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LESSONS LEARNED ON EARLY ELECTRIC VEHICLE FAST-CHARGING DEPLOYMENTS

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EXECUTIVE SUMMARY

Many barriers to electric vehicles are incrementally being overcome. Falling battery costs help address the initial cost barrier and increasing availability of electric vehicle models of different types is attracting more prospective vehicle owners. The development of sufficient charging networks, however, is a work in progress. Although regular at-home charging remains one of the great advantages of electric-drive technology, it does not fulfill every charging need, and a mix of workplace charging, public charging, and fast charging is needed to extend range and increase charging access to those customers with no home charging.

Our report focuses on lessons learned from fast-charging deployments in many markets around the world through mid-2018 and on the usage by battery electric vehicles (BEVs). The report reviews recent developments in fast-charging technology and also the amount and distribution across major electric vehicle markets. The study also summarizes research into the impacts on the electric grid under increasing electric vehicle demand, and approaches to mitigate any associated issues. We also review planning issues related to fast-charging station use and siting strategies, as well as cost and business cases for the deployment of fast-charging stations. Based on this review, we make several conclusions and present several associated policy implications.

Early lessons learned in fast-charging deployment. With this analysis, several high-level lessons emerge. First, key determinants for how much fast charging will be needed are uptake of fast charge-capable electric vehicles, the electric ranges of vehicles, and the extent to which slower home, public, or workplace charging is available. The highest electric vehicle uptake markets, such as Oslo, Norway, and San Jose, California, show lower observed ratios of fast chargers per electric car compared with many less developed markets across Europe and the United States. These leading markets demonstrate how, as electric vehicle markets grow, more vehicles can better utilize existing chargers. However, there are differences between countries suggesting that the number of chargers needed must be adjusted to match local conditions. Comparing the two top markets of San Jose and Oslo shows there is a smaller number of fast chargers per BEV at this point in San Jose. Access to home charging, workplace charging, and other slower public charging that varies from region to region suggests a possible explanation for the differences in observed fast charging-to-BEV ratios.

Amount of fast charging needed in early and mainstream markets. There is great uncertainty about exactly how much fast charging will be needed in the future. Despite this, there is a clear trend toward initially needing more fast charging to obtain extensive geographic coverage and region-to-region connectivity. Based on leading electric vehicle markets and future-looking studies, the ratio of electric cars supported per fast-charge point increases over time from less than 100 electric cars in most markets in 2017, up to at least 700 electric cars being supported per fast charger as the market grows and electric range increases. To put this in perspective, a large auto market could have electric vehicle market growth by a multiple of 40, whereas the fast-charging network needed to support this increase would have to grow by a factor of 3. This is an important result: The number of fast chargers will need to greatly increase as the electric vehicle market grows, but the required increase in fast charging will be less than proportional to the increase in electric cars, as stations become better utilized and charging speed increases. However, if more new electric car buyers lack home charging or other slower charging options, more fast charging would be needed, especially in population centers. Outside urban areas, highway fast-charging networks are important to increase the attractiveness of purchasing BEVs and confidence in their use. But growth in their usage is likely to be slower and may require more initial government and utility support.

Gaps in fast-charging infrastructure development. The research reveals several gaps in the build out of fast-charging networks. Emerging trends show a small but growing number of users using fast chargers very close to home. Studies suggest these users have more limited access to home charging. Urban fast-charging plazas help address the needs of these users and complement the need for continued installation of better home, apartment, and workplace charging. Where investments are directed toward increasing access to charging in communities that are typically without home charging, urban fast-charging plazas appear to be an appropriate candidate for these investments. From examples in Norway, the Netherlands, Canada, China, Japan, Germany, the United Kingdom, California and others, we see that improved coordination among the government, industry, and utilities can help to pave the way for rapid deployment of fast charging to support current and future electric vehicles.

Emerging promising and uncertain business cases. The business case for fast-charging investments is improved when electricity cost is well below the equivalent price of gasoline. This allows station operators a profit margin to cover capital and operational costs. High utilization rates help offset high fixed monthly electricity costs in the case of demand charges. Urban sites are more likely to see higher usage, driving down prices while still being profitable. The ideal electricity price would be set to allow electric vehicles to compete with gasoline on per-mile costs and still allow a positive business case. This means the solution will be region-specific, involving setting the right fast-charging price and matching the growth of fast charging to electric vehicle demand. When charging revenue is lower than the cost to build and operate, improved business cases have so far been achieved through several strategies. These strategies include automaker investments in fast-charging networks that increase the value of a vehicle, such as with Tesla's Supercharging network; networks that cross-subsidize low performing sites with higher performing ones, such as with EVgo in the United States; and government grants that share in the early costs to reduce cost recovery requirements at low-utilization sites, such as with the West Coast Electric Highway.

Addressing uncertainties to help spur investment in fast charging. There are many factors that influence how many fast chargers are needed to support the market. The most fundamental uncertainty in all the fast-charging questions is how to plan for the changing electric vehicle technology and its uncertain uptake. Better electric vehicle projections, factoring in minimum compliance with regulatory frameworks, would provide much greater certainty to plan for expanding the electric vehicle fast-charging networks. This requires analysis of future year-by-year electric vehicle penetration, including low-to-high approximations through 2025–2030 that match regulatory goals. In addition, improved local-level analysis is important to factor how mainstream consumer uptake may be more concentrated in markets with greater local and provincial policies to accelerate electric vehicle uptake. Estimates of vehicle volumes can be further disaggregated into the electric ranges and charging speed capabilities of those vehicles to provide a basis from which to create scenarios regarding the appropriate mix of fast charging and slower home, workplace, and public charging.

I. INTRODUCTION

The electric vehicle market continues to grow, representing more than 1% of the global new passenger vehicle market and more than 5% in several leading regional markets in 2017. These vehicles have the potential to significantly reduce greenhouse gas emissions and air pollution, leading many governments to support their adoption with a wide array of policies. Falling battery prices and continued government support are moving electric vehicles into the mainstream; nonetheless, barriers of cost, convenience, and consumer awareness remain.

Among the benefits of electric vehicles is the ability to recharge the vehicle's batteries from any outlet location, including at the driver's home. Regular, overnight charging can satisfy most daily driving, frequently at lower cost than fueling a comparable gasoline-powered vehicle. On the other hand, the extensive, standardized network of gasoline fueling stations provides seamless support for daily as well as longer-distance travel. Such a network for electric vehicles has only developed in a limited and partial way, primarily in early-adopter electric vehicle markets and with public support. In order to develop "range confidence" for electric vehicle drivers, governments and private companies alike are working to deploy charging infrastructure in various settings. In a 2017 survey, automotive industry executives stated that charging infrastructure was the greatest long-term challenge for electric vehicles, and that comprehensive, user-friendly urban and long-distance charging networks are a precondition to growth of the market (KPMG, 2017).

Figure 1 shows the growth in electric vehicle sales and total public charging station construction worldwide, including all charging types and speeds, indicating the close connection between these two trends. Through 2017, approximately 3.2 million electric vehicles were sold worldwide, along with more than 400,000 public charging stations installed. Numerous studies have confirmed the importance of public charging infrastructure, linking its availability to electric vehicle uptake (Hall & Lutsey, 2017; Harrison & Thiel, 2017; Slowik & Lutsey, 2017; Sierzchula, Bakker, Maat, & van Wee, 2014). Some have suggested that fast charging is a stronger driver of uptake than Level 2 charging (Neaimeh et al., 2017). Many of these studies also typically show that public charging infrastructure availability, be it in absolute numbers in given markets, per capita, or per electric vehicle, varies greatly across markets. The figure illustrates that charging and electric vehicles are growing in unison in the major markets of China, Europe, and the United States. It is also clear that there is not yet any universal benchmark to help predict the precise amount of charging needed as electric vehicle deployment continues to increase.

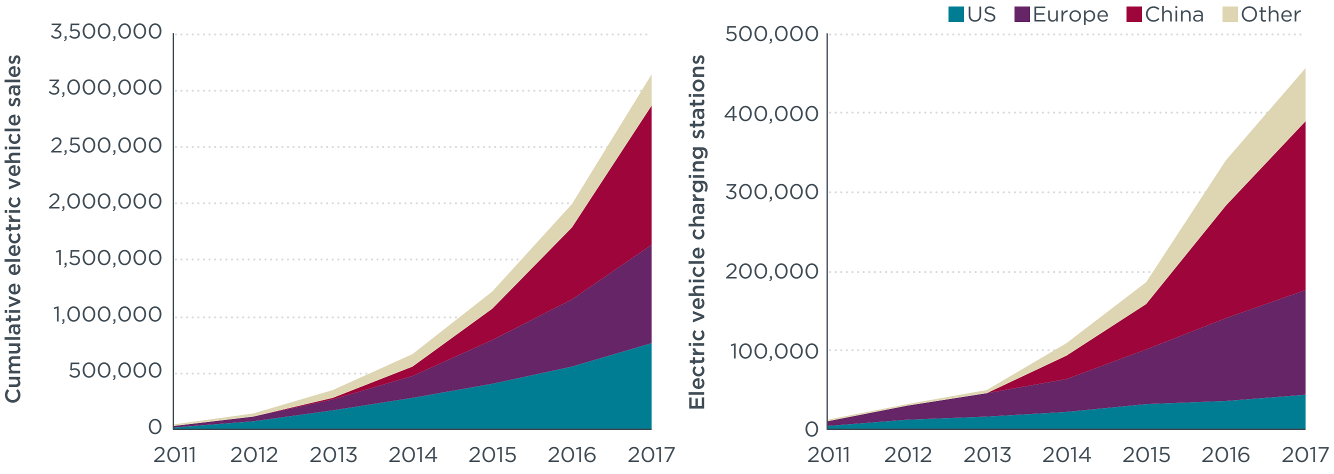


Figure 1. Global electric vehicle sales and charging infrastructure deployment by region through 2017.

Figure 1 also broadly shows that growth of infrastructure has developed differently in different regions, highlighting the need to investigate these differences and identify early lessons learned. As with the electric vehicle market overall, fast-charging technology is continuously evolving, and costs are falling as experience grows. Nonetheless, these charging stations currently account for only a small percentage of total public charging installations worldwide—ranging from about 2% in the Netherlands to 40% in China—and face barriers such as high upfront cost, high operating costs, standards fragmentation, and potentially high demands on the power grid (Hall & Lutsey, 2017).

With many thousands of fast-charging installations in place worldwide and several times more fast chargers on the way, what lessons can be learned and applied to future installations? In this report, we discern lessons learned from fast-charging projects around the world, including such topics as the grid impact of high-powered direct-current fast charging, upfront and operational costs, coordination with electric power utilities, optimal planning for fast-charging networks, and user data from already installed fast charging. We also discuss the roles that fast charging plays in different electric vehicle markets. From this analysis, we distill lessons and best practices to help guide future fast-charging deployments.

II. STATE OF FAST CHARGING IN 2018

Fast charging has evolved continuously since its introduction. In this section, we provide background on the role of fast charging compared to other charging options, a brief overview of current and future standards for fast charging, a review of current numbers of fast chargers, and consumer prices. We also highlight future fast-charger deployment schemes.

FAST CHARGING IN CONTEXT

Typically, as the speed of a charger increases, so does its cost, prompting the need to weigh where the benefits of fast charging outweigh the costs of slower charging. We start by examining what role fast charging plays in the electric vehicle charging ecosystem. The role it plays in the ecosystem is idealized in a charging pyramid, depicted in Figure 2 where fast charging is distinct from other slower charging. The charging pyramid concept loosely defines where electricity has been dispensed for users in the current market, with many drivers primarily using home charging (Santini et al., 2014). This representation is not applicable to a single user, but represents the location where electricity is dispensed for the entire market. Users with no home charging will have no home charging component and will increase the proportion of the other categories. Charging at home, at the workplace, and at other publicly accessible locations is assumed to be at Level 1 or Level 2 in the United States, modes 1–3 in Europe, and public alternating current (AC) in China.

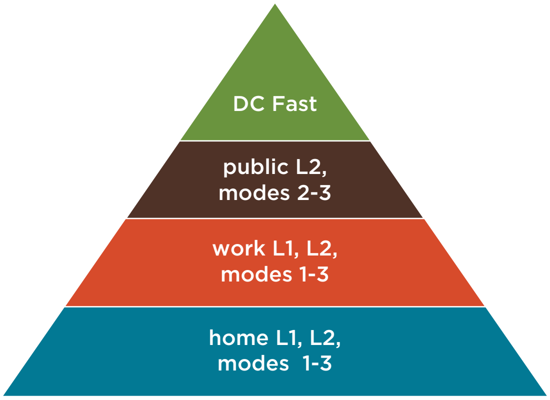


Figure 2. Charging pyramid defined by charging location and speed.

In a setting where home charging is available, ideally everyone would first charge at home, and then when necessary at the workplace or in public to complete needed travel. Only for long trips where range is exceeded and desired parking time is short would fast charging be used.

However, an idealized charging model of course does not match the complex driving and charging patterns for all electric vehicle owners. This is the case for many reasons. For example, when home charging is not available, some use public charging, work charging, or fast charging (Nicholas & Tal, 2017). Similarly, when workplace charging is not available, charging that would have occurred there is done in public or at fast chargers. There are also other possibilities such as neighbors sharing home chargers. These dynamics show that there is not one solution to charging needs and that if one charging location type is insufficient, demand will increase for charging elsewhere. In addition, many drivers value their time and may respond differently to the prices of charging at various places. A survey from the UK found that most users would prefer to use fast chargers over Level 2 chargers for both inter- and intra-urban travel (Blythe et al., 2015). If and when fast-charging monetary costs are perceived as especially low, public fast charging becomes more likely (Nicholas & Tal, 2017). Another factor is the value of the time saved from fast charging, as often time savings are not explicitly costed in electricity price or network membership pricing models (Bedir, Crisostomo, Allen, Wood, & Rames, 2018). These dynamics all help to motivate this study of early fast-charging deployments.

Several different fast-charging technologies are in use across global markets. Fast charging, as assessed in this paper, is defined as any power level over 36 kilowatts (kW) that is direct current (DC). This excludes the household AC power levels, which can reach 22 kW in Europe and 19 kW in the United States (Society of Automotive Engineers [SAE], 2017). We also exclude AC fast charging, which can reach 43 kW, as there are only a few models that use it, and it is unlikely to increase in power. Fast charging is mostly related to battery electric vehicles (BEVs), which use no gasoline; however, we note that the Mitsubishi Outlander and BMW i3 range extender plug-in hybrid electric vehicles (PHEVs) are exceptions. They can use both gasoline and fast charging.

There are two main organizations that define plug types and power levels, the International Electrochemical Commission (IEC) and the Society of Automotive Engineers (SAE). These categorizations of charging levels and modes are defined in Table 1 and Table 2 below. In this section, we focus on the connector types (plug form factor) and power levels currently available and proposed. Although some refer to fast charging as Level 3, this nomenclature has had a different technical meaning in SAE's classification, so we avoid this terminology and instead use the term fast charging or direct current fast charging (DCFC).

Table 1. Characteristics of charging levels as defined by the SAE and charging modes as defined by the IEC.

Charging level	Voltage	Charging mode	Protection type	Typical power	Setting
Level 1	120 V AC	-	None or breaker in cable	1.2–1.8 kW AC	Primarily residential in North America
Level 2	200–240 V AC	Mode 1	None	3.6–11 kW AC	Wall socket in Europe; primarily for 2- and 3-wheelers
		Mode 2	Pilot function and breaker in cable	3.6–22 kW AC	Home and workplace with cable or basic station
		Mode 3	Pilot function and breaker in hardwired charging station	3.6–22 kW AC	Home, workplace, and public with hardwired station
Fast charging	400 V – 1000 V DC	Mode 4	Monitoring and communication between vehicle and EVSE	50 kW or more	Public, frequently intercity

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

There are five different types of DC fast-charging plugs that can transmit power above 36 kW. These plug types are referred to as CHAdeMO, the European Combined Charging System (CCS type 2, or sometimes referred to as "Combo"), the U.S. Combined Charging System (CCS type 1), Tesla, and GB/T. The CHAdeMO and Tesla systems are used in many markets, and the GB/T system is used only in China. New standards are enabling the maximum energy transfer rate for each plug type to increase. Table 2 shows the current power maximum and the future maximum power for each standard. This maximum power is obtained by multiplying the maximum voltage (V) by the maximum amperage (A). For example, the maximum voltage for CCS is 1,000 V and the maximum amperage is 400 A, enabling a maximum power of 400,000 watts (W) or 400 kilowatts (kW). The most common type of fast charger currently is 50 kW with 125 A and 400 V. The 150 kW chargers being introduced maintain the same voltage range, but increase the amperage to 375 A. The 150 kW chargers are listed as a maximum in Table 2 as it represents the maximum power at lower voltage.

Table 2. Current and future power levels of AC and DC fast charging.

Connector type	Regions used in 2018	Typical power in 2018	Maximum power in 2018	Proposed power
CHAdeMO	Japan, Europe, North America	50 kW	200 kW, 400 kW	-
CCS Europe	Europe	50 kW	150 kW, 400 kW	-
CCS North America	United States, Canada	50 kW	150 kW, 400 kW	-
GB/T	China	50 kW	237.5 kW	900 kW by 2020 (new plug)[a]
Tesla	Worldwide	125 kW	145 kW	200+ kW (potentially >350 kW no date specified[b])

[a] *See Yoshida, 2018*
[b] *See Musk, 2016*

In practice, a vehicle is unlikely to accept power at the maximum rate. Because a standard limits the current, when battery voltage is low either because of battery design or a low state of charge, the power delivered at maximum amperage is lower. For example, 50 kW chargers in practice often dispense no more than 40 kW depending on the vehicle and state of charge and maximum battery pack voltage. For this reason, 400 kW chargers are often referred to as 350 kW chargers and this terminology will be used.

Even when a charger is capable of providing high power, smaller battery packs are unlikely to be able to accept this much power. For example, if 350 kW power is available to a smaller 25 kWh pack, battery protection circuits will limit the current and the pack will not accept the higher power. No vehicle on the market in 2018 can accept 350 kW and technological progress must be made in battery cooling or chemistry to fully utilize a 350 kW charger. Vehicle hardware improvements to enable these higher fast-charging speeds could cost approximately $1,000, assuming no change in battery size (Burnham et al., 2017). However, the higher voltage 350 kW chargers can reduce voltage output and still charge present vehicle models at a reduced power.

Fast-charging speed is linked with developments in electric vehicle battery technology and vehicle range. The technology of battery chemistry and cooling limit how fast a battery can proceed from empty to approximately 80% recharged (the state of charge when charging rate generally reduces), currently ranging from about 38 minutes in a

Tesla Model S 100D using a 125 kW charger to 14 minutes in a Kia Soul electric vehicle (EV) using a 100 kW charger. Charging a battery with too much power could cause lithium plating and dendrite formation around the anode, permanently reducing capacity; at a pack level, it can cause cells to age at different rates and pack overheating (Ahmed et al., 2017). If the Kia Soul EV battery capacity were doubled it hypothetically could accept 200 kW, but would still be limited to a 14-minute charging time. This relationship between acceptance power and capacity is shown on a cell level in Figure 3. Battery packs in vehicles consist of many cells connected together, but each cell has a maximum charging rate.

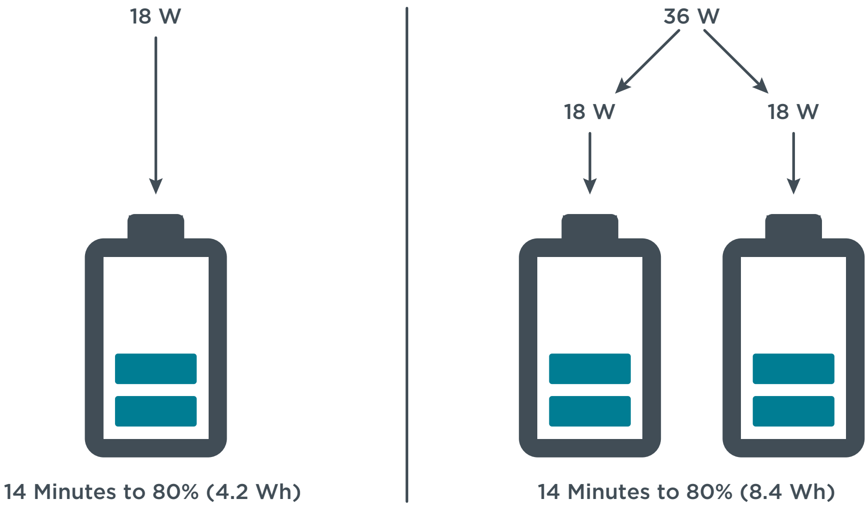


Figure 3. Doubling battery capacity by adding more cells increases the overall power a battery pack can accept, but charging time remains constant.

When battery pack capacity is increased, the ability to accept more power increases proportionally, but the charging time from empty to 80% remains constant. This simplistic doubling of capacity also assumes that the space for the battery is doubled, but in reality doubling capacity often involves arranging the battery cells more tightly, affecting the ability to cool the battery which slows charging time. For example, the Chevrolet Bolt has approximately double the battery capacity of the Soul, but does not allow for a maximum acceptance rate of 200kW, which would be double the Soul, reflecting the complexities related to cell arrangement and thermal management. This relationship between charging speed and battery capacity or battery technology is shown in Figure 4. Note that the relationship is not linear, and the horizontal axis has been adjusted to illustrate the relationship for the three battery packs. The current charging rate limit in power and time is represented by the gray dotted circles for three battery capacities in three vehicles: the Tesla Model S 100D with a 100 kWh capacity, the Chevrolet Bolt with a 60 kWh capacity, and the Kia Soul EV with a 30.5 kWh capacity.

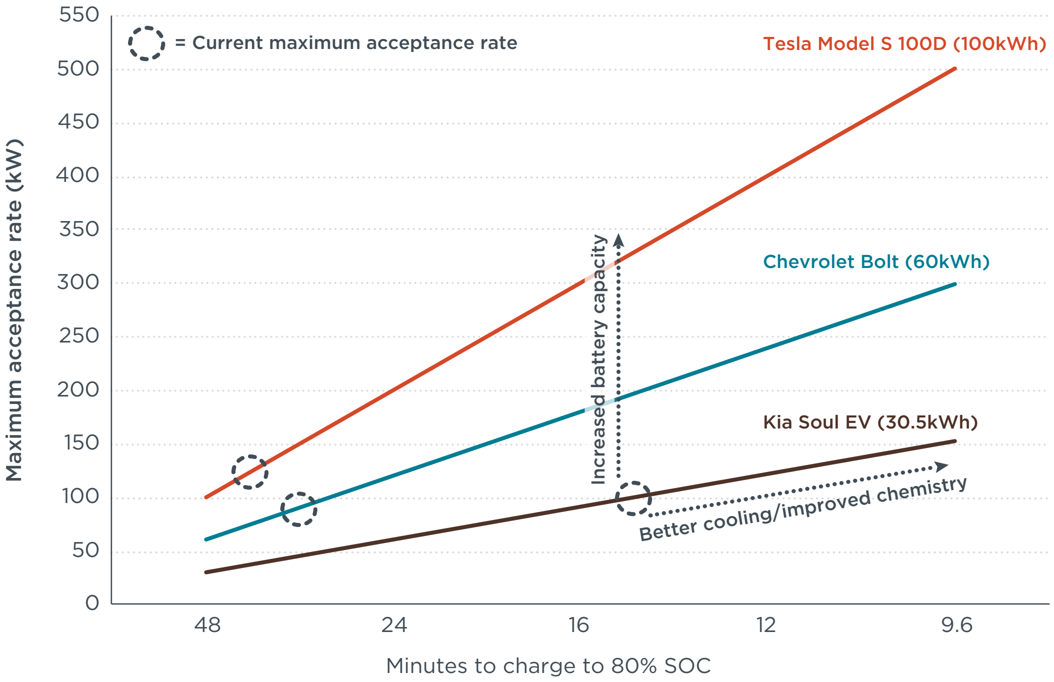


Figure 4. Relationship between maximum power acceptance rate of a vehicle versus battery capacity and pack technology with current vehicle examples.

In general, the “current maximum acceptance rate” circles in the figure represent more advanced battery pack design, more robust chemistry, or better cooling. Alternatively, it can represent more conservative battery management to preserve battery life. Tesla’s charging rate is fairly modest considering the large battery capacity. If the Kia Soul EV’s battery were scaled to the size of the Tesla Model S 100D, a 14-minute charge time would require 328 kW indicating that current battery designs can utilize 350 kW charging if the battery capacity is large enough. In general, because vehicle range is increasing, there is an increased ability for vehicles to accept higher charge rates. Based on a variety of industry announcements, using variants of current battery chemistries and battery pack designs, the time to recharge is expected to be reduced to below approximately 14–16 minutes to charge to 80%. Corresponding with these general goals, the number of vehicle models that are able to accept higher power is expected to increase in the next several years. However, charging to 80% is unlikely to fall below 10 minutes in the near term, meaning smaller capacity, shorter-range vehicles will not be able to use this power. In the longer term, technology improvements could enable higher charging speeds as well; possible improvements include alternative anode chemistries, more complex cell management to ensure even charging, higher pack voltage, and improved liquid battery cooling (Ahmed et al., 2017; Meintz et al., 2017).

For reference, gasoline has a much higher refueling rate. A gasoline vehicle with a 335-mile range and a gasoline efficiency of 25 miles per gallon would need 13.4 gallons. The maximum allowable refueling rate in the United States is 10 gallons per minute for a 1 minute and 20 second fill time. Assuming the EPA efficiency of a Tesla Model S 100D of 3.03 mi/ kWh and an all-electric range of 335 miles, the same refill rate as gasoline would require 4,950 kW, 14 times faster than the 350 kW chargers now being introduced. Many current gasoline vehicles have lower efficiency and not all pumps operate at the maximum rate meaning a longer filling time. A 3-minute fill time corresponds to a 2,195 kW rate using the previously stated assumptions.

The fundamental limitations of minimum fill time, independent of battery capacity, show that in the near term, many existing low-range electric vehicles will not be able to take advantage of chargers operating at 350 kW. A mix of charging speeds available at a charging site, controlling power output at a single charger, or sharing power among a group of chargers will usually satisfy the mix of vehicles that arrive with the ability to charge at their maximum power acceptance rate.

FAST-CHARGING STATION AVAILABILITY

Currently, there are major deployments of fast chargers worldwide. The growth in the number and location of fast charging has occurred organically or as a result of national plans. Figure 5 shows the number of fast-charging ports by country disaggregated by charger type in January 2018. Some double counting may occur as many fast-charging units have two ports, one for CCS and one for CHAdeMO, but only one port can be used at a time. In the San Francisco Bay area, 28% of stations are double-counted in this way (PlugShare, 2018). As shown, the availability of the three fast-charging types is relatively evenly split in each market. CCS is more prevalent than CHAdeMO in Austria, Finland, and Germany, while CHAdeMO is more common in all other markets, with the highest share in France and the United States. Tesla fast charging represented half of all fast-charging points in the United States outside of California and also made up a large fraction of charging in Belgium and France. China has the greatest number of DC fast chargers and uses the GB/T standard.

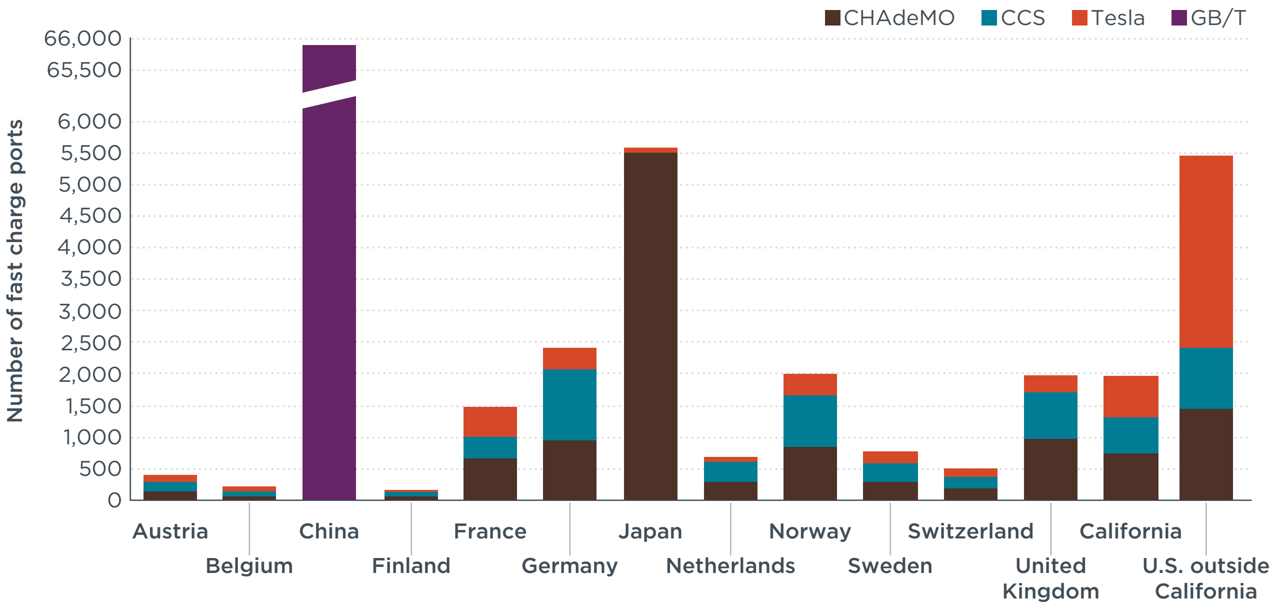
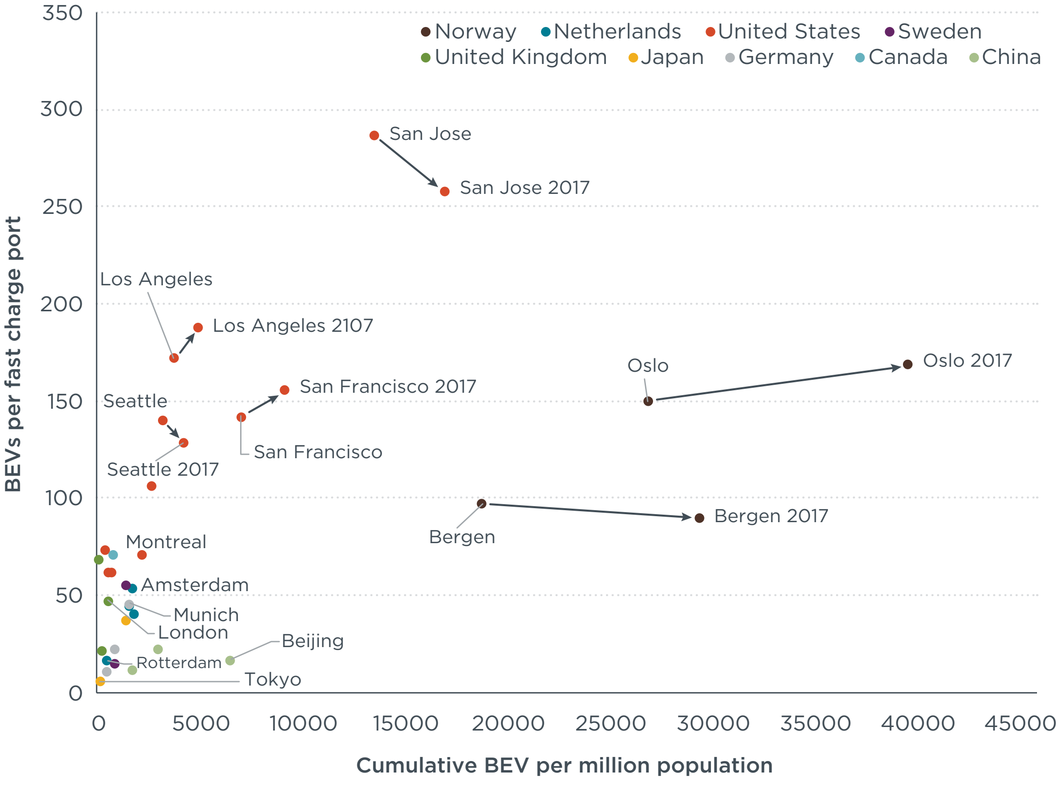


Figure 5. Number of fast-charge points in major electric vehicle markets by plug type as of January 1, 2018.

From the deployments so far, we can start to see patterns that are instructive in assessing what might be necessary for the future. As analyzed elsewhere, electric vehicle charging availability per capita in metropolitan areas provides an important measure of how extensive charging infrastructure is, and is statistically linked with electric vehicle uptake (e.g., Hall & Lutsey, 2017; Slowik & Lutsey, 2017). Metropolitan areas are defined according to various official designations that generally include a major urban center as well as surrounding counties or smaller cities that are located within the typical vehicle commuting radius. To better understand the emerging relationship for how extensive fast charging is, we examined electric vehicle markets in the United States, Europe, and Asia on fast-charging deployment and the total number of BEVs, which typically do have fast-charging capability.

In Figure 6, we present the amount of fast charging in select metropolitan areas. The metropolitan areas are those with the highest shares of new vehicles that are electric vehicles in cities in Europe, Asia, and the United States, based on Hall and Lutsey (2017). Although it is still very early in the growth of electric vehicles, these areas represent many of the leading markets. BEVs per DC fast charge port is displayed on the vertical axis, representing how many BEVs are supported by the available fast chargers. BEVs per million population residents in the area is on the horizontal axis and is a measure of the relative penetration of electric vehicles, adjusted for overall market size. The data are from 2016 except as noted. The arrows show the 2016–2017 trend. As shown, each fast-charge port supports about 260 BEVs in San Jose, California, compared to about 170 BEVs in Oslo, Norway.



Note: Arrows represent the development of the market from 2016 to 2017 for select markets.

Figure 6. BEVs per fast-charge point as a function of market penetration in select leading markets as of the end of 2016 (except as indicated).

Figure 6 points to several insights related to the development of early fast-charging systems. First, the figure suggests that, as the population of BEVs increases within a country, one fast charger can support more BEVs. This is evident looking at the U.S. points where one fast charger supports only 60–70 BEVs in a market with low penetration, but in more developed markets with more BEVs per million population, one fast charger supports more BEVs. This introduces the idea of coverage versus capacity. Initially, sufficient geographic coverage is needed even for a small number of vehicles (Wood, Rames, Muratori, Raghavan, & Melaina, 2017). Initial stations are likely to be underutilized. As the number of BEVs grows, the increased BEV population may pioneer new locations, but is likely able to more fully utilize the original locations. Eventually, a station reaches capacity at a location and instead of adding a station in a new location, additional fast chargers can be added to address capacity concerns in the same location.

Second, by adding 2017 data for several of the larger markets as shown by the arrows, we see an unclear trend from 2016–2017. Some markets saw an increase in the number of BEVs per fast-charge point and some saw a decrease. An increase suggests that chargers are being more highly utilized if all other factors remain constant. A decrease suggests lower utilization. The relationship is very sensitive to large deployments of chargers and some fluctuation in the general trend of arrows pointing upward is to be expected year over year. An increase in the number of stations, in general, provides better coverage and capacity for the consumer, but lower utilization decreases profitability for the operator.

Lastly, Figure 6 shows that different countries have different trends in the number of BEVs per fast charger. Intuitively, this makes sense, in that countries have differing local conditions such as the prevalence of home and public charging, different models available, and different metropolitan densities. Therefore, trends observed in one country cannot be applied wholesale to another country. However, lessons and benchmarks from one country may be more applicable in regions with similar demographics, geography, and vehicle markets.

Figure 6 shows a dynamic where the largest U.S. markets have more BEVs per fast charger than elsewhere. Electric vehicle markets in the United States are more typically composed of drivers who have access to home charging or work charging. This differs from markets in other countries, for example in Europe, that typically have denser urban areas, in many cases with more apartment dwellers without private dedicated garages with home charging. The same is true in Beijing, which shows a BEV-to-fast-charger ratio of 16:1 even though the BEVs per million population is similar to San Francisco and Los Angeles. If electric vehicle purchasing trends change, fast charger relationships could change in multiple ways. For example, with an increasing number of apartment dwellers without home-charging access or reliable public or workplace charging buying BEVs, fast charging per BEV might need to increase to handle demand. This highlights the importance of creating reliable slow charging for BEV drivers, but also the role fast charging can play if reliable slow charging is not available or is unreliable.

CONSUMER FAST-CHARGING COSTS

While fast-charging technology is becoming increasingly standardized around the world, the consumer experience and costs vary widely. In this section, we provide a brief review of current consumer costs and pricing structures in use in several markets.

Drivers pay for fast charging in different ways. Common pricing schemes include a cost per kWh, a cost per minute or longer period of time, an initiation or session fee, membership costs per month or per year, and discounts for vehicle type or being a utility customer. In some cases, station operators are allowed to charge only in specific ways due to local regulations. For example, in some jurisdictions only regulated utilities are allowed to sell electricity per kWh.

Figure 7 illustrates the effective user price per kWh in several fast-charging networks in North America and Europe. The vertical axis displays the effective price per kWh dispensed in 2016 U.S. dollars. The horizontal axis shows the average price per gallon of gasoline in the country of a fast-charging network, with selected countries labeled with vertical lines, as DC fast charging provides the experience most similar to gasoline refueling for longer-distance travel (Nigro, Welch, & Peace, 2015). We also include two lines to illustrate the equivalent electricity price at which driving a Nissan Leaf versus two similar-specification gasoline cars at a given gasoline price. We establish equivalencies between the vehicle energy cost per mile based on the consumer label energy consumption in kWh or gallons per mile. The upper (brown) line shows when driving a Nissan Leaf BEV is equivalent in cost per mile to driving a Nissan Versa gasoline car, while the lower (blue) line shows when driving a Nissan Leaf BEV is equivalent in cost per mile to driving a Toyota Prius gasoline hybrid car. Therefore, the lines show the boundary above which electricity prices shown represent a higher energy cost per mile in an electric vehicle than the gasoline alternative. Many of the networks considered in this figure offer memberships, where drivers could pay a monthly or annual fee in order to secure lower rates. In these cases, we amortize the membership cost over the estimated monthly kWh and add it to other costs. We display pricing for members (in yellow) and non-members (in red) to illustrate the rates experienced by different customers.

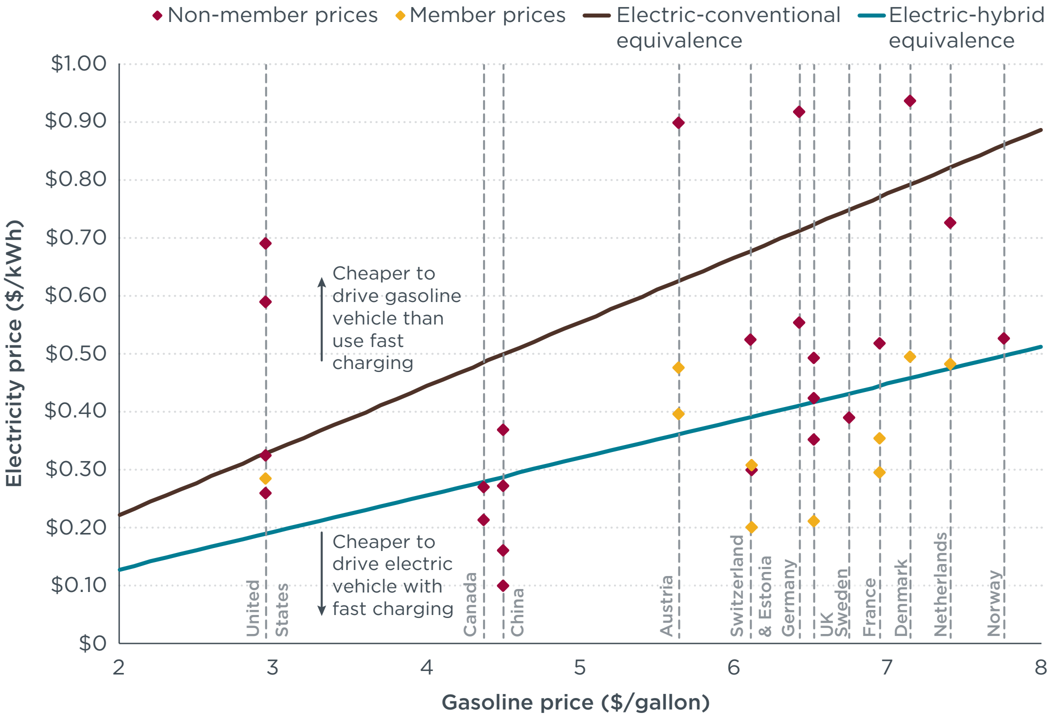


Figure 7. Fast-charging prices in U.S. dollars per equivalent kWh delivered in different fast-charging networks compared to the gas prices in each region.

In order to compare fast-charging networks with different pricing schemes presented in Figure 7, we made several approximations to account for how some networks levy fees monthly, by the hour, or by the kWh. We assumed the case of a frequent user with 20 sessions per month, with each charge consuming 12 kWh, equivalent to 240 kW monthly, at an average rate of 37 kW, the estimated average rate of a Nissan Leaf.

This figure shows there is a wide range of prices even within each market. In almost every case, the cost to fast charge is more expensive than typical residential rates, which are typically around $0.10–$0.20 per kWh in the United States and up to $0.30 in Europe, reflecting more expensive hardware costs, utility demand charges, and profits for the station operators. Fast charging at most stations costs more per mile driven than the cost of gas for a Toyota Prius gasoline hybrid, which gets 52 miles per gallon, and several networks have higher per-mile costs than driving a Nissan Versa gasoline car, which gets 29 miles per gallon. This situation is especially pronounced in the United States, where gas prices are lower; each of the networks surveyed—Tesla, EVgo, and Blink—had prices near or above the equivalent per-mile cost of driving a comparable gasoline vehicle. In Europe, where gas prices are generally much higher, many networks offered pricing schemes comparable to or cheaper than driving a similar gasoline-powered car on a per-mile basis. In general, membership subscriptions significantly reduce prices for these heavy users, and in all cases studied fast charging with a membership was less costly than the price of driving a conventional car.

As discussed, fast charging makes up only a small fraction of all electric vehicle charging and requires more expensive hardware and higher utility costs than Level 1 or Level 2 charging in most settings. Therefore, these costs are not surprising, and fast charging need not necessarily cost less per mile than alternatives so long as less expensive home, workplace, or Level 2 public charging options are widely available for everyday needs. However, if a user does depend on frequent fast charging because of a lack of other options, that user may be more cost sensitive than the occasional user. The complex and variable pricing structures found in our survey, shown in Figure 7, indicate that this also might present an uncertainty for consumers seeking to use these fast-charging networks.

MAJOR FAST-CHARGING DEPLOYMENT SCHEMES

Organized attempts at deploying DC fast charging have been carried out by government, utilities, auto companies, and private network companies. A review of these schemes and their frameworks provides important lessons applicable to future deployments.

One of the first deployments of DC fast charging was by the Tokyo Electric Power Company (TEPCO) (Anegawa, 2010). The utility placed DC fast chargers around the Tokyo metro area to provide charging options to utility employees on call around the city. Vehicle travel was monitored before and after the fast chargers were installed. A review of data showed that although the chargers were not extensively used, the drivers were much more willing to use a greater percentage of their range because they had a backup option. This study introduced the idea that the presence of fast chargers can improve range confidence, even when no charging takes place.

Tesla's Supercharger network was another early deployment that continues to grow, consisting of more than 9,000 superchargers worldwide as of early 2018 (Tesla, n.d.). This was funded by Tesla and showed the value of creating a comprehensive network to give range-confidence and increase the value of its vehicles. It was initially provided for free for life as a part of the purchase price of the vehicle. Although most customers used the stations rarely, the fact that they could drive their vehicle on long trips was a major selling point of the brand. Similar to the early study from TEPCO, this network showed the importance of coverage and access independent of the actual use of the network. Another important lesson learned is that free charging can create over-usage and because of this, new Tesla buyers are only given free Supercharger use to cover about 1,000 free miles each year, roughly equal to the number of miles a household travels on trips beyond 200 miles in a day (Nicholas, Tal, & Turrentine, 2017).

Another early deployment of fast charging was the EV Project funded by the U.S. Department of Energy. The total project budget was $225 million of which approximately $115 million was granted to provider ECOtality to deploy charging stations that included 69 fast chargers (Francfort, 2014). This project ultimately included five regions with fast chargers: Seattle, Washington, to Portland, Oregon; San Francisco, California; San Diego, California; Phoenix, Arizona; and Chattanooga, Tennessee. The network included a mix of intercity highway and intra-metro area stations. Initially the charging was free, but fees soon were added. This study began to highlight several themes: the challenging business case due to high demand charges for electricity in certain utility regions, the amount of increased use of stations based on free charging, and a maximum utilization benchmark of 400 events per month in Washington state.

Since these early deployments, many types of organizations have installed fast-charging infrastructure, often funded by government at the local, regional, or national level. In Europe, power companies have constructed large fast-charging networks; this includes private companies (e.g., EnBW and RWE in Germany) and state-owned networks (e.g., EDF's Corri-Door in France). In North America, private operators of charging networks are more prominent, securing individual agreements with site hosts and frequently implementing government-funded projects. In China, the state-run utility State Grid has constructed tens of thousands of fast-charging stations, and many smaller companies operate local networks in the quickly expanding market.

A number of major new fast-charging networks and installations have been announced around the world, providing indications about the future of the industry and technology. Table 3 summarizes plans in major markets around the world, including the number of charging stations, technical specifications, major funders or partners, and timeline. In addition to the deployments highlighted here, many additional programs have been announced by cities, utilities, and other governments. Furthermore, a number of governments have announced targets for fast-charging stations. In Europe, for example, most governments have prepared plans to provide electric vehicle charging infrastructure to support the market, including a goal of building fast-charging stations every 40 km on all major highways (Platform for Electro-Mobility, 2018). However, only those plans with funding and installation partners are included in this table.

Table 3. Characteristics of in-progress fast-charging deployments in leading markets.

Network name	Region	Number of fast chargers	Station types	Major partners and funders	Timeline
Electrify America	United States	About 1,800	CHAdeMO, CCS up to 350 kW	Volkswagen	Cycle 1 to be completed in June 2019, with activities continuing until 2027
Ionity	Europe (19 countries)	About 400	CCS up to 350 kW	BMW, Daimler, Ford, and Volkswagen with its subsidiaries Audi and Porsche	Under construction through 2020
Trans-Canada	Canada (Ontario and Manitoba)	102	CHAdeMO, CCS	Natural Resources Canada, eCamion, Leclanche, SGEM	In operation by early 2019
Porsche	United States	189 dealership locations	Unknown, 800 volts	Porsche (Volkswagen Group)	Unknown, likely to coincide with launch of Mission-E in 2019
State Grid	China	10,000 locations, 120,000 units	GB/T	State Grid	Completed in 2020, 29,000 stations in 2018
Rapid Charge Points for London	Greater London, UK	300	Unknown	Transport for London	150 by end of 2018, all completed by 2020
Ultra-E	Germany, Netherlands, Belgium, Austria	25 locations, 50–100 chargers	350 kW	Allego, Verbund, Smatrics, Bayern Innovativ, Audi, BMW, Magna, Renault, Hubject, European Union	Completed in 2018
MEGA-E	Central Europe, Scandinavia (20 countries)	322	350 kW	Allego, Fortum Charge & Drive, European Union	Construction from 2018–2025
NEXT-E	Eastern Europe (6 countries)	252	50–350 kW	E.ON, European Union, MOL Group, PETROL, Nissan, BMW	2018–2020

From this short summary, several trends become apparent. While fast-charging speeds have remained relatively constant at 50 kW since the introduction of modern battery electric vehicles, many new charging networks are installing much faster stations, typically promising 150–350 kW. These stations are coming online just as charging standards are updated to support these higher speeds, and vehicles capable of charging at higher speeds are expected to be released beginning in 2019. Nonetheless, many of the deployment plans are planning a mix of charging speeds within their networks (e.g., from 50–350 kW), indicating that different speeds are more appropriate for different settings.

Second, automakers are becoming increasingly involved in installing fast-charging infrastructure. In the past, several automakers including Nissan and BMW have contracted with third parties to provide free or discounted charging for electric vehicle drivers. Many of the future infrastructure deployments, however, are directly financed and planned by automakers or groups of automakers. Porsche is installing charging stations at all dealerships in the United States to support their electrification efforts

(Wilson, 2018). BMW, Daimler, Ford, and the Volkswagen group are each working in partnerships to install major networks across Europe (Ionity GmbH, 2017). Volkswagen is also installing thousands of stations across the United States through its Electrify America subsidiary as part of the settlement for excess NO_x emissions from diesel cars (Electrify America, n.d.). Tesla, which has operated proprietary fast charging stations since 2012, continues to expand the network globally, and is beginning to emphasize deployment within urban areas with dedicated high-density supercharging stations (Tesla, 2017).

Third, as previously mentioned, these new announced networks are much larger in scale than earlier installations, indicating growing confidence in the technology and its importance. Coupled with the growing adoption of open standards and streamlined payment options, this could improve the user experience for fast charging.

III. IMPACTS OF FAST CHARGING ON THE ELECTRIC GRID

Key questions about the impact of fast charging on the electric grid are related to the deployment of electric vehicles over time, how much and when they rely on fast charging, and whether the various fast-charging locations require electric grid upgrades. Figure 8 shows the three main parts to the utility system: generation, transmission, and distribution. Although electric vehicles will consume a significant amount of electricity when deployed in large numbers, it will nonetheless represent a relatively small share of total electricity demand. One study estimates that in 2050, electric vehicles representing 80% of the European Union's passenger vehicle fleet will consume 9.5% of the total electricity load (Kasten, Bracker, Haller, & Purwanto, 2016). On the other hand, distribution systems are the most likely to need upgrades resulting from electric vehicle charging, especially if demand for fast charging occurs at the period of other distribution loads. In addition, if energy is demanded at the same time as general system peak loads, transmission and generation may need to be upgraded. If electric vehicle market share grows gradually, new power generation and transmission upgrades needed may happen in the normal cycle of utility upgrades albeit at a slightly faster pace than if there were no electric vehicles.

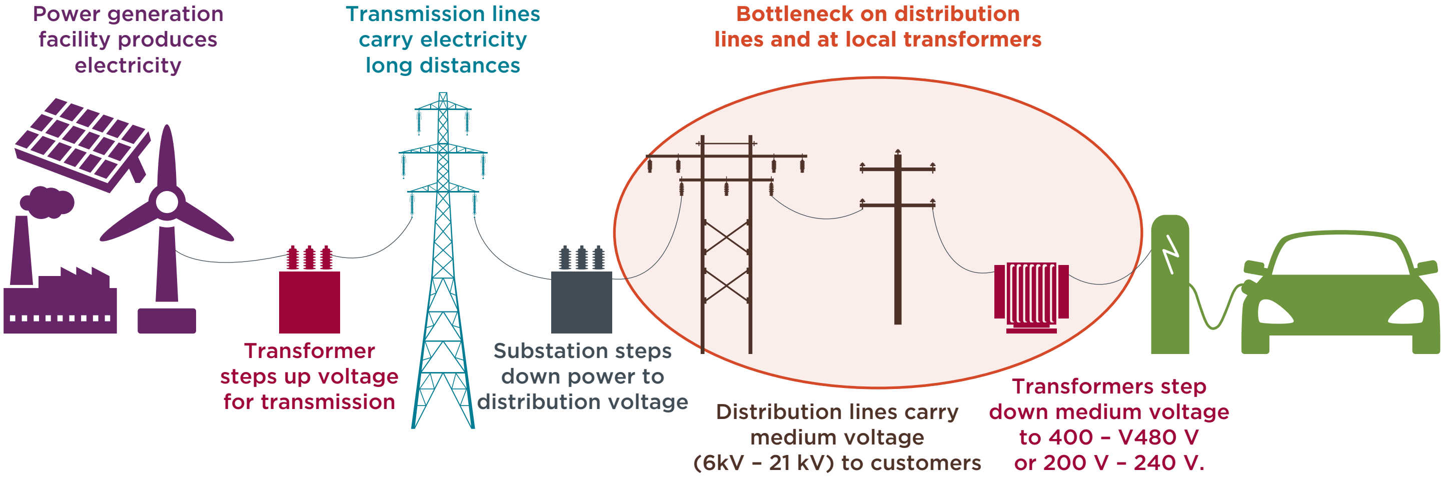


Figure 8. Schematic of the utility grid.

Figure 8 shows how electricity is delivered to the end customer. Power plants generate the electricity and increase the voltage as power is transmitted to the transmission lines. The transmission lines bring power to a substation near a population center to step down the voltage. At these substations, there is very likely to be enough power to handle any fast-charging load as it represents a small fraction of power demand. From the substation, the power is delivered at medium voltage of 6,000 V to 21,000 V (6 kV – 21 kV) in the United States and Europe to smaller transformers, which step down to the appropriate voltage for connecting a fast charger, usually 480 V three-phase AC in the United States, 480V-600V in Canada and 400 V AC in Europe. This AC is then converted to DC in the fast charger to match the battery voltage of the vehicle.

Studies suggest that except for a few hours during the year on exceptional days, power plants, transmission lines, and substations are likely to be able to handle the load from fast chargers (California Public Utilities Commission [CPUC], n.d.). Instead, the distribution lines and the final transformers are the most likely to require an upgrade to accommodate fast chargers. A typical Electrify America highway installation with two 350 kW chargers and four 150 kW chargers would total 1,200 kW, representing 5%–10% of the maximum load of a distribution line in the United States. Although a few 50 kW chargers can frequently be added to an existing transformer, an additional 1,200 kW would likely require an upgraded or a separate transformer off the distribution line. In China, a specific example of 27 residential communities showed that when the share of vehicles reached 20% electric, 21 of the 27 communities needed to upgrade distribution transformers to handle fast charging and 12 out of 21 commercial buildings needed this upgrade. One community and five commercial buildings needed to upgrade the 10 kV distribution line (Li, 2016).

In the UK, the National Grid utility studied 50 strategic locations along highways where sites of up to one hundred 350 kW chargers could be located creating a potential demand of 35 megawatts per site (Evans, 2018). These sites generally matched well with the nation's high-voltage transmission network. Together, utility upgrades for these 35,000 chargers would cost 500 million pounds to 1 billion pounds, or 14,285–28,571 pounds ($20,328–$40,653) per charger.

A study on fast-charging stations in the Ottawa, Ontario, region also provides insight into the scale of utility upgrades needed (Ribberink, Wilkens, Abdullah, McGrath, & Wojdan, 2017). Overall, it was estimated that fast charging would account for approximately 1% of total electricity consumption in the city in 2037 but up to 2.5% of peak demand. The study considered three representative station locations and found that grid connection costs ranging from $46,000 to $120,000 for an eight-station (150 kW each) plaza, with prices reduced by approximately 25% for 50 kW stations and increased by 25%–50% for 400 kW stations. None of the locations required distribution grid upgrades for peak capacities of under 1,600 kW, which consisted of four 400 kW stations. However, for fast-charging plazas with more than 1,600 kW, upgrade costs reached as much as $390,000 for some sites.

A 2016 fast-charging utility study in the Pacific Gas and Electric territory in California provides an indication of the scale of upgrades needed (Pacific Gas & Electric [PG&E], n.d.). The study analyzed how much fast charging was needed to comprehensively cover a territory and if sufficient capacity existed at current transformers to handle a scenario of 807,266 BEVs in 2025. The results of how many locations could be accommodated with 50 kW fast chargers are summarized in Table 4.

Table 4. Pacific Gas and Electric analysis of distribution capacity for fast charging.

Category	Generalized locations	Fast-charging ports
Number needed	300	574
Number met with existing capacity	206	447
Percentage needing additional capacity	31%	22%

At the 14,416 possible addresses near the 300 generalized locations, more than 6,000 had capacity for two or more 50 kW chargers with no transformer upgrades. At the more than 6,000 addresses, there was existing transformer capacity for more than 51,000 fast chargers (50 kW). Although this is a very large number, the capacity was unevenly distributed and the capacity was diffuse and did not allow for a high-power, multi-charger plaza without upgrades. In cities, there was almost always an address within a mile of the target location with capacity. But in areas farther from a business district, including in rural areas, transformer upgrades sometimes were needed. Approximately 31% of locations fit into this group needing additional transformer capacity. Cities were likely to require more ports per location, and because capacity was sufficient, only 22% of territory-wide ports required additional capacity.

This availability of transformer capacity within San Francisco is illustrated in Figure 9. A subset of the 300 general locations of demand are shown with a 1-mile (1.6 km) buffer. Likely sites for fast charging within those buffers including coffee shops, grocery stores, banks, movie theaters, and so on are evaluated for transformer capacity. Those with low transformer capacity are shown in white. Some buffers with few high-capacity options show many white dots because capacity filters for sites are removed. Those with spare capacity for two or more 50 kW fast chargers are indicated in blue.

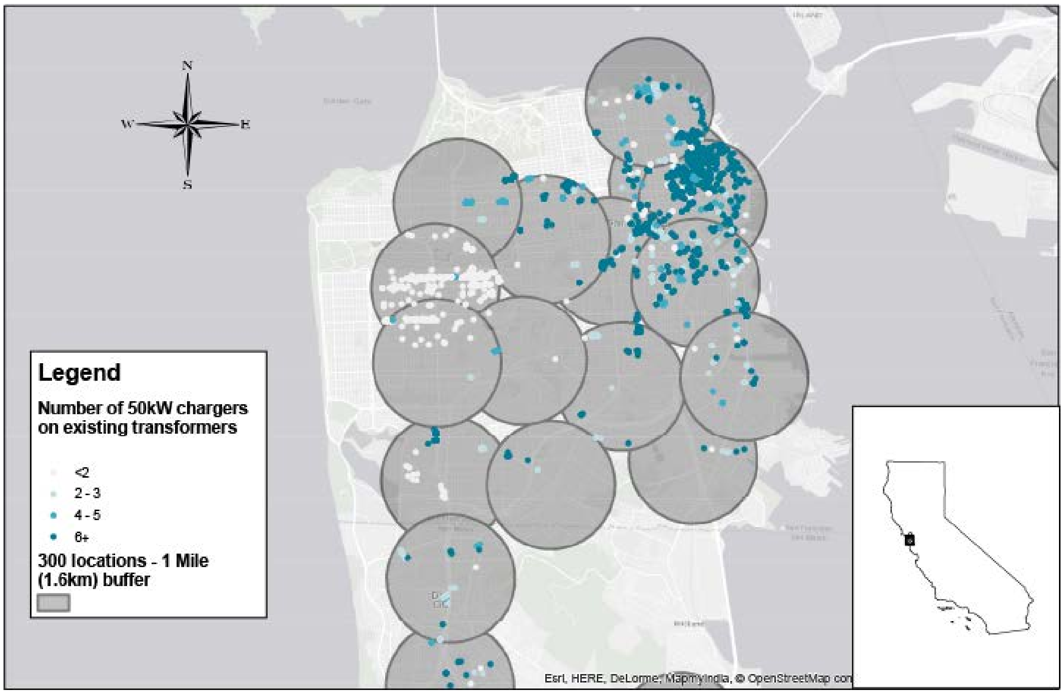


Figure 9. Transformer capacity at possible fast charging sites in San Francisco.

Figure 9 shows the unequal distribution of transformer capacity. In the central business district, there is ample capacity and many locations. In residential locations, there is less transformer capacity. This study did not include the need to serve those with no home charger, but these locations most often would be in cities where capacity exists. Although the above analysis is for the Pacific Gas and Electric service territory, similar such planning efforts are important to investigate needed upgrades in different utility territories. Studies such as this can provide transparency to potential host sites and even prepare the utility to encourage site development.

STRATEGIES TO MITIGATE FAST-CHARGING GRID IMPACTS

As outlined in the previous section, transformer and distribution upgrades are the most likely impacts to the grid from new fast-charging installations. These impacts can be mitigated with several strategies including choosing locations with low grid impacts, smart charging, and combining fast charging with energy storage. Larger system-level impacts including generation and transmission can be mitigated with time-of-use rates.

First, the locations at which fast chargers are located can be chosen based on abundant capacity and low cost of installation. As shown in Figure 9, some locations that are appropriate from a consumer perspective are not conducive from a utility perspective. Because vehicles can move to a location of high grid capacity, as opposed to the traditional utility model of bringing power to a particular location, the unequal distribution of capacity can be mitigated more easily, making the integration of fast charging easier.

Smart charging is when a vehicle can respond to signals from the utility grid to start, stop, or attenuate charging (Ashley, 2017). This sort of control can be accomplished if either the vehicle or the charger is communicating with the grid. In order to not exceed transformer capacity, limits on total power are common at fast-charging installations. At Tesla supercharging stations with multiple fast chargers at one site, when all chargers are occupied, the stations cannot operate at full power simultaneously. The power is shared such that the total power through the transformer does not exceed a threshold.

Combining fast charging with energy storage is a strategy to mitigate grid impacts, especially at the distribution level. During times of low utilization, the battery can be charged at a constant rate from the grid or from on-site solar. When vehicle power demand exceeds the transformer threshold, the stationary battery augments site power. This can mitigate grid impacts and reduce host site costs by avoiding utility demand charges (discussed further in Section VI). This strategy can result in significant savings for the station operator, especially as charging power increases. One estimate finds that a location with six 350 kW charging stations would achieve savings of $157,000 annually, paying off the initial investment in less than two years (Francfort, Salisbury, Smart, Garetson, & Karner, 2017).

Another grid mitigation strategy is a time-of-use rate where the rate for energy or power varies by time of day or by local grid capacity (Fitzgerald & Nelder, 2017). Whereas a higher price per kWh does not guarantee that a charge event will not occur on-peak, this strategy is helpful for distribution lines, transmission lines, and generator capacity as depicted in Figure 8. These assets are stressed on occasion and in the aggregate, a higher price at certain time periods will depress systemwide demand for fast charging, lessening the impact to the grid.

Utilities also are helping potential site owners with tools to help assess costs and mitigate grid impacts. Pacific Gas and Electric in California conducted a study looking at fast-charging demand projections along with existing distribution and transformer capacity at selected sites (PG&E, n.d.). It placed these transformer capacities on a web-based map available for potential site owners to assess possible upgrade and installation costs.

FUTURE-PROOFING OF FAST-CHARGING NETWORKS

The future-proofing of fast-charging networks requires consideration of upgrade timing as well as realistic estimates for lower and upper bound electric vehicle deployment. When installing a fast charger or group of chargers, utility upgrades often are needed. When sizing these upgrades, there is a risk of sizing only for the immediate future without considering the possibility for future growth. However, there is an opportunity to increase the growth potential of a site to save money in a future expansion phase. The best practice is to look at potential growth over the next 10–20 years for both the increase in the number of chargers and the growth in charging power (Francfort et al., 2017). The easiest and most inexpensive way to future-proof a site is to install the necessary connection points for future fast chargers and to plan for upgrades in the number and size of transformers. Standard utility practice is to swap transformers as more power is needed and/or add another transformer that supplies more capacity, but this process is made easier if it is planned for initially by creating space for transformers. Likewise, increasing the connection points to the transformers and conduit to future fast chargers is inexpensive so that when more chargers are added in the future, the cost is not as high as it would be for additional construction.

Another future-proofing strategy is to install chargers along long-distance travel corridors that can provide a high power, such as 350 kW, but limit the output power until it is needed. For example, a 350 kW charger can be limited to 150 kW or 50 kW to match the vehicle acceptance rate and transformer capacity. As more power is needed, the charger requires a simple software change and transformers can be swapped for larger ones.

IV. PLANNING AND LOCATING FAST-CHARGING INFRASTRUCTURE

There are many studies that examine questions regarding how many fast-charging stations are needed and the most appropriate sites at which to locate them. In this section, we review studies estimating the number needed and the methods used to give context for the estimates.

There are two basic approaches to determining the appropriate number of stations necessary to support a given number of vehicles through models: the coverage approach and the capacity approach. Each highlights two basic needs in a fast-charging network: freedom of travel and sufficient capacity to serve the number of vehicles that arrive. In their simplest form, coverage models consider the number of lane-miles or land area and a threshold for coverage is assumed, such as one station per 100 mi (160 km) along a road or per 4 square miles (10.4 square kilometers). Coverage models are important in a nascent network because even a small number of vehicles will desire freedom of movement throughout their area but estimates of chargers needed are less tied to the number of vehicles that will use them. Capacity models attempt to determine the number of people who will use charging services at a given location and are often used in conjunction with coverage models to adjust the number of chargers needed per location. Capacity models use various inputs to try to predict demand, but there is little agreement in the modeling on how to accurately assess this demand.

MODELS AND INPUTS FOR DETERMINING A SUFFICIENT NUMBER OF FAST CHARGERS

Even before the development of a significant electric vehicle population, modelers made estimates using assumptions about technology and customer behavior and these assumptions are adjusted over time to reflect new information. Modelling conducted in the 2010–2015 time frame assumed a vehicle range of 80–100 miles, home charging availability, and an assumption of fast charging being priced higher than any other form of charging.

Early model assumptions have not been universally true to real-world experiences in early electric vehicle markets. Vehicle range has grown, home charging or nearby public charging has not become universally available, and fast charging has been provided free in many circumstances. Other factors have also been found to affect usage of fast chargers such as the ability to switch to another vehicle for long distance travel (Nicholas, Tal, & Turrentine, 2017), lack of public charging (Nicholas & Tal, 2017), and a high value of time (Blythe et al., 2015). Table 5 shows new developments in the electric vehicle market not considered in most of the early models, with the directional effect these changes have on the demand for DC fast charging indicated by a plus sign or minus sign.

Table 5. New market developments relevant to capacity models and their qualitative impact on fast charging demand.

	Home charging unavailable	L2 work unavailable	L2 public unavailable	Vehicle range increases	Low priced dcfc	Alternate travel options available	Charging speed increase
Effect on the quantity of DCFC demanded	+	+	+	-	+	-	-

The scale of the effects is not shown here, but sensitivities are defined in other models and studies (Wood et al., 2017; Nicholas & Tal, 2017; Nicholas, Tal, & Turrentine, 2017; Ji et al., 2015; Francfort et al., 2017). With this context, Figure 10 displays estimates of fast-charging demand based on several different studies. As shown, charging demand varies widely depending on the assumptions used. As with Figure 6, the horizontal axis shows how many battery electric vehicles, relative to the population of the target area, and the vertical axis is the number of fast chargers per BEV. As shown, the estimates range from about 27 BEVs per fast charger to about 1,800 BEVs per fast charger. All of these studies have different assumptions on vehicle range and home charging availability. A clear conclusion from the chart is that there is great uncertainty about exactly how much fast-charging infrastructure is needed for a given number of future BEVs. Although there is great uncertainty, it is also clear the ratio of BEVs supported per fast-charge point gets higher over time. As shown in Figure 6, major electric vehicle markets had 50–300 BEVs per fast charger in 2016–2017 where there were up to 40,000 BEVs per million residents. Forward looking studies indicate that more like 700–1,600 BEVs can be supported per fast charger.

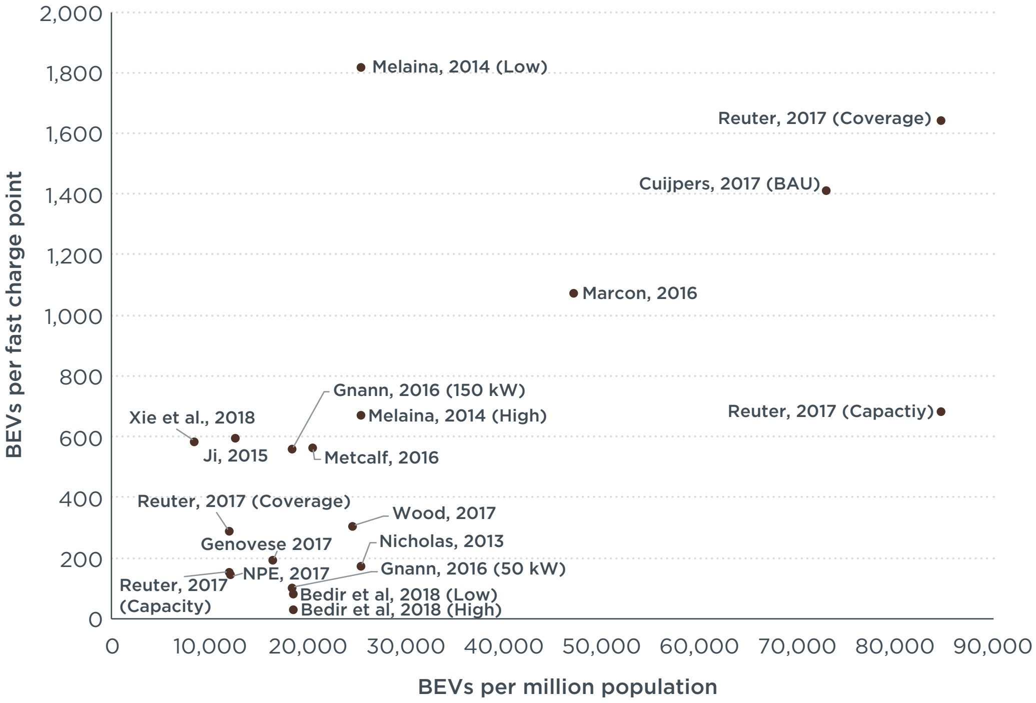


Figure 10. Estimates of BEVs per fast charger at various stages of market development in select models.

The ratios identified in Figure 10 vary widely in part due to differences in study methodologies and assumptions. Table 6 provides additional details on the selected studies and provides a brief description of their findings. In general, the time horizons used range from 2020 to 2035, therefore portraying very different states of market development. Additionally, they vary in the assumed fast-charging speed, from today's 50 kW up to 300 kW, and the types of vehicles, with some studies modeling a mixed fleet and other selecting only one type of BEV with a given range or battery size. The country context also makes a difference as each country has different travel patterns, access to home charging, and housing density. North America tends to be less dense with more automobile travel compared to Europe and much of Asia.

Table 6. List of studies identifying BEV/fast-charge point ratio and key assumptions.

Study	Region	Coverage	Capacity	Year	Charging power	Vehicle fleet	BEV/ DCFC ratio	Key Message
Bedir et al., 2018	California	X	X	2018	50–105 kW	Mixed BEV 120-210	29–80	Uses California household travel data to determine charger location and capacity
Cuijpers et al., 2016	Netherlands	x	x	2030-2035	100 kW average, up to 300 kW	BEV100	1,409–2,331	Considers scenarios of uptake and infrastructure with autonomous, renewable. Only includes corridor fast chargers.
Genovese et al., 2017	Italy	x	x	N/A	50 kW	Mixed up to 60 kWh	190	Uses GPS data to estimate fast charging needs for Rome electric vehicle drivers.
Gnann et al., 2016	Germany		x	2030	50–150 kW	40 kWh battery	100–556	Models fast charging needed to prevent queuing with various charging speeds, based on a goal of 1.5 million BEVs in Germany.
Ji et al., 2015	California	x	x	2025	50–150 kW	Mixed between BEV80 and BEV300	593	Models demand in California considering different vehicle ranges and charging technologies.
Jochem et al., 2016	Germany	x		2020	Unknown	Mixed BEVs	152	Models demand for DCFC along the Autobahn based on two methods, coverage and traffic, and assessed costs
Marcon, 2016	Canada	x		2025	50 kW	Mixed fleet with increasing range	1,072	Focuses on profitability of stations in different settings
Melaina, 2014	California	x	x	2020	50 kW	BEV100	667–1,815	Plans infrastructure to accomplish California's EV uptake goals, including public, private, and workplace charging for different scenarios.
Metcalf, 2016	California	x	x	2025	Up to 120 kW	BEV100 and 200	563	PG&E utility assesses DCFC grid impacts in California and mitigation strategies
Nicholas et al., 2013	California	x	x	2025	50 kW	BEV80	169	Assumes fast charging as only public charging option for statewide travel across California based on survey data
German NPE, 2015	Germany		x	2020	50–150 kW	Mixed fleet	141	Creates comprehensive set of recommendations to enable 1 million BEVs in Germany. Fast chargers primarily for highways.
Reuter-Oppermann et al., 2017	Germany	x	x	2030	50–130 kW	BEV200	152–1,639	Compares coverage and capacity approaches to the needs for the German Autobahn up to 2030.
Wood et al., 2017	United States	x	x	2030	150 kW (central)	Mixed fleet (up to 250 mile range)	300	Models infrastructure needs for urban and rural areas nationwide. Reaffirms that home and workplace charging are primary
Xie et al., 2018	California	x	x	2025	50 kW	BEV100 (baseline), BEV75-300	583	Examines needs for inter-city fast charging in California. Adding multiple chargers per station is preferred. Charging needs depend strongly on vehicle range.

One notable study in Germany illustrates the potential difference between the coverage and capacity methods and provides two estimates of PEV penetration for a total of four estimates of the number of chargers (Reuter-Oppermann, Funke, Jochem, & Graf, 2017). Looking at the two capacity model estimates, we see a good illustration of the effect of how greater utilization results in one fast charger being able to serve more vehicles when fully utilized. It shows that when queueing time is considered, more chargers are needed to reduce that time. The capacity model by Reuter-Oppermann for 85,000 BEVs per million population shows a ratio of about 700 BEVs per fast charger. In this formulation, all users are satisfied and have to wait no more than 5 minutes to begin charging. They also present a scenario to serve 1 million users (12,000 BEVs per million population) and estimate approximately 150 BEVs per fast charger. Reuter-Oppermann uses an electric range of 200 miles for calculations, about double that of other models, and assumes 50 kW fast charging in the near term and 130 kW chargers in the long term. The coverage model, on the other hand, provides nationwide connectivity but is not closely connected to the number of drivers served. This shows the importance of adding a capacity correction factor in coverage models.

Wood et al. (2017) assumes universal home charging, but provides sensitivities for the number of chargers needed as a function of vehicle range, preference for fast charging over home charging, station spacing, urban versus rural uptake, and charging power. The greatest increases are a result of a preference for shorter range vehicles and the preference for public charging over home charging. This study employs a coverage strategy first to ensure minimum coverage and then adds capacity where necessary to the coverage network. The “central scenario” assumes 2,500 chargers on interstate corridors and a BEV-to-fast-charger ratio of 333:1 in cities, 227:1 in towns and 161:1 in rural areas. This generally shows that denser areas can provide basic coverage with fewer chargers.

Bedir et al. (2018) creates a California statewide infrastructure analysis and has the lowest BEV-to-fast-charger ratio ranging from 29:1 to 80:1. This is a large number of chargers relative to the number of BEVs compared to other studies. The study proposes to examine the needs of “mainstream drivers” as opposed to early adopters. The study includes the preference for fast charging over Level 2 and also includes scenarios for serving those with no home charger with fast charging. In the high scenario they assume two events per fast charger per day, considerably fewer than the maximum of 10–13 observed in usage studies. Additionally, they size the network for peak usage such as might be experienced on Friday evenings driving the estimates higher.

Ji et al. (2015) shows the effect that range has on the number of chargers needed with longer range vehicles generating fewer events than shorter range vehicles. The estimate of 593 BEVs per fast charger is an average assuming a mix of ranges of 80 miles (129 km), 150 miles and 300 miles. However, if all BEVs were BEV80s, the requirement would be 169 BEVs per fast charger, and for BEV300s the requirement would be 3,333 BEVs per fast charger assuming one charger is used 10 times per day, which in turn assumes faster charging for longer range vehicles. The need for fast charging is not linear with range because travel days of around 300 miles are fairly rare. Ji et al. (2015) assumes universal home charging.

Other studies shown in the figure use similar methods to estimate charging demand and are described in Table 6. The general consensus of 200–600 BEVs per fast charger may be primarily due to the fact that traffic patterns have similarities around the world and that models based on determining how often BEVs would run out of range based on these traffic patterns will have a central convergence. Other assumptions that modelers chose to incorporate, such as those listed in Table 5, will increase or decrease these estimates.

Combining the findings from Figure 6, which shows fast charging and BEVs in 2016–2017, and Figure 10 showing fast charging for much higher future BEV uptake, we offer a rough estimate of how much more fast charging is needed for a given growth in electric vehicles. Table 7 summarizes what can only be called approximate benchmarks, considering the uncertainties previously described for the BEV-to-fast-charging ratios in the early market developments. To provide some sense of scale for various population sizes, results are shown for three metropolitan sizes of 1, 2, and 4 million people. The table is based on three levels of uptake from 2,000 to 85,000 cumulative BEVs on the road per million people, essentially showing multiyear growth of the market by a factor of 5 (10,000 versus 2,000 cars) and then by to a factor of 8.5 (85,000 versus 10,000). The ratio of BEV-to-fast-charge points rises from 50 to 150, and then to 700 as the electric vehicle market grows (per Figure 6 and Figure 10). As a result, the increase from a low electric vehicle market to a medium one results in 5 times as many BEVs with about a 70% increase in fast-charge points. The next step, from a medium to high electric vehicle uptake market, involves an increase in electric cars on the road by a factor of 8.5, but only increases fast charging approximately by another 80%.

Table 7. Approximate benchmarks for fast chargers to support various electric vehicle numbers for given metropolitan area population sizes.

	Metropolitan area resident population	Low electric vehicle market (2,000 bevs per million)	Medium electric vehicle market (10,000 bevs per million)	High electric vehicle market (85,000 bevs per million)
Battery electric vehicles (for given population)	1,000,000	2,000	10,000	85,000
	2,000,000	4,000	20,000	170,000
	4,000,000	8,000	40,000	340,000
BEVs per fast charger		50	150	700
Fast charge points (for given population)	1,000,000	40	67	121
	2,000,000	80	133	243
	4,000,000	160	267	486

Note: Summary based on data trends from Figure 5 and Figure 9.

To interpret the Table 7 summary findings in absolute terms, we can take just the 4 million population metropolitan area example. Based on the functional urban area designation this is near the population of Copenhagen, Denmark, as well as the metropolitan areas of Columbus, Ohio, and San Jose, California, in the United States, although greater population density may decrease the number of chargers necessary in the low electric vehicle market. Such cities could hypothetically increase from 8,000 to 340,000 BEVs over a many-year period. This would likely require that the fast charging to support these BEVs would increase from 80 to more than 240 charge points to meet the increased public charging capacity demand. This is an important result in that it shows that fast charging will need to greatly increase as the electric vehicle market grows; however, the required increase in fast charging will be considerably less than proportional to the increase in BEVs. We emphasize that there are major uncertainties related to different area conditions (e.g., availability of home and work charging) and evolving vehicle technology (e.g., increasing electric range), crowding at stations due to coincident demand, and other factors previously noted in Table 5.

FAST CHARGING IN-USE DATA AND RELATED BEHAVIOR

Modeling approaches make certain assumptions based on assumed consumer behavior and then adjust those assumptions as new data become available. A study of California fast-charge session data from users in California (Nicholas & Tal, 2017) suggests some important trends in fast-charge usage that may have an impact on the modeling estimates previously shown.

Users are not using fast chargers exclusively for long distance trips as many studies assume. This is illustrated in Figure 11 showing the cumulative percentage of paid sessions and unique users at a charger for Leafs and Bolts as a function of the straight-line distance a customer travels to the charger. The data represent 15,863 Leaf sessions from 3,970 unique users over a 70-day period in early 2017 at 238 charging locations in California. The Chevrolet Bolt data are from 1,229 sessions from 402 unique users over the same period.

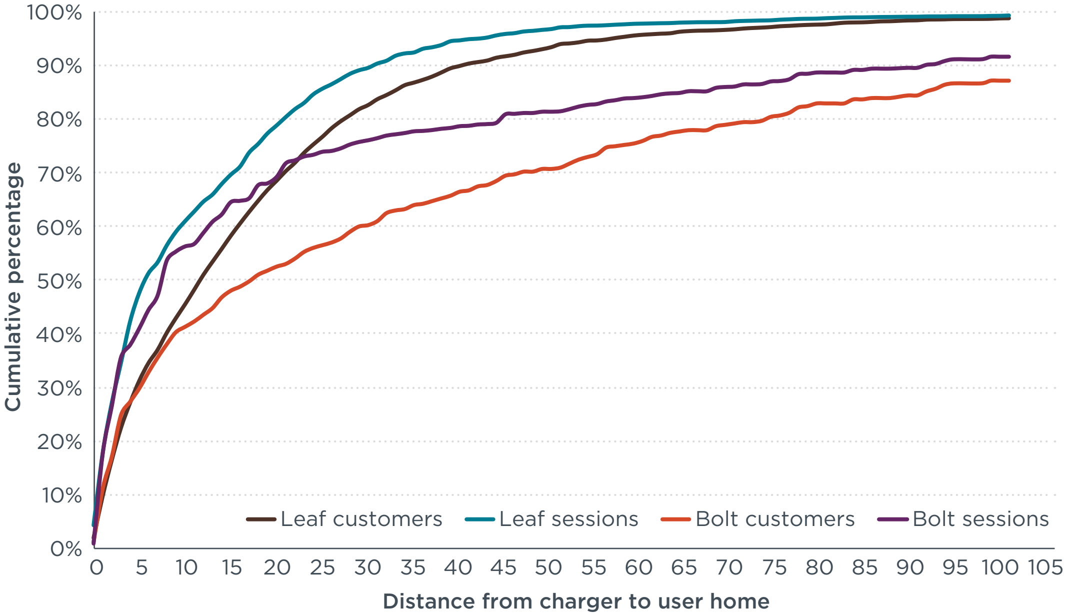


Figure 11. Percentage of fast-charge sessions and unique customers as a function of distance from charger to home.

The figure shows 50% of Leaf sessions are from users less than 6 miles (10 km) from home but these sessions came from only 34% of users, so people close to a charger are more likely to be repeat users. Corresponding numbers from the Bolt are 37% of users at 7.5 miles (12 km) from home. The relationship between sessions and distance from home scales with range. About 10% of sessions are past the point of no return—half the range of a vehicle and only 1% are beyond the range of a vehicle. A study based on in-use data from the UK and Ireland found a similar situation: On days when fast charging was used, the median driving distance was 51 km (32 miles), indicating that most fast charging is used for trips close to home (Blythe et al., 2015). Nonetheless, on days when driving distance exceeded the electric vehicle range, a fast charger was used 85% of the time, indicating that these fast chargers enable longer journeys.

Sorting the users from the California survey based on the frequency of use per month showed that heavy users averaging 20 sessions per month were likely to be close to home and occasional users farther away. This suggests that heavy users are skewing the numbers shown in Figure 11. In fact, 10% of users accounted for 50% of all sessions irrespective of distance from home. Paying for charging does little to alter these estimates, 10% of paying customers accounted for 50% of paid sessions, but these sessions accounted for only one third of the top 10% of the heaviest users.

Further investigation in the study using a survey questioning the users while they fast charged suggested some possible explanations. Alternative charging was an issue for 18% of respondents because they did not have access to home charging, although another 19% had charging but were not using it. BEVs not having a home charger was not accounted for in first generation models. Not having a home charger was correlated with heavy fast charging usage.

If these heavy users are taken into account, they will affect the models' estimated number of chargers needed. Numbers from the study and external sources suggest that a 50 kW charger can support 15 nearby users if they use it instead of home or other public charging—a much higher ratio than those suggested by studies in Figure 10.

This ratio of 15:1 is based on determining how many users charging 20 times per month will completely occupy a fast charger's capacity of 300 events per month (Smith & Castellano, 2015). The ratio of 15 BEVs per fast charger must be reconciled with the higher estimates of hundreds or thousands to one in proportion to the number of people who don't have home charging. The speed of charging also affects the estimates such that the number of chargers needed in this scenario may be halved if 100 kW charging is assumed giving a ratio of 30:1 given perfect queueing.

EQUITY IN SITING AND ACCESS

Equity in charging access involves increasing access for anyone with no home or public charging at similar price and convenience. Many renters and apartment dwellers only have access to slow home chargers or perhaps no charging at all. Likewise, people who live in condominiums or single-family homes without off-street parking may have no access to home charging. Without reliable access to charging, pure battery electric vehicles will not be purchased even if they are affordable. Fast charging is part of the charging ecosystem and, in conjunction with apartment installations and other workplace or other publicly accessible charging, can promote equal access to electromobility for all vehicle drivers.

Lack of high quality home or public charging options (Level 2 or other high amperage outlet in the United States) or the ability to install or afford them correlates with lower incomes (Nicholas & Tal, 2017). To address this, publicly developed charging plans often have an equity component where a certain percentage of chargers must be sited in areas of low income or areas of high pollution. For example, Electrify America's California plan includes 25% of super-fast charging stations to be sited in communities representing the bottom quartile of income and environmental exposure (Electrify America, n.d.). California investor-owned utilities pledged to site more than 10% of charging, including fast charging, in disadvantaged communities (California Energy

Commission [CEC], 2017). An EVgo plan coordinated with government set a minimum of 20% of stations in disadvantaged communities. Programs such as these are important to provide a robust charging network that includes fast charging for all potential drivers.

The problem of equitable access to charging in general and fast charging in particular is not limited to low income areas and can be applied more broadly to any potential customer with poor access to charging. By assessing the potential needs of nearby residents, equal access is possible by providing more public chargers per customer in some areas and fewer in other areas that have more private charging options, such as at home and at work.

V. CONSIDERATIONS FOR URBAN FAST-CHARGING PLAZAS

Given that users have relied on fast charging instead of home and other public charging as revealed by surveys and in-use data, it appears possible that fast chargers in urban centers can serve as an important component in the charging ecosystem. A site with multiple chargers in an urban area in this context is termed an urban fast-charging plaza.

FAST-CHARGING DEMAND FROM DRIVERS IN MULTI-UNIT DWELLINGS

Fast charging can provide an option for those with no home charger as a complete replacement for it, or as a supplement to other public charging options. Reliably being able to charge at any time is important for the confidence of an electric vehicle buyer without access to home charging. Even if a driver relies primarily on other slower forms of public charging, that charging has the potential to be in-use or blocked at any time. Fast charging provides a reliable, flexible option to accommodate these situations and help with the growing pains of providing universal home charging access.

Access to plugs at home and the ability to add a charger differs by country and by region. In the UK only 48% of households and 55% of car-owning households had access to a garage (Department for Transport, 2009). Only 23% of car-owning households actually parked in their garage. The access to plugs in the garages is unknown, but at least 45% of car-owning households did not have access to a garage and are less likely to have access to a plug, and instead rely on public charging.

In the United States 74% of households were single family structures with high access to garages compared to other markets. Access to a garage and parking, however, does not guarantee access to a plug. A U.S. Energy Information Administration survey (2015) asked respondents about access to plugs near parking giving a disaggregated examination by structure type and rental status. Overall, 52% of households park no vehicle within 20 feet of an electrical outlet (Figure 12). An estimated 9% answered “no” because they don’t have a household vehicle (Weinberger et al., 2013). This suggests that at least 43% of U.S. households would need to install new wiring for a charger or depend on public charging if they wanted to drive an electric vehicle.

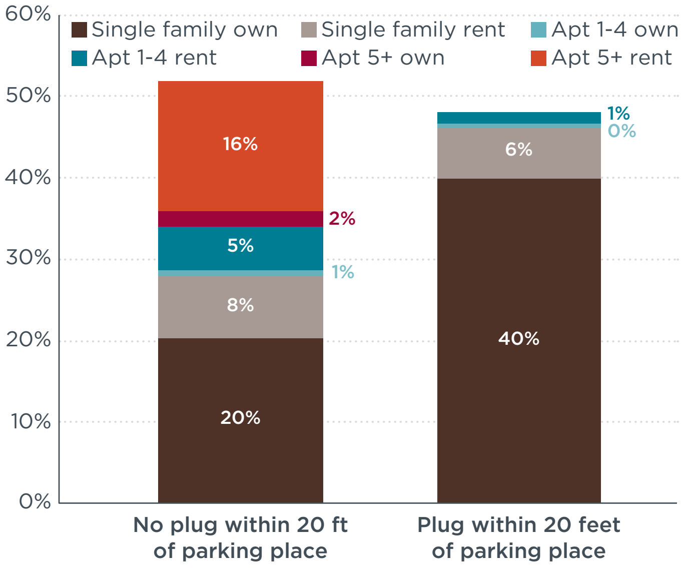


Figure 12. Access to household plugs near parking location in the United States.

The question, therefore, is how to enable this share of the population who could drive electric vehicles but have no easy access to charging. The first option, for those who are able, is to install their own chargers at home. But for renters, in houses or apartments, enabling charging near where a vehicle parks requires a variety of solutions such as landlords installing plugs or chargers, or a potential electric vehicle driver relying on public charging being installed nearby. This public charging can be Mode 1 to Mode 3 (including Level 1 and Level 2) or it can be fast charging. Survey data from Norway confirms that apartment dwellers use public charging infrastructure (both Level 2 and DC fast) more frequently than those who live in single-family homes, although 64% of apartment dwellers have access to regular home charging (Lorentzen, Haughneland, Bu, & Hauge, 2017). Survey and usage data in the U.S. suggest that 2% - 6% of Leaf users are using fast chargers as their primary source of driving energy (Nicholas and Tal, 2017).

There may be a limit to the percentage of people using primarily fast charging as other solutions are likely to be cheaper and more convenient in the long term. Buyers who originally depended on fast charging may encourage a landlord to install charging, may move to a different building with charging access, or may find a cheaper public or workplace solution.

GRID CAPACITY IN URBAN SETTINGS

As shown by Figure 9, spare distribution and transformer capacity is more likely to exist in cities than outside of cities. As an example, inside a one-mile radius circle in downtown San Francisco, the electric utility identified existing transformer capacity for 782 or more 50 kW fast chargers. This is an undercount as PG&E transformer estimates are capped at six 50 kW fast chargers per site. Abundant distribution capacity also exists in cities, suggesting that adding another transformer for higher power is feasible as well. High capacity in urban areas is attributable to greater general power demands, building efficiency improvements, and the fact that fast charging would represent a smaller fraction of area load than in a rural area. For example, a typical 28-story high-rise office building can require transformer capacity of about 7,000 kW, enough for one hundred and forty 50 kW fast chargers (Shaffer, 2011). Additionally, for urban areas, if precise location is not imperative, there are more potential sites from which to find spare capacity in a general area. Further, if an area was formerly an industrial district, but is transitioning to a commercial district, there is likely excess grid capacity. A challenge in some urban settings is the difficulty of upgrading underground transformers. As transformer capacity increases, so does physical size. Some size-restricted underground locations would be prohibitively expensive to upgrade. Finally, the farther a site is from the urban core, the less likely excess capacity for fast charging exists.

EXAMPLES AND BEST PRACTICES

Instructive best practices for urban fast-charging plazas are beginning to emerge through early developments. They relate to the price to fast charge, number of chargers, mix of charging speeds, interoperability, location, and site characteristics.

The cost of electricity is increasingly important for users who rely primarily on fast charging. Occasional users may be willing to pay a large per kWh fee for the convenience of fast charging, but many heavy users are likely to only be willing to pay a price equivalent to the gasoline alternative. Therefore, fast charging priced near the price of fueling a competing gasoline vehicle or pricing that is differentiated by frequency of usage will be effective at keeping price low for heavy users with no other charging option. Pricing dichotomy is instituted today by monthly membership fees. At some networks, in exchange for a fixed membership fee, the price per kWh is lower than the equivalent price of gasoline on a per-mile basis. When the fixed fee is amortized over all the charging done in a month, heavier users have lower effective cost per kWh than lighter users. Special membership options could be targeted to encourage adoption of EVs for those with less reliable access to other charging. When pricing schemes become too complex or opaque, electric vehicle users commonly call for greater pricing transparency. This helps give drivers improved certainty and helps them choose between lower cost networks and charging speed options in a given area.

The number of chargers and the mix of charging speeds is also important at urban fast-charging plazas. Building multiple fast chargers per site reduces the average wait time at the site and can increase per-station utilization, improving the business case (Jabbari & MacKenzie, 2016). Siting multiple fast chargers at one site has been an increasing trend. Figure 13 shows the cumulative number of both fast charging sites and ports at those sites on an annual basis in the U.S. through the end of 2017 (PlugShare, 2018).

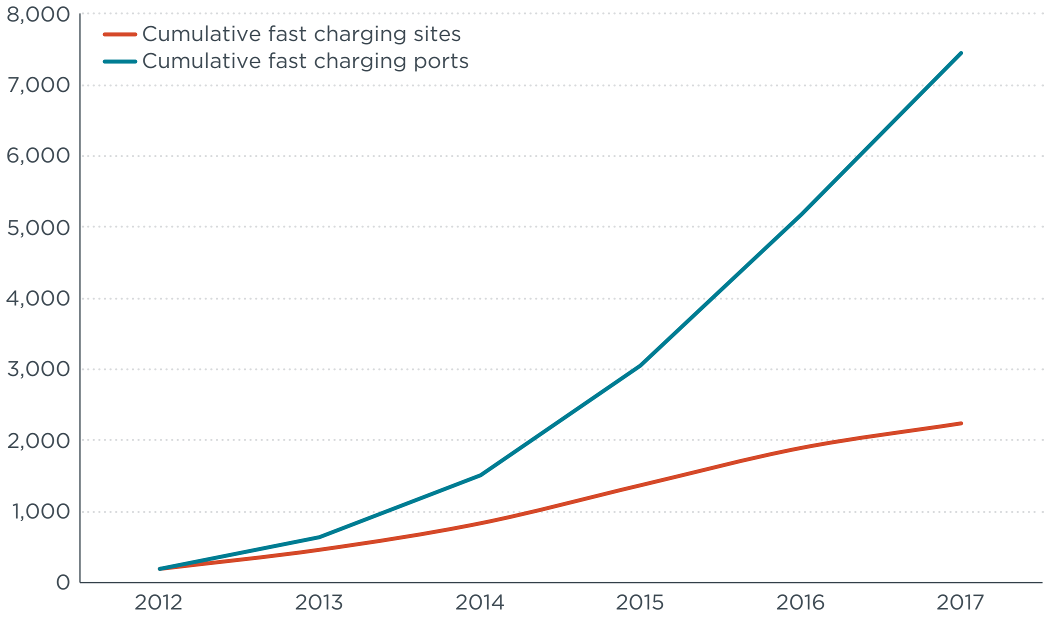


Figure 13. Growth in cumulative fast charging sites and ports in the U.S. by year.

As shown in Figure 13, the number of fast charging sites grows steadily from 2012 through 2017 while the number of outlets grows at a substantially faster rate. Initial installations in the U.S, typically had one fast charging outlet per site, but now multiple ports per site is typical. Some of this differential growth is attributable to the new multi-standard stations with both CHAdeMO and CCS ports, some is due to new installations with multiple ports, and some is due to upgrading single-port sites to multi-port sites. Tesla Superchargers employ a multi-port strategy, constructing up to 40 charging stations at one location for their highway sites. Tesla also has begun to construct urban fast-charging plazas in Chicago and Boston to “make Tesla ownership easy for everyone, including those without immediate access to home or workplace charging” providing a guaranteed 72 kW per station to fully charge a vehicle in about an hour (Tesla, 2017).

A mix of charging speeds or power sharing is also desirable to minimize the cost of delivering high power. Electrify America, a subsidiary of Volkswagen, has plans for a minimum of four chargers per location with a maximum of 10 (Electrify America, n.d.). Urban sites with “community chargers” will have a mix of 50 kW and 150 kW chargers while highway sites have a mix of 150 kW and 350 kW chargers. Ionity in Europe has a plan to install 2–12 chargers per site with each able to supply 350 kW or no less than 210 kW if all chargers are operating simultaneously. Ionity and Electrify America’s plans show two different ways to accomplish the same goal of limiting transformer load. Ionity uses power sharing and Electrify America uses a mix of charging speeds. Both are effective at providing high and low power and have advantages and disadvantages. Power-sharing among a group of chargers is very flexible and allows for any charger to operate at full capacity, but power is reduced if all chargers are occupied simultaneously. A mix of charging speeds guarantees a certain charging power, but requires the drivers to choose the charging that matches their vehicle or charging time preference.

Interoperability among charging networks is another key enabler for users. In the United States and in some European locations, users often must have multiple cards to access the multiple fast-charging networks. In Europe, Hubject is a private service roaming platform that acts as a clearinghouse for charging transactions. The service covers roaming on charging infrastructure for 100% of Finland, Iceland, and Denmark; 80% of Norway; and 50% of Sweden as well as providing service for many other European countries. Open charge point protocol (OCPP) is another step toward interoperability of stations providing a common means of communication between stations and among networks. A new standards organization, eMI3, is advancing OCCP to create the ability to roam among networks.

Location and phasing of fast-charger locations is also important. Early fast-charger installations often can serve multiple functions. For example, in many cases, they must serve local and long-distance travelers. Siting near highways near population centers serves this dual purpose, thus meeting two high-priority needs in the growth of electric vehicle markets. Outside of population centers, coverage on most major highways will eventually be needed, but travel between nearby population centers and along commute routes anecdotally makes up more of the pressing needs for most drivers, compared to supporting very long-distance cross-country travel. Related to this, some regions have begun to make more consistent signage for charging types and speeds. It would be hard to generalize universal best practices for signage, but major charging deployment programs such as those established by utilities, automaker consortia, charging providers, and multi-state groups ideally would coordinate at least on a regional basis to the extent possible to reduce redundancy and provide consistent information.

VI. COSTS AND BUSINESS CASES ASSOCIATED WITH FAST CHARGING

Some of the early fast-charging networks and installations have been profitable, but many have not. The fast-charging business model continues to develop and has not been standardized to this point. We review the cost drivers and the conditions that make a successful business model and the conditions that hinder profitability.

INSTALLATION COSTS OF FAST-CHARGING STATIONS

Electric vehicle fast chargers typically require significant site preparation and electrical infrastructure. For this reason, fast-charging hardware represents only a portion of costs, and the total cost of installing fast-charging stations can vary substantially based on the site. Because these variances are inherently local, exact labor costs and infrastructure needs in addition to hardware and materials must be assessed on a site by site basis.

Despite these variances, we present some estimates based on several scenarios and sites considered for fast-charging stations in Ottawa, Ontario (Ribberink et al., 2017) that illustrate some key points. Figure 14 shows cost estimates for stations at three different sites labeled A, B, and C in the city of Ottawa in terms of dollars per charger. Estimates are shown for stations of four different charging speeds (50 kW, 100 kW, 150 kW, and 400 kW) as well as for installing four or eight stations per site, providing indications of the impacts of future developments. The costs for transformer upgrades, grid upgrades, and site preparation range from less than $5,000 per charger to more than $125,000 per charger. Notably, these costs do not include the cost of the chargers themselves.

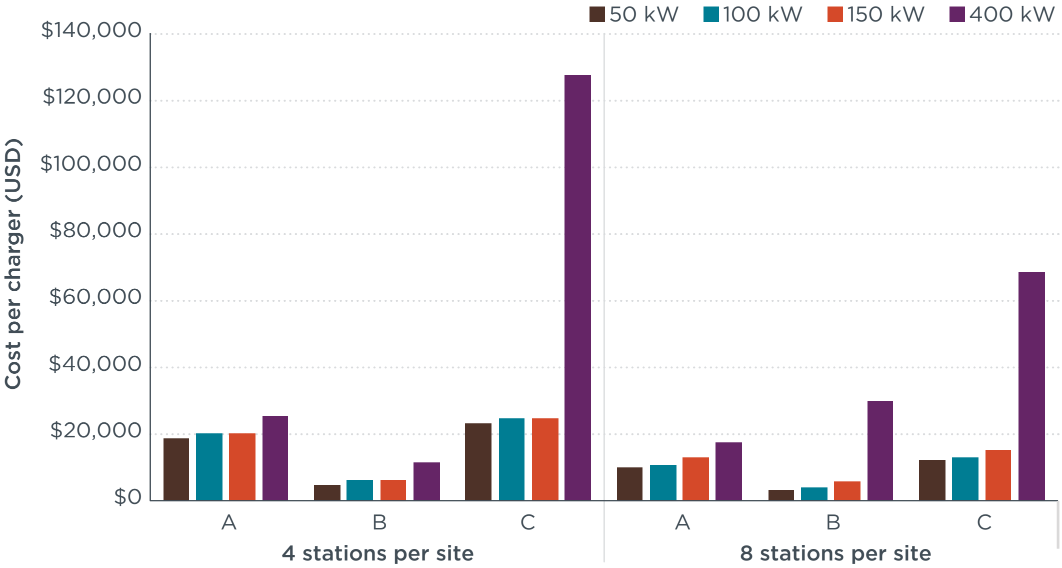


Figure 14. Estimated installation costs for charger locations based on Ribberink et al. (2017).

A number of observations can be drawn from these data that may hold lessons for future deployments. First, in these cases, installing eight stations per location resulted in lower per-station costs than installing only four stations, because of the ability to amortize increased electrical infrastructure over additional stations. Second, cost increases to go from 50 kW to 150 kW were quite limited in all cases—less than $3,000 per station—but the increase from 150 kW to 400 kW resulted in a massive increase in the cost in some cases. This was due to the need to upgrade the distribution grid with new capacity and switching infrastructure at some of the locations, an expense triggered only by the highest-power stations. Although this will of course vary in every location, this experience shows that with higher power comes a greater chance of expensive (and sometimes unpredictable) upgrades, but some locations were relatively insensitive to the higher power.

The estimates for these locations in Ottawa are similar to estimates from other deployments. The first large deployment and cost analysis of fast chargers in the United States was done in conjunction with the EV Project, with sixty-nine 50 kW chargers installed and costs analyzed in 2015. This survey found installation costs ranging from $4,000 to $51,000 (Smith & Castellano, 2015). These were 50 kW chargers that often could be accommodated on existing service, and typically were installed as single chargers rather than as part of plazas. Rural sites in the EV Project were the most likely to need new service upgrades, averaging around $40,000. In the UK, utility upgrade costs for 50 kW chargers at highway stations were $1,500–$30,000 (Evans, 2018), whereas the Rapid Charge Network stations typically required approximately $21,200–$28,500 in installation costs, about one quarter of which was due to grid connections (Serradilla, Wardle, Blythe, & Gibbon, 2017). Because installation costs are driven by labor, construction, and utility components, these costs are unlikely to decline significantly in the future.

Hardware costs, which were not included in the previous cost estimates, increase with power and complexity. The EV Project found hardware costs ranging from $10,000 to $40,000, primarily based on their charging power, their ability to charge multiple cars without power-sharing, and their network connections (Smith & Castellano, 2015). The currently available 25 kW Chargepoint Express 100 with CCS or CHAdeMO is $12,500 and the 50 kW Chargepoint Express 200 with CCS and CHAdeMO is $35,800. Nissan sells its 44 kW CHAdeMO unit for $15,500. For the rapid-charge network in the UK, hardware purchase costs averaged approximately $28,500 for a dual-standard 50 kW station (Serradilla et al., 2017).

Porsche has estimated a cost of $1 million for hardware and installation of a pilot site in Atlanta with six 350 kW stations, but it is unknown if this cost will be similar for widespread deployments (Wilson, 2018). In China, the estimate for a fast-charging plaza with ten 140 kW chargers is 4.1 million yuan ($642,367) total station cost (China Industry Information Network, 2016). This is similar in transformer power to the Porsche site but total costs are lower. Station costs are expected to decline to some degree as new technology and economies of scale emerge.

UTILITY RATE STRUCTURES FOR FAST CHARGING

The rates charged by utilities for fast charging vary widely and there is no consensus as to the best way for utilities to recover costs of serving this type of load. In some ways, fast charging is similar to any other type of electrical load but in some ways it is different. The cost per kWh a host must pay and the speed at which vehicles can be economically served has large implications for the future of fast charging. Cheaper utility rates will generally encourage the construction of stations and the use of fast chargers.

Utility rate structures for fast charging often are different than those for residential customers. For residential rates, customers are charged primarily by energy measured in kWh. Energy-only rates are available to some commercial customers as well. However, for most commercial and industrial rates, power in kW and energy in kWh are often billed individually. Demand charges measured in kW are independent of the number of times the peak power has occurred. Energy charges measured in kWh are often lower per kWh than with residential rates because power is charged separately. To visualize the impact of fast charging demand, a 31-day commercial load profile is shown in Figure 15 with three 50 kW fast charging events added to the load. Power demanded is shown in kW on the vertical axis and the day of month is shown on the horizontal axis.

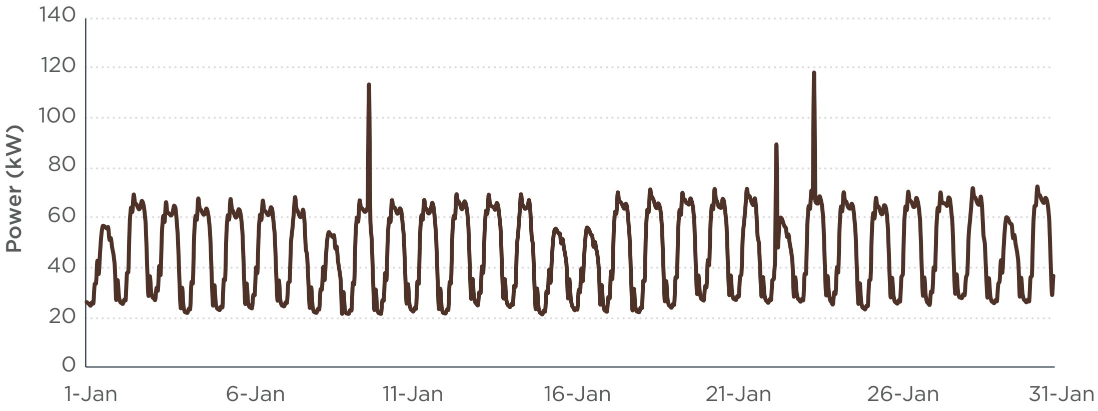


Figure 15. Sample monthly load profile for a commercial business with three fast-charge events.

The demand charge in this case would be scaled to the monthly peak of 119 kW. If a demand charge were $12 per kW then this would be $1,428 added on a host site's bill of which up to $600 is due to the presence of a charger. The demand charge assesses the monthly peak kW regardless of how many times it occurs in a month. Energy use in kWh is billed in addition to the peak power use in kW. Per kWh rates with no demand charge are also available for fast chargers in some utilities. Typically, the per kWh rate is higher for these rates in exchange for no demand charges.

Demand charges can present challenging economics to station operators and may not represent true system cost of the electricity use. Alternative rate structures that better reflect overall cost of electricity used have been proposed. The most straightforward alternative rate structure is to simply eliminate demand charges and charge a higher flat rate per kWh. This strategy has been adopted by Southern California Edison for a period of 5 years at which time system impacts will be reassessed with better data.

San Diego Gas and Electric has proposed a more nuanced approach addressing each of the four cost drivers for the utility grid (Fitzgerald & Nelder, 2017). First is a basic charge per kWh of electricity, proposed at $0.14/kWh. Second is the generation cost, typically $0.03/kWh. Third is a dynamic adder for the top 150 hours per year of the total grid system peak in kW and an additional $0.51/kWh is assessed. Fourth is a dynamic adder for distribution during the top 200 hours of circuit peak reflecting the stress in the local distribution grid, proposed at $0.19/ kWh.

If costs were passed directly on to the consumer under these proposed San Diego rates, a driver charging during the grid peak hours of the year would pay at least $0.87/kWh, many times the equivalent cost of gasoline. When charging off-peak, the rate would be $0.17, generally less than the cost of gasoline. If these rates were implemented, transparency to the users would be a key issue to ensure that demand is shifted and charging costs are not unexpectedly high. A degressive tariff system, in which demand charges decrease as electricity consumption rises, also may be helpful, especially for fast-charging plazas with multiple stations on site (Ministry of Economic Affairs, 2017).

BUSINESS CASES FOR FAST-CHARGING STATIONS

Fast charging represents a business opportunity for the utility and/or a charging provider. Currently there is not one dominant business case as both utilities and operators are responding to different gasoline prices, electricity prices, vehicles, driving patterns, and charging preferences. Some operators such as FastNed are currently profitable through electricity sales alone, and in Norway, with the highest density of electric vehicles, recent fast-charging deployments have been built without public support, indicating that these stations can be operated profitably (Lorentzen et al., 2017).

In a UK business case study, it is estimated that with heavy utilization a 40% electricity price markup over host electricity cost is required to break even on installation and hardware from electricity sales alone whereas a 15% internal rate of return would require a markup of 100% under the same scenario (Serradilla et al., 2017). Across the United States, profitability in the early market stage is difficult due to low gasoline prices, high upfront costs, low utilization, and demand charges (Nigro et al., 2015).

The challenges of low utilization rates and high energy costs are a large barrier to many operators. A scenario illustrates the relationship between utilization and cost per kWh delivered. This relationship between the number of charge events per month versus the effective cost per kWh to serve that event is shown in Figure 16. For this example, demand charges are $12 per kW, energy is $0.10/ kWh, the charger power is 50 kW, and each vehicle fills with 10 kWh of energy. This relationship holds for higher charging speeds as well assuming energy dispensed per charge scales with power; one study found that a 400 kW charging station used only once per day would require prices of over $1/kWh to break even, but with 24 uses per day, breakeven prices would be about $0.22/kWh, similar on a per-mile basis to gasoline priced at $2.00/gallon (Burnham et al., 2017).

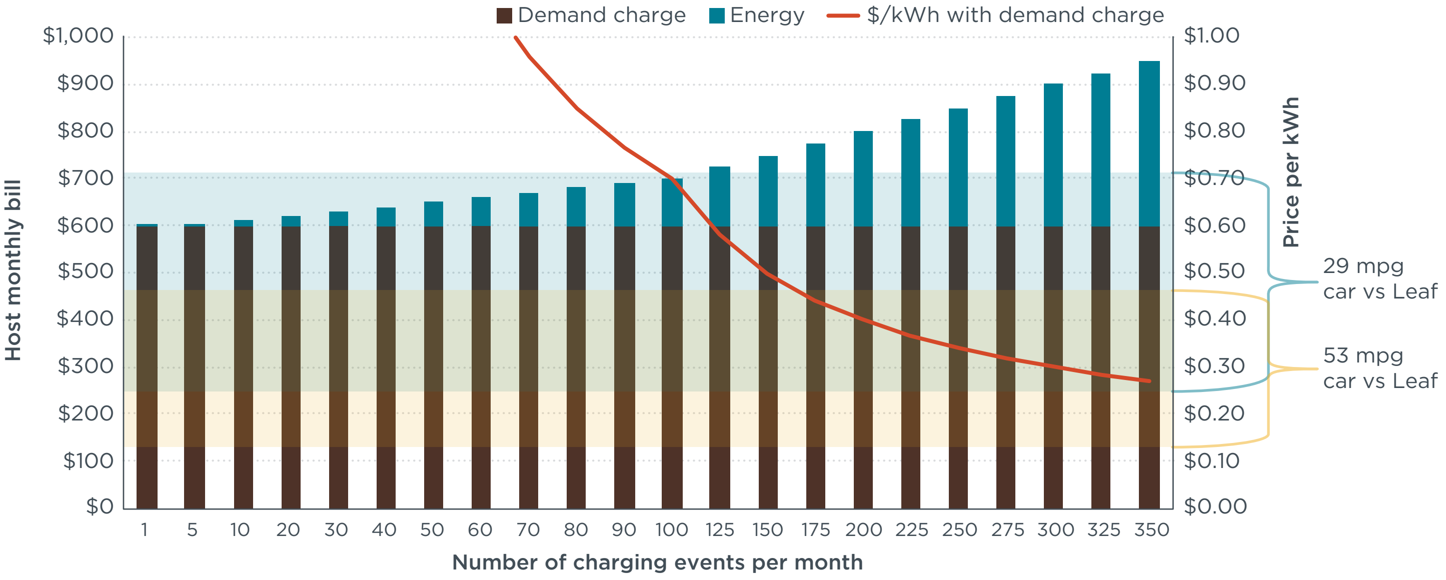


Figure 16. Fast-charger host site bill as a function of charge events per month with shaded region showing area of competition with gasoline priced between $1.80 and $7.00 per gallon.

If a charger is used just once in a month, the cost is $600 + $1 for 10 kWh of energy for a cost per kWh of $60.10. If a site is used once a day for 30 days this would be a cost of $600 + $30 or $630 for 300 kWh of energy. The effective cost per kWh in this case is $2.10. A charger with 45 events per month starts competing on a cost per mile basis with a 29 mpg vehicle using $7/gallon gasoline with an effective price per kWh of $0.70. In this example, the cost per kWh never competes with an efficient vehicle and low gasoline price of $1.80/gallon, shown as the lower limit of each shaded region. In the future, stations with higher power could face increased demand charges in addition to their higher upfront costs, further negatively affecting the economic viability of these stations.

Rural sites are more likely to have low utilization as suggested by the map in Figure 9. This may be inversely proportional to their importance in the purchase decision if potential buyers want to be assured of access to far away locations independent of the actual usage of the chargers that enable those trips. These uneconomic stations can be cross-subsidized with profits from other chargers in the same network or by charger network membership fees.

Because of the more difficult business case of fast-charging stations in rural areas, governments have invested in the deployment of stations in rural regions where lower utilization is expected. In Norway, private fast-charging stations have been built in large numbers near major cities like Oslo, but the federal agency Enova has issued tenders to build out a network of stations every 50 km along all major corridors including the rural northern region to enable seamless travel across the country (Nilsen, 2016). Similarly, the state governments of Washington, Oregon, and California in the United States have dedicated funding to complete the sections of the West Coast Electric Highway, providing drivers a continuous fast-charging network from Mexico to Canada, with funding focused on sections outside of major cities (Washington State Department of Transportation, 2014).

There is evidence that a site host may generate profit from goods and services while consumers charge, similar to the gasoline convenience store model. One survey (Nicholas & Tal, 2017) showed that 43% of respondents shopped while charging, spending an average of $29 in a variety of shopping contexts including outlet malls, grocery stores, and home goods stores even though charging, not shopping, was the primary reason for their visit.

Automobile manufacturers themselves recognize the potential for fast-charging access to increase the sales of their vehicles. Tesla has constructed and provided unlimited access to its proprietary charging network to increase the attractiveness of its vehicles. Now the company offers 1,000 free miles of charging with some vehicles and charges a reasonable rate for other Telsa models (Tesla, 2018). Nissan and BMW provided free fast charging for a period of 2 years after purchase and assisted in funding and placement of some stations.

Perhaps among the more promising business cases for fast charging are in projects involving transportation network companies (TNCs) such as Lyft and Uber. An early indication that such business cases appear to be emerging came when Tesla began to restrict the use of its Supercharging network by commercial drivers, like those driving for TNCs (Liptak, 2017). This shows that even a relatively expensive vehicle like a Tesla Model S can be a commercially attractive case for use in TNC operation if fast charging is inexpensive (i.e., free, in this case). As more affordable long-range electric vehicles enter the market, more business cases will open up, and this appears to be happening with Maven. Maven rents Chevrolet Bolt BEVs to TNC drivers and has partnered with EVgo to build dedicated fast chargers for the program due to high usage (EVgo, 2018). TNC drivers do not have home charging in many cases, and they typically drive many more miles per day than an average driver. This increases the use of public charging, and more fast charging in urban areas in particular. For fast-charging operators, this offers the potential for more regular and high-utilization use of charging stations. More broadly, if electric TNC operation accelerates, this would increase the demand for urban fast-charging plazas.

Finally, utilities are proposing plans for, or are in the process of building, fast charging in their jurisdictions because of a sometimes tenuous business case in an early market. The Irish utility ESB led a consortium that installed a nationwide network of 70 fast chargers enabling travel throughout Ireland. The French utility Engie is partnering with ChargePoint to build a Europe-wide fast-charging network of up to 350 kW chargers. Clever, a consortium of Danish utilities, has a fast-charging network in Denmark, Sweden, and Germany with plans to extend to France, the UK, and Italy. German utility E.ON has partnered with Clever for this expansion phase. Hydro Québec has likewise built the Electric Circuit charging network in Québec and Ontario.

In the United States, several utilities have installed fast chargers including Vermont's Green Mountain Power; California's Sacramento Municipal Utility District and Los Angeles Department of Water and Power; and Washington's Avista and Seattle City Light. Other utilities have expressed interest in installing fast charging, but require regulatory approval. Pacific Gas and Electric, in California, has received regulatory approval to install 52 fast-charging connection points for private operators to utilize (CPUC, 2018).

VII. CONCLUSIONS

Fast-charging networks for electric cars are rapidly developing around the world. As the market develops, there are many lessons learned from studies and past deployments that provide guidance for the future. However, there are many gaps in knowledge showing the need for continued research as charging speed increases, range increases, and the market broadens to include new users with different driving needs and uncertain access to charging options. The business case for fast charging is likewise uncertain but current deployments suggest possible opportunities given the right conditions. The impact to the grid drives costs going forward and operational experience and future-looking studies provide some guidance into minimizing these costs.

One of the more fundamental questions is related to how much fast charging is needed as electric vehicle markets develop. A partial answer to this is derived through observation of how much charging is associated with electric vehicle uptake in the leading markets through 2017, shown in Figure 6. Ratios in different metro regions show a range of about 50 BEVs per fast charger to about 300 BEVs per fast charger. In general, early markets that have 1,000 to 3,000 BEV per million people have about 50 BEVs per fast charger and more developed markets that have 15,000–40,000 BEVs per million people have a ratio of 100-–300 BEVs per fast charger. The 300 BEVs per fast charger occur in the United States perhaps in relation to the relatively available home charging, whereas the 100 BEVs per fast charger occur in Norway suggesting regional differences or more aggressive planning playing a role in the resulting ratio. In an early market, more fast chargers are needed per vehicle to attain sufficient geographic coverage. In general, as the market develops, fewer fast chargers are needed per BEV as utilization increases, as individual chargers serve more diverse travel schedules.

The ideal ratio of electric cars per fast charger in the future is less certain. Projections for future BEV uptake per fast charger have been investigated in studies estimating the BEVs per fast charger range from 27 to 1,800, with many being in the 200–700 range. The estimates are very sensitive to assumptions, which means that estimates must be matched to local conditions and assumptions must reflect reality. The number of DC fast chargers needed is affected by conditions including home or public charging availability, gasoline price, electricity price, charging speed, longer range electric vehicles, enabling long-distance travel, and multi-charger installations.

Combining the observed ratios of BEVs per fast charger with future projections, we plot three sample market trajectories in Figure 17. The ratio of BEVs to fast charger needed is on the vertical axis and the market development approximated by the BEVs per million people is on the horizontal axis. Each line is meant to illustrate differing local conditions, vehicle stock, or charging speed assumptions. There are three phases shown to illustrate that desirable ratios of BEV per fast charger change over time.

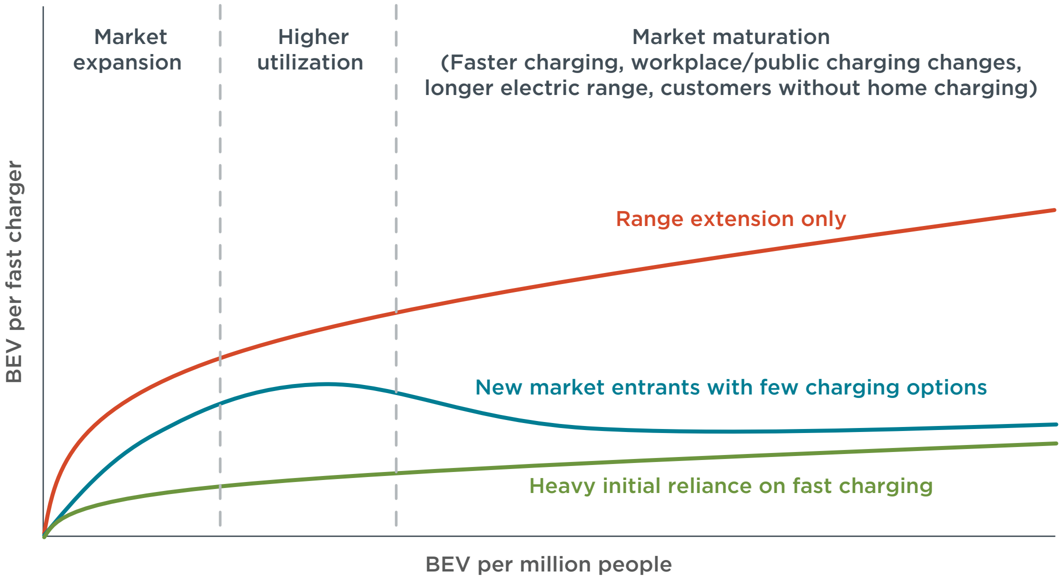


Figure 17. Possible fast chargers needed to respond to different market conditions.

During the market expansion phase, both BEV and fast charger numbers are low, but to obtain geographic coverage, relatively more fast charging is needed per BEV than in later phases. All other things being equal, chargers become better utilized in the second phase. The top line illustrates that fewer fast chargers will be needed per BEV over time if sufficient Level 2 charging is available at home or elsewhere. As vehicle range and charging speed increase, fewer chargers are needed per vehicle. The middle line suggests a trajectory similar to the top line initially, but as the market broadens to include those with poor home access and other public charging becomes insufficient, fast charging plays a larger role. The bottom line suggests a scenario where fast charging is the main public charging option and regional access to home charging is poor.

Some understanding of gaps in fast-charging infrastructure development is emerging from analysis of high electric vehicle-uptake markets. Robust urban fast-charging centers appear to be an important early action to provide an immediate benefit to the public charging ecosystem. One important lesson learned is that fast charging is being used not only for long journeys, but also used as a substitute for home and slower public charging. This indicates that fast charging can play a flexible role in the charging ecosystem. If fast chargers are deployed relatively rapidly they may be a solution for some regions to allow time for other more convenient public charging to be installed. One study showed that when electricity is priced close to gasoline price, 10% of users accounted for 50% of demand and were not using home charging. Their median distance from home to the charger was 5–7 miles. Further, among the users with home charging but needing public charging, many had the time to use Level 2, but Level 2 did not exist or was occupied, indicating the relative need for fast charging options.

Rural stations along highways face a more challenging business case initially because of their low use, so they require support and funding from government. Enabling long journeys is an important function of fast charging to give consumers confidence they can travel anywhere they wish in their electric vehicles even though rural stations may be lightly used initially. Grants can help defray the cost of these chargers making the business case more attractive. Grants in the past, such as with California's portion of the

West Coast Electric Highway and with grants for chargers to reach Norway's rural north, have included funding for chargers that enable these long-distance journeys, but are otherwise uneconomic. These networks also have been privately financed, as has been done with Tesla's supercharging network. The network conveys value on the vehicle and so the cost of the network is paid for though vehicle purchase. Ionity is a joint venture among automakers to fund a comprehensive European fast charge network. Electrify America's Cycle 1 investment also features nationwide connectivity. Some networks will overlap, similar to the way gasoline station providers overlap today.

Having multiple fast chargers at one site is important in giving confidence to drivers that a charger will be available upon or soon after arrival. Electrify America has a minimum of four and a maximum of 10 chargers per site. Ionity in Europe specifies two to 12 fast chargers per site. Future proofing a site by making connections for larger transformers and additional chargers expected in the next 10–20 years will help accommodate future growth and reduce upgrade costs.

The increase in charging speed to 350 kW promises to make long-distance travel more feasible and reduce the number of stations needed per BEV. However, the drive toward ever-higher charging speeds is counterbalanced by many other factors. Initially, only long-range BEVs will be able to accept this power level with current battery technology and improved battery pack design. Because providing high power is more costly, enabling all chargers at a location to simultaneously provide maximum power risks making a site uneconomic to operate. In addition, fast charging at over 100 kW will not be necessary for all fast charging needs, considering there are many instances of electric vehicles at particular locations for 30–45 minutes. As a result, allowing power sharing among chargers and installing fast chargers with different speeds including 50 kW and 150 kW can be good solutions for many locations.

The business case for fast charging varies around the world based on local conditions. If gasoline price is high relative to the price of the electricity cost alternative, then it is easier to have a positive business case simply by selling electricity at a premium. European countries are more likely to have high gasoline prices relative to electricity, leaving a margin for profit even with existing utility rates. High utilization at a site is the key to profitability, with one study suggesting a 40% electricity cost markup can result in a station being profitable. There are some sites, especially rural sites, that have low utilization and may not be profitable. In these situations, alternative business cases are needed. Early examples to date include automaker investments in fast-charging networks that increase the value of a vehicle, networks that cross-subsidize low performing sites with higher performing ones, and government grants that share in the early costs to reduce cost recovery requirements at low-utilization sites.

Utility rates for fast charging are being reduced in line with their impact on the grid system, but more consistency is needed to reduce rates. As more experience is gained, cost can be more accurately assessed. Demand charges in particular are a major cost barrier and there is evidence that demand charges can be eliminated with proper pricing of other cost components. The Southern California Edison utility has suspended demand charges for a period of five years to allow a better assessment of costs. San Diego Gas and Electric has proposed lower prices for the majority of the time, and only assessed high prices for the 1%–2% of hours that cause negative impact to the grid. The role for policy is to share these lessons with regulatory commissions to help justify reasonable rates for fast charging. Grid impacts for fast chargers do not appear to be significant in urban areas where sites with ample capacity are abundant, but in rural areas, fast chargers may require additional capacity. Grid impacts and high costs can be mitigated in these cases with battery storage connected to the station to handle the temporary high power fast-charger load.

One of the largest sources of potential demand for fast charging not covered in this report is the demand from transportation network companies—for example, Didi, Lyft, and Uber—and the potential for fast charging to be the primary source of energy for these ride-hailing services. Two pilot projects from Evercar and Chevrolet's Maven have been very successful in providing low cost per mile transportation primarily using fast chargers. In the case of Maven, fast charging is included with the rental of a Bolt electric vehicle. People who rent these vehicles can use them for ride hailing. Fast charging is used extensively to provide these services logging over 9 million electric miles in approximately one year (EVgo, 2018) and individual TNC drivers can log more than 50,000 miles a year. The system has been successful enough to warrant dedicated fast-charging stations for Maven drivers to reduce crowding at public stations. These are early projects, and clearly deeper investigation into such cases is warranted.

The development of batteries that allow for faster charging also will affect the requirements for fast-charging stations. In 2018, current battery technology suggests that the applicability of anything past 350 kW is limited for all but the largest battery packs. But 1,000 kW charging is conceivable for bus batteries at this rate. Solid state batteries, which are in development, could make use of these 1,000 kW chargers and charge 300 miles in 6 minutes at about one quarter the rate of gasoline. Charging at these rates would generally decrease the number of chargers needed and create an experience more similar to refueling with gasoline, opening up new customer segments.

This broad overview of lessons learned prompts the need for further investigation into the exact relationship between the number of fast chargers needed relative to home, workplace, and regular public charging. Also, the numbers of chargers needed as a function of charging speed and vehicle range can be better defined, as both of these trends are apparent with new electric vehicle models entering the market. A deeper investigation into fast charging and utility rates in Europe, the United States, and Asia also would be instructive to better understand the barriers and challenges faced in the rollout of fast-charging infrastructure.

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