detached house BEV	Attached house PHEV	Attached house BEV	Apartment PHEV	Apartment BEV	Totals
No home charging	124,429	67,272	46,129	30,467	102,185	89,171	**459,653**
Level 1 no upgrade	484,233	234,054	121,330	60,841	66,920	37,426	**1,004,803**
Level 1 outlet upgrade	36,228	18,606	6,709	4,824	5,905	3,364	**75,636**
Level 1 charger upgrade	8,296	10,927	2,236	4,020	3,543	3,154	**32,177**
Level 2 no upgrade	38,195	89,917					**128,112**
Level 2 outlet upgrade	48,644	180,114	12,281	44,473	5,200	16,212	**306,925**
Level 2 charger upgrade	132,960	312,477	23,026	43,375	12,712	27,731	**552,282**
Total	**872,985**	**913,367**	**211,712**	**188,001**	**196,465**	**177,058**	**2,559,588**

Note: BEV = battery electric vehicle, PHEV= plug-in hybrid electric vehicle

require electrical work and those that do not. As indicated, approximately 967,000, or 38%, of the 2.6 million electric vehicle owners are estimated to either need to install a dedicated charger or do an outlet upgrade. These include the four categories of Level 1 outlet upgrades, Level 2 outlet upgrades, Level 1 charger upgrades, and Level 2 charger upgrades. This also highlights that more than 1.1 million electric vehicle owners (or 44%) will use existing 120-volt or 240-volt outlets, and the remaining 18% either do not plug in or exclusively use workplace and public charging infrastructure.

In Figure 2, the data from Table 6 are represented graphically to show the fraction of electric vehicle drivers in our 2019–2025 analysis by home charging investments needed. The figure shows the percentage of electric vehicle drivers in three housing types (detached, attached homes, apartments) and home charging categories (No home charging, Level 1 home charging, and Level 2 home charging). The hashed bars indicate that there is no additional cost incurred for home charging for these drivers. For example, in the leftmost column, 70% of electric vehicle drivers in the analysis are in detached homes, and this includes 29% that are estimated to be complete home charging upgrades (26% Level 2 and 3% Level 1) and 41% without any upgrades. Electric vehicle buyers in attached houses and apartments are less likely to use home charging than those in detached houses, likely reflecting challenging installations and lack of control over upgrades.

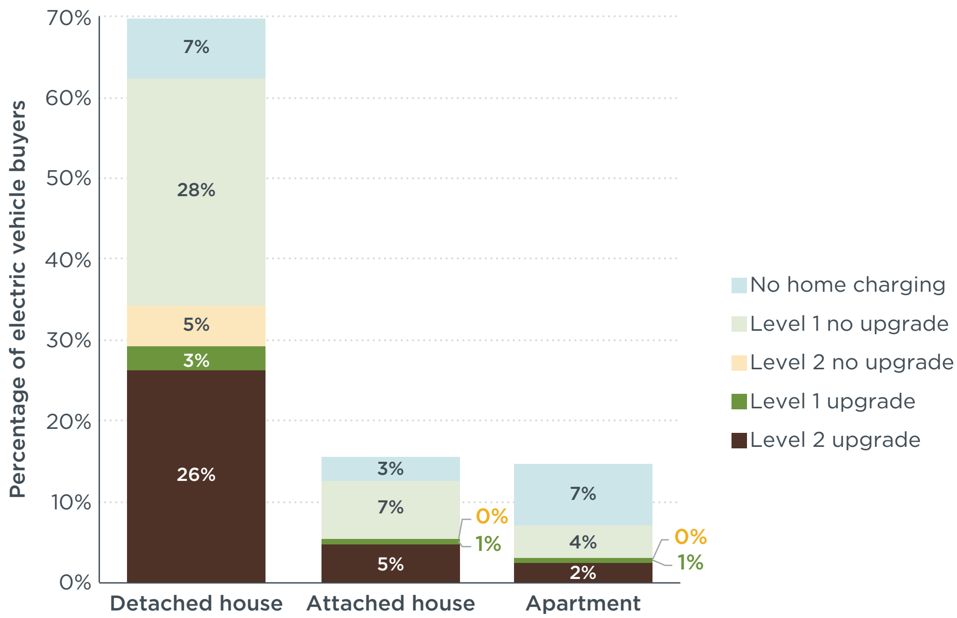

Figure 2. Percentage of new electric vehicle drivers by home charging access and upgrade.

Based on Figure 2 the majority of electric vehicle drivers will not be installing additional home infrastructure given current trends. Approximately 39% will simply use existing Level 1 (28% in detached houses, 7% in attached houses, and 4% in apartments), and 5% will use existing Level 2 charging (i.e., dryer outlet, largely in detached houses). The approximately 18% of all drivers not using home charging includes 5% of electric vehicle drivers rarely charging at all (primarily using PHEVs as hybrids) and the remainder relying on public and workplace charging.

Costs for the above electric vehicle driver, housing, and home charging calculations include the charging equipment costs from Table 5 and Table 6 for the 100 metropolitan areas.

The total cost for the 38% of customers assumed to undertake upgrades including upgraded outlets and installed chargers totals $1.3 billion. Averaged over all the new electric vehicle drivers, this represents $520 per new electric vehicle, decreasing from about $540 to $510 over the 2019–2025 period. A weighted average over only those electric vehicle drivers that had an upgrade at their residence results in $1,400 per vehicle. If costs are calculated separately for electric vehicles by housing type, and once again assigned only to those undergoing upgrades, we estimate $1,100 for those in detached houses, $2,100 for those in attached houses, and $3,100 for those in apartments.

PUBLIC AND WORKPLACE CHARGING

Total public and workplace charging infrastructure costs across the 100 metropolitan areas over the 2019–2025 period are estimated from the per-charger costs from Table 2, Table 3, and Table 4 and the distribution of outlets per site shown in Figure 1. Although overall costs are tallied based on the specific needs across the 100 areas, the results are presented here for all the areas combined to inform the overall charging infrastructure costs, the primary underlying cost components, and the costs on a per-electric-vehicle basis.

Figure 3 shows the overall 2019–2025 costs for workplace, public Level 2, and DC fast charging disaggregated by labor, materials, permits, taxes and hardware. The vertical axis shows the total costs for that charger category, which are approximately $190 million, $360 million, and $390 million for workplace, public Level 2, and DC fast, respectively. As indicated, hardware costs are the largest cost component in each case, representing 43%, 40%, and 68% of the total costs, respectively, for the three charging types. Workplace chargers and public Level 2 charger costs are similar in terms of the breakdown by cost component, but DC fast charging hardware is more expensive, especially for the highest power stations driving a relatively high hardware cost, as indicated on a per-charger basis in Table 2. Summing the costs by cost component, hardware costs are about $490 million, followed by labor at $230 million, materials at $190 million, taxes at $12 million, and permits at $9 million.

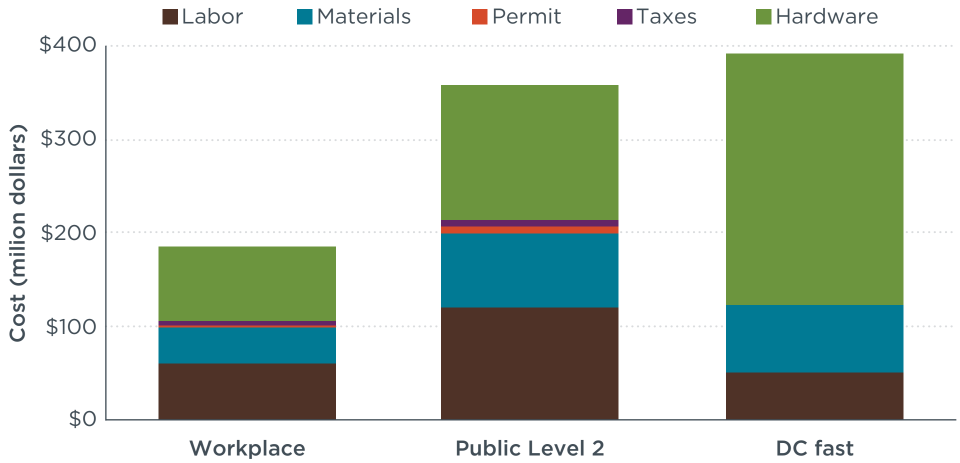

Figure 3. Workplace, public Level 2, and DC fast charger costs from 2019 through 2025.

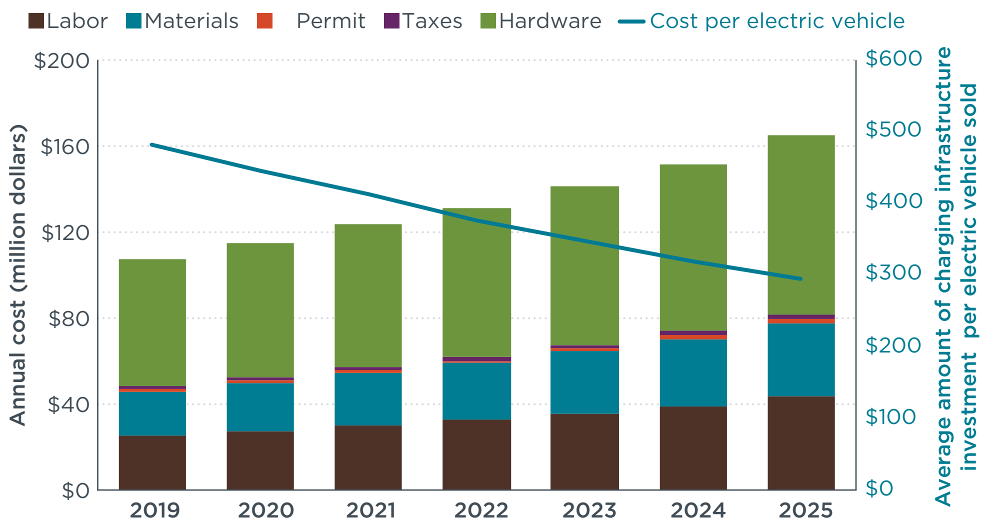

Figure 4. Total cost of public and workplace infrastructure and associated average aggregate charger cost per new electric vehicle sold for 2019 through 2025.

Figure 4 shows how annual charging infrastructure costs increase over time with higher electric vehicle sales volumes, and also how average charging costs for additional charging needed in each year decline on a per-electric-vehicle-sold basis. This decline is due to three factors. First, higher utilization of chargers, in terms of hours of active charging per day per charger, results in fewer chargers needed per electric vehicle. Second, installation costs decline as the number of chargers per site increases with growing market penetration. Third, we assume a 3% decline in per-charger hardware cost per year. The figure shows the installation and hardware costs increase from approximately $110 million to $165 million dollars in 2025. The blue line (right vertical axis) shows the average cost per electric vehicle, calculated by dividing public and workplace charging costs in each year by the number of electric vehicles sold in that year, and declines from $480 in 2019 to $300 in 2025.

To provide a more detailed understanding of how the charging infrastructure costs differ by electric vehicle type, Figure 5 shows the average cost of home and nonhome infrastructure separately for BEVs and PHEVs. The nonhome costs include workplace, public Level 2, and DC fast charging. The figure shows the average cost per new electric vehicle in the year sold and according to the year in which costs are incurred. Per BEV, the average home charger cost declines from $760 to $720 over 2019–2025, and the average nonhome charger cost declines from $690 to $420. Per PHEV, the average home charger cost declines from $320 to $300 over 2019–2025, and the average nonhome charger cost declines from $260 to $180. The BEV nonhome line includes DC fast charging cost whereas the PHEV nonhome line does not.

DC fast charging adds a significant cost to the average nonhome costs for BEVs. This is largely driven by the high cost of 150 kW and 350 kW hardware as shown in Table 2. Although a 3% cost reduction per year is applied to all nonhome charging hardware costs, the higher power DC fast charging hardware is relatively new and its cost may decrease faster as suppliers recoup development costs and move to higher production volume. Home costs are also greater for BEVs because more of the BEVs upgrade to Level 2 rather than use existing Level 1.

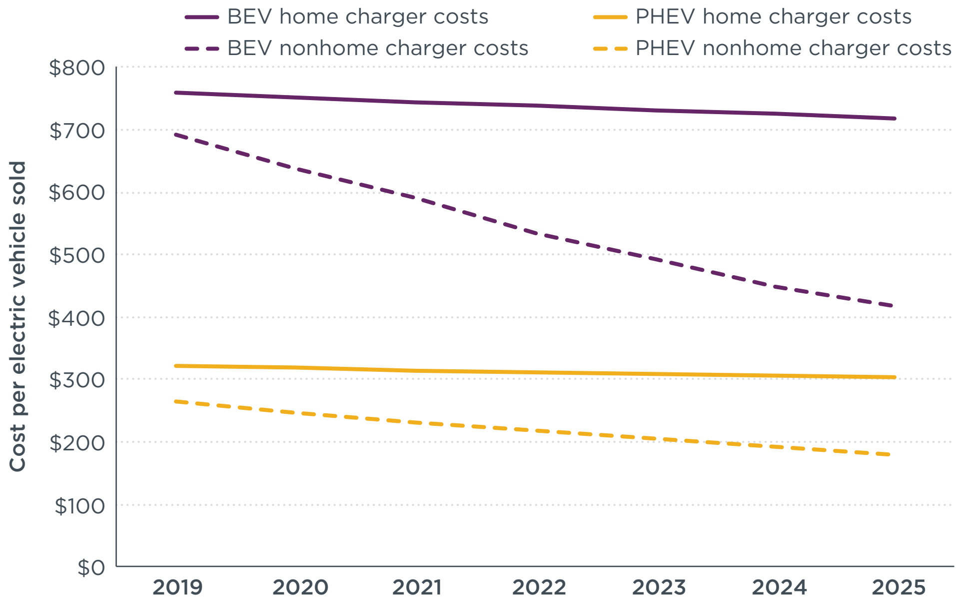

Figure 5. Average home and nonhome charger costs for BEVs and PHEVs.

Table 7. Summary of needed charging infrastructure and associated costs across 100 U.S. metropolitan areas over 2019–2025, by charging category.

Charging category	Chargers	Total 2019–2025 cost	Average 2019–2025 capital cost per charger
Home Level 1 no upgrade	1,005,000		
Home Level 1 outlet upgrade	76,000	$33 million	$440
Home Level 1 charger upgrade	32,000	$24 million	$735
Home Level 2 no upgrade	128,000		
Home Level 2 outlet upgrade	307,000	$339 million	$1,104
Home Level 2 charger upgrade	552,000	$948 million	$1,716
Workplace	48,000	$186 million	$3,880
Public Level 2	66,000	$359 million	$5,440
DC fast charging	5,000	$392 million	$81,818

Table 7 summarizes the total home, workplace, and public charging needed and the associated costs for the 2.6 million new electric vehicles in the 100 most populous U.S. metropolitan areas over 2019–2025. The home charging needs are shown by charging category (i.e., availability of Level 1 and Level 2) in the top six rows. Nonhome charging is shown in rows seven to nine. Counts refer to the number of new chargers in that category. As shown, the analysis finds that 5,000 DC fast, 66,000 public Level 2, 48,000 workplace, and 967,000 home charger upgrades will be needed from 2019–2025. In addition, within this analysis there are 1.1 million electric vehicle drivers who will use existing home charging outlets. Although not shown, there are another 460,000 electric vehicle drivers in this analysis who do not have home charging and will rely on public and workplace charging.

The costs in Table 7 show the relative contributions of the various charging types to the overall charging infrastructure costs for the major U.S. electric vehicle markets. The home charging costs ultimately result in more than half of the overall costs ($1.3 billion of $2.3 billion), followed by DC fast charging ($392 million), public Level 2 ($359 million), and workplace charging ($186 million). As indicated by the far right column, the average cost per charger is much higher for the DC fast charging ($81,818), followed by public Level 2 ($5,440), workplace ($3,880), and various home charging types. Home charging costs are a weighted average across housing types, and cost differences for those housing types are detailed in Table 5. Nonhome charging costs are similarly averaged across all years and metropolitan areas. This summary reinforces that there is a significant number of new electric vehicle buyers who will not need home upgrades.

In addition to the preceding summary analysis, similar results for two specific metropolitan areas are provided as examples of underlying analysis on charging infrastructure needs and the associated costs evaluated across the 100 metropolitan areas. Table 8 summarizes the home, workplace, public, and DC fast chargers needed over 2019–2025 and the associated estimated charger costs for the Portland and San Francisco metropolitan areas. These two examples are chosen because they represent large and growing electric vehicle markets and also are areas where there are many utility, state policy, and city activities to actively fill the charging needs.

Table 8. Example results for amount of needed charging infrastructure and associated costs over 2019–2025 by charging category for two metropolitan areas.

Charging category	Portland area: Charger outlets	Portland area: Total 2019–2025 cost	San Francisco area: Charger outlets	San Francisco area: Total 2019–2025 cost
Home Level 1 no upgrade	29,000		90,000	
Home Level 1 outlet upgrade	2,000	$1 million	7,000	$3 million
Home Level 1 charger upgrade	1,000	$1 million	3,000	$2 million
Home Level 2 no upgrade	5,000		13,000	
Home Level 2 outlet upgrade	10,000	$10 million	32,000	$37 million
Home Level 2 charger upgrade	19,000	$32 million	57,000	$101 million
Workplace	1,600	$6 million	4,300	$17 million
Public Level 2	2,000	$10 million	5,400	$30 million
DC fast charging	160	$13 million	440	$36 million

Note: Metropolitan areas are the core-based statistical areas and represent populations of approximately 2.5 million residents in the Portland area and 4.7 million in the San Francisco area.

In the Portland area, our scenario has the total electric vehicle stock increasing by 75,000 electric vehicles from 2019–2025. As shown in Table 8, the associated Portland area charging costs for home, DC fast, public Level 2, and workplace charging are $43 million, $13 million, $10 million, and $6 million, respectively. In the San Francisco area, our scenario has the total electric vehicles increasing by 220,000 vehicles from 2019 to the end of 2025. The respective San Francisco area home, DC fast, public Level 2, and workplace charging costs are $143 million, $36 million, $30 million, and $17 million, respectively. These two cases provide examples and local-level context for the level of investment this analysis implies for electric vehicle owners, electric utilities, governments, and private charging providers.

Conclusions

In this analysis, we evaluate the capital costs, including installation and hardware, for a scenario with 2.6 million new electric vehicle sales in the top 100 U.S. metropolitan areas over the 2019–2025 period. Our basic findings here are that home charging costs to support these electric vehicles total $1.3 billion, whereas new workplace, public Level 2, and DC fast charging costs total $940 million.

The home and public charging costs analyzed here exclude several major aspects of a comprehensive charging ecosystem. This analysis excludes the necessary charging infrastructure for fast-charging corridors to link cities, which has been the early focus of some auto industry efforts.[13] The 100 metropolitan areas analyzed here represent 88% of all new electric vehicles sold and 75% of the overall U.S. vehicle market, but smaller markets are outside the scope of this analysis. Also excluded from this analysis are the project management and land-related costs, which can be highly variable and location-specific. Finally, charging infrastructure for the potential increased electrification of ride-hailing services is not included in these cost estimates. Nonetheless, the estimates provided here are important to provide capital cost estimates to inform the scale of infrastructure investment needed in major markets.

We also note that investments are underway for substantial fractions of the necessary charging buildout. Electric utility charging infrastructure activities are proliferating and

13 For example see "Charge on the Road," Tesla, accessed June 11, 2019, https://www.tesla.com/supercharger; "About Ionity," Ionity, accessed June 11, 2019, https://ionity.eu/en/about.html; General Motors, "General Motors to collaborate with EVgo, ChargePoint and Greenlots to enhance the charging experience for customers," news release January 9, 2019, https://media.gm.com/media/us/en/gm/home.detail.html/content/Pages/news/us/en/2019/jan/0109-charging.html

increasingly including direct support for infrastructure to partially fill charging gaps.[14] For example, three California utilities received approvals in 2018 to invest $738 million in charging infrastructure although some of it is dedicated to heavy duty vehicle infrastructure and items outside the scope of this report.[15] Volkswagen dieselgate settlement funds are also substantial. Volkswagen's Electrify America funding has allocated $360 million for fast charging corridors, $330 million for public and workplace charging, and $14 million for home charging.[16] In addition, up to 15% of the settlement's $2.7 billion environmental mitigation funding can be spent by states on charging infrastructure.[17]

However, this analysis of charging indicates there remains a need for charging infrastructure funding to support electric vehicle growth trends in the United States through 2025. We make the following conclusions regarding our analysis of electric vehicle charging infrastructure costs in the 100 most populous U.S. metropolitan areas.

Substantial charging infrastructure investments are needed to fill the charging gap. Our findings indicate that, to serve the growing electric vehicle market, necessary investments in workplace, public Level 2, and DC fast charging infrastructure would increase from approximately $110 million in 2019 to $270 million in 2025, amounting to a total of about $940 million. In addition, home charging investments of $1.3 billion are needed, largely for the upgrades and installation of Level 2 charging in houses and apartment buildings. These charging infrastructure costs are approximately 25% for hardware, 50% for labor, 20% for materials, and 5% for permits.

Infrastructure costs are relatively modest—and steadily decrease—on a per-electric-vehicle basis. Costs for public charging infrastructure decrease substantially on a per-electric-vehicle basis. This is due to public chargers becoming more heavily utilized, the shift to more outlets per charging site, and decreased hardware costs as the market grows. The result is that the total public infrastructure costs per electric vehicle decline from $480 per electric vehicle in 2019 to $300 in 2025. Averaged over all electric vehicles, some of which need home charging upgrades, home infrastructure costs are around $510–$540 per electric vehicle sold.

Investing in home charging will remain important. More than half of electric vehicle owners are expected to continue using their existing home charging options without home upgrades. Around 38% of electric vehicle owners are expected to have upgrades to improve their home charging, with an average cost of $1,400 to install home outlets or chargers. However, this average includes charging costs that are typically much higher in apartments. Incentives such as off-peak electricity rates and smart charging could remain important as the market expands to ensure more charging at apartment complexes and ensure home charging is mutually beneficial to drivers and utilities. Although many will utilize Level 1 charging with existing 120-volt outlets, higher power Level 2 charging at home will become increasingly important as battery size and vehicle range increase.

Based on these findings, charging infrastructure buildout is a strong candidate for large-scale federal funding. Although state-level utility support is growing, city and state funding for charging is generally limited. Cost-sharing federal and local funding would help leverage limited funding to help fill the charging gap and allow local authorities to align the federal support with their own action plans. Federal grants, perhaps directed at cities that demonstrate high electric vehicle uptake, comprehensive electric vehicle action plans, and city policies (e.g., streamlined infrastructure permitting, aggressive electric vehicle-ready building codes) could also be effective.

Many related questions remain. These charging infrastructure costs, clearly substantial, are presented here in the absence of vehicle electrification benefits. Follow-on analysis of how electric vehicle costs decline and fuel-saving and emission benefits increase, would likely show a strongly positive case for charging infrastructure investments.[18] Determining the lowest-cost pathways for a sufficient charging ecosystem will require persistent tracking of developments with electric vehicle charging speeds, electric range, charging preferences, and charger utilization. Finally, if the electrification of ride-hailing fleets were to ramp up, this would greatly increase the need for charging infrastructure investments.

14 Smart Electric Power Alliance, "Utilities and electric vehicles: Evolving to unlock grid value," (March, 2018), https://sepapower.org/resource/utilities-electric-vehicles-evolving-unlock-grid-value/

15 Decision on the transportation electrification standard review projects, California Public Utility Commission May 31, 2018, http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M215/K380/215380424.PDF

16 The Electrify America funds are referred to as "Appendix C" funds per the settlement. "Our Investment Plan," Electrify America, accessed April 25, 2019, https://www.electrifyamerica.com/our-plan

17 These are "Appendix D" environmental mitigation funds. See U.S. District Court, Northern District of California, San Francisco Division, Case No: MDL No. 2672 CRB (JSC), Third Partial and 3.0L Second Partial and 2.0L Partial and Amended Consent Decree, retrieved from https://www.epa.gov/enforcement/third-partial-and-30l-second-partial-and-20l-partial-and-amended-consent-decree

18 Previous analysis with much higher electric vehicle costs than today indicated as much, with benefits many times greater than the infrastructure costs. See National Research Council, Transitions to Alternative Vehicles and Fuels (Washington, DC: The National Academies Press, 2013), https://doi.org/10.17226/18264.