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QUANTIFYING THE ELECTRIC VEHICLE CHARGING INFRASTRUCTURE GAP ACROSS U.S. MARKETS

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EXECUTIVE SUMMARY

The electrification of the United States vehicle market continues, with the most growth occurring in markets where barriers are addressed through policy, charging infrastructure, and consumer incentives. Key questions about electric vehicle market growth include how much charging infrastructure will be needed to sustain growth and whether to invest in various types of this infrastructure.

This report quantifies the gap in charging infrastructure from what was deployed through 2017 to what is needed to power more than 3 million expected electric vehicles by 2025, consistent with automaker, policy, and underlying market trends. Based on the expected growth across the 100 most populous U.S. metropolitan areas, we estimate the amount of charging of various types that will be needed to power these vehicles. Our evaluation of charging needs is based on best available observed data on the growing electric vehicle market, charging availability, and emerging charging behavior patterns.

Figure ES-1 illustrates the deployment of public and workplace charging infrastructure through 2017 as a percentage of what will be needed by 2025 across the 100 most populous U.S. metropolitan areas (the 50 most populous are labeled). Shades of red indicate that less than 50% of the needed charging has been installed through the end of 2017, while blues indicate that more than 50% of charging needed in 2025 was in place by 2017. Of the 100 areas, 88 had less than half of the total needed charging infrastructure in place, based on their expected electric vehicle growth.

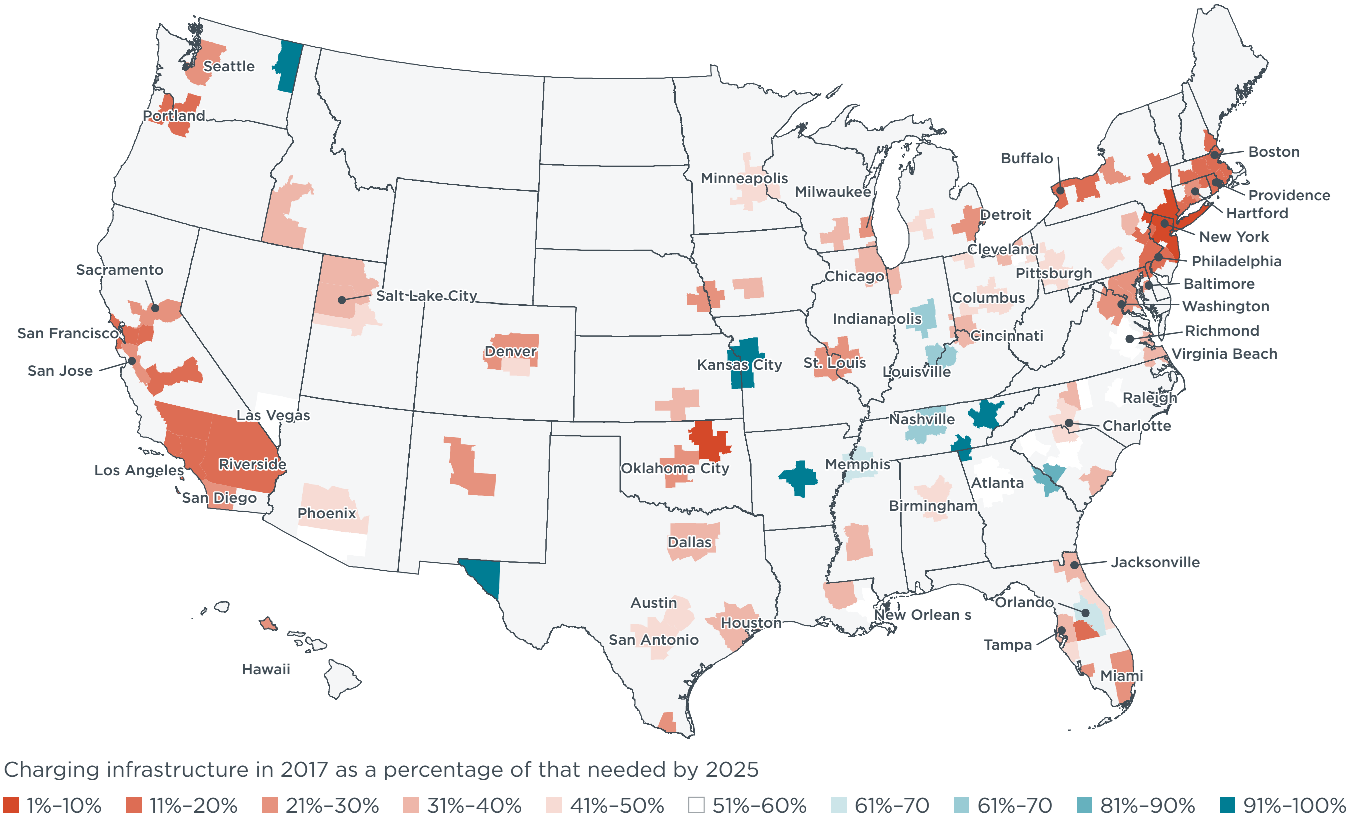

Figure ES-1. Public and workplace charging infrastructure in place in 2017 as a percentage of infrastructure needed by 2025 by metropolitan area

The widespread distribution of electricity offers the potential for highly convenient charging of electric vehicles if the right ecosystem of charging outlets is matched to complex driver charging behavior. While the vast majority of electric vehicle charging is and will continue to be at home, public and workplace charging options allow drivers to take advantage of the times and places where electric vehicles are parked. Our analysis leads us to three high-level conclusions.

> ***Much more charging infrastructure is needed to sustain the transition to electric vehicles.*** Across major U.S. markets through 2017, about one-fourth of the workplace and public chargers needed by 2025 are in place. Charging infrastructure deployment will have to grow at about 20% per year to meet the 2025 targets identified in this report. The largest charging gaps are in markets where electric vehicle uptake will grow most rapidly, including in many California cities, Boston, New York, Portland, Denver, and Washington, D.C.
>
> ***Planned infrastructure deployment activities are promising, but uneven***. There are many government and industry developments underway to deploy the necessary charging infrastructure, and electric utilities are especially positioned to support this infrastructure deployment. In California and other Zero Emission Vehicle markets, announced measures and planned installations are slated to fill the charging gaps, but such utility and government efforts are largely absent in much of the country. Cities, states, automakers, and utilities with electric vehicle growth ambitions can learn from these leading markets to fill the charging gaps. Our analysis provides motivation for more policy and more industry investment to expand charging infrastructure in nearly every major U.S. metropolitan area.
>
> ***Increased charger utilization brings infrastructure investment opportunities***. Across U.S. markets where the most charging is needed by 2025, automaker commitments to deploy electric vehicles and the Zero Emission Vehicle regulation virtually assure increasing electric vehicle uptake. In addition, market expansion, economies of scale, and improved charging technologies will promote higher utilization of chargers. The number of electric vehicles supported by each charger is anticipated to increase by 35% for public Level 2 and 65% for fast chargers by 2025. This analysis suggests that automakers, utilities, and charging providers in many U.S. cities could make low-risk, high-utilization investments to meet the needs of expected electric vehicle deployments.

This analysis provides a reference for the charging infrastructure needs for a growing electric vehicle market in the United States, including detailed estimates of the amount of each type of charging needed at a metropolitan-area level. The broader conclusion is that, despite the many uncertainties, there will be attractive opportunities for the foreseeable future to deploy charging infrastructure to power a growing electric vehicle fleet. As the electric vehicle market expands, sustained policy and collaboration among government and private industry players is needed. To this end, leading markets are already deeply engaged and serving as models. Although much work remains, progress toward the charging infrastructure system of the future is well underway.

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I. INTRODUCTION

Modern plug-in electric vehicles were introduced in 2010, and their cumulative U.S. sales surpassed 1 million units in 2018, joining China and Europe as the only markets to pass that milestone. National, state, and local governments have promoted electric vehicles with a diverse mix of policies to meet air quality, climate, and energy security goals. Although new models are steadily entering the market and battery costs continue to decrease, electric vehicles still face a number of barriers to mainstream adoption, including affordability, awareness, availability, and convenience. Widespread charging infrastructure is a key to overcoming these barriers and growing the electric vehicle market.

As the electric vehicle market continues to grow and evolve, so too does the charging infrastructure to support it. New electric vehicle models, including fully battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), which have a gasoline engine to power the vehicle when the battery is depleted, are being introduced with longer range and the ability to charge faster. The customers buying the vehicles are changing as well. Whereas early adopters were primarily commuters with garages and home charging, more public charging will be needed to serve a broadening market with less access to home charging.

This paper evaluates the necessary charging infrastructure to align with the electric vehicle penetration scenarios through 2025. The analysis relies on an examination of deployed charging infrastructure across U.S. markets through 2017. Before describing our approach, we first introduce the various charging types and their characteristics based on their typical locations, as applicable to our analysis. We then describe some existing analytical approaches to modeling charging needs as background to our own analysis.

BACKGROUND ON CHARGING INFRASTRUCTURE IN THE UNITED STATES

Table 1 summarizes basic information regarding the different levels of electric vehicle supply equipment (EVSE), their voltage, power, specifications, and typical number of electric miles they are capable of delivering to electric vehicles. These definitions are used throughout the paper. Throughout, we assume that home and workplace charging will be done with Level 1 and Level 2 EVSE, while public charging will generally take place on Level 2 and direct current (DC) fast chargers.

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

Charging level	Voltage	Protection type	Typical power	Electric vehicle miles of range per hour	Setting
Level 1	120 V AC	None or breaker in cable	1.2–1.4 kW AC	3–4 miles	Primarily home and some workplace
Level 2	208 V–240 V AC	Pilot function and breaker in hardwired charging station	3.3–6.6 kW AC	10–20 miles	Home, workplace, and public with hardwired station
DC fast	400 V–1,000 V DC	Monitoring and communication between vehicle and EVSE	50 kW or more	150 –1,000 miles	Public, frequently intercity

AC = alternating current; DC = direct current; EVSE = electric vehicle supply equipment; kW = kilowatt; V = volt

Public charging infrastructure in the United States has grown from approximately 6,900 workplace, public, and DC fast chargers nationally in 2012 to about 61,000 by the end of 2017. Of the total U.S. workplace and public chargers, about 74% were in the 100 most populous metropolitan areas, which are the primary focus of this analysis. Within these 100 metropolitan areas, there were approximately 11,400 workplace outlets, 30,700 public Level 2 outlets, and 3,400 DC fast charging stations (based on data from Plugshare, 2018). The year-over-year increase in charging stations from 2016 to 2017 for these three categories was 35%, 39%, and 46%, respectively.

A number of players have been influential in building the electric vehicle charging infrastructure to date. The Electric Vehicle Project from the Department of Energy was responsible for installing much of the early charging infrastructure through 2013. Many of the largest initiatives as of 2018, in California and increasingly elsewhere, are led by electric utilities, usually in cooperation with charging service providers. Going forward, investments from Electrify America, as part of Volkswagen's settlement for its diesel emission violations, will also significantly grow the charging network across the country, particularly for fast charging stations.

The existing deployment of infrastructure in the United States gives insight into how this infrastructure is growing as a function of market penetration of electric vehicles. Earlier work shows how electric vehicle uptake increases with public and workplace charging per capita (Slowik & Lutsey, 2018). Work on fast charging shows how early deployments had lower concentrations of BEVs per DC fast charger, whereas in later markets each fast charger was able to support more BEVs (Nicholas & Hall, 2018).

RELATED CHARGING INFRASTRUCTURE ANALYSES

Several organizations have created analytical models for charging infrastructure planning in different contexts. One example is the Electric Vehicle Infrastructure Projection Tool (EVI-Pro) developed by the the National Renewable Energy Laboratory in collaboration with the California Energy Commission. EVI-Pro uses travel pattern simulations to determine the necessary amount and ideal types of locations for charging stations on a regional basis. This model serves as the basis for several applications, including a U.S. national infrastructure analysis (Wood, Rames, Muratori, Raghavan, & Melaina, 2017), state level planning analyses for California (California Energy Commission, 2018), and the EVI-Pro Lite public online tool. M.J. Bradley & Associates (2018) and the Georgetown Climate Center created a GIS-based charging infrastructure planning tool to identify optimal locations for charging infrastructure in the U.S. Northeast, focusing on corridor fast charging.

Other models assess other aspects of charging infrastructure, including workplace charging and the relative gap in necessary charging to support electric vehicle market growth. The University of California, Davis (2015) created the GIS Infrastructure Planning Toolbox to estimate the market distribution of electric vehicles and site workplace and fast charging in California at a highly spatially resolved level. Another GIS-based tool created by the Joint Research Centre of the European Commission determines optimal charging allocation at local and regional levels (e.g., Gkatzoflias et al., 2016). The Red Line/Blue Line model created by the Electric Power Research Institute (2014) calculates the number and locations of public and workplace charging stations to enable additional electric vehicle miles traveled, and this model has been used to assess the further charging infrastructure investments needed (Cooper & Schefter, 2017). Electrify America identifies a "supply-demand gap" based on driver behavior analysis at a metropolitan area level (Electrify America, 2018).

These analyses use different approaches with different objectives; to date, there has been no clear, long-term assessment of the amount of charging needed with practical specificity. As electric vehicle sales continue to grow, many public and private groups are trying to plan the necessary charging infrastructure. Although uncertainty remains around the ratio of vehicles to chargers that will ultimately support the expected fleet, governments and private industry charging providers need clear and specific estimates to provide needed charging infrastructure.

In this paper, we create a metropolitan area-level model to estimate the needed growth in the charging infrastructure. We do so by using realistic expected electric vehicle growth rates and applying charging assumptions based on observed charging behavior, and doing so consistently across metropolitan areas. We quantify the amount of charging infrastructure required to serve the growing U.S. electric vehicle market at a local level through 2025. Section II discusses the analytical methodology behind the charging gap analysis, including the analysis of each market's electric vehicle and charging infrastructure baseline in 2017, assessment of existing charging by metropolitan area, the evolution of vehicle to charging ratios, and the shift beyond early adopters. Section III presents key findings of the work in terms of the charge points of different types needed by metropolitan area and a relative progress report for 2017 charging versus 2020 and 2025 charging needs. Section IV offers a discussion of policy-related conclusions from the analysis.

II. ASSESSING CHARGING INFRASTRUCTURE NEEDS

This section describes the steps for our analysis of future needs for charging infrastructure and the growing gap through 2025. We estimate the charging infrastructure needed to serve future electric vehicle market growth, basing charging patterns on observed driver behavior in the context of an expanding and evolving market. An analytical, Python-based model translates vehicle uptake, local demographic data, and charging behavior data into public and workplace charging infrastructure needs for the years 2018 through 2025.

Figure 1 illustrates how the model generates charging infrastructure estimates for each metropolitan area in a given year. The primary steps in the analysis are shown in blue boxes moving from top-left to bottom-right. The gray ovals contain the questions that are sequentially answered at each step, moving from vehicles, to drivers by housing type, to required charging energy needed, to time spent charging, to necessary charging by activity and location. Each step is discussed in more detail below. The yellow trapezoids indicate the data inputs and assumptions required to calculate each step. The driver "groups" referred to in the chart are distinguished by their vehicle type, their access to home charging, and their need for and access to workplace charging. "Activity" in the chart refers to charging at home, charging while working (or long-term away-from-home charging), public Level 2 charging, and DC fast charging. "Location" refers to private residential, private workplace, public Level 2, and public DC fast.

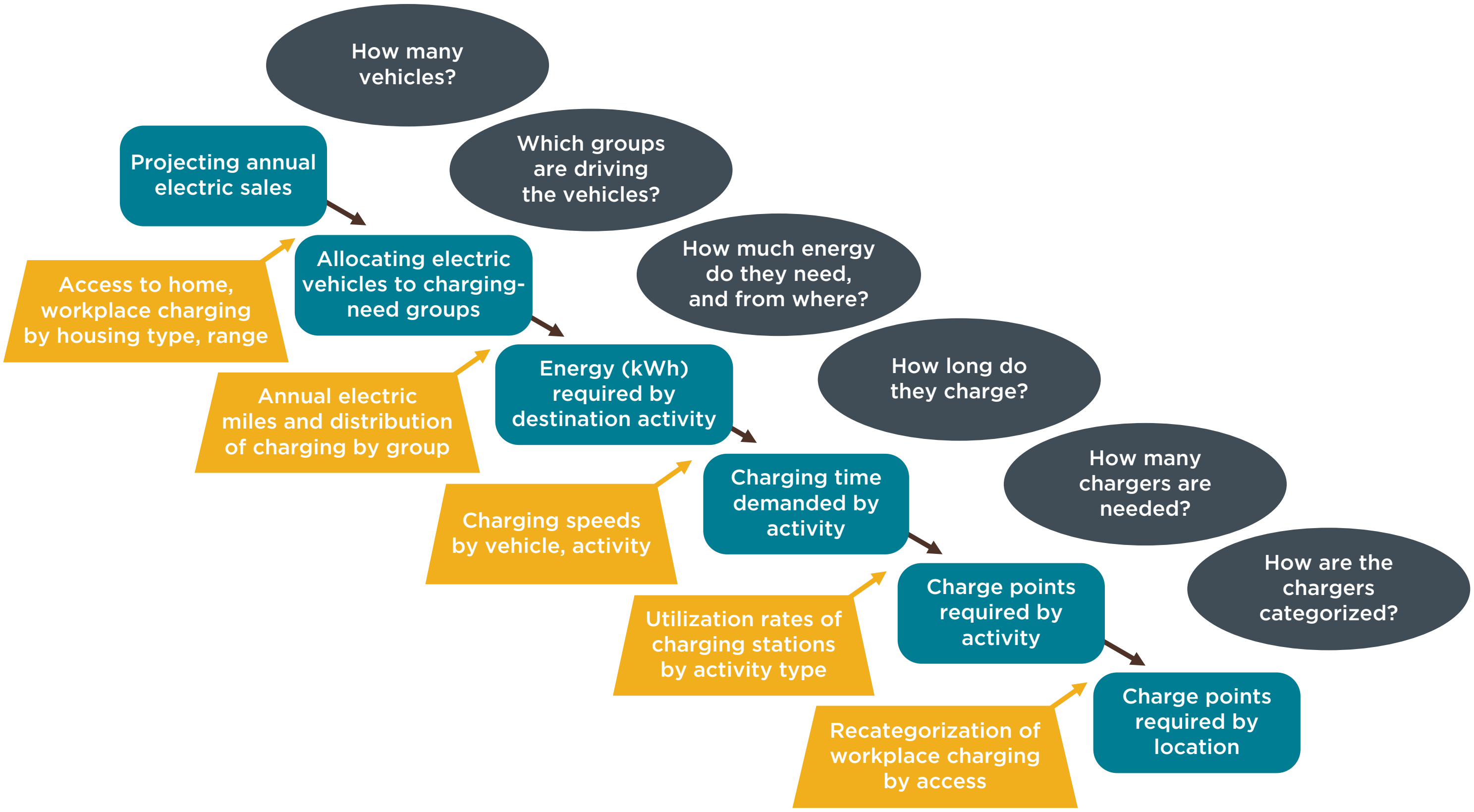


Figure 1. Illustration of underlying model processes to determine future electric vehicle charging infrastructure needs

The steps of the analysis draw from many data sources. Table 2 summarizes the primary data sources used in this analysis. The analysis builds upon recent research about charging infrastructure and the growth in the U.S. electric vehicle market (Hall & Lutsey, 2017; Slowik & Lutsey, 2018; Nicholas & Hall, 2018; Lutsey, 2018a). We draw on two commercially purchased datasets: baseline charging infrastructure by metropolitan area from PlugShare (2018) and vehicle registrations from IHS Markit (2018). Data from Tal, Lee, & Nicholas (2018), including self-reported electric vehicle charging behavior from more than 2,800 electric vehicle drivers in California in 2017, was critical for our characterization of electric vehicle driver use of charging infrastructure by electric vehicle type, charging type, and location. As shown, several other data sources were used to vary charging estimates by metropolitan area and to help validate basic relationships regarding electric vehicles, charging equipment, population, housing, and vehicle-miles traveled.

Table 2. Data sources supporting underlying assumptions for this analysis

Data area	Variables	Source
Metropolitan area statistics	Core-based statistical area, focus on highest population areas	United States Census Bureau, 2018a
Demographics	Residential charging availability	United States Census Bureau, 2018b California Air Resources Board (CARB), 2017a
Baseline 2017 electric vehicle market by metropolitan area	Registrations and shares of new electric vehicles, including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)	Slowik & Lutsey, 2018 IHS Markit, 2018
Baseline 2017 charging infrastructure	Charging outlet counts by metropolitan area, including by charge type and location (e.g., public and workplace)	PlugShare, 2018
Charging infrastructure to electric vehicle relationships	Ratios of electric vehicle to charge point, based on market size and/or electric share	Nicholas & Hall, 2018 Hall & Lutsey, 2017
Charging behavior	Observed rates of charging for residential, workplace, public and DC fast chargers	Nicholas, Tal, & Turrentine, 2017 Nicholas & Hall, 2018 Tal et al., 2018
Planned future deployment of charging infrastructure	Announced charging deployment plan	Electrify America, 2017b, 2017c; 2018 Utility investment plans (multiple)
Future electric vehicle deployment	Minimum compliance with existing vehicle policies	CARB, 2017 Lutsey, 2018a
Commute data	Commute distribution by metropolitan area	LEHD Origin Destination Employment Statistics (LODES), United States Census Bureau, 2018b
Travel behavior	Annual mileage, commute distance, vehicle information	National Household Travel Survey (NHTS) United States Department of Transportation (DOT) 2017

ELECTRIC VEHICLE SALES PROJECTIONS

Electric vehicle sales in the United States grew substantially between 2010 and 2017. A major driver behind the growth has been the Zero Emission Vehicle (ZEV) regulation, adopted by California and nine other states, along with the many complementary local actions in the adopting states. In California, 5% of new vehicle sales were electric in 2017, compared with 1.2% in other ZEV markets, and 0.6% in the rest of the country.

ZEV markets account for two-thirds of U.S. electric vehicles (Lutsey, 2018a). Moreover, automaker commitments to electrify are now surpassing requirements for plug-in electric vehicles, as technology and market developments allow for greater-than-required electric vehicle deployment. Plug-in electric vehicle announcements by many major automakers indicate that electric vehicles could make up 10% to 15% of new vehicle sales globally by 2025 (Lutsey, 2018b).

In 2017, there were more than 190,000 new electric vehicle sales across the United States, with a national average of 1.2% electric share; however, the 50 largest metropolitan areas saw over 150,000 new electric vehicles and a 1.6% electric share (Slowik & Lutsey, 2018). The metropolitan areas with the highest electric shares were San Jose with 13% and San Francisco with 7%. Many markets in ZEV states in the Northeast and Oregon had 2%–3% shares, as did areas in Washington state and Colorado. The highest number of new 2017 vehicle registrations outside California, in order, were the metropolitan areas of New York City, Seattle, Washington, D.C., Boston, and Chicago.

To go from the actual 2017 electric vehicle market to our assumed electric vehicle stock in 2025, the primary assumption is that the fleet follows recent trends including compliance with existing regulations. To do so, we apply three broad regional trends: California, non-California ZEV markets, and non-ZEV markets. For California, we assume that the industry exceeds minimum compliance for the ZEV regulation, moving from 5% in 2017 to 15% electric share of new vehicles in 2025. There are some indications of strengthening future policy (e.g., Office of Governor Brown, 2018), but these are not analyzed. For the non-California ZEV states, we assume that the industry minimally complies with the ZEV regulation, increasing from 1.2% in 2017 to 9% electric vehicle share in 2025 (CARB, 2017a). For markets outside the ZEV states, we assume a general incremental trend from 0.6% in 2017 to 1.4% in 2025 considering no more ZEV uptake is needed to comply with national or state regulations. These are the broader trends, but the extent to which each area is above or below that trend in 2017 is retained into the future (e.g., San Jose remains 2.5 times the California average share). As for the more general auto market trend, we assume 1% growth in annual light-duty vehicle registrations in all metropolitan areas.

Figure 2 shows how electric vehicles accumulate in the fleet over time based on our uptake scenario. Electric vehicles in the United States increase from about 730,000 at the end of 2017 to 3.6 million at the end of 2025. Of these 3.6 million, about 3.2 million, or 88%, of the U.S. electric vehicles in 2025 are expected to be in the 100 most populous metropolitan areas that are the focus of this analysis. The three underlying trends are highlighted for California (green), non-California ZEV markets (blue), and other markets (yellow). The figure also names the 20 highest electric vehicle uptake metropolitan areas, including six in California, five in other ZEV markets, and nine in non-ZEV markets. To account for vehicle retirement, we assume that vehicles retire from the fleet at an increasing rate as they age and have a 14 year median vehicle lifetime (Bento, Roth, & Zuo, 2016; Oak Ridge National Laboratory, 2017). The total number of electric vehicles in California in 2025 is 1.6 million, or about 4.5 times as many as in 2017. Electric vehicles in the non-California ZEV states increase by a factor of 9 from 2017 to surpass 950,000 in 2025. Overall, this scenario equates to plug-in electric vehicles making up 4% of new U.S. vehicle sales in 2025.

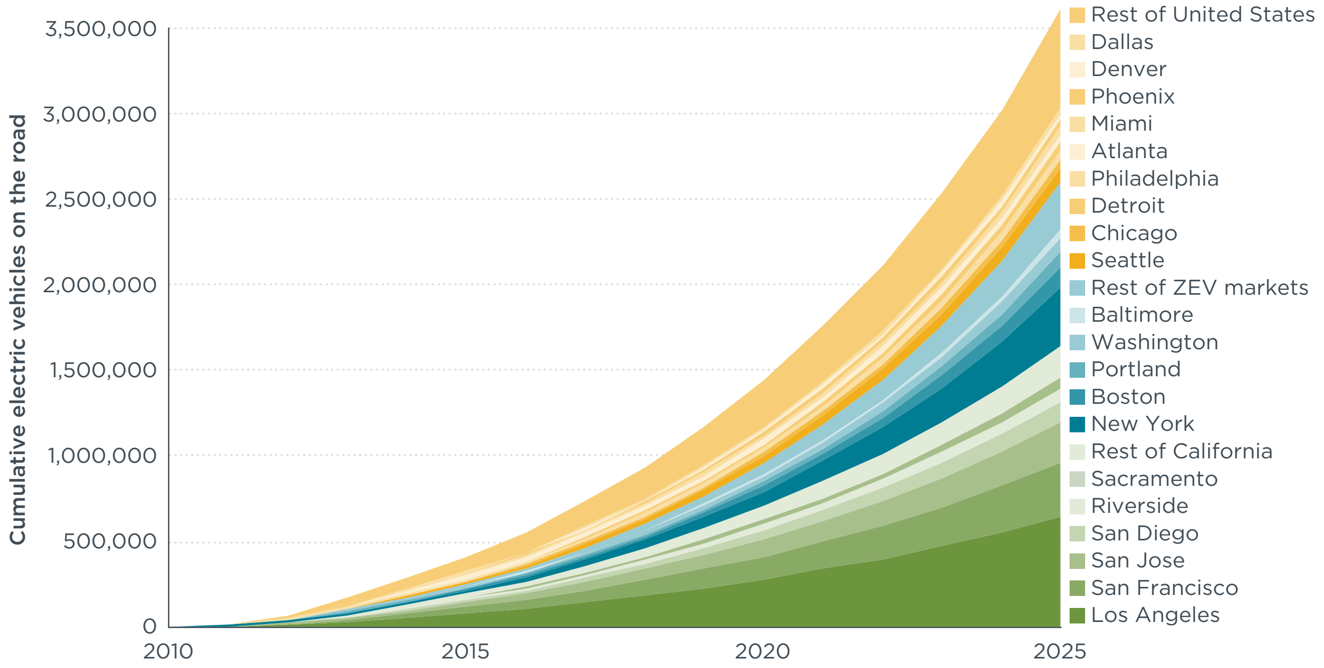


Figure 2. Increase in electric vehicles on the road to meet existing policy and market trends in California, other ZEV regulation markets, and other U.S. markets

We make several additional assumptions regarding future electric vehicle sales. Two key assumptions are in the splits of electric vehicles that will be BEVs and PHEVs in each market and the battery capacity of both of those vehicle types. We assume the same BEV-PHEV split in each area into the future as seen in 2017 as a reflection of factors such as consumer preference, demographics, and weather. Among the large electric vehicle markets, the ones with the highest PHEV portion were Detroit with 77% and New York with 62% compared with the more BEV-heavy markets of Seattle and San Jose with 32%–35% PHEVs. We assume that, by 2021, 36% of BEVs sold will be relatively short range (i.e., less than 150 miles), with the remainder long-range (average 200 miles), based on the share in 2017 in cities with high electric vehicle penetration and model availability. For PHEVs, we assume a future 50-50 split between short range of less than 30 miles and long range exceeding 30 miles of electric range. From 2018 to 2021, the mix of BEVs and PHEVs shift linearly from the 2017 mix to these future scenarios. These splits among short- and long-range BEVs and PHEVs are then maintained from 2021 to 2025.

ALLOCATION OF ELECTRIC VEHICLES TO DRIVER PROFILES

To determine charging behavior, we first allocate future electric vehicles among groups determined by their vehicle type, access to home charging, and access to workplace charging. In total, we count 36 typologies, based on four vehicle types (short- and long-range PHEVs and BEVs), three home-charging options (no home charging, Level 1, and Level 2), and three workplace categories (non-commuter, commuter with ability to charge near workplace, and commuter unable to charge while working).

Home charging access and type. Access to home charging is closely correlated with home type, with drivers in detached houses much more likely to have home charging than those in apartments or attached houses. Electric vehicle owners to date have been concentrated in detached houses. Table 3 shows the differences between California electric vehicle buyers and general new vehicle buyers in California through mid-2015 (CARB, 2017a). As indicated, 83% of electric vehicle buyers in California are living in detached homes, compared with 70% in the general new vehicle purchasing market and 58% of California households at large. To reflect the shift from pioneers and early adopters to more mainstream buyers, we assume the distribution of electric vehicle buyers across housing types will approximately match that of general new vehicle buyers over time. In our model, we start with the high percentage of electric vehicle drivers who are in detached households in 2018, and then decrease the detached-home percentages (e.g., to 70% in the California case) by 2025.

Table 3. Housing breakdown for electric vehicle buyers, general new vehicle buyers, and the California households at large in 2017

	Detached house	Attached house	Apartments and other
California electric vehicle buyers	83%	8%	9%
California general new vehicle buyers	70%	15%	15%
California households	58%	15%	27%

These housing percentages are also adjusted by metropolitan area in proportion to the local housing stock. Figure 3 illustrates how the percentages of electric vehicle buyers in different housing types vary in two metropolitan areas. In 2018, we estimate that 78% of electric vehicles sold were to those in detached homes in San Francisco, compared with 89% for Atlanta. By 2025, attached houses and apartments make up a larger share of electric vehicles (e.g., from 10% apartments in 2017 to 17% apartments in 2025 for San Francisco). Because San Francisco has more households in apartments than Atlanta, the percentage of electric vehicle drivers in apartments in San Francisco is higher than in Atlanta in all years. This impacts the availability of home charging, and therefore the need for away-from-home charging, as we discuss below.

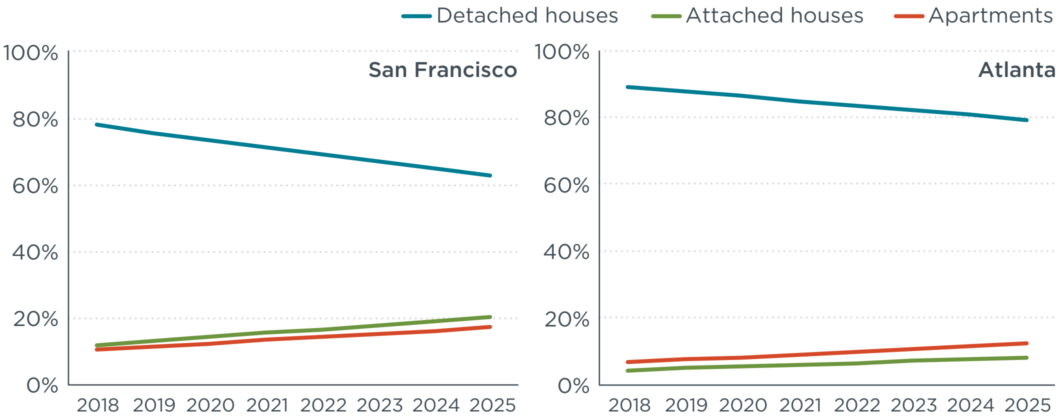


Figure 3. Estimated percentage of electric vehicle buyers by housing type in San Francisco and Atlanta from 2018 to 2025

Along with the distribution of housing types, we use the distribution of home charging access by housing type to estimate the number of vehicles with no charging, Level 1, or Level 2 at home. Figure 4 illustrates the reported charging access of households with electric vehicles based on a California survey of 2,831 electric vehicle drivers (Tal et al., 2018). The figure shows the percentage of electric vehicle-owning households (broken down by the four vehicle types with electric range breakpoints separating "Low" and "High" of 30 miles for PHEVs and 150 miles for BEVs) that reported using home charging (Level 2 and Level 1) in the past 30 days for those that live in detached homes, attached houses with one to three units, and apartments. Home charging use is shown in blue (darker blue for Level 2, lighter blue for Level 1); those who only charged away from home (in the past 30 days) are in red. Tesla Model S and X drivers are excluded in our breakdown of charging patterns here, as we believe free "supercharging" and higher average income make these drivers less representative of the 2025 electric market. Also shown, some PHEV drivers, especially those living in apartments, had not regularly plugged their vehicle in during the past 30 days (gray bars). The right-most bar is the breakdown of the total sample of electric vehicle drivers, illustrating that 83% of surveyed electric vehicle drivers overall use home charging, while 11% rely mostly on nonresidential charging.

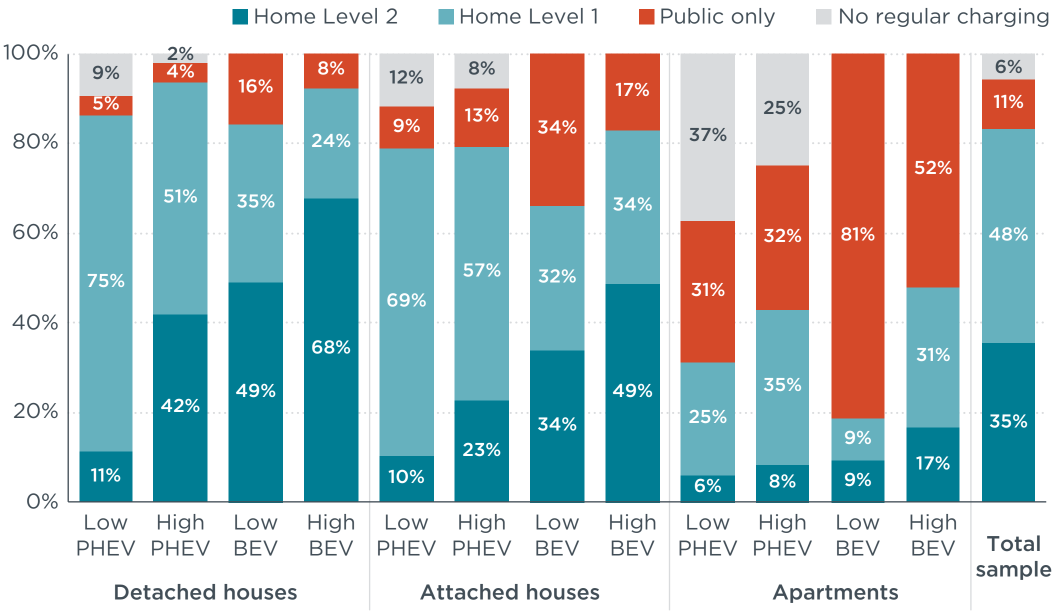


Figure 4. Percentage of electric vehicle households that use home and public charging in detached homes, attached homes, and apartments by vehicle type

This figure shows several important points about home charging behavior. Electric vehicle drivers in detached houses most frequently have access to home charging (84%–94% depending on vehicle type), with more high-range BEV owners typically having Level 2 at home. Those in attached houses also mostly have access to home charging (66%–83%), while fewer than half (18%–48%) of those in apartments use home charging. Home charging access, as determined by housing type and varied city by city, is a key determinant for additional charging needs (i.e., at workplaces and in public locations) in this charging gap analysis.

Commute patterns and workplace charging access. Electric vehicles used for commuting have the potential to charge while working and also typically drive more miles. In the previously referenced California survey (Tal et al., 2018), 75% of electric vehicles were used for commuting. This compares with 49% of individuals' primary vehicles being used for commuting in the general population (U.S. DOT, 2017). In our model, we adjust this ratio of commuters to match the general population by 2025 (i.e., 49% of new electric vehicles will be used for commuting) as the electric vehicle market expands into the mainstream.

Access to charging at the workplace has been far from universal. For broader context, there were about 11,000 workplace chargers in the top 100 most populous metropolitan areas at the end of 2017, compared with approximately 645,000 electric vehicles in those markets. If half of those electric vehicles drove to work any given day, this would mean about 2% of these drivers have all-day access to workplace charging (or 4%, if the workplace chargers were used for two drivers per day). However, survey data indicates that 52% of electric vehicle commuters had at least some access to workplace charging through 2017 (Tal et al., 2018). This suggests that many of the drivers have access to workplace charging but only infrequently use it (either because it is congested, it is largely not needed at any given time, or the commute frequency is low). Additionally, many drivers report charging at public Level 2 while working, accounting for another source of discrepancy.

Despite this contradiction, there is evidence that workplace charging can play a larger role in the charging ecosystem of the future, especially for those without home charging. Workplaces are typically the second-most frequent parking location (after homes) and offer the potential for high-utilization, low-grid-impact charging that could coincide with solar energy production. For that reason, major utilities are becoming involved in charging deployment to serve workplaces. Based on 2017 data, we assume that 52% of electric vehicle commuters will have the ability to charge while working (but will not necessarily choose to do so regularly) through 2025. We assume that 15% of workplace charging is Level 1, with the remainder being Level 2, based on observed data in leading states (CARB, 2017b).

We assume electric vehicle drivers with greater commute distances and larger batteries, will be more likely to take advantage of workplace charging than those with shorter commutes or smaller batteries. We calculate the number of recoverable electric commute miles for each metropolitan area using the assumed electric ranges of vehicles and the LEHD Origin-Destination Employment Statistics (U.S. Census 2018b) dataset, which contains commuting distances and number of workers to and from each census block group nationwide. Average commuting distances in each city were compared with the California baseline to determine the variation in the amount of energy workplace charging could provide in each metropolitan area. Each additional average commute mile above that of the California average that could be recovered increases the likelihood of electric vehicles there plugging in by 1.44% (Nicholas et al., 2017).

DETERMINING REQUIRED CHARGING ENERGY BY ACTIVITY

Beyond access to home and workplace charging, we also utilize the Tal et al. (2018) survey data to estimate general charging behavior for each group of drivers. As an example of how we apply this survey data, Figure 5 shows the average reported charging events per day for each activity (at home, while working, public Level 2, and DC fast) for commuters with access to charging, disaggregated by home charging access and vehicle technology type. The figure also shows the average annual miles driven (including electricity- and combustion-powered miles) for the vehicles on the right vertical axis. We also apply the corresponding survey data for drivers who do not commute, and those who commute but are unable to charge at their workplace.

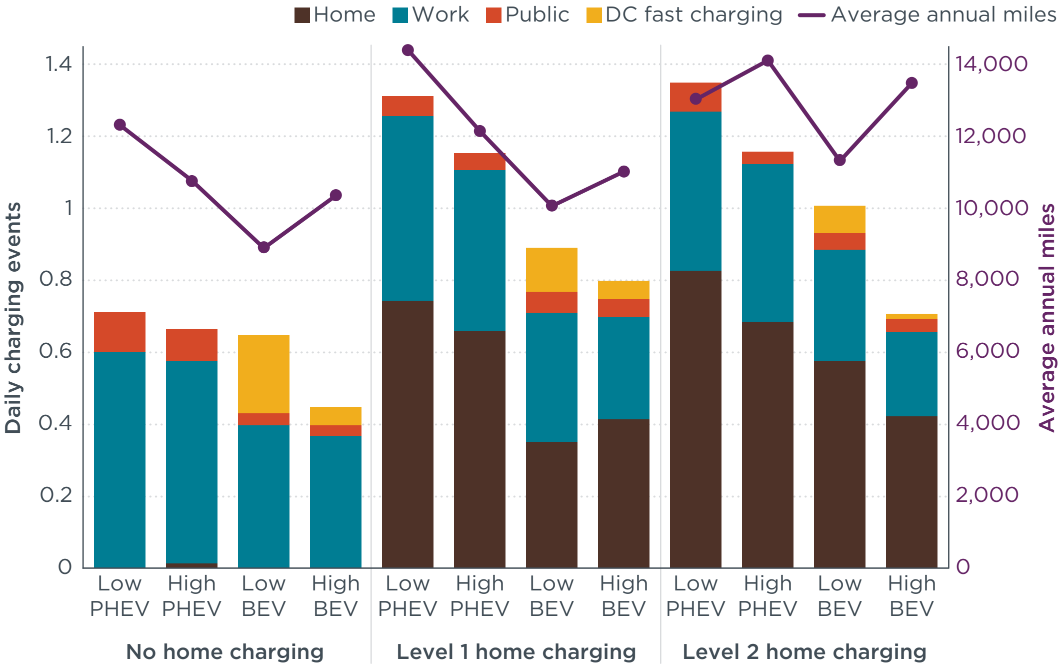


Figure 5. Average daily charging counts and annual miles traveled for electric vehicle commuters with access to work charging, depending on home charging access

Figure 5 shows several important relationships that drive our charging estimates. Interestingly, longer-range BEVs charge fewer times per day than the short-range BEVs, but have more annual miles. This implies that that each charging event represents more kilowatt-hours (kWh) of electricity delivered. Secondly, those with poorer access to home charging will charge more at work and at public chargers (and especially DC fast charging for BEVs) than those with home Level 1 or Level 2 charging. Those who use Level 1 and Level 2 at home exhibit similar patterns for daily charging events for each vehicle type, but those who use Level 2 at home tend to drive slightly more miles per year. Third, among BEVs, fast charging usage increases when electric range is lower. Fourth, annual miles are generally highest with low-range PHEVs (although only 40%–85% of PHEV miles on average are powered by electricity).

Because the driver survey measured only events, rather than energy transmitted, a critical assumption to estimate total charging needs is the total electrical energy per charging event. Our assumptions on charging energy (in kWh) per event, by vehicle technology and charging type, are shown in Table 4. Due to limited data on this subject and uncertainty about many competing trends, we do not explicitly vary these values across cities or years.

Table 4. Assumed electricity delivered (in kWh) per charging event by vehicle technology and charging type

Vehicle type	Workplace	Public level 2	DC fast
Low-range PHEV	6	3	-
High-range PHEV	9	3.5	-
Low-range BEV	12	5	12
High-range BEV	19	6	20

Although comprehensive data on kWh by charging event are not available, our model assumptions are consistent with the relationship shown in Figure 5, where fewer events in longer range vehicles translate to more annual miles. As shown in the table, a high-range BEV, with 200 miles or greater electric range, would recover approximately 19 kWh in a workplace charging event (typically longer period, regular charging speed), 6 kWh in a public Level 2 charging event (shorter period, regular charging), and 20 kWh in DC fast charging (shorter period, fast charging). PHEVs would recover fewer kWh from workplace and public Level 2 charging because they charge more slowly and are limited by battery capacities, and they do not use DC fast charging in our model.

HOURS OF CHARGING DEMANDED BY ACTIVITY

While energy dispensed is the fundamental unit of our calculations, the amount of time spent charging is important in determining the number of charging stations. Translating from energy (kWh) to time (hours) is a function of charging speed, which is determined both by the vehicle and the charging station. Charging speeds for Level 2 and DC fast charging for each vehicle type in 2018 are based on the representative real-world vehicles (for example, the charging speeds for the short-range BEV category are based on the 6.6 kilowatt rate of the Nissan LEAF).

In the future, we expect DC fast charging will become faster, in line with automaker announcements and planned infrastructure projects from Electrify America and utilities. We expect that many long-range BEVs will be capable of charging at 150 kW or higher in the mid-2020s, and many charging stations will be capable of providing such speeds. However, we expect the average charging speed experienced to still be well below 150 kW through 2025, due to lower speeds at the beginning and end of each session, a mix of charging infrastructure capable of different speeds, and higher vehicle and infrastructure costs for higher-power charging. Therefore, we model average charging speeds experienced during fast charging to increase up to an average of 80 kW for long-range BEVs sold in 2025. We do not expect AC charging speeds to increase, except for the case of Level 2 charging in the long-range PHEV category, in line with improvements in recently announced vehicle models.

NUMBER OF CHARGE POINTS REQUIRED BY ACTIVITY

After calculating the total number of hours of charging demanded at different activities, we determine the number of stations required to provide this charging. Utilization of the charging infrastructure is the fundamental bridge between these two quantities. Higher utilization can allow for fewer charge points, but may also result in greater congestion.

Data from 2017 indicate that while cities with low electric vehicle penetration have lower-utilization charging networks that provide necessary geographic coverage, cities with higher electric vehicle sales tend to develop more efficient networks designed to provide the necessary charging capacity with fewer chargers. Figure 6 illustrates this relationship for the 50 most populous metropolitan areas in 2017. The number of BEVs per DC fast charge point is on the vertical axis. The horizontal axis, showing the number of BEVs per million residents in the metropolitan area, is a proxy for relative market development, with more developed markets to the right in the graph. Each point represents one of the 50 most populous metropolitan statistical areas for the 2017 market. At low market penetration there is a low ratio of BEVs per DC fast charge at approximately 50 to 1, where many of the markets are clustered. Representative markets for BEVs are labeled. As shown, the highest electric vehicle uptake market, San Jose, has approximately 200 BEVs per DC fast charge point.

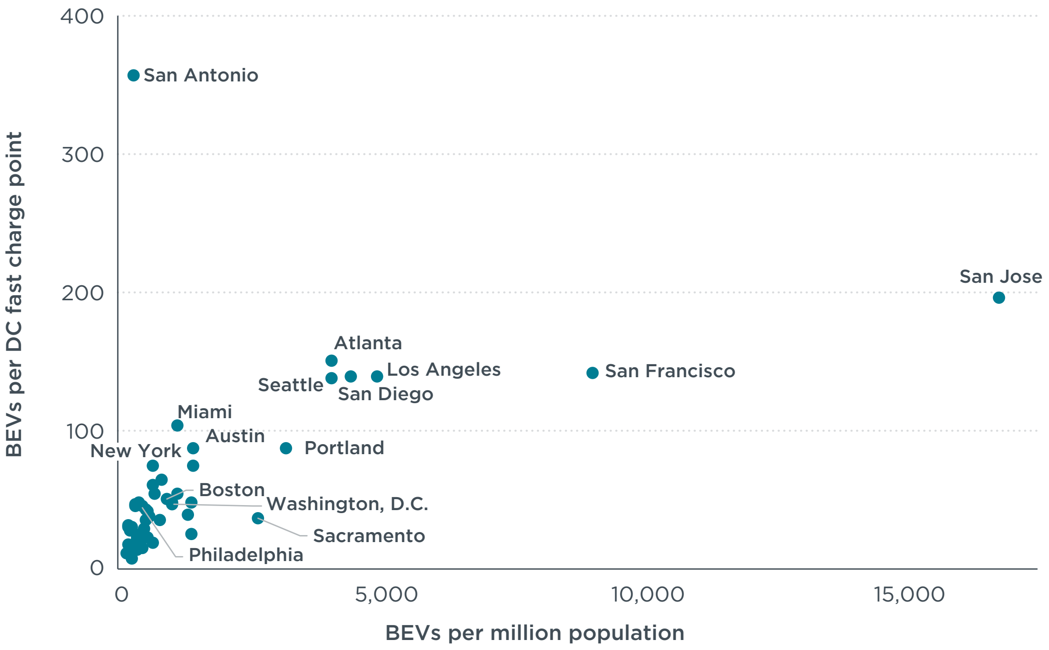


Figure 6. BEVs per fast charge point versus BEVs per million population for the 50 most populous U.S. metropolitan areas

A similar coverage versus capacity relationship can be seen in Figure 7 for non-fast charging. Figure 7 illustrates the ratio of electric vehicles per workplace and Level 2 public charging (on the vertical axis) versus the relative per-capita electric vehicles in each market (on the horizontal axis). In this figure, both BEVs and PHEVs are included in the vehicle-to-charger ratios since both types of electric vehicles can use Level 1 and Level 2 public charging. Moving up in the graph vertically represents fewer chargers available per vehicle, while moving to the right represents higher electric vehicle penetration. Several of the largest and highest-penetration markets are labeled; the three highest uptake markets (Los Angeles, San Francisco, and San Jose) have between 17 and 28 electric vehicles per charger.

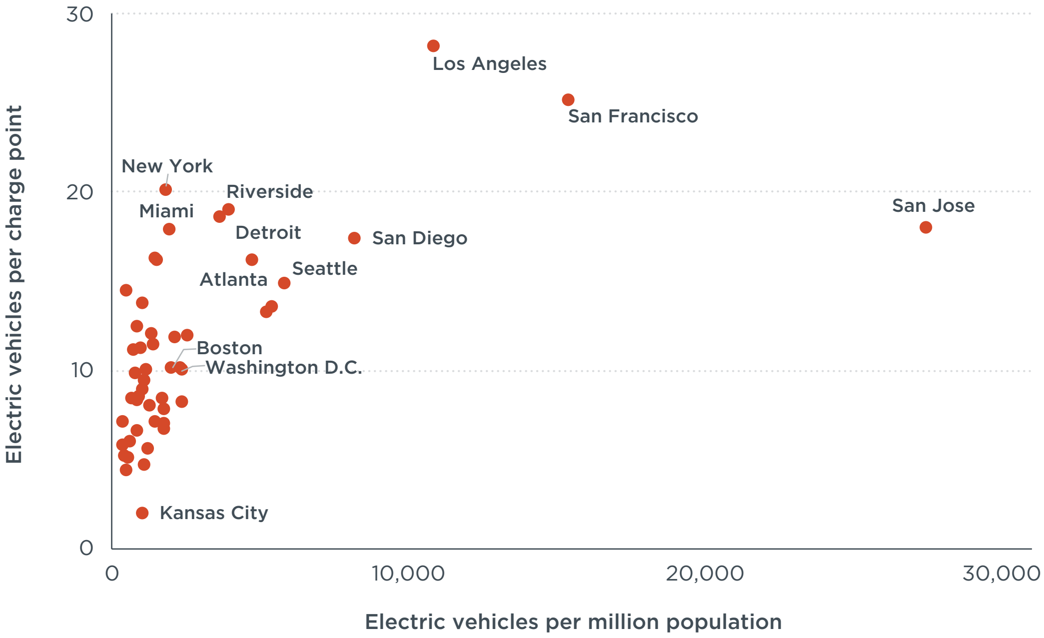


Figure 7. Electric vehicles per workplace and public Level 2 charge point versus electric vehicles per million population for the 50 most populous U.S. metropolitan areas

In basic terms, these shifts to higher vehicle-to-charging ratios can be seen as a transition from a basic charging network as a safety net to increase driver confidence, to a charging network that meets the fundamental charging needs. The implication of these increasing ratios of electric vehicles per charger is that charging infrastructure in markets with fewer electric vehicles per million population are likely to have lower utilization in terms of events and charging energy per day than those in more developed markets. This changing ratio implies that this low utilization may be a necessary phase to obtain sufficient geographic coverage early in the electric vehicle market development.

In light of these trends, we incorporate initial low utilization into our model, shifting to higher utilization over time. Specifically, we assume that the average utilization of chargers in hours actively charging per day follows a logarithmic pattern as a function of electric vehicle penetration, as shown in Figures 3 and 4, normalized to observed data for early deployments. The maximum average hours per day of active charging for public Level 2 is 8 hours for San Jose in 2025, which remains the market with the greatest electric vehicle penetration. For DC fast charging, the maximum utilization approaches nearly 3 hours per day in San Jose in 2025. We assume that workplace charging utilization is constant over time, experiencing an average of 6 hours of use per day on weekdays. Higher utilization rates than these assumptions would ultimately reduce the number of outlets needed as compared with our results below.

REALLOCATION OF CHARGING BY ACCESS TYPE

Finally, we assume that 27% of charging while at work in 2018 is done at public chargers (Tal et al., 2018). However, we expect more workplace charging to be fulfilled by publicly accessible chargers in the future (up to 50% of added workplace charging in 2025). The conversion of activity (charging while working) to location (charging at public chargers) for workplaces is important as public garages are very common parking locations for commuters in most major cities, but can serve other uses outside of traditional working hours. Additionally, employees at retail establishments that provide charging to their customers also may use those public chargers. We report our numbers corresponding to the locations of the chargers rather than the activity meaning that many of the needed public chargers are actually used by commuters.

III. CHARGING INFRASTRUCTURE GAP FINDINGS

In this section, we summarize the results from our model and present our estimates for the additional charging infrastructure needed by U.S. metropolitan area through 2025. These estimates could satisfy the regional driving needs of the projected electric vehicle fleet, provided that these chargers are accessible, distributed to match where the electric vehicle uptake is, and see higher utilization as described above. Although we offer these results as a reasonable scenario for what is needed across markets, additional charging could help to spur faster market growth, enable higher shares of electric driving for PHEVs, and further improve driver experience.

OVERALL TRENDS IN CHARGING BY LOCATION

In terms of overall aggregate growth across the 100 most populous U.S. metropolitan areas, we project a need for 82,000 workplace charging stations, 103,000 public Level 2 stations, and 10,000 DC fast stations in 2025. Compared with what was in place at the end of 2017, these 2025 charging estimations are 7 times, 3 times, and 3 times, respectively, the amount of charging of each type. Combining these three types of nonhome charging, the 195,000 charge points are 4.3 times as many charge points as were available at the end of 2017. These estimates do not include home charging, corridor fast charging between metropolitan areas, or other stations in rural areas, which are outside of the scope of our analysis. These infrastructure estimates are based on what we know about charging behavior through 2017 by electric vehicle type and the housing differences across metropolitan areas.

We can gauge the overall impact of the many market and technology trends assessed in our charging gap model by analyzing the distribution of charge points and electricity use for 2017 and 2025. Figure 8 shows the percentage of charge points and breakdown of total electrical energy delivered by charging type in aggregate for the 100 most populous U.S. metropolitan areas. The amount of charging of all types increases from 2017 to 2025, but the percentage shares shown in the figure illustrate the shifts in energy delivered to electric vehicles.

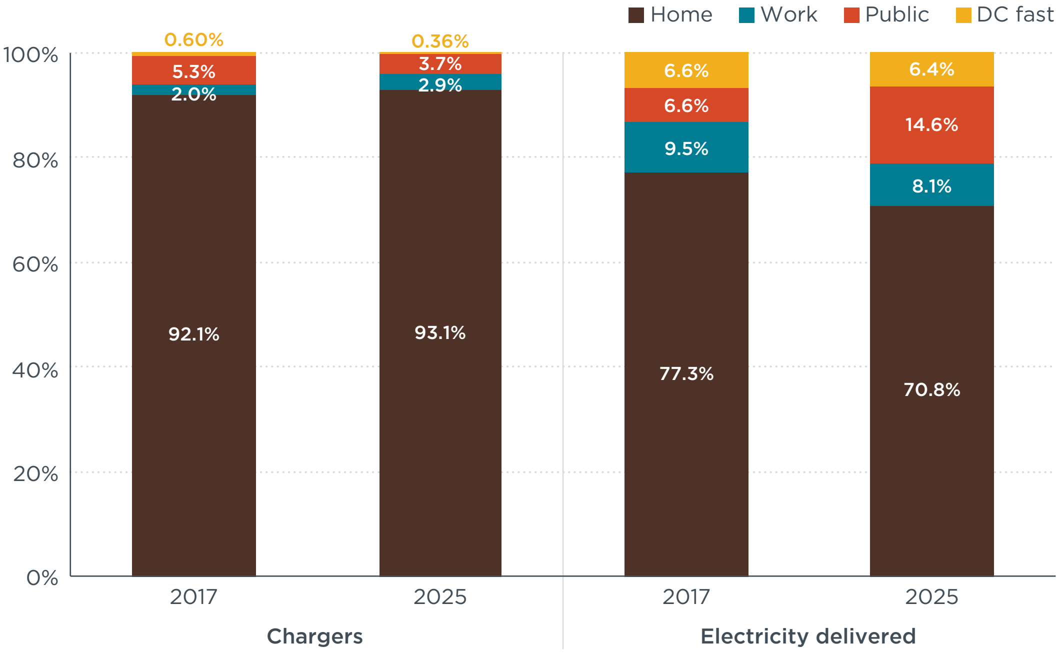


Figure 8. Breakdown of location of charge points and charging energy source for 2017 and modeled for 2025 for the 100 most populous U.S. metropolitan areas

As indicated in Figure 8, the percentage of chargers at homes (both Level 1 and Level 2) in our analysis increases slightly from 92% to 93% between 2017 and 2025 even though the percentage of drivers with home charging access decreases. Higher utilization in 2025 of nonhome charging accounts for these opposing trends. The percentage of electric vehicle chargers at workplaces increases from 2% to 3% of the total charger counts by 2025, while public and DC fast percentages show slight declines in terms of percentage (despite large increases in absolute terms). We note that DC fast charger numbers in 2025 do not include power sharing (such as with some dual standard chargers that are only able to charge one vehicle at a time at full power despite two outlets). Some chargers in 2017 do have this capability, also accounting for the decline in percentage of DC fast in 2025. The changes in aggregate electric energy delivered provide a different view of charging patterns through 2025. Total electric vehicle energy delivered drops from 77% to 71% from home charging, remains effectively the same for DC fast, decreases slightly from 10% to 8% from private workplace chargers, and more than doubles (7% to 15%) for public Level 2 chargers. We emphasize that some drivers who charge while working will charge at publicly available chargers instead of at private workplace chargers.

Overall, Figure 8 shows that, although there will need to be significant growth in the absolute amount of all charging types (home and nonhome), most charging electrical energy will still come from residential charging in 2025. However, the figure also shows that workplace, public charging, and DC fast charging have higher utilization than home charging in terms of energy delivered per charge point. Our analysis below provides more detailed implications on the charging needed by charging type and metropolitan area.

CHARGE POINTS BY METROPOLITAN AREA

The numbers of charging stations of each type required vary widely based on electric vehicle uptake, local demographics, and other factors. Los Angeles, with an estimated 15% electric vehicle sales share in 2025 and the most estimated total electric vehicles in absolute terms, requires the greatest number of charging stations at about 35,000 (nearly

7 times its total at the end of 2017). After that, New York (over 21,000 chargers by 2025), San Francisco (17,000), San Jose (12,000), and Boston (7,000) are next, each needing 4 to 11 times their 2017 charging infrastructure by 2025. Table A1 of the annex outlines detailed results, including the number of charge points of each type (workplace, public Level 2, and DC fast) needed by 2020 and 2025 in the 50 largest metropolitan areas in the United States. The table also contains the associated electric vehicle stock projections.

We provide an example of the year-by-year development of charging infrastructure needs in one market, San Francisco. Figure 9 depicts the projected increase in each type of charging (i.e., workplace, public Level 2, public DC fast) needed in the San Francisco metropolitan area from 2017 to 2025, along with the current number of charging. San Francisco is one of the leading U.S. markets in terms of electric vehicle uptake and charging infrastructure deployment, yet we find that there is insufficient infrastructure to serve the likely near-term growth of the electric vehicle fleet. By 2025, this gap grows significantly, with more than 6,000 additional charge points needed in workplace and public Level 2 charging, and more than 700 in DC fast charging. This analysis of charging infrastructure needs was similarly performed in each of the 100 most populous metropolitan areas to arrive at the estimated 2025 charge points needed.

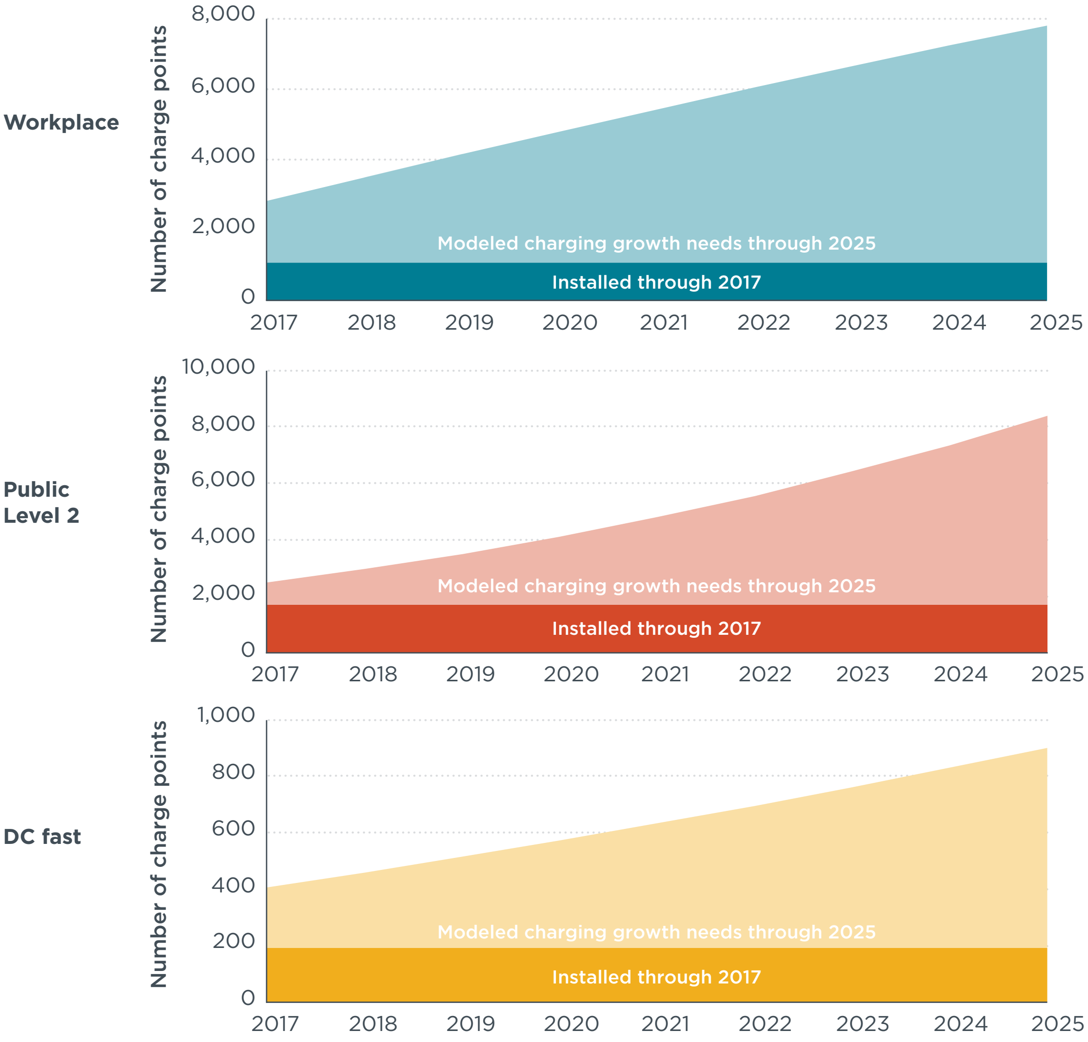
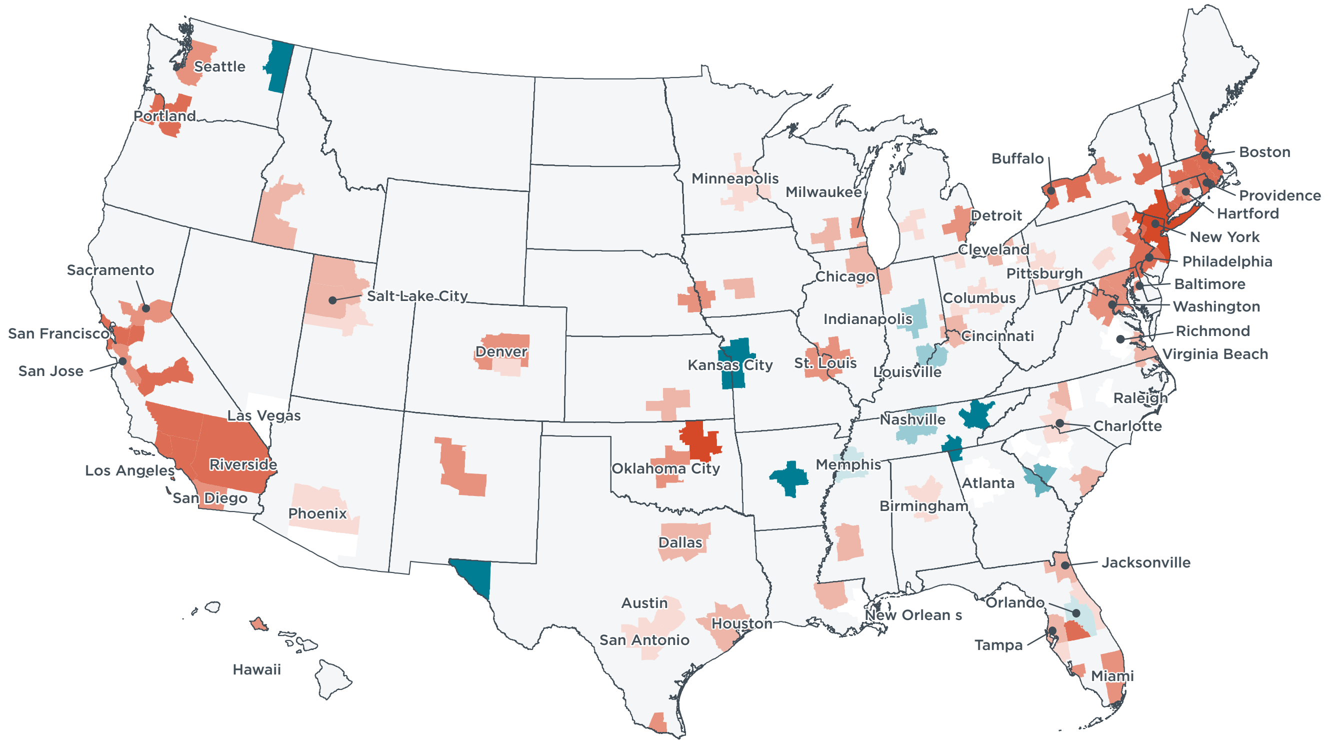


Figure 9. Example of modeled charging infrastructure needs through 2025 and charging gap from installed 2017 infrastructure: San Francisco metropolitan area

RELATIVE CHARGING GAP BY METROPOLITAN AREA

In this section, we present our results on the relative progress in charging infrastructure deployment across U.S. markets by comparing our modeled charging infrastructure needs against the charging infrastructure already deployed through the end of 2017. As above in the San Francisco example, we term the difference between these two the charging "gap" to be filled by 2025. We illustrate the results in several different ways, including a nationwide map with results for the 100 most populous metropolitan areas, a figure with the 50 most populous areas to provide greater granularity on the types of charging, and a more detailed figure indicating the magnitude of additional charging needed in the 10 largest electric vehicle markets.

Figure 10 illustrates the progress toward our modeled charging needs in 2025 in the 100 most populous metropolitan areas in the United States. The 100 metropolitan areas are shaded based on the percentage of needed public and workplace charging infrastructure (i.e., all the nonresidential charge points) that were built as of 2017. The top 50 metropolitan areas are labeled. Shading of the metropolitan areas ranges from dark red, indicating that less than 10% of charging needed by 2025 was in place at the end of 2017, to dark blue, indicating that the share of 2025 charging already constructed is greater than 90%. The vast majority of metropolitan areas are shaded dark or light red, especially those areas in California and the Northeast where higher electric vehicle uptake is expected. Only 12 metropolitan areas are shaded blue (i.e., with at least 60% of the modeled 2025 charging in place). These are mostly in the Southeast and Midwest regions where relatively lower electric vehicle uptake is expected through 2025. For the 100 largest metropolitan areas combined, about one-fourth of the needed charging was in place by the end of 2017.



Charging infrastructure in 2017 as a percentage of that needed by 2025

■ 1%–10% ■ 11%–20% ■ 21%–30% ■ 31%–40% ■ 41%–50% □ 51%–60% ■ 61%–70 ■ 61%–70 ■ 81%–90% ■ 91%–100%

Figure 10. Charging infrastructure in place in 2017 as a percentage of infrastructure needed by 2025 to support electric vehicle market by metropolitan area

Figure 11 offers a more granular view of the charging gap, displaying the percentage of 2025 charging needs for each charging type (workplace, public Level 2, and DC fast) that was constructed as of the end of 2017 in the 50 largest metropolitan areas. Data points near the bottom of the figure indicate that a relatively low percentage of that type of charging infrastructure has been built relative to 2025 targets, while points near the top indicate that an area contains nearly sufficient charging infrastructure toward 2025 needs. The brown "total" for each area refers to the progress toward the unweighted sum of these three charging types; cities may fare well on this total score despite lagging in one category. The figure is ordered from left to right according to which markets in 2017 had the highest electric vehicle uptake per capita. Of the 50 largest metropolitan areas, only Kansas City has sufficient total charge points to serve the projected electric vehicle fleet in 2025. In contrast, we find that 38 of these 50 metropolitan areas have less than half of the total charging points needed by 2025, and 15 areas have less than 25%.

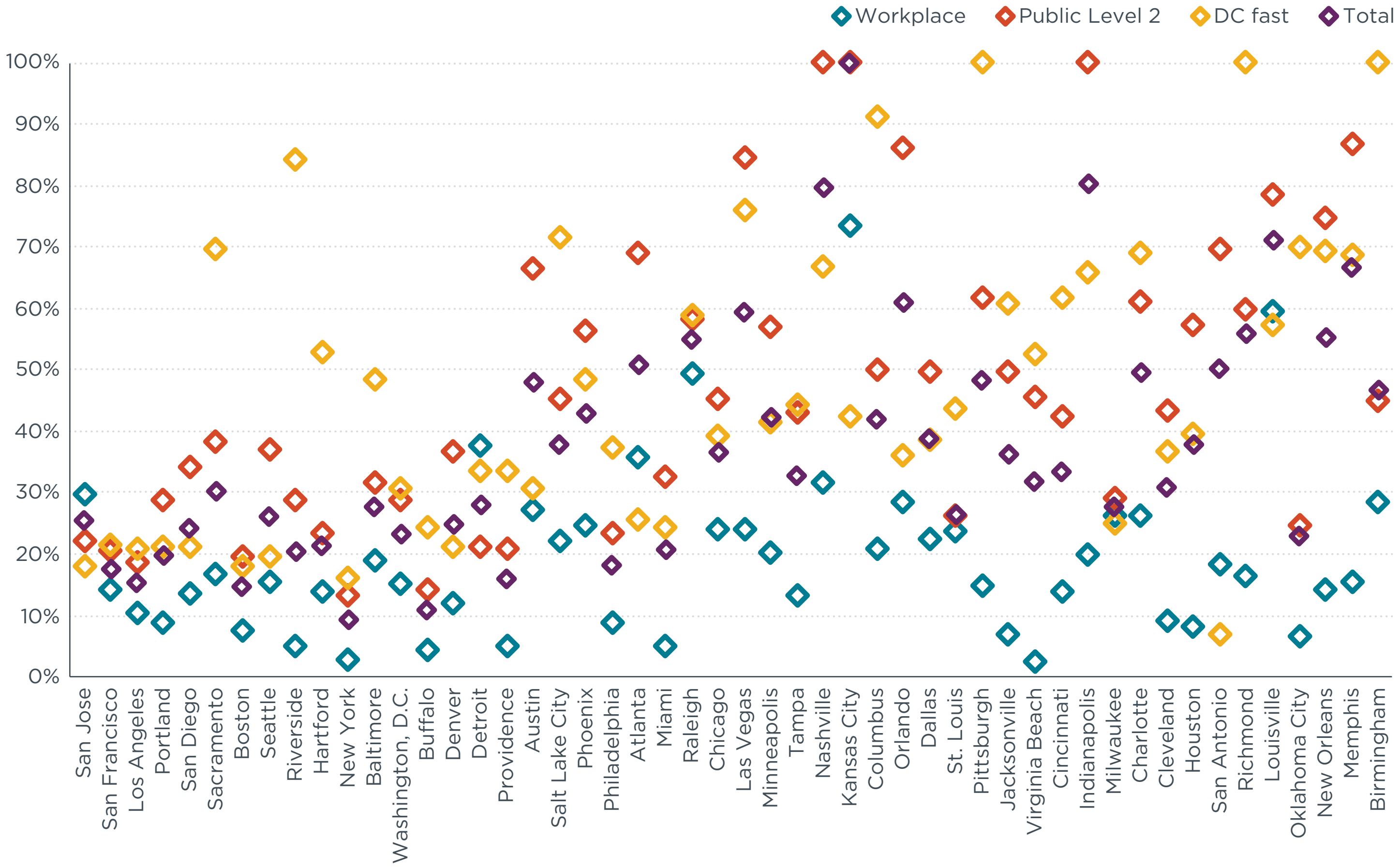


Figure 11. Charging infrastructure deployment status as of 2017 relative to modeled 2025 needs in the 50 most populous U.S. metropolitan areas

Although most metropolitan areas require more charging of all kinds, the charging gap varies not only by city, but also by the type of charging. Workplace charging infrastructure is the category with the largest gap: Half of the 50 largest metropolitan areas have less than 16% of the estimated workplace infrastructure that will be needed by 2025. On the other hand, three metropolitan areas (Pittsburgh, Richmond, and Birmingham) appear to have approximately sufficient DC fast charging to meet the needs of vehicles in 2025, and many others have over 50% of the needed DC fast charging. Much of this seeming sufficiency is due to large Tesla Supercharger stations, which are available only to a portion of BEVs and have historically offered free charging. If these Superchargers are not counted, only Pittsburgh has sufficient fast charging for 2025; several areas currently have no fast charging available for non-Tesla electric vehicles.

Considering the recent steady growth, converting the needed charging infrastructure into a compounded annual growth rate helps bring additional perspective to the challenge of filling the charging gap. We calculate the annual percentage increase in charging outlets necessary to achieve 2025 targets. Although our projected pace of construction need not match a compounded annual growth, it provides a useful lens to assess the pace of deploying the charging infrastructure. Across the top 100 metropolitan areas, the necessary average annual growth rate for all charge points would have to be 20% to meet this assessment's 2025 targets. Examining the various charging types separately, the annual growth rate would have to be 15% for DC fast charging, 16% for public Level 2, and 28% for workplace. As noted previously, charging infrastructure increased by 36%–46% across these charging types for the same 100 markets from 2016 to 2017. Although this analysis clearly indicates that much more charging infrastructure will be needed, the rate of annual growth required to meet 2025 targets is lower than that of previous growth rates across the United States.

We provide a deeper look into the charging gaps for the 10 electric vehicle markets that we expect to be the largest in 2025. Figure 12 shows the number of charge points (workplace, public Level 2, and DC fast) constructed as of 2017 and the number of charge points required in 2025 in these 10 metropolitan areas, ordered by 2025 charging needs. As seen in the figure, each of these areas faces a major gap in charging infrastructure by 2025, but the 2017 and anticipated 2025 mixes of the workplace and public charging types vary based on local electric vehicle charging factors, as described in the section above on assessing charging infrastructure needs. These 10 metropolitan areas are expected to make up more than half of the cumulative electric vehicle sales nationwide through 2025. We expect that the number of electric vehicles on the road in 2025 in these metropolitan areas will range from 84,000 in Portland to over 600,000 in the Los Angeles area.

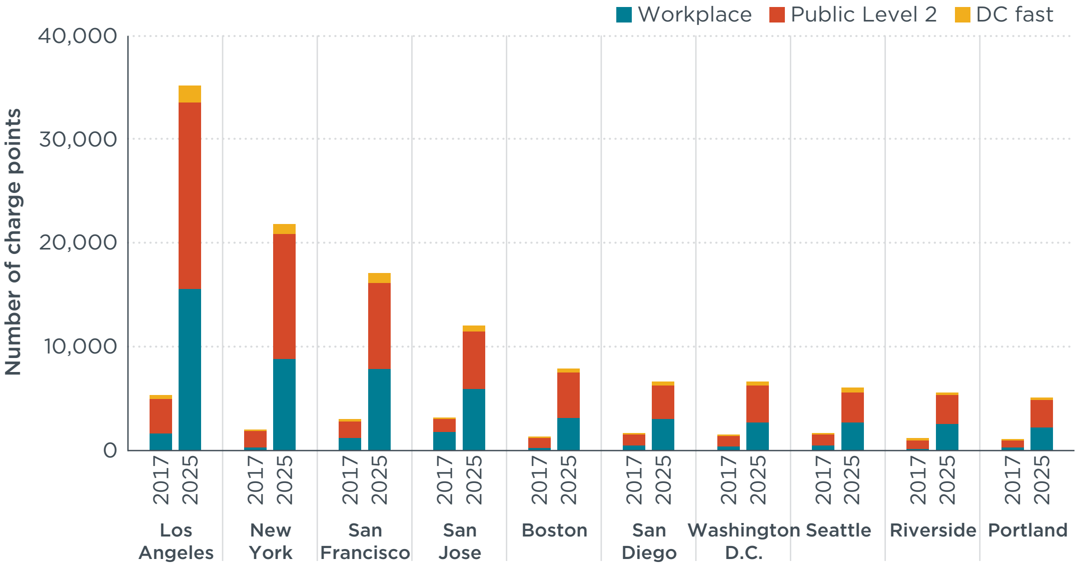


Figure 12. Charge points in 2017 and estimated needs in 2025 in the projected 10 largest electric vehicle markets

Although these markets had relatively high charging infrastructure in place in 2017 compared with other metropolitan areas, they still require high growth to meet their expected electric vehicle sales by 2025. These 10 markets had from 9% (New York) to 26% (Seattle) of their expected 2025 charging built through 2017, compared with 23% for the top 100 metropolitan areas. The metropolitan areas in this chart would have to see compounded annual growth rates in total charge points from 18% to 35% to successfully deploy the targeted 2025 charge points as assessed here. Markets with especially large infrastructure gaps to fill by 2025 include New York (needs a 35% average annual increase in charging through 2025), Boston (27%), Portland (23%), Riverside (22%), and Washington, D.C. (20%). Again we note that the increase in U.S. charging infrastructure growth from 2016 to 2017 was higher than these annual growth rates, suggesting that charging infrastructure providers are moving in this direction. The specific growth rates to meet our targets for different types of charge points vary, with workplace charging typically requiring a higher growth rate.

A number of charging infrastructure programs have been announced or are already being constructed in 2018 that help reduce the charging gap identified in this report. Such charging infrastructure installation activities, especially by electric power utilities, are very active, but a comprehensive review of those developments is beyond the scope of this analysis. Nonetheless, we do offer a simple comparison of our charging gap results with several related developments in California, where some of the more comprehensive charging infrastructure deployment efforts are underway.

Table 5 summarizes the impact of several announced programs that are slated to deploy substantial charging infrastructure in California and compares them with our charging gap results for the California markets through 2025. The charging gap and current charging numbers only include the 10 largest metropolitan areas in California, which represent 86% of the state's population: Los Angeles, San Francisco, Riverside, San Diego, San Jose, Sacramento, Fresno, Bakersfield, Oxnard, and Stockton. Our analysis indicates that about 84,000 charge points will be needed by 2025, with nearly 16,000 (15%) installed through the end of 2017. The five announced statewide infrastructure construction projects (including Electrify America and three major electric power utilities) could cover approximately 27,000 workplace and public charge points across California. If all of these installments were built within these 10 metropolitan areas, they could cover up to 40% of the charging gap. After these installations, 41,000 charging points would remain to be constructed, a substantial gap to be filled through public and private efforts.

Table 5. Charging gap in California metropolitan areas and impact of announced programs by Electrify America and utilities

Category		Estimated nonresidential chargers	Percentage of 2025 charging needs
This analysis' estimated chargers needed by 2025		84,101	100%
Existing and planned installations statewide	**Chargers constructed through 2017**	15,739	19%
	Electrify America Cycle 1	2,000	2%
	Electrify America Cycle 2	718	1%
	PG&E EV Charge Network	5,067	6%
	SCE Charge Ready 2	18,000	21%
	SDG&E Power Your Drive	1,000	1%
Remaining gap		41,487	49%

Sources: Electrify America, 2017a, 2018; California Public Utilities Commission, 2017; Southern California Edison, 2018

As another point of comparison, a key report by the California Energy Commission (2018) indicates that 108,000 to 158,000 workplace, public, and fast chargers will be needed statewide by 2025 to match the state's goal of deploying 1.5 million zero-emission vehicles by 2025. Our estimates, which include only charging stations within the major metropolitan areas, are significantly lower than this. The California-specific summary in Table 5 is meant to provide basic context for the evolving situations in all the major markets. There are many other workplace, utility, city, state, and auto industry-related projects to deploy charging infrastructure in California and across the country that were underway in 2018 (i.e., after the 2017 counts we use as a reference) and planned for future years to reduce the charging gap identified.

KEY SENSITIVITIES IN CHARGING INFRASTRUCTURE ANALYSIS

In this section, we outline the impact that changes in assumptions regarding home charging and vehicle fleet development have on our model's estimates for charging infrastructure required through 2025. Figure 13 shows the impact on charging needs under six scenarios, three regarding home charging patterns and three regarding vehicle fleet makeup. The percentages refer to the increase or decrease in the number of nonhome charge points required across the 100 largest metropolitan areas in 2025, relative to our baseline scenario as outlined in Section II, to assess charging infrastructure needs. We assess the effects of changing these assumptions on each type of charging infrastructure: private workplace, public Level 2, and DC fast.

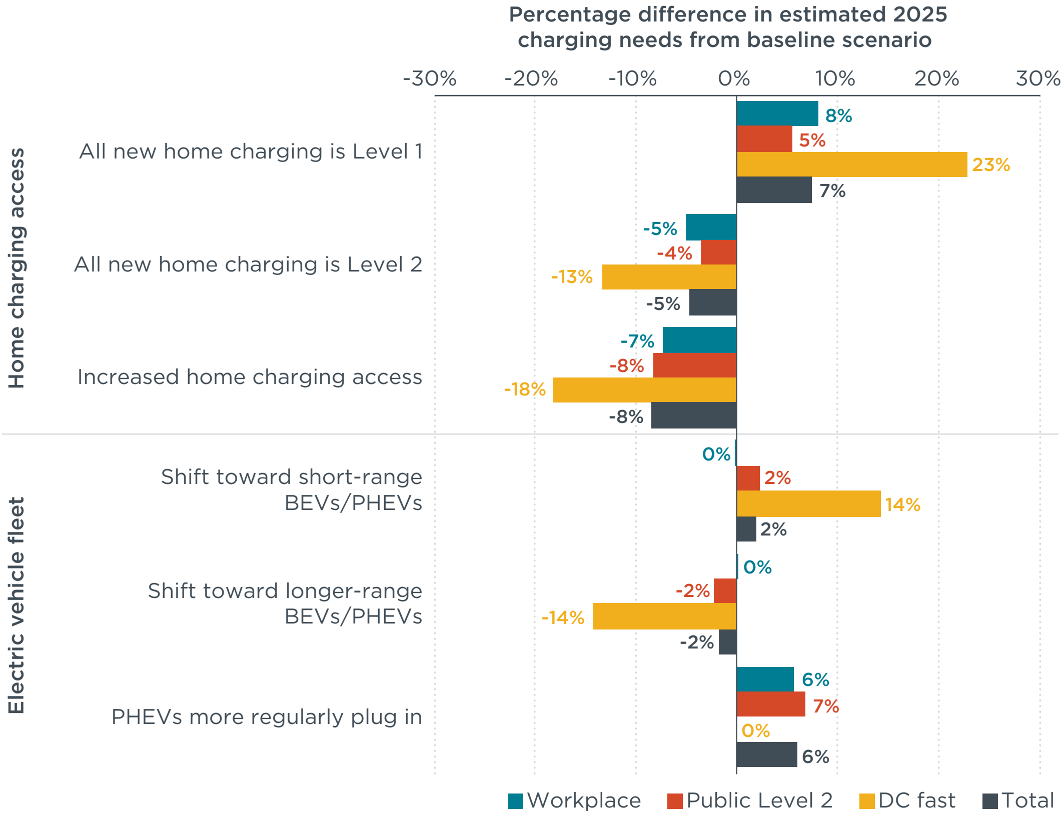


Figure 13. Sensitivity of 2025 charging needs to changes in home charging and fleet composition compared with baseline scenario

For the first two sensitivity cases, we assume that all new home charging is Level 1, or all new home charging is Level 2, instead of the baseline mix of speeds (depicted in Figure 4). As shown, this basic assumption about home Level 1 versus Level 2 is quite consequential, resulting in a swing from needing 7% more charging (over 14,000 more public and workplace chargers overall) to 5% less charging (about 9,000 fewer chargers). This differentiation is especially consequential for DC fast charging in our model; if more home charging in the future is ultimately Level 1, this would increase the need for DC fast charging by 23%, but providing universal home Level 2 reduces DC fast charging needs by 13%.

In another sensitivity case regarding increased access to home charging (the third case in Figure 13), we consider the impact of electric vehicle drivers in apartments and attached houses having the same access to residential charging as drivers in detached houses. As indicated in Figure 13, providing increased home charging access to apartments and attached homes reduces the need for nonresidential charging in 2025 by about 8% overall, meaning about 16,000 fewer workplace and public chargers would be needed. This case results especially in reduced needs for DC fast charging (by 18%), as many drivers in apartments and attached homes would otherwise be more dependent upon fast charging. Because residential charge points typically see lower overall utilization than public or workplace charge points, this scenario would result in more total charge points. The financial impacts of such an approach are not analyzed here but present a compelling opportunity for future research.

We also explore the impacts of moving to electric vehicles with shorter and longer electric vehicle ranges. Exploring several electric vehicle fleet changes (in the bottom portion of Figure 13) helps us understand how sensitive the overall charging assessment is to the electric driving range of the electric vehicles. Our baseline scenario assumes a 50/50 mix of high (around 45 miles) and low (approximately 20 miles) electric range PHEVs and a mix of 64% high (over 200 miles) and 36% low (120 miles) electric range BEVs after year 2021. In these two test cases, we assume shifts of 20 percentage points by 2025 in both directions: 70% short-range PHEV and 56% short-range BEV in the shorter-range case, and 70% long-range PHEV and 84% long-range BEV in the longer-range case. Electric vehicles with larger electric capacity can make better use of each charging opportunity, thus reducing the overall need for charge points. As shown in the figure, the electric range does not have a major impact on overall charging needs (i.e., plus or minus 2%), but the effect on DC fast charging is stronger, decreasing the 2025 needs for DC fast charging by 14% with more long-range electric vehicles or causing an equal but opposite increase with more short-range electric vehicles.

For the final sensitivity in Figure 13, we consider the effect of how often PHEVs are plugging in on the amount of nonresidential charging needed through 2025. In our base scenario, 37% of apartment dwellers with low-range PHEVs (and smaller shares of other PHEV drivers) are assumed to derive almost all of their energy from gasoline due to a lack of access to charging or lack of motivation. If all PHEVs regularly plug in (powering 40%–45% of miles with electricity for short-range PHEVs and 75–85% for long-range PHEVs), but home charging access is unchanged from our baseline scenario, the needs for public and workplace charging are increased by 6%–7%. Increased rates of charging among PHEVs could reflect some combination of actions by automakers, policymakers, utilities, and consumer awareness campaigns to encourage such behavior to ensure increased shares of electric miles over time.

IV. CONCLUSIONS

The U.S. electric vehicle market continues to grow, supported by policy and promotion actions at the local, state, and national levels. Charging infrastructure is a key enabler for the market, and although there has been growth in charging networks, there remains significant uncertainty about the amount and type of charging infrastructure needed. In this paper, we quantify the amount of charging infrastructure required to support the electric vehicle fleet through 2025 in major U.S. metropolitan areas. We analyze the needed charging infrastructure to charge over 3 million electric vehicles by 2025. This electric vehicle growth corresponds with an increase in the electric vehicles share of new vehicle sales from 1% in 2017 to 4% in 2025, consistent with automaker, policy, and market trends.

The transition to electric vehicles is made possible by the widespread availability of electricity. What remains is to develop a charging infrastructure ecosystem to deliver this electricity to diverse vehicle types based on complex electric vehicle driver charging behavior as the market grows. Our analysis shows that over 90% of the charge points and over 70% of all the required electric energy for electric vehicles is likely to come from home charging for the foreseeable future, although the use of nonhome charging will grow more rapidly. Although the majority of charging happens at home, public and workplace charging are critical to provide options for mainstream electric vehicle adopters and to take advantage of all the times and places where electric vehicles are parked.

This study provides specificity on those charging needs across U.S. markets, based on an underlying framework and best available observed data on electric vehicle demand and charging behavior patterns. From this analysis, we draw several conclusions related to defining the charging infrastructure gap, describe some ongoing efforts to fill the gap, suggest potential implications of the work on emerging business cases, and discuss areas to improve upon this type of research.

Much more charging infrastructure is needed to sustain the transition to electric vehicles. Across major U.S. markets through 2017, about one-fourth of the workplace and public chargers that are needed by 2025 were built. Across the 100 most populous U.S. metropolitan areas, over 195,000 nonresidential electric vehicle charging points will be needed by 2025, over 4 times the charge points these markets had at the end of 2017. Public and workplace charging infrastructure deployment overall across U.S. metropolitan areas will have to grow at about 20% per year to meet the 2025 targets identified in this report. This growth in infrastructure will be critical to support the growth of an overall U.S. electric vehicle market from about 1 million in late 2018 to what we assess is likely to be over 3 million cumulative electric vehicles on U.S. roads by the end of 2025.

Future charging needs differ by charging type and by metropolitan area. Our overall U.S. estimates are built from local-level estimates of workplace, public Level 2, and DC fast charging infrastructure for each metropolitan area. We find workplace charging will likely need to be expanded much more than the other types. We expect a sevenfold increase will be needed in workplace charging—or 28% per year—from 2017 to 2025. This compares with approximately threefold increases in public Level 2 charging and DC fast charging from 2017 to 2025, meaning an annual average increase of 15%–16%. This increased use of various charging types helps to round out a charging ecosystem, filling in key gaps where and when electric vehicles are frequently parked. In turn, this growing network will enable these vehicles to travel more electric miles and will make electric vehicles more attractive to more prospective buyers.

The largest charging gaps between installed 2017 and needed 2025 charging outlets are where electric vehicle uptake is growing most rapidly. Many California cities, as well as Boston, New York, Portland, and Washington, D.C., each need to average at least 20% annual growth in their charging infrastructure from 2017 to 2025. Los Angeles, the largest U.S. electric vehicle market, faces the largest gap in absolute terms, needing over 35,000 new charge points by 2025, or a 27% average annual increase from its 2017 level. Top electric vehicle markets with large infrastructure gaps to fill by 2025 include New York (35% average annual increase needed), Boston (27%), Portland (23%), Riverside (22%), and Washington, D.C. (20%).

Planned infrastructure deployment activities are promising, but uneven. The average growth rate for 2017 to 2025 to meet the charging targets across U.S. markets identified in this analysis is approximately 20% per year. This amounts to substantial and potentially challenging growth. However, the observed 2016–2017 infrastructure growth rates were greater, suggesting the overall U.S. trend is broadly in line with the needed charging infrastructure as analyzed here. Further, there are many charging infrastructure developments underway that virtually ensure greater levels of charging infrastructure installation in the next several years in many of the markets. For example, infrastructure projects with Electrify America and three major electric power utilities would cover about 40% of the charging infrastructure gap in California markets.

There are many city- and state-level efforts that could further expand charging infrastructure networks. Cities can act in many ways—including through streamlined permitting, building codes, and zoning—to accelerate residential, parking garage, right-of-way, and curbside charging within their jurisdiction. States can act with their regulatory authority, tax rebates, and through cost-sharing to support charging providers as they develop more durable business models. Major electric power utilities and state utility commissions increasingly develop their own plans for infrastructure investments as they prepare for greater electric vehicle uptake. Utility efforts especially can go a long way to fill the charging infrastructure gap, and efforts for utility-funded charging infrastructure appear imminent in many places. However, as pointed out in policy assessments (e.g., Slowik & Lutsey, 2018), these city, state, and utility charging infrastructure support activities are not underway across much of the United States. Instead, such efforts are primarily concentrated in ZEV regulation markets.

Private industry efforts are also filling some strategic charging gaps to help meet electrification commitments. For example, Tesla has built the most extensive automaker charging network, to connect cities and also support various local networks, to make a more attractive electric vehicle purchasing proposition. As part of Volkswagen's diesel scandal settlement, Electrify America is in the early stages of deploying its $2 billion charging network, and it includes a focus on 17 metropolitan areas in addition to its intercity highway network. Several auto companies have partnered with charging providers in California, the Northeast, and selected cities with much smaller investments as part of their electric vehicle rollout plans. However, many automakers have invested little in charging infrastructure to match their electric vehicle plans. Our analysis helps provide motivation for more such action in nearly every major U.S. metropolitan area to better match charging infrastructure to electric vehicle growth.

Although this study was focused on public and workplace charging needs, home charging remains the essential backbone of the charging ecosystem due to general convenience and lower cost of service compared with public locations. Ensuring more homes have Level 2 (versus Level 1) charging, and increasing access to home charging for those in attached homes and apartments (who are typically without private parking and garages) is important. We find that if electric vehicle drivers' access to Level 2 at home is increased, this increased speed reduces the need for public and workplace charging by 5% (i.e., 9,000 fewer charge points). Further, if electric vehicle drivers in apartments and attached houses received increased access to home charging to match that of detached houses, overall public and workplace charging needs are reduced by 8% (i.e., 16,000 fewer charge points). This suggests utility programs and policies to encourage home Level 2 installations and charging for multi-unit dwellings will remain important—not only to help grow the market, but also to reduce public Level 2 and DC fast charging needs.

Increased charger utilization brings infrastructure investment opportunities. The case for investing in charging infrastructure is strengthening due to a confluence of trends, including regulatory and automaker developments, economies of scale, improving charging technology, and increasing charging utilization. In the markets where the most charging is needed by 2025, the ZEV regulation, adopted by California and nine other states, provides assurance of increased future electric vehicle sales. Technology advancements, including lower-cost batteries, and electric vehicle market developments around the world are enabling much greater electric vehicle deployment. As a result, we are now seeing automaker electrification commitments that are greatly surpassing electric vehicle requirements, bolstering the trend toward electric vehicles (Lutsey, 2018b)

Further, our analysis here shows utilization of charging infrastructure will increase, which allows greater use of charging stations and therefore greater ability to recoup charging infrastructure investments. Early electric vehicle market growth required more charging per vehicle to provide the essential geographic coverage and instill confidence in prospective drivers, but more mature markets need fewer public charge points per vehicle. We find that electric vehicles per public Level 2 chargers, on average, will increase from 21 to 28, representing a 35% increase in utilization on each charge point by 2025. DC fast charging installations in U.S. markets will see an even greater effect. Battery electric vehicles per DC fast charge point will increase from 95 in 2017 to 156 by 2025—meaning a 65% increase in utilization. This boost in charger utilization helps improve the business case for new charging installations.

These trends toward more electric vehicles and greater charger utilization help policymakers, businesses, and investors make low-risk, high-utilization investments in charging infrastructure. In particular, automakers, utilities, charging providers, and retailers could use this analysis to help match investments to expected electric vehicle deployments in underserved metropolitan areas. Higher charger utilization provides opportunities for increased charging revenues to help recover charging station costs in public and private locations. As seen with the 10,000 charge points at workplaces through 2017, many employers are installing charging as a perk for their employees. As these electric vehicle commuters proliferate, they will begin to demand more of this service. Utilities in many jurisdictions appreciate the prospects of workplace charging for the long daytime vehicle dwell time that can match Level 2 charging to increasing solar electricity generation. Many retail businesses already see a case for charging installations to help lure customers, and this analysis suggests this will be increasingly attractive, with more electric vehicle drivers opportunistically seeking charging in the years ahead.

Although this analysis allows us to assess many specific U.S. charging questions, this study has broader implications that warrant much greater exploration. Adding a cost optimization dimension to this charging gap analysis would be very valuable. Another rich area for analysis is to assess how different ratios for the different charging types (home, public, workplace, DC fast) could enable more electric miles from a given electric vehicle fleet. The work is based on real-world behavior and emerging trends through 2017, but the electric vehicle market and charging behavior are constantly evolving, so continued re-examination will be important. Future research could also consider the impacts of many intersecting developments, such as electric ride-hailing fleets, smart charging to mitigate grid impacts, and perhaps autonomous vehicles in longer-term models. Similar local-level examination of other large and growing electric vehicle markets, such as China, Germany, and the United Kingdom, could also be valuable in informing charging needs.

This analysis provides a reference for the charging infrastructure needs for a growing electric vehicle market in the United States, including detailed implications for charging needed in U.S. markets. The broader conclusion is that, despite the many uncertainties, it is clear there will be attractive opportunities for the foreseeable future to deploy charging infrastructure to power a growing electric vehicle fleet. As the electric vehicle market expands, sustained policy and collaboration among many government and private industry players will be needed to build the accompanying charging ecosystem. To this end, leading regions are already deeply engaged and serving as models for others. Although much work remains, progress toward the charging infrastructure system of the future is well underway.

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ANNEX

Table A1. Estimated cumulative electric vehicles and estimated workplace, public level 2, and DC fast charge points in 2020 and 2025 for the 50 most populous metropolitan areas in the United States

AREA	2020 BEV	2020 PHEV	2020 Workplace charge points	2020 Public level 2 charge points	2020 DC fast charge points	2025 BEV	2025 PHEV	2025 Workplace charge points	2025 Public level 2 charge points	2025 DC fast charge points
Atlanta	26,535	7,107	1,250	1,303	374	32,971	15,203	1,423	1,695	374
Austin	5,319	3,736	355	384	58	10,903	8,035	535	678	82
Baltimore	5,071	6,963	414	544	59	20,048	25,118	1,022	1,629	134
Birmingham	371	539	31	98	13	798	1,109	46	125	13
Boston	12,064	17,172	1,194	1,372	146	47,928	66,139	3,058	4,426	351
Buffalo	1,025	3,045	157	212	17	4,128	11,173	380	603	33
Charlotte	2,043	2,282	161	261	32	4,503	4,962	248	430	45
Chicago	15,801	10,317	875	1,085	153	35,175	21,004	1,342	1,891	240
Cincinnati	1,711	2,222	156	242	28	3,854	4,336	230	372	39
Cleveland	1,178	1,759	121	195	22	2,624	3,511	178	294	30
Columbus	2,156	2,150	158	225	31	5,112	4,366	246	377	45
Dallas	9,744	6,150	570	779	119	20,888	12,581	863	1,316	174
Denver	9,589	6,263	684	674	125	22,922	13,620	1,133	1,287	176
Detroit	4,281	21,451	882	1,156	54	10,319	39,638	1,199	1,773	81
Hartford	1,978	3,271	188	246	26	8,008	12,309	475	743	55
Houston	5,781	4,323	398	560	85	12,054	8,934	595	895	116
Indianapolis	1,829	1,942	149	247	32	3,750	3,697	211	368	41
Jacksonville	1,452	1,321	103	172	21	3,325	2,917	163	298	33
Kansas City	2,150	2,307	175	282	37	5,073	4,868	275	470	52
Las Vegas	3,428	2,818	222	252	33	7,476	6,026	339	439	50
Los Angeles	132,009	149,349	9,564	8,949	1,008	308,249	337,283	15,528	18,010	1,604
Louisville	580	810	48	97	12	1,371	1,708	74	143	14
Memphis	603	505	36	100	12	1,319	954	52	129	16
Miami	12,510	9,491	956	1,031	146	26,023	20,111	1,443	1,824	222
Milwaukee	1,010	1,630	105	160	19	2,187	3,377	157	249	24
Minneapolis	4,562	4,567	360	483	63	10,500	9,309	554	822	94
Nashville	4,105	1,205	168	232	55	7,623	2,389	240	371	66
New Orleans	518	529	37	78	11	1,105	1,192	57	111	13
New York	33,680	57,305	3,526	3,896	405	129,215	213,473	8,783	12,045	924
Oklahoma City	612	663	51	125	18	1,365	1,327	76	171	20
Orlando	2,986	2,647	238	312	45	6,210	5,587	357	519	61
Philadelphia	6,997	11,870	763	945	98	18,216	30,056	1,335	1,904	156
Phoenix	11,152	7,450	624	694	101	25,152	15,255	962	1,237	153
Pittsburgh	1,646	2,645	154	220	24	3,624	5,770	235	354	31
Portland	16,533	10,728	980	875	138	54,653	36,306	2,229	2,586	266
Providence	1,656	3,014	183	283	28	6,652	11,322	457	812	60
Raleigh	2,374	1,860	151	196	29	4,818	3,831	223	329	39
Richmond	761	853	61	134	16	1,772	1,924	98	217	22
Riverside	13,580	22,628	1,529	1,452	164	32,502	52,085	2,485	2,790	229
Sacramento	11,792	12,607	951	865	119	26,763	29,202	1,542	1,678	162
Salt Lake City	2,769	2,017	172	199	33	5,613	4,507	261	347	42
San Antonio	1,400	1,858	102	200	21	3,043	4,327	160	327	29
San Diego	27,986	24,540	1,824	1,646	223	63,289	56,749	2,972	3,301	329
San Francisco	81,951	55,710	4,791	4,101	573	187,038	124,870	7,779	8,368	901
San Jose	64,359	37,908	3,631	2,732	392	147,045	82,573	5,865	5,553	600
Seattle	28,451	12,933	1,704	1,561	311	59,544	27,937	2,656	2,906	414
St. Louis	3,016	2,445	198	321	46	6,577	5,079	301	520	62
Tampa	3,538	4,075	265	408	43	7,904	8,126	393	666	68
Virginia Beach	1,437	1,347	101	182	30	3,724	2,856	170	306	40
Washington	14,150	17,205	1,342	1,502	181	41,097	48,974	2,636	3,597	333