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Learning from worldwide fast charger deployments

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Summary

As charging infrastructure networks continue to expand worldwide, early deployments of direct current fast charging (DCFC) provide valuable lessons to guide future installations. In this paper, we examine early lessons on fast charging, including the amount of fast charging needed, usage patterns by different groups, fast charging pricing, and regional variations in these developments. We explore what future trends may be inferred from these observations, as well as key uncertainties for the growth of this technology.

Keywords: fast charge, EVSE, infrastructure, conductive charger, cost

1 Introduction

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 fast charging infrastructure in various settings.

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 pricing of fast charging, requirements for fast charging at different stages of market growth, 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.

1.1 Fast charging technology today

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 up to 22 kW in Europe and 19 kW in the United States [1]. We also exclude AC fast charging, which can reach 43 kW, as there are few models that support it, and it is unlikely to increase in power. Fast charging is mostly relevant for battery electric vehicles (BEVs), which use no liquid fuels; however, we note that the Mitsubishi Outlander and BMW i3 range extender plug-in hybrid electric vehicles (PHEVs) are exceptions, as they can use both gasoline and fast charging.

There are five different standard 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, while 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 1 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 provides 50 kW at 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 1 as it represents the maximum power at lower voltage.

Table 1: Characteristics of leading DC fast charging standards

Connector type	Regions active (as of 2018)	Typical power (as of 2018)	Maximum power (as of 2018)	Proposed power
CHAdeMO	Japan, Europe, North America	50 kW	200 kW	400 kW (end of 2018)
CCS Europe	Europe	50 kW	150 kW, 400 kW	-
CCS North America	U.S., Canada	50 kW	150 kW, 400 kW	-
GB/T	China	50 kW	100 kW	150 kW – 200 kW by 2020
Tesla	Worldwide	125 kW	145 kW	>350 kW (no date specified)

In practice, a vehicle is unlikely to accept power at the maximum rate. These standards limit the current, so 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, state of charge, and maximum battery pack voltage. For this reason, 400 kW chargers are often referred to as 350 kW chargers – we will use this terminology in this report.

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 [2]. 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 80% state of charge (SOC), after which charging speed decreases. Capabilities in 2017 models range from about 38 minutes in a Tesla Model S 100D using a 125 kW charger to 14 minutes in a Kia Soul 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 [3]. If the Kia Soul EV battery capacity were doubled it could hypothetically accept 200 kW, but would still be limited to a 14 minute charging time. 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 and slowing 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 1. 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.

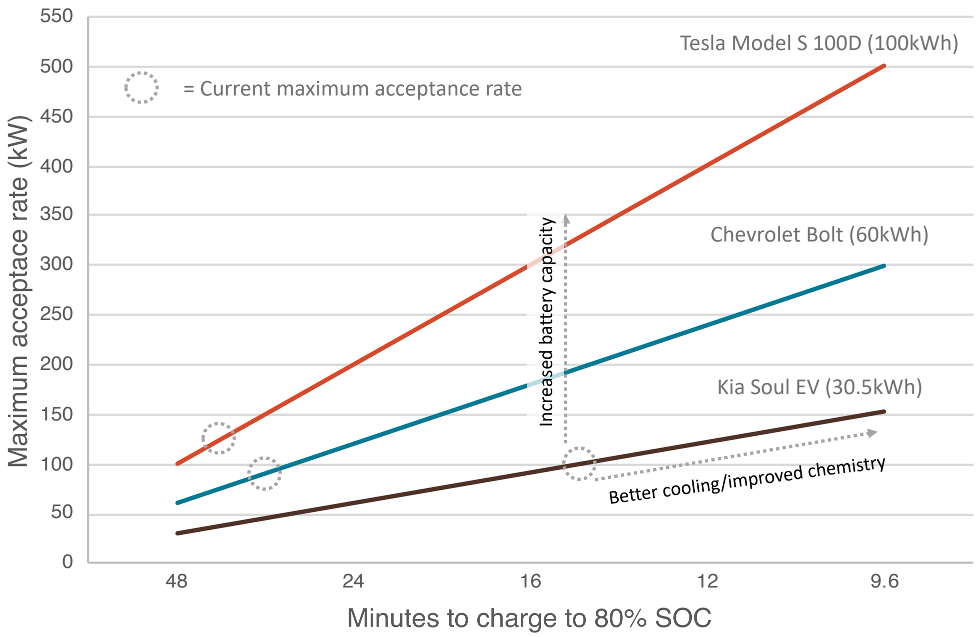

Figure 1: Relationship between maximum power acceptance rate of a vehicle versus battery capacity and pack technology with vehicle examples

In general, the “current maximum acceptance rate” circles to the right of the figure represent more advanced battery pack design, more robust chemistry, or better cooling. Alternatively, values towards the left of the figure 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 technology could 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 [3] [4].

By comparison, gasoline has a much higher energy transfer 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.

1.2 Past deployments

Fast charging deployments have grown substantially in the past years, both organically and as a result of government policy. Figure 2 shows the number of fast charging ports by country disaggregated by charger type in January 2018. As shown, the availability of the three fast-charging types is relatively evenly split in markets in North America and Europe. CCS is more prevalent than CHAdeMO in Austria, Finland, and Germany, while CHAdeMO is more common in all other markets, especially in Japan where it makes up over 95% of fast charge points. Tesla fast charging represented half of all fast charging points in the U.S. outside of California and also makes up a large fraction of charging in Belgium and France. China has the greatest number of fast chargers and almost exclusively uses the GB/T standard.

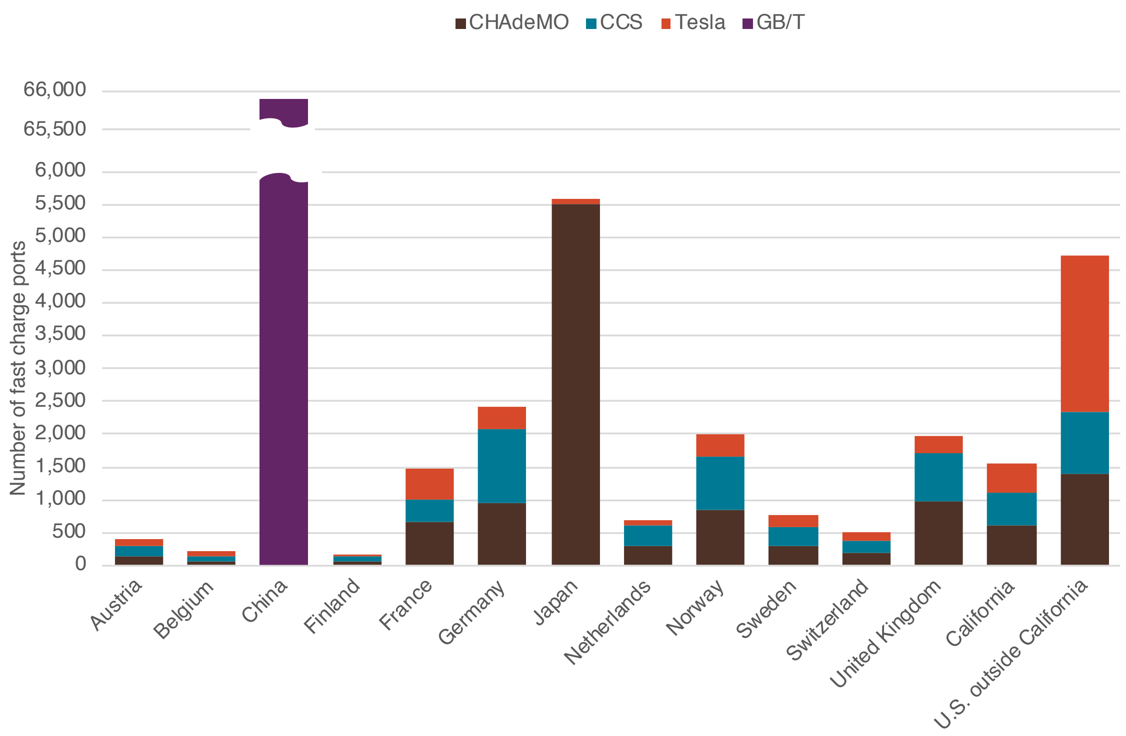

Figure 2: Number of fast charge points in major electric vehicle markets by plug type as of January 1, 2018.

Analysing electric vehicle charging at the metropolitan area provides an important measure of how extensive charging infrastructure is and is statistically linked with electric vehicle uptake (e.g., see [5], [6]). In Figure 3, we present the amount of fast charging in selected 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 U.S. [5]. BEVs per DC fast charge port is displayed on the vertical axis. 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 where noted. The arrows show the 2016-2017 trend for selected markets. As shown, each fast charge point supports about 260 BEVs in San Jose, California, compared to about 170 BEVs in Oslo, Norway.

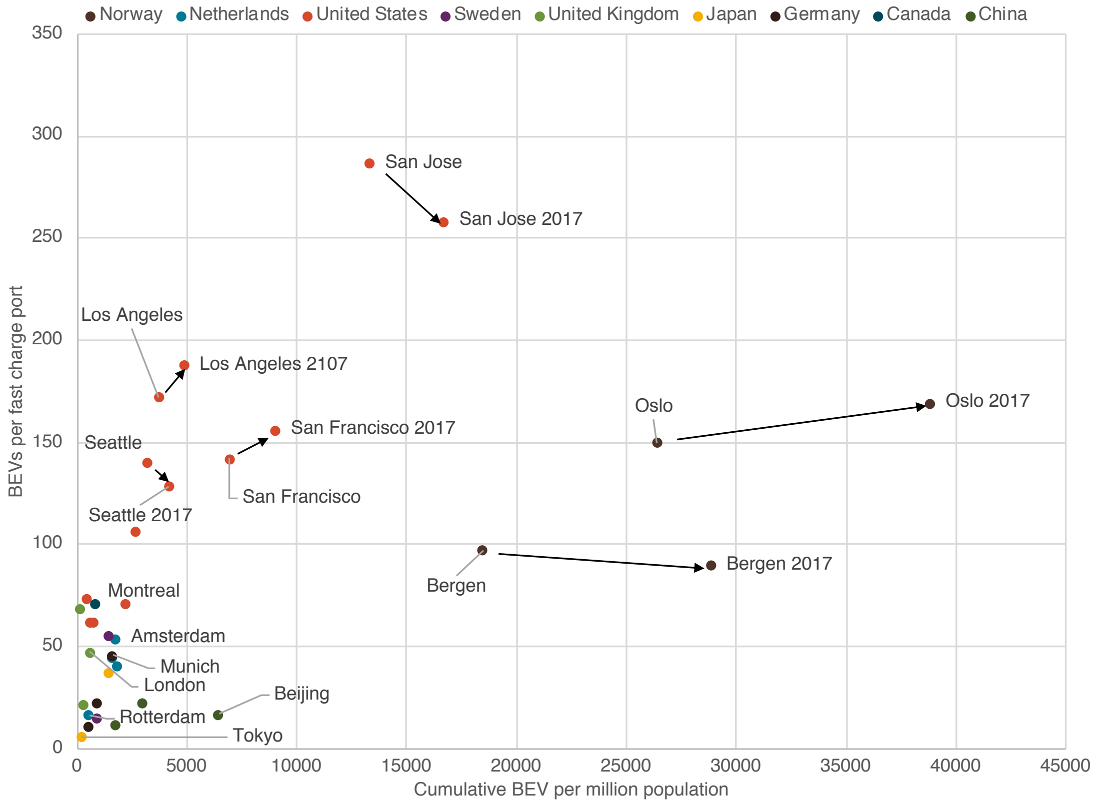

Figure 3: BEVs per fast charge point as a function of market penetration in selected leading markets as of the end of 2016 (except where indicated). Arrows represent the development of the market from 2016 to 2017 for selected markets.

Figure 3 points to several insights related to the early developing of fast charging networks. First, different countries may have different numbers of BEVs per fast charger. This likely stems from the 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.

Second, the figure suggests that, as the population of BEVs increases within a country, one fast charger can support more BEVs. This is most evident looking at the U.S. data points, where one fast charger only supports 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 [7]. Initial stations are likely to be underutilized. As the number of BEVs grows, the increased BEV population may pioneer new locations, but are likely able to more fully utilize the original locations. Eventually, a station reaches capacity at a location and instead of building a new station in a new location, additional fast chargers can be added to address capacity concerns in the same location.

Third, 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 upwards is to be expected year over year. A greater geographic distribution of stations provides better coverage and capacity for the consumer, but lower utilization decreases profitability for the operator.

Lastly, Figure 3 shows that the largest U.S. markets have more BEVs per fast charger than elsewhere. Electric vehicle drivers in the U.S. more frequently have access to home charging or work charging than in other countries, such as in Europe, which have 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 ratio of 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, if more BEVs are purchased by apartment dwellers without home-charging access or reliable public or workplace charging, the fast charger per BEV ratio may need to increase to handle demand. This highlights the importance of constructing reliable slower charging for BEV drivers, but also the role fast charging can play if slower charging is not available or is unreliable.

2 Fast charging usage experiences

Although fast charging is frequently presented as a solution for long-distance driving on intercity routes, this technology can actually play many different roles in different settings. A study of California fast charge session data from users in California suggests some important trends in fast charge usage which may be important for planning future growth [8]. Figure 4 shows one such relationship from this study, the cumulative percent of paid fast charging sessions and unique users 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.

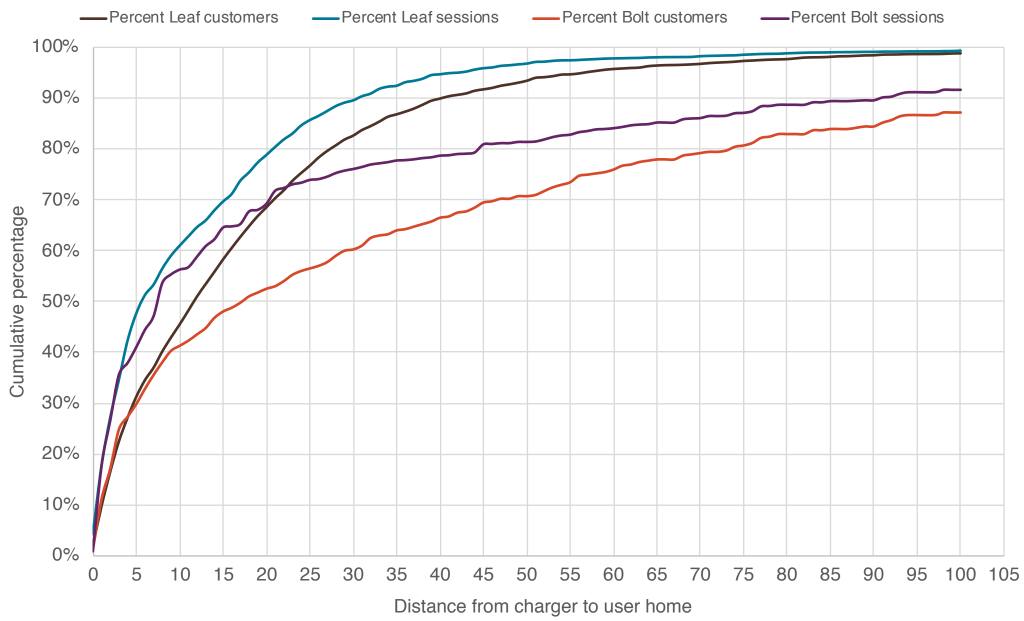

Figure 4: Percent of fast charge sessions and unique as a function of distance from charger to home.

The figure shows that 50% of LEAF fast charging sessions are from users less than 6 miles (10 km) from home, while these sessions came from only 34% of users. A corresponding share of sessions for the Bolt occur at 7.5 miles (12 km) from home and are initiated by only 37% of users. The relationship between sessions and distance from home scales with range. About 10% of sessions are beyond half the range of a vehicle, and only 1% are beyond the full 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 and well within a vehicle's driving range [9]. 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 showed that heavy users averaging 20 sessions per month were likely to use charging closer to home, while occasional users charged farther away. This suggests that heavy users are skewing the numbers shown in Figure 4. In fact, 10% of users accounted for 50% of all sessions. 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. Not having a home charger was correlated with heavy fast charging usage.

2.1 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. 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 [10]. Only 23% of car-owning households actually parked in their garage. This 45% of car-owning households without access to a garage and are less likely to have access to a plug, instead having to rely on public charging.

In the U.S. 74% of households were single family structures, which have high access to garages compared to other segments. Access to a garage, however, does not guarantee access to a plug. Figure 5 provides a breakdown of access to electricity near car parking by home type and ownership status [11]. Overall, 52% of households park no vehicle within 20 feet of an electrical outlet. An estimated 9% answered “no” since they don’t have a household vehicle. 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.

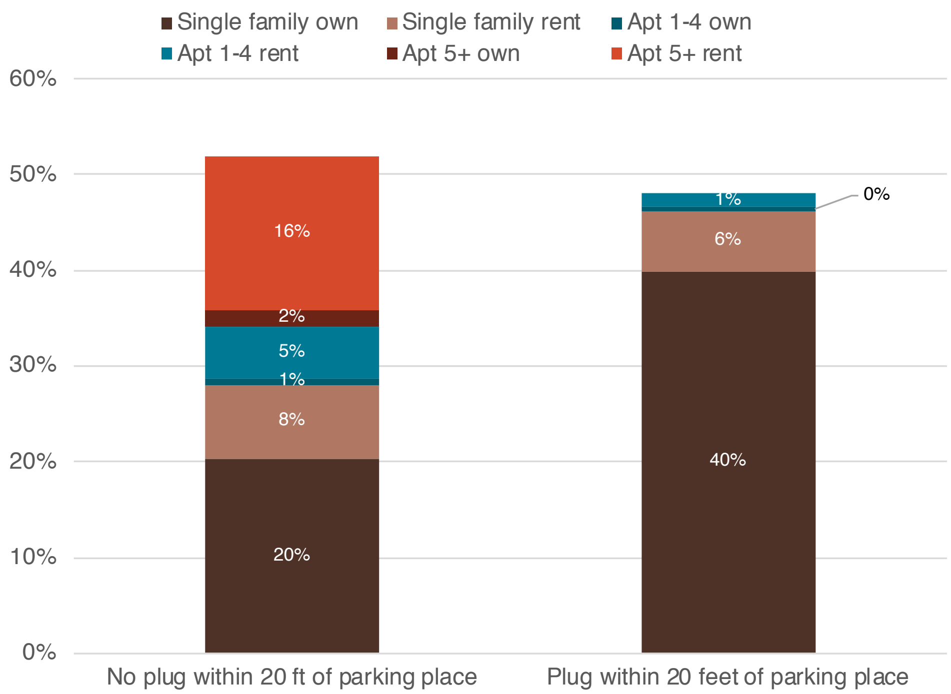

Figure 5: Access to household plugs near parking location in the U.S.

For renters or for those without dedicated parking spots, enabling charging 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. 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 in Norway have access to regular home charging [12].

Charging network usage data allows us to estimate the percentage of Nissan LEAF drivers using fast charging more than 10 or 15 times a month to give an idea of how frequently users are foregoing home charging [8]. Looking at actual charging data from EVgo fast chargers in California, we find 9,031 unique LEAF customers as of May 2017. There were 1,209 users that charged more than 10 times per month and 830 charge more than 15 times per month, representing 2.8% and 1.9% of the California customer base respectively. The true number of heavy fast charging users are likely higher, as the EVgo stations surveyed represent only 45% of fast chargers in the state. The prevalence of this behavior could grow as the market expands to those with no home charger, if fast charging is available at prices competitive with gasoline. Furthermore, the share of drivers without home charging is likely higher in markets outside of North America, indicating higher demand for urban fast charging solutions in those cities.

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 less costly public or workplace solution.

2.2 Consumer fast-charging costs

The cost of fast charging, relative to the cost of other charging options and to fossil fuel vehicle alternatives, is a major driver of fast charging demand and of the business case for fast charging network operation. Drivers pay for fast charging in different ways, including a cost per unit of energy (kWh), a cost per unit of time, an initiation or session fee, membership costs per month or per year, and discounts for vehicle type or being a utility customer. Figure 6 illustrates the effective user price per kWh at several fast-charging networks in North America and Europe. The vertical axis displays the effective price per kWh dispensed in U.S. dollars, as of mid-2018. 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.

We also include two lines on the figure to illustrate the electricity price at which driving a Nissan Leaf is equivalent to similar 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 boundaries for costs at which an electric vehicle costs more or less to drive than the gasoline alternative.

Some 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 green) and non-members (in red) to illustrate the rates experienced by different customers. In order to compare fast-charging networks with different pricing schemes, we assume 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.

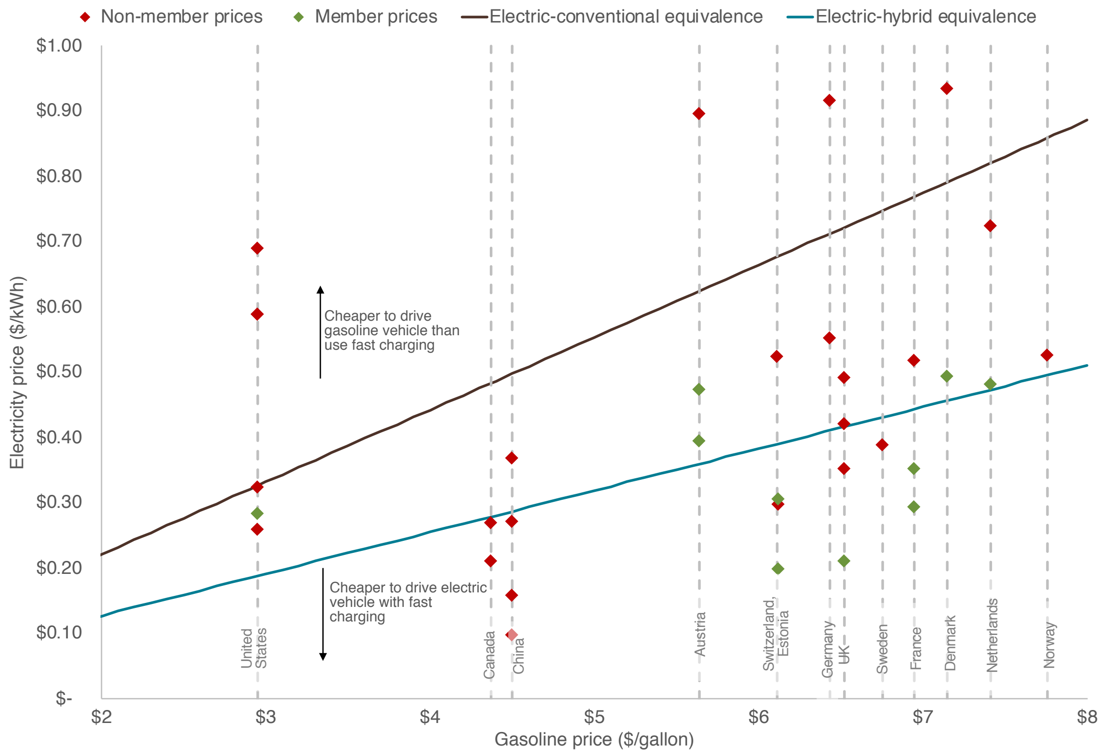

Figure 6: Fast-charging prices in U.S. dollars per equivalent kWh delivered in different fast-charging networks compared to the gas prices in each region.

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 per kWh in Europe, reflecting more expensive hardware costs, utility demand charges, and administration costs for station operators. Fast charging at the majority of stations costs more per mile driven than the cost of gas for a Toyota Prius (52 miles per gallon) and several networks have higher per-mile costs than driving a Nissan Versa gasoline car (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 for all cases studied, fast charging with a membership was less costly than the price of driving a conventional gasoline car.

3 Trends for future deployment

Even before the development of a significant electric vehicle population, researchers and governments modelled estimates of fast charging demand using assumptions about technology and customer behavior. Modelling conducted in the 2010-2015 timeframe typically assumed a vehicle range of 80-100 miles (129 – 161 km), home charging availability, and an assumption that fast charging would priced higher than other forms of charging. Reality in early markets has not always played out according to these assumptions. Vehicle range has grown, home charging or convenient public charging is not universally available, and fast charging has been provided for no cost with the purchase of several vehicle types.

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 [13], availability of public slower charging [8], and a high value of time [9]. In general, studies have found that greater availability of home, workplace, and public Level 2 charging; increased vehicle range; increased fast charging speed; and the ability to substitute trips using conventional or plug-in hybrid vehicles each reduce the total demand for fast charging.

Using a variety of assumptions about these and other factors, researchers have created many estimates of fast charging network requirements for a growing electric vehicle market. Figure 7 illustrates several such estimates from selected studies, plotting the BEV penetration on the horizontal axis versus the ratio of BEVs per fast charger on the vertical axis. Full references and details on the methodology of each of the indicated studies can be found in [14]. As shown, the estimates range from about 27 BEVs per fast charger to about 1,800 BEVs per fast charger. A clear conclusion from the chart is that there is great uncertainty about exactly how much fast charging is needed for a given number of future BEVs. However, there is also general agreement that the ratio of BEVs supported per fast charge point increases over time, a conclusion in agreement with the observations from metropolitan areas in Figure 3.

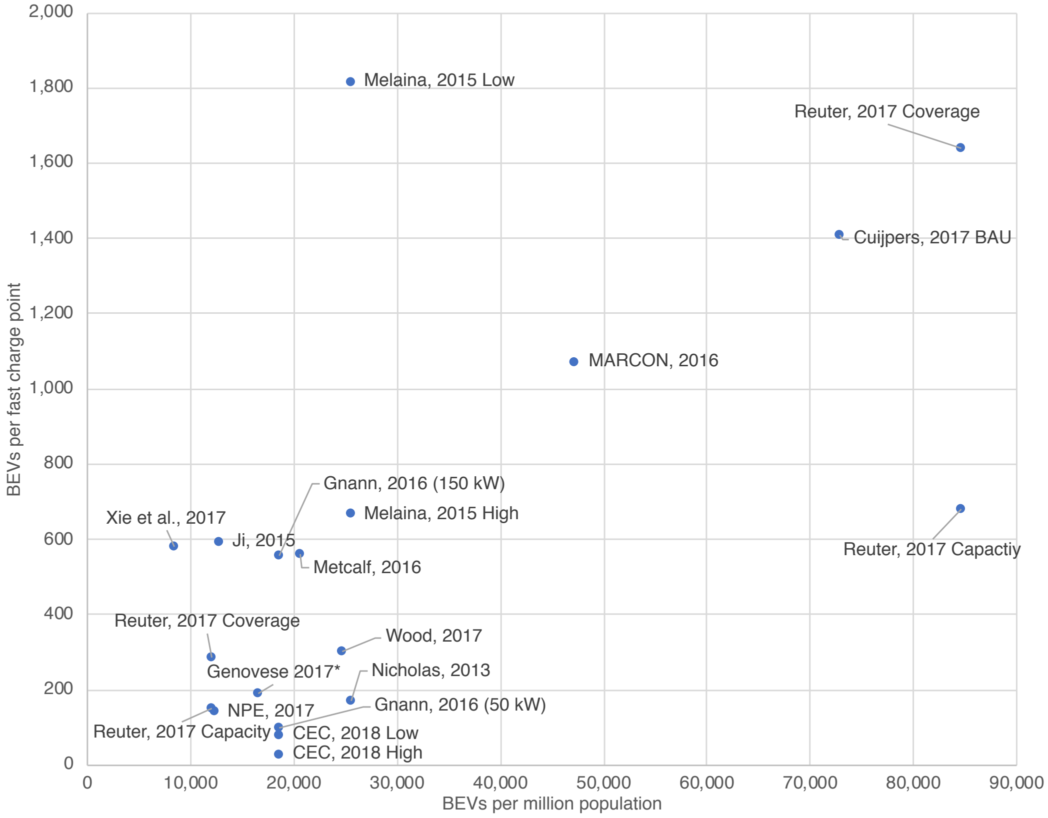

Figure 7: Estimates of BEVs per fast charger at various stages of market development in selected models

Combining the findings from Figure 3 (metropolitan area-level observations in 2016-2017) and Figure 7 (model estimates of future demand), we offer a rough estimate of how much more fast charging is needed for a given growth in electric vehicles. Table 2 summarizes approximate benchmarks from these results, acknowledging the many uncertainties described above which affect BEV-to-fast charging ratios. To provide some sense of how these benchmarks are manifested in different markets, results are shown for three hypothetical metropolitan areas of 1, 2, and 4 million people. The columns show three levels of uptake from 2,000, 10,000, and 85,000 cumulative BEVs on the road per million people. The ratio of BEV-to-fast charge points rises from 50 to 150 to 700 as the electric vehicle market grows (per Figure 3 and Figure 7). As a result, the increase from a low electric vehicle market to a medium one results in a 400% increase in the number of 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 the number of fast charge points by another 80%.

Table 2: Approximate benchmarks for fast chargers to support various electric vehicle numbers for given metropolitan area population sizes.

	Metropolitan area population	Low-penetration market	Medium-penetration market	High-penetration market
Battery electric vehicles	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
BEV per fast charger		50	150	700
Fast charge points	1,000,000	40	67	121
	2,000,000	80	133	243
	4,000,000	160	267	486

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. New electric vehicle models will help to clarify how these relationships will change with larger batteries and faster charging. As the electric vehicle market advances towards the mainstream, analyses such as these must be reassessed and strengthened in order to better overcome the barriers and challenges faced in the rollout of fast-charging infrastructure.

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Authors

Dr. Michael Nicholas is a senior researcher in ICCT's electric vehicle program. He is currently conducting research on electric vehicle markets and infrastructure. Emphases include charger usage, location, and pricing as well as the role of utilities in the transition to vehicle electrification. He additionally focuses on the market for electric vehicles and the effect of incentives, infrastructure and policies to grow the market. Michael previously worked as a Professional Researcher at the University of California, Davis and holds a Ph.D. in Transportation Technology and Policy from the Institute of Transportation Studies at the University of California, Davis.

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