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EMERGING BEST PRACTICES FOR ELECTRIC VEHICLE CHARGING INFRASTRUCTURE

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EXECUTIVE SUMMARY

Electric vehicles offer great potential to dramatically reduce local air pollution, greenhouse gas emissions and resulting climate change impacts, and oil use from the transport sector. With electric vehicle costs steadily falling, the transition continues to become more feasible. This potential is enabled and made compelling by the ubiquity of electricity and the growing availability of low-carbon, renewable energy sources. Yet there are unanswered questions about the deployment of electric vehicle charging infrastructure and the associated policy that will need to be addressed to help pave the way for electrification.

This report provides a global assessment of charging infrastructure deployment practices, challenges, and emerging best practices in major electric vehicle markets, with an emphasis on public charging facilities. Although most early adopters charge their vehicles at home, public charging is an important part of the electric vehicle ecosystem. We analyze public charging infrastructure in the top electric vehicle markets globally, including a statistical analysis of the relationship between public charging and electric vehicle uptake. Our analysis is at the metropolitan-area level to better discern local infrastructure variation, practices, and circumstances.

Figure ES-1 depicts electric vehicle uptake and public charging infrastructure development in the top electric vehicle markets by share of new vehicles in 2016. Norway and the Netherlands, which have seen electric vehicle shares higher than 5% of new sales, have public charging infrastructure per capita that is several times that of other leading markets. China, the world's largest electric vehicle market by volume, has the highest number of charging stations, with more than 100,000 Level 2 and 38,000 direct current (DC) fast charge points. Other countries with an electric vehicle share of new sales greater than 1% have varying amounts of public charging infrastructure and different fractions of DC fast charging, reflecting different roles of public charging infrastructure that vary according to demographics and policy priorities.

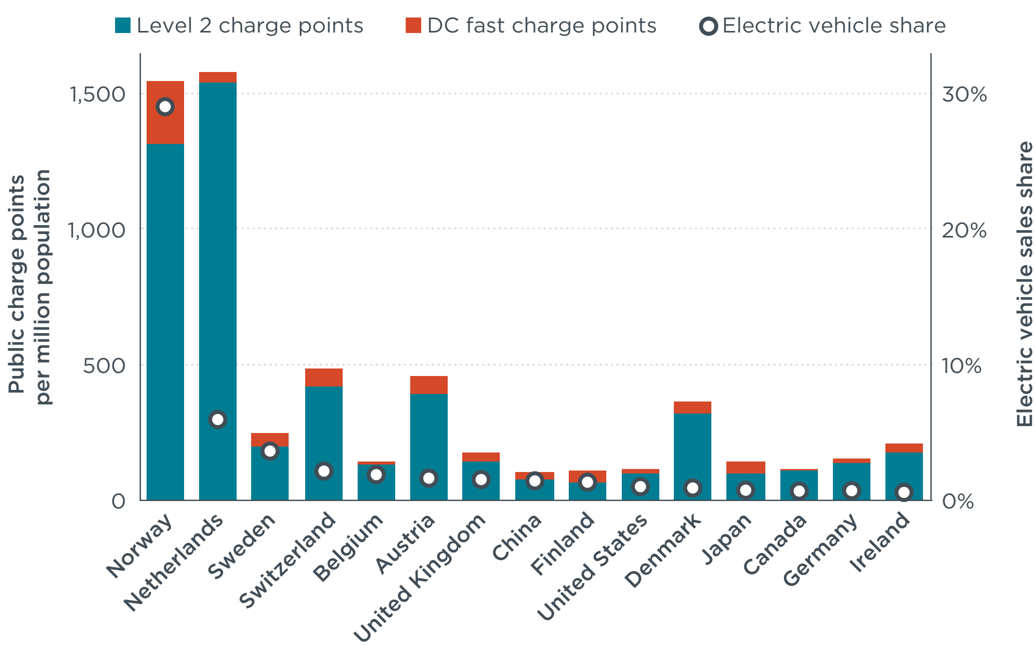

Figure ES-1. 2016 electric vehicle sales share and public charge points per million population in major national markets.

We find that charging infrastructure availability varies greatly at a local level. We offer four high-level conclusions on the fast-developing charging infrastructure around the world.

Public charging infrastructure is a key to growing the electric vehicle market. Using a multivariable regression of 350 metropolitan areas, we find that both Level 2 and DC fast charging infrastructure are linked with electric vehicle uptake, as are consumer purchase incentives. We therefore corroborate other research on the importance of developing charging infrastructure in unison with electric vehicle deployment. The leading electric vehicle markets of Norway and the Netherlands have more than 10 times as many public charge points per capita as average markets, and leading markets in California and China had three to five times the average. Yet the significant charging variability across the hundreds of cities analyzed in this study points to major differences across the electric vehicle markets regarding the role of public charging. As the global electric vehicle market grows—likely by at least a factor of 10 by 2025—so too will the need for much more public charging infrastructure.

There is no universal benchmark for the number of electric vehicles per public charge point. Electric vehicle owners in California more frequently have access to home and workplace charging, and one public charger per 25 to 30 electric vehicles is typical. In the Netherlands, private parking and charging are relatively rare, and one public charger per 2 to 7 electric vehicles is typical. This ratio ranges from 3 to 6 in major markets in China, and these cities typically had the highest percentages of rapid charging. Given the wide variation of public charging availability across markets with higher electric vehicle uptake, and their differing housing and population density characteristics, it seems clear that there is no ideal global ratio for the number of electric vehicles per public charge point. Comparisons of similar markets still offer an instructive way to understand where and how charging is insufficient. Lagging electric markets can strive toward the leading benchmarks of comparable cities, while top markets continue to set new benchmarks as the market and its charging infrastructure coevolve.

Multifaceted and collaborative approaches have been most successful in promoting early charging infrastructure buildout. Governments at the local, regional, and national levels around the world have used varied strategies to promote public and private charging infrastructure. Successful programs have transparently engaged many stakeholders through integration of driver feedback on charger deployment, implementation of smart charging systems, distribution of funding to local governments, creation of public-private partnerships, and consultation with electric utilities. To address changing needs in this growing market, governments create and fund programs that target difficult market segments, such as curbside charging stations, multi-unit dwellings, and intercity fast charging.

Barriers to the deployment of the ideal electric vehicle charging network remain. Despite all the electric vehicle improvements entering the market, charging infrastructure still suffers from fragmentation, inconsistent data availability, and a lack of consistent standards in most markets. Open standards for vehicle–charge point communication and payment may mitigate some of these issues by enabling interoperability between charging networks, increasing innovation and competition, and reducing costs to drivers. As demonstrated by successful efforts in the Netherlands, governments may wish to require data collection and the use of open standards for publicly funded projects to help market development.

I. INTRODUCTION

Electric vehicles offer the potential to dramatically reduce local air pollution, climate change impacts, and oil use from the transport sector. Petroleum-fueled combustion vehicles have dominated the past century, but the recent growth of electric vehicles presents an opportunity to transform the transportation sector. With increased production volumes and battery cost reductions over the next 10 years, electric vehicles are projected to approach cost-competitiveness with conventional vehicles (Slowik & Lutsey, 2017; UBS, 2017). In just the past 6 years, electric vehicles have gone from a fringe technology with no mass production to a fast-growing part of the vehicle market. In early 2017, the two-millionth electric vehicle was sold, and electric vehicles have surpassed 10% of new vehicle sales in multiple local markets.

The potential benefits of electric vehicles are enabled, and made much more compelling, by the attributes of electricity. Electricity is ubiquitous and available for electric charging nearly everywhere, including in and near many homes. The cost of electricity can be lower per effective energy unit than petroleum fuels, and is typically made much lower than petroleum by the greater efficiency of electric motors relative to internal combustion engines. Whereas renewable and lower-carbon liquid fuels have been relatively elusive, electricity is generated from many renewable and low-carbon energy sources, which represent an ever-growing fraction of global electricity generation.

Yet a lack of charging infrastructure still presents a barrier to growth in the electric vehicle market. Although electricity itself is ubiquitous, its transmission, distribution, and retail charging options for electric vehicles are not. The fueling infrastructure to support combustion-powered vehicles is already in place, with a robust network of gasoline and diesel fueling stations around the world. Taking the U.S. situation as an example: Through 2016, there were more than 150,000 filling stations for gasoline and diesel fuel in the United States, most of which have many pumps (API, 2017). This network of stations has evolved in number and location to be able to fuel the approximately 250 million gasoline and diesel vehicles in the United States (Davis et al., 2016). Compare this with the electricity availability for electric vehicles. Beyond the electricity that is widely available at most households, there were about 15,000 publicly accessible charging stations at the end of 2016 (U.S. DOE, 2017a). If publicly accessible charging infrastructure for electric vehicles remains limited, this would restrict drivers' ability to take longer trips and would practically limit the utility and attractiveness of electric vehicles for any household without a private garage to charge the vehicle.

As a result, the development of a robust charging infrastructure network is widely considered a key requirement for a large-scale transition to electromobility. Such infrastructure would not only provide more charging options for drivers, but would also promote awareness and range confidence for prospective electric vehicle owners. Several automakers have begun to directly build out their own charging infrastructure networks, while others have engaged in partnerships with other automakers and charging providers. Many governments have created programs to encourage the construction of charging infrastructure through incentives, regulations, and partnerships. Nonetheless, there is relatively little consensus about the optimal concentration and distribution of charging infrastructure or the relationship between charging infrastructure and electric vehicle uptake. Even getting access to the number and location of available charging points can be difficult.

At this stage, governments, auto industry experts, and researchers around the world have many questions about electric vehicle charging infrastructure. How much charging infrastructure is required for a mature market, and what types are likely to be needed in the future as electric vehicle technology continues to evolve? What policy frameworks and funding mechanisms can help to ensure that the necessary charging infrastructure is in place for electric vehicles? Finally, are there strong global examples of policies and initiatives that demonstrate how best to overcome prevailing barriers and deploy charging infrastructure for electric vehicles?

This paper seeks to address these questions with a comprehensive review of the current status of charging infrastructure in major electric vehicle markets in North America, Europe, and Asia. Although the majority of charging in most regions occurs at home, this analysis focuses primarily on public charging infrastructure to help inform topical government policy and funding questions. We assess the relationship between charging infrastructure and electric vehicle uptake at the metropolitan-area level. Through this analysis, we quantify emerging benchmarks for charging infrastructure deployment and best practices for charging infrastructure promotion, construction, and operation. Additionally, we compare major government programs to increase charging infrastructure and discuss some of the barriers and exemplary programs that are helping to overcome these barriers.

II. BACKGROUND ON ELECTRIC VEHICLE CHARGING INFRASTRUCTURE

ELECTRIC VEHICLE CHARGING TECHNOLOGY

As electric vehicle charging technology continues to advance, several standards and guidelines have become widely accepted across the industry. To provide a technical background for the following analysis and policy discussion, this section gives a brief overview of charging infrastructure technology, standards, and terminology.

Charging speeds. Charging power, which determines the time required to charge a vehicle, can vary by orders of magnitude across charge points, as shown in Table 1. A small household outlet may charge as slowly as 1.2 kW, while the most advanced rapid charging stations can charge at up to 350 kW. Charging infrastructure is broadly broken into three categories based on speed: Level 1, Level 2, and direct current (DC) fast charging (sometimes referred to as Level 3).

Table 1. Characteristics of Level 1, Level 2, and DC fast charging.

Charging level	Voltage (V)	Typical power (kW)	Setting
Level 1	120 V AC	1.2–1.8 kW	Primarily residential in North America
Level 2	200–240 V AC	3.6–22 kW	Home, workplace, and public
DC fast	400 V DC	50 kW or more	Public, primarily intercity

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

Many electric vehicles are limited in the maximum charging power they can accept, because of restrictions in their ability to convert AC power from the grid to DC power that charges the batteries. For example, the Chevrolet Volt, a plug-in hybrid vehicle (PHEV), is limited to 3.6 kW, and the Nissan Leaf, a battery electric vehicle (BEV), is limited to 6.6 kW. Furthermore, some electric vehicle models, including most PHEVs, are not capable of DC fast charging.

Charging infrastructure can also be categorized by “mode,” which specifies the type of electric and communications connection between the vehicle and the charging infrastructure (Bräunl, 2012). Mode 1 consists of 120 or 240 V charging up to 16 amperes (A) on a shared circuit without safety protocols. Mode 2 consists of 120 or 240 V charging up to 32 A from a standard outlet, on a shared or dedicated circuit, with safety protocols including grounding detection, overcurrent protection, temperature limits, and a pilot data line. Mode 3 allows 240 V charging at any amperage on a wired-in charging station on a dedicated circuit, with the same safety protocols as Mode 2 and an active communication line with the vehicle. This enables smart charging—the coordination of charging according to utility needs, fleet schedules, or renewable energy availability. Finally, Mode 4 is defined as DC fast charging on a 400 V, wired-in connection, and requires more advanced safety and communications protocols.

Charging connector standards. Depending on region and speed of charging, the type of plug and socket used for charging electric vehicles may vary. The most common plug types are illustrated in Table 2 and Table 3. Although these plug types are generally well-defined and each works well for its specific application, the variety of standards may lead to confusion among drivers and hesitation from industry.

In North America and Japan, most electric vehicles use the SAE J1772 connector, which contains five pins and a mechanical lock. In Europe, Level 2 charging uses the Type 2 or Mennekes connector, which has seven pins and takes advantage of the three-phase alternating current grid. China also requires (as of 2017) a variant of the Type 2 plug (under the standard GB/T 20234.2-2015), although legacy vehicles and charging stations have not yet been converted (NDRC, 2015). The exception to this regional breakdown is Tesla, which uses a proprietary connector for its vehicles sold in North America, although adapters to SAE J1772 are available. In Europe and Asia, Tesla vehicles have a Type 2 plug.

Table 2. Comparison of the most popular AC charging connector types.

SAE J1772	Type 2 (Mennekes)	Tesla (US)
		
North America and Japan	Europe and China	Tesla vehicles in North America

Photo credit (left to right): National Alternative Fuels Training Center, Mennekes AG, Silverstone Green Energy

For DC fast charging, connector types vary by automaker in addition to region, with the most common connectors shown in Table 3. Nissan and Mitsubishi created and promoted the CHAdeMO (short for Charge de Move) fast charging standard beginning in 2011 (Mitsubishi Motors Corporation, 2014). This type is still used on electric vehicles produced by Nissan, Mitsubishi, Kia, Citroën, and Peugeot. In contrast, several automakers from the United States and Europe have advocated for the Combined Charging System (CCS), which uses the SAE J1172 or Mennekes AC plugs along with two additional DC pins for fast charging. This standard has now been adopted by BMW, Daimler, Ford, Fiat Chrysler, General Motors, Honda, Hyundai, and Volkswagen. Whereas CCS (sometimes referred to as SAE Combo or Combo2 in North America and Europe, respectively) uses the same receptacle on the car as a Level 2 charger, CHAdeMO requires a separate port. As in the case of Level 2 charging, Tesla uses its proprietary plug for its DC Supercharger stations in the United States, although the company also makes Tesla-to-CHAdeMO adapters. China has recently mandated the use of a new standard (GB/T 20234.3-2015) for all new vehicles and fast charging infrastructure; Tesla vehicles sold in China will also use this standard (Lambert, 2016; NDRC, 2015).

Table 3. Comparison of the most popular DC fast charging connector types in general use by major automobile manufacturers.

CHAdeMO	CCS (North America)	CCS (Europe)
		
Nissan, Mitsubishi, Kia, Citroën, Peugeot	BMW, Daimler, Ford, Fiat Chrysler, General Motors, Honda, Hyundai, Volkswagen	

Photo credit (left to right): National Alternative Fuels Training Center, SAE, Hadhuey via Wikimedia Commons

CHARGING DATA AVAILABILITY

In the rapidly evolving charging infrastructure industry, availability and access to accurate, up-to-date data can be limited in various markets. This situation can be problematic for drivers, who may have a more difficult time finding a place to charge; for charge point operators, who may see lower use at their stations; for governments, unable to direct investment efficiently; and for auto dealers, who need to assure customers of charging availability. There are several kinds of data regarding charging infrastructure that can be recorded, including location, type, operational status, and usage.

In many markets, there are numerous services attempting to advertise station information to drivers, although some of this information is likely to be incomplete or outdated at any given moment. Many different stakeholders offer these services, including governments (the Alternative Fuels Data Center in the United States), nonprofits (Open Charge Map or LEMnet in Europe), for-profit companies (ChargeHub in Canada, Zap-Map in the United Kingdom), automakers (the Nippon Charge Service consortium in Japan), and charge networks (ChargePoint in the United States, State Grid Corporation in China). Although most of these services offer maps (and in some cases mobile apps) for drivers, few offer open access to data.

A lack of information about maintenance and operational status can present an issue for charging stations, leading to higher downtime and frustration for drivers. Many newer charging stations are connected to the internet and can provide live information about their status and any problems, which can be incorporated into online charging station locating services. For stations without such capabilities, or on services that cannot access privately held data, allowing users to easily report a station's status or successful charge (such as the "Check In" feature on PlugShare) can be useful in providing frequently updated status information. In turn, sharing such data can help charging station managers quickly repair the infrastructure.

Finally, more advanced networked stations frequently collect usage data from charging stations; these data can provide helpful lessons for governments and researchers, and may eventually lead to more efficient charging station construction and management practices (i.e., OLEV, 2013; Winn, 2016). Some governments choose to make usage data reporting a precondition for funding—for example, in British Columbia and the United Kingdom (evCloud, 2017; OLEV, 2016a).

LITERATURE REGARDING CHARGING AND ELECTRIC VEHICLE UPTAKE

Many governments consider transportation electrification an important step toward climate, air quality, and energy independence goals. To help achieve these goals, governments have invested substantial funding to promote electric vehicles and the associated charging infrastructure. Although charging infrastructure is a major priority for governments seeking to accelerate electric vehicle adoption, specific relationships between charging infrastructure availability and increased electric vehicle sales have been elusive. Likewise, there are no universally accepted goals or standards for charging infrastructure density, either on a per-capita or per-vehicle basis. Nonetheless, several studies in the past few years have provided helpful insights into this question.

Sierzchula et al. (2014) assessed factors influencing electric vehicle adoption across 30 countries in 2012 at a national level, focusing primarily on financial incentives. In their analysis, charging infrastructure was included as an explanatory variable, measured as charging stations per 100,000 residents in each country. A regression of several variables, with electric vehicle market share as the dependent variable, showed that charging infrastructure is the best predictor of national electric vehicle market share. Nonetheless, there are exceptions to this trend, such as Israel and Ireland, with relatively extensive charging infrastructure and low electric vehicle sales shares.

Harrison and Thiel (2017) modeled the impact of several factors, including charging infrastructure, on electric vehicle market share in Europe. This model calculated the utility and respective market share of different powertrain types, using feedback loops to capture realistic decision-making patterns by drivers, manufacturers, charging infrastructure providers, and policymakers. The model also assessed the profitability of charging stations under various scenarios and considered subsidies and government targets for charging infrastructure. The authors found that the private market can profitably support 95% of public charging stations, up to a ratio of 25 electric vehicles per charge point. They also found that electric vehicle market share increases as the electric vehicle/charge point ratio decreases from 25 to 5 electric vehicles per charge point. Charging infrastructure availability also appears to have the strongest impact on uptake once electric vehicle stock share exceeds 5%, which is currently the case only in Norway.

Slowik and Lutsey (2017) followed an approach similar to that of Sierzchula et al. (2014), but for the United States. Unlike other analyses, however, they focused their analysis on the 50 largest metropolitan areas in the United States, breaking down charging infrastructure at a regional level. Overall, the study found a significant relationship between public charging (measured in charge points per capita) and electric vehicle uptake, and identified 275 charge points per million residents as a benchmark for leading U.S. markets. The number of fast charging points per capita was also found to correlate with electric vehicle sales share, as was workplace charging. However, the authors more broadly concluded that a robust electric vehicle market requires multiple types of supporting policy, including charging infrastructure, consumer incentives, and local promotion actions that address consumer awareness barriers.

In general, there is broad agreement that public charging infrastructure is important to the growth of the electric vehicle market, among other factors related to electric vehicle cost and awareness. However, there has been limited research into how much charging infrastructure is needed for a given market and how strongly charging infrastructure encourages electric vehicle sales, even within one market. This may be partially due to the data availability problems described above. It may also be due to the quickly evolving state of electric vehicle technology, where electric vehicles and charging infrastructure will grow and coevolve together with patterns that still remain largely unclear.

Although this paper cannot comprehensively and definitively answer these questions, we seek to provide greater clarity about the existing relationship between charging infrastructure and electric vehicle sales in major electric vehicle markets around the world as of 2016. The next sections describe the policy context and offer an analysis of public charging deployment around the world.

III. GOVERNMENT PROGRAMS FOR PUBLIC CHARGING INFRASTRUCTURE

Since the introduction of modern electric vehicles, many governments at the local and national level have promoted electric vehicle charging infrastructure in recognition of the necessity of charging stations for a mature market. However, these plans vary widely in scope and focus, reflecting the uncertainty and pace of change in this industry. Here, we summarize major government programs promoting charging infrastructure in selected markets and highlight some emerging best practices. We focus on programs to increase the stock of public charging infrastructure through subsidies, grants, and public-private partnerships.

ASIA

China. Many stakeholders in China, including the central government, local governments, and utilities, have been active in quickly building a charging infrastructure network in that country. The charging network will serve China's ambitions to greatly increase its electric vehicle market in the years ahead. The market, with more than 300,000 electric car sales and 1% of new sales in 2016, is set to meet increasing New Energy Vehicle quotas that are under development to at least triple electric sales in the 2020 time frame. The central government has announced the goal of having electric vehicles reach 20% of national vehicle production, or about 7 million electric vehicles per year, by 2025 (MIIT, NDRC, & MOST, 2017).

The number of charge points has expanded dramatically in China in the past few years, especially in the 88 designated pilot cities funded by the central government, led by Shanghai, Beijing, and Shenzhen. As part of the program, these cities are required to provide one charge point for every 8 electric vehicles, and charging stations should be no farther than 1 km from any point within the center area of the city (NDRC, 2015). The municipal governments in these cities have sometimes funded many of the local stations (typically called "charging piles"), often in collaboration with the national utility State Grid (Research in China, 2017). The State Grid is also working to construct fast charging plazas within cities and along major intercity corridors as part of a plan to build 120,000 fast charging stations and 500,000 total public stations by 2020 (NDRC, 2015; Xin, 2017). Furthermore, some automakers in China have constructed charging stations in the regions where they are headquartered to benefit drivers of their vehicles, although there still remain some issues with interoperability of stations between automaker brands (Yuan, 2016). China represents almost half of the global supply of electric vehicle charging infrastructure—a proportion likely to increase in the coming years, given the strong government support at many levels and high electric vehicle volume there.

Japan. Since the introduction of modern electric vehicles in Japan in 2011, the government and the country's major automakers have supported charging infrastructure, viewing it as a key requirement for increased electric vehicle sales. In 2013, the government created the massive Next Generation Vehicle Charging Infrastructure Deployment Promotion Project to fund charging stations around cities and highway rest stations in 2013 and 2014 (CHAdeMO Association, 2016). The Development Bank of Japan partnered with Nissan, Toyota, Honda, Mitsubishi, and power company TEPCO to construct the Nippon Charge Service (NCS), a nationwide network of charging stations (including many fast charging stations) now operated as a private joint venture. Almost 7,500 stations are now part of this network, with continued funding at least through 2018.

EUROPE

Charging infrastructure in Europe has been constructed by a combination of private charge point providers, power companies, automakers, and governments, primarily at the national and city levels. Many countries within the European Union have created funding schemes or public-private partnerships to increase charging infrastructure, sometimes targeting specific regions in order to create leading electric vehicle markets. Some countries, such as Norway and the Netherlands, have provided incentives for charging infrastructure for several years; others, like Germany, have recently launched major new charging infrastructure programs, indicating growing recognition of the benefits of charging station investments.

The European Union has indicated that electric vehicles and charging infrastructure are a major transportation priority, and is considering extending its vehicle CO_2 regulations to 2025 or 2030 to promote electric vehicles, among other policy approaches (Lutsey, 2017). The European Union has also directed all member states to “ensure that recharging points accessible to the public are built up with adequate coverage, in order to enable electric vehicles to circulate at least in urban/suburban agglomerations and other densely populated areas” (European Parliament, 2014). In addition, the European Commission has supported more than a dozen electric vehicle infrastructure projects through the TEN-T/CEF-T program, with a focus on trans-European corridors and linking the projects operated by member states (TEN-T, 2016). The European Union has also taken an active role to promote interoperability, open standards, and smart charging, as demonstrated in the Green eMotion and PlanGridEV research projects conducted with industry partners (Green eMotion, 2015; RWE Deutschland, 2016).

France. Building on earlier goals to accelerate the shift to electric vehicles, the French government in 2017 has stated a goal of shifting all vehicle sales to electric by 2040. Promotional programs for charging infrastructure have been in place for several years in France. The primary program, operated by the French Environment and Energy Management Agency, distributes funding to municipalities and regional governments, helping to fund more than 12,000 charge points (Environment and Energy Management Agency, 2016). Recipients must commit to building at least 20 charge points and offer free parking for charging vehicles. Currently, most charging stations are eligible for a 30% subsidy. The state-owned utility EDF has also taken a lead role in charging infrastructure, constructing the Corri-Door fast charging network with more than 200 locations across the country (Lefevre, 2016). The federal government’s strong role is evident in the large numbers of charging stations in France.

Germany. Germany has sought to ramp up its charging infrastructure to match its electric mobility ambitions. Sales of electric vehicles had reached 100,000 by early 2017, and the German federal government has goals to reach 1 million by 2020 and 5 million by 2030. Despite these stated goals, the government did not widely support public charging infrastructure until recently. Beginning in 2009, the government supported more than 200 projects in eight “model regions” with €130 million, boosting charging infrastructure in areas such as Hamburg and Saxony (BMVBS, 2011). A few cities created their own programs to provide incentives for charging infrastructure; for example, Munich provided a 20% subsidy for private, public, and workplace charging stations (Mobility House, 2017). Most other early charging stations were built by power companies and various private companies.

In early 2017, the government announced a major new nationwide program to promote electric vehicles, including €300 million earmarked for public charging infrastructure through 2020. Of this, €200 million is intended for the construction of 5,000 DC fast charging stations and the remaining €100 million for 10,000 Level 2 stations, with stations distributed across the country (BMVI, 2017). Businesses may apply for funding to cover 60% of the hardware and network connection costs of the stations, and grant recipients must conform to the Open Charge Point Protocol (see below). The scale of this project indicates a substantial commitment to electromobility in Germany, and its results may hold lessons for other governments attempting to support charging infrastructure.

The Netherlands. As a global leader in electromobility, the Netherlands has been on the forefront of charging infrastructure for several years, and many of its cities already have a dense network of charging stations in place. The Netherlands has ambitions to have electric vehicles reach 10% of new vehicles by 2020 and 50% by 2025, and to deploy a nationwide network of charging points to ensure they remain a frontrunner in electric mobility. Much of the early construction of charging infrastructure was initiated by ElaadNL, a foundation created by six power network operators in the country; this group continues to maintain and upgrade about 3,000 stations around the country (ElaadNL, 2016). The federal government also provided €16 million in incentives for charging infrastructure through their 2011 "Electric Mobility Gets Up to Speed" program (Netherlands Enterprise Agency, 2011). More recently, the federal government consolidated various programs and began to promote charging stations through its "Green Deal," including forming partnerships with businesses (Green Deal, 2016).

Regional and local governments in the Netherlands have shown similar ambition in promoting electric vehicle charging infrastructure. The province of Noord-Brabant began a smart charging trial project in 2014 with the installation of public smart charging stations in major cities, and has announced tenders for the installation of 2,000 new smart charging stations beginning in 2017 (Nederland Elektrisch, 2016). The city-operated Amsterdam Elektrisch program, in partnership with utility Nuon, will install curbside chargers on demand, ensuring that all residents have a place to charge an electric vehicle. A similar model has also been adopted by other cities such as Utrecht and The Hague (Gemeente Amsterdam, 2017). Several other provinces and municipalities offer incentives or trial programs for electric vehicle charging infrastructure, leading to the high number of charge points in the Netherlands today. Moreover, the Netherlands has become a leader in charging standardization and interoperability, as discussed below.

Norway. Norway is the global leader in national electric vehicle sales share, with approximately 30% in 2016, and it seeks to shift to 100% electric vehicle sales by 2025. The country has a number of unique challenges relating to charging infrastructure, related to both its high density of electric vehicles and its cold climate. The government has been a key driver of charging infrastructure through the early stages of the electric vehicle market and will continue to invest in this area. The 2016 National Transport Plan states that "Power charging facilities or fuel supply for zero-emission vehicles should be so easily available that long distance driving is possible and unacceptable waiting times are avoided both in the city and for long-haul operations" (Norwegian National Rail Administration et al., 2016).

The key sponsor of Norway's charging infrastructure has been Enova (formerly known as Transnova), an agency funded through petroleum and natural gas sales that promotes greenhouse gas emissions reductions and energy efficiency improvements. Transnova first began construction of charging infrastructure with an investment of €6 million in 2009 and has since steadily continued funding (Nobil, 2012). In 2015 and 2016, the agency issued four calls for proposals, and most recently it has focused on the installation of fast charging stations on remote highways in northern Norway. In addition to this federal investment, many Norwegian cities and towns also have a long record of investing in charging stations; for example, Oslo budgeted €2 million for initial buildout of charging stations through 2011 (Nobil, 2012).

United Kingdom. The government of the United Kingdom, through the Office of Low Emission Vehicles (OLEV), operates a diverse set of programs to encourage the buildout of charging infrastructure in that country. In addition to support for domestic and workplace charge points, OLEV operates the On-street Residential Chargepoint Scheme, which provides funding to local authorities to install public Level 2 charging stations in residential areas for residents without private off-street parking (OLEV, 2016a). This program, designed to cover 75% of hardware costs for these stations, is also notable for its clear guidance for reducing costs and maximizing convenience for installers, drivers, and cities. At the same time, Highways England has plans to install charging infrastructure every 20 miles along the major road network as part of its Road Investment Strategy (Jones, 2015). With EU funding support, the electricity provider Ecotricity has installed at least one rapid charger in each of the United Kingdom's Motorway Service Areas.

Local governments have also been involved in construction of charging infrastructure. Like Germany, specific cities and regions received special funding for trial projects in the Plugged-In Places program through 2014, which included matching funds to businesses that installed charging stations. This has resulted in eight popular regional charging networks with a total of more than 6,400 charge points installed, including Plugged-in Midlands, with almost 1,000 charge points covering East and West Midlands. This was followed by various national schemes that concentrated funding on DC fast charging.

In 2016, the U.K. government announced the Go Ultra Low Cities scheme, which awarded £40 million to a number of cities to roll out pioneering initiatives to assist them in becoming internationally outstanding examples for the promotion of ultralow-emission vehicles. Charging infrastructure is a key part of the initiatives, with funding made available for rapid charging hubs, residential and car club charge points, and trials of various on-street charging initiatives. The program is expected to fund 750 stations in total (Go Ultra Low, 2016). Additionally, under the leadership of Transport for London and various private-sector partners, London has created the Source London network and plans to add 4,500 charge points by 2018 (Source London, 2016). Plans have also been announced to take forward legislative measures to ensure that sufficient charging infrastructure is available at Motorway Service Areas and can be required to be installed at large fuel retailers.

NORTH AMERICA

Canada. Canada's electric vehicle market, driven by early growth in Québec and British Columbia, reached cumulative sales of more than 30,000 electric vehicles in early 2017. The Canadian government is undergoing a broad zero-emission vehicle strategy to set new goals for electrification and its associated policy and charging infrastructure.

Charging infrastructure in Canada has primarily been deployed through a number of provincial and local programs, and the federal government is becoming increasingly involved in the sector. The government is working to write a national zero-emission vehicle strategy and has already committed $182.5 million for electric vehicle charging and hydrogen fueling infrastructure through 2017 (Transport Canada, 2017). Québec, which has about half of the country's electric vehicle stock, has been especially active: The Electric Circuit network, operated by public utility Hydro Québec, includes almost 1,000 stations as of July 2017, and it has expanded into Ontario (Electric Circuit, 2017). Three other charging networks are also active in the province, bringing the number of public charging stations available around 1,600. The province also provides support for charging at private homes, workplaces, and multi-unit dwellings, and is working with neighboring U.S. states to create cross-border fast charging corridors. Ontario and British Columbia have also invested substantially in public charging infrastructure, Ontario through its Ministry of Transport and British Columbia through its utility BC Hydro.

United States. The U.S. electric vehicle market continues to grow, helped by a combination of federal and state consumer incentives and investment, zero-emission vehicle regulatory policy, and a series of state and local city promotion activities (Slowik & Lutsey, 2017). The California zero-emission vehicle policy, adopted by states representing nearly one-third of the U.S. vehicle market, is expected to increase electric vehicles in the market from more than 600,000 in early 2017 to several million by 2025. To serve the early growth, much of the initial investment in charging infrastructure in the United States came from the American Recovery and Reinvestment Act of 2009, which provided federal funding through the EV Project and the U.S. Department of Transportation's Transportation Investment Generating Economic Recovery program, among many infrastructure projects in the United States from 2010 to 2013. By the end of 2014, there were about 18,000 public Level 2 and DC fast electric charge points in the United States (U.S. DOE, 2017a). Since then, charging infrastructure has been deployed with funding and authority from many different federal, state, and local agencies and has increased to more than 27,000 charge points by the end of 2015, and to 36,000 charge points at the end of 2016 (U.S. DOE, 2017a). Almost all of these government-funded stations are operated by private networks.

As of 2016, one of the most promising developments for sustained investment in charging infrastructure consists of electric power utilities providing mutual benefits to all ratepayers through their investments in charging infrastructure. This new movement has been led by major utility actions in California (see CPUC, 2017; Edison International, 2016; SDG&E, 2016). A number of utilities and public utility commissions in other states are following California's lead, while in other states, utility commissions and stakeholder groups are considering the costs and long-term benefits of rate-based utility investment in charging infrastructure and other transportation electrification programs. As input to help guide charging deployment, California developed the EVI-Pro model, a tool that projects the number of home, workplace, and public charge points needed by 2025 in each county to correspond to the expected growth in the electric vehicle fleet (CEC & NREL, 2017).

As part of the settlement of the Volkswagen diesel scandal, VW will invest approximately $2 billion in charging infrastructure and other programs to support clean transportation across the United States for a 10-year period commencing in 2017, 40% of which will be invested in projects in California. The first phase will result in several thousand charge points at more than 900 sites across the country, including local community charging and intercity fast charging corridors, with some stations capable of providing 350 kW DC charging (Electrify America, 2017). The settlement also establishes an Environmental Mitigation Trust that allocates funds to the states and allows them to use up to 15% of their allocation for zero-emission vehicle fueling infrastructure.

SUMMARY AND LESSONS

As the electric vehicle market evolves, governments are increasingly working to promote charging infrastructure. Table 4 summarizes some of the major national-level charging infrastructure programs in leading electric vehicle markets, illustrating that there are multiple ways for governments to promote this part of the market. Additionally, in markets such as the United States and the Netherlands, local governments have played a strong role in building charging infrastructure.

Table 4. Summary of major national-level charging infrastructure programs in selected markets, including budget and form of award.

Country	Program	Budget	Mechanisms of support
China	• State Grid national fast charging corridors • Regional investments by automakers • City government-funded construction in pilot cities		• State-owned utility programs • Public-private partnership • Grants to local governments
France	• Funding given 3,000 cities for 12,000 charge points • EDF power company building nationwide DC fast charging network		• Local governments apply for grants
Germany	• €300 million for 10,000 Level 2 and 5,000 DC fast charging stations	€300 million ($285 million)	• Subsidies for 60% of costs for all eligible businesses
Japan	• Next Generation Vehicle Charging Infrastructure Deployment Promotion Project • Nippon Charge Service government-automaker partnership	Up to ¥100 billion ($1 billion)	• Grants to local governments and highway operators • Public-private partnership
Netherlands	• “Green Deal” (curbside chargers on request)	€33 million ($31 million)	• Contracts tendered to businesses on project-by-project basis
Norway	• Enova grant scheme from 2009 onward		• Quarterly calls for proposals for targeted projects
United Kingdom	• Curbside stations for residential areas • Highways England building DC fast charging stations along major roads in England	£2.5 million ($2 million) £15 million ($12 million)	• Municipalities apply for grants; installers reimbursed • Grants and tenders administered by public body
United States	• Grants for funding public charging stations through American Recovery and Reinvestment Act	$15 million	• Matching grants for local governments

Although there is no conclusively superior design for a charging infrastructure program, several lessons can be gleaned from these government programs. In particular, there is evident value in targeting specific charging needs, making the charging program information clear and easily accessible, and promoting competition. Naturally, all recommendations must be tailored to fit local political, geographic, and demographic contexts for each market.

» It is important to target specific, known charging needs. The problem of charging infrastructure availability is complex and large, and constructing a comprehensive charging network would be prohibitively expensive. Furthermore, because the industry is evolving quickly, current assumptions about technology and driver preferences may not hold in the future. Therefore, it is usually preferable for a government program to focus on one form of charging infrastructure where there is a clear need (e.g., intercity DC fast charging or curbside residential charging). This can also help to encourage broader geographic coverage and will lead to a more accurate assessment of the costs of a given program.

» Clear, accessible information on charging programs helps all stakeholders. For programs offering subsidies or accepting applications, it is important to make information and guidance about the program easily accessible and simple to understand. This includes posting basic information online, requiring only one or two clicks from the primary electric vehicle informational website. Ideally, the most important provisions of the rule for different actors (such as drivers, local governments, and businesses) would be identified. If a government offers multiple programs, these would ideally be displayed together, along with links to other similar programs at a local level (or at a national level for local governments). A strong example of this is OLEV's programs in the United Kingdom: Three schemes are laid out on one webpage with clear guidance for all parties, accessible in only one click from the main OLEV page.

» Competition among charging providers will facilitate growth of the early infrastructure and will also help to identify the leading business models over time. It is generally accepted that the charging infrastructure industry will eventually shift to the private sector as electric vehicle sales increase the demand for charge points and the profitability of their operation. In the near term, although incentives are needed, regulators can set the stage for robust private-sector leadership by promoting competition and innovation through government programs. This could include holding frequent bids for projects (as in the Netherlands), adding bonuses to subsidies for specific advanced features, or capping the reimbursable price of stations while mandating a particular functionality.

IV. ANALYSIS OF PUBLIC CHARGING INFRASTRUCTURE

Governments and private companies have been constructing public charging infrastructure for several years, resulting in more than 200,000 stations of various types around the world. The status of charging infrastructure varies greatly from country to country as well as from city to city, and comparison of these local markets can help to elucidate broader trends within the electric vehicle market. This section presents and analyzes data on charging infrastructure in major electric vehicle markets. For each market, we use the most complete publicly available data on charge point counts for the end of 2016, unless otherwise noted. We include both BEVs and PHEVs in our counts of electric vehicles, and we define a charge point as a single outlet or plug; a charging station may have one or more charge points. We also break down the public charging data into Level 2 or DC fast charging to identify differences across the major electric vehicle markets. Further information on data sources is given in the Annex.

To help inform topical questions around the world about public electric vehicle charging, we present data according to several different metrics that are each relevant in different contexts. We present charging infrastructure data in terms of charge points per 1 million residents in each area, which allows comparison of the extent of charging with an adjustment for different jurisdiction sizes. This metric is key in comparing markets of different sizes, and also provides a measure that is independent of the number of electric vehicles. Having a metric that is separate from the size of the city and the electric vehicle population is necessary to analyze the statistical link between electric vehicle uptake and charging deployment. We also assess and compare charging infrastructure on a per–electric vehicle basis. Such a charger/vehicle ratio (or the inverse) offers additional input to help approximate the number of charging stations for a given electric vehicle market. Some jurisdictions find such ratios more useful in projecting the necessary charging infrastructure to match electric vehicle growth. Both of these metrics can clarify differences across global electric vehicle markets, as illustrated below.

At a national level, the availability of charging infrastructure varies widely, as shown in Figure 1. The global leaders in electric vehicle uptake, Norway and the Netherlands, are also leaders in charge point availability, with far more total charge points per million residents than other countries. While the Netherlands has the most Level 2 charge points per population, Norway has the highest concentration of DC fast charge points per capita. Before adjusting for population, China is the clear leader by charge point volume, with more than 100,000 Level 2 charge points and 38,000 DC fast charge points, followed by the United States (36,000 total charge points), the Netherlands (27,000), Japan (18,000), Germany (12,000), and the United Kingdom (11,000). As shown, there are major differences across the markets in terms of the percentage of charging that is DC fast. In Belgium, the Netherlands, and Germany, DC fast chargers constitute less than 10% of the charging points. In most countries, DC fast chargers represent 10% to 20% of charger deployment. China, Japan, and Finland have the highest share of rapid charge points, 25% to 45%.

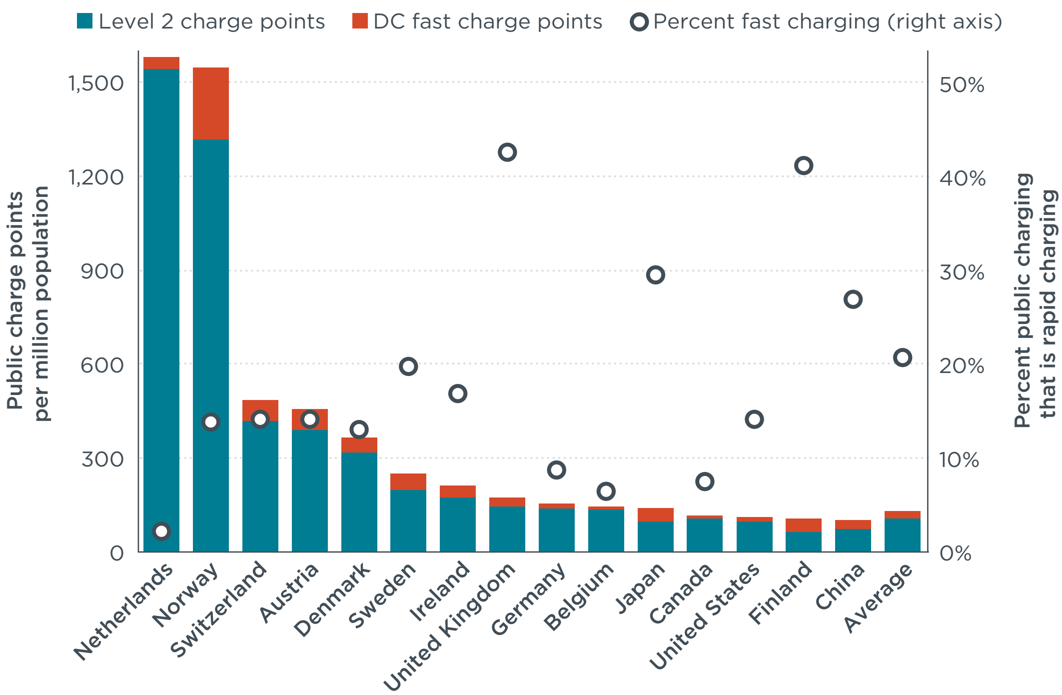

Figure 1. Comparison of electric vehicle charging infrastructure per million population in selected national markets around the world.

PUBLIC CHARGING INFRASTRUCTURE BY METROPOLITAN AREA

A national-level outlook is useful for considering broad electric vehicle readiness and the impact of national charging infrastructure programs, but it does little to clarify the relationship between charging infrastructure and electric vehicle uptake. Within countries (especially large markets such as China and the United States), there is significant variability among cities with regard to electric vehicle uptake and charging infrastructure density. Furthermore, charging infrastructure is part of a regional ecosystem, where drivers can make use of charging stations in a wide area as they commute and take additional local trips. For these reasons, our primary analysis is focused at a metropolitan-area level (see Table A-2 for definitions).

For the following analysis, we include metropolitan area–level data from 14 countries: Austria, Belgium, Canada, China, Denmark, Finland, Germany, Japan, the Netherlands, Norway, Sweden, Switzerland, the United States, and the United Kingdom. These markets were targeted primarily because they have the highest electric vehicle uptake, and also because data in these markets were available for both local-level electric vehicle uptake and public charging infrastructure. We estimate that these national markets effectively include about 90% of global electric vehicle sales. The only substantial national market for which we could not find comparable electric vehicle and charging data is France, which is therefore excluded. We note that in the relationships depicted in Figure 2, Figure 3, and the statistical data, we include only metropolitan areas with resident populations of at least 200,000. This excludes many smaller markets with few electric vehicle sales that could have otherwise skewed the results. The data are for 2016, with the exception of China markets, where some of the most recent available local-level data are for 2015.

Figure 2 illustrates charging infrastructure deployment and electric vehicle uptake in major metropolitan areas around the world. Cumulative electric vehicle sales (including both BEVs and PHEVs) per million population are plotted on the vertical axis; public charge points (both Level 2 and DC fast) per million population are plotted on the horizontal axis. The bubble size indicates the number of electric vehicles sold in 2016 in a given market. Data points are colored according to country; selected markets with high electric vehicle uptake are labeled.

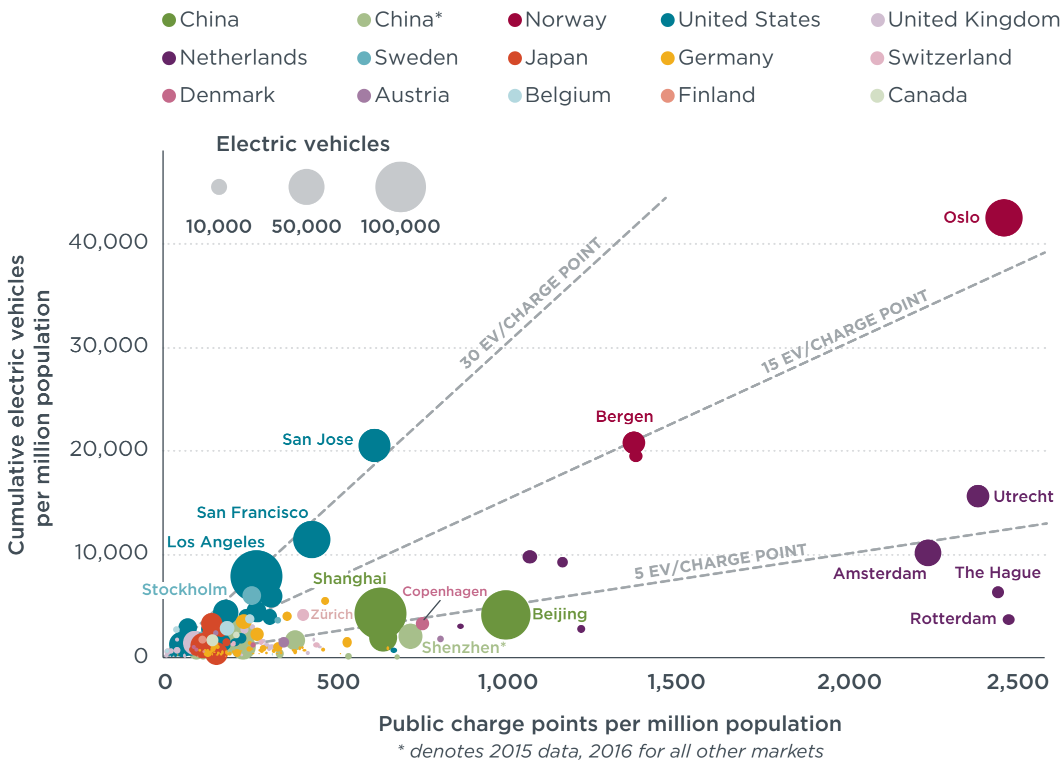

Figure 2. Public charging infrastructure and electric vehicle registrations per million population by metropolitan area, with size of circles indicating total electric vehicles.

Several conclusions can be drawn from Figure 2. As with the national-level data in Figure 1, the data demonstrate that there are some rough apparent patterns between electric vehicle uptake and charging infrastructure availability. There is also substantial variability across the markets. If the electric vehicle–public charger relationship were a clear universal one, the data would line up more diagonally. We overlay three diagonal trend lines within the figure, indicating ratios of 30, 15, and 5 electric vehicles per charge point, to highlight how the cities compare. The cluster of data points at the lower left is a clear testament to the early state of electric vehicle market development at present. In most of the markets below 5,000 electric vehicles per million population and fewer than 400 charge points per million electric vehicles, fewer than 1% of new vehicle sales are plug-in electric.

Electric vehicle charging and uptake data from the various metropolitan areas within each country show approximate patterns. Oslo and Bergen, the two major metropolitan areas in Norway, are labeled. These two, with about one-third of all new vehicle sales being plug-in electric vehicles, have the highest uptake, and they each show a relationship of about 14 to 17 electric vehicles per public charger. The markets in the Netherlands tend to have a lower ratio of electric vehicles per charge point, at 3 to 6 electric vehicles per charger for the three largest electric vehicle markets, Amsterdam, Utrecht, and The Hague. This could be due to the relatively low rate of private garage ownership in these markets (see below). In contrast, the large California markets tend to lie above the other cities with a higher vehicle/charge point ratio, approximately 25 to 30 electric vehicles per charge point. This could be due to greater access to private home charging, as well as workplace charging in northern California. The major China markets had a range of 3 to 11 electric vehicles per charge point.

Over all markets considered in this study, we find an average of approximately 7 electric cars per public charge point. Given the wide variation observed across the markets, including the successful high-uptake markets, it seems clear that this average ratio does not represent a consistent or universal metric for assessing the maturity of local electric vehicle markets. We further examine this ratio of electric vehicles per charge point, along with factors such as city housing type and population density, below.

RAPID VERSUS NORMAL PUBLIC CHARGING INFRASTRUCTURE

As charging infrastructure continues to expand, a key issue is in establishing the correct balance between convenient-yet-expensive DC fast charging and inexpensive-but-slower Level 2 charging. Along with the variation in overall amount of charging infrastructure shown above, the various electric vehicle markets also vary greatly by their different numbers of Level 2 (normal) and DC fast (rapid) charging infrastructure. Figure 3 illustrates these differences, plotting Level 2 charge points (horizontal axis) and DC fast charge points (vertical axis) per million population for the major metropolitan areas with substantial electric vehicle uptake. Data points to the lower right have less, and points to the upper left have more, DC fast charging. Again, we note that some of the regional data for China are through 2015 rather than 2016. Selected major markets are labeled. We also overlay three diagonal trend lines to illustrate how the cities compare with respect to 40%, 15%, and 5% of their public charging infrastructure being rapid charging.

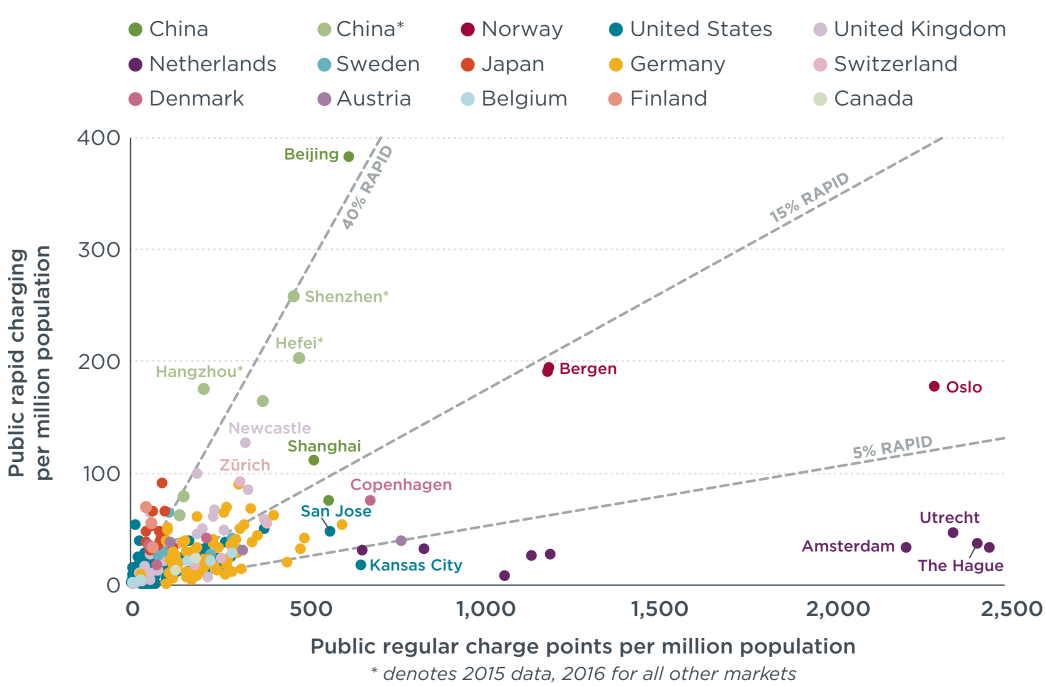

Figure 3. Relative numbers of public regular Level 2 and DC fast charge points per million population in selected major metropolitan areas.

A consistent ratio of Level 2 charge points to DC fast charge points would show more of a clear diagonal line; however, there is no such universal trend in these data. Some approximate patterns do emerge, revealing that local conditions diverge greatly from the global average of about 20% fast charging. The cities in China, to the upper left, tend to have the highest proportion of fast charge points—about 30 to 40% of all public charging facilities—at least in part because of installations by their major utilities. Cities in the Netherlands generally have the most charging overall but the lowest percentage of rapid charge points, about 1.5 to 2%. The low percentage of fast charge points may reflect the large numbers of curbside charging stations intended for overnight use and the large numbers of PHEVs lacking fast-charging capability. The highest electric vehicle uptake markets in Norway had high amounts of both regular Level 2 and DC fast charging, and had 6% (Oslo) and 13% (Bergen) of the charging as DC fast charging. The three largest U.S. markets, Los Angeles, San Francisco, and San Jose, had 7 to 11% of their charging as DC fast charging. However, there can also be substantial variation within each country. For example, although the Kansas City area leads the United States with 664 charge points per million population, it has less than half as many fast charging points, adjusted for population, relative to the San Francisco or San Jose areas.

STATISTICAL LINK BETWEEN PUBLIC CHARGE POINTS AND ELECTRIC VEHICLE UPTAKE

As previously noted, public charging infrastructure has often been found to be linked with greater electric vehicle uptake. With the detailed local-level data from most major global electric vehicle markets, we sought to test this relationship with a stepwise multiple linear regression to find the best fit among the factors analyzed. In addition to analyzing the link between charging availability and electric vehicle uptake, we sought other data that also might help to partially explain the variation in Figures 2 and 3 above.

On the basis of the research literature, we sought to include housing and demographic data to help control for known major differences across global cities. We were able to collect data on the percent of households that are multi-unit dwellings, which could serve as a rough proxy for the number of households that are less likely to have their own private parking or garage. In addition, we included a population density (number of residents per land area within the metropolitan area) in the analysis to account for significant land use and travel pattern differences across the areas. In addition, we included consumer financial incentives in the analysis, applying the methodology from Yang et al. (2016). We felt it necessary to include the major differences in available consumer incentives among the electric vehicle markets, considering the strength of the relationship with uptake in previous analyses (as mentioned above).

The results of this regression are summarized in Table 5. The statistical test is for the dependent variable of electric vehicle share of new 2016 vehicle sales, with several different charging, incentive, housing, and land use variables as independent variables in different combinations. For the analysis below, we conducted a multivariate linear regression using StatPlus software (AnalystSoft, 2017a, 2017b). As above, we included only metropolitan areas with populations of at least 200,000. For this statistical analysis, we included only a smaller subset of cities for data availability and data quality considerations: metropolitan areas from the United States, Norway, the United Kingdom, the Netherlands, Germany, Denmark, Austria, Finland, Belgium, and Japan. The remaining four countries were excluded because we could not find comparable data on housing attributes or electric vehicle incentive policies. The resulting regressions are based on 350 metropolitan areas with populations more than 200,000.

We used separate variables for regular Level 2 charging and DC fast charging to discern whether they were both significant. For the consumer incentives, we included electric vehicle purchase incentives (tax credits, rebates) as well as tax incentives (e.g., exemptions from vehicle taxation). As shown in Table 5, we conducted separate electric vehicle regressions for BEVs and PHEVs based on separate data for each type's incentives and uptake.

In Table 5, the variables marked X had the strongest statistical fit (*P* values less than 0.05) and were part of the statistical regression for electric vehicle uptake. For the consumer incentives, we included a weighted incentive between BEVs and PHEVs for the general electric vehicle regression. As summarized in Table 5, we found a significant statistical link between electric vehicle uptake and charging infrastructure, incentives, housing characteristics, and population density (R^2 = 0.78). Table A-3 shows the statistical regression outputs related to Table 5.

Table 5. Summary of statistical regression for electric vehicle uptake with charging infrastructure, incentives, population density, and housing type.

	Electric vehicle share	BEV share	PHEV share
Level 2 charge points per million population	X	X	X
DC fast charge points per million population	X	X	X
Consumer electric vehicle incentive (weighted BEV/PHEV) value	X		
Consumer BEV incentive		X	
Consumer PHEV incentive			X
Percent of households that are in multi-unit dwellings	X	X	
Population density	X		X
Adjusted R^2 value	0.78	0.65	0.78

Variables with X are statistically significant ($P < 0.05$)
BEV = battery electric vehicle; PHEV = plug-in hybrid electric vehicle

When isolating BEVs and PHEVs, the statistical fits were similar, with charging and incentives still significant in each case, but for BEVs the population density was not significant, and for PHEVs population density was significant. In each of these regressions, both Level 2 and DC fast charging are shown to be statistically significant, which suggests that they both play a role for electric vehicle drivers. Although fast charging is predominantly used for BEVs, we note that PHEV models such as the Mitsubishi Outlander and BMW i3 Rex version include fast charging capability. The R^2 values of 0.65 to 0.78 indicate that unexplained variation remains in the relationships. This could include the many different national, state, and local policies that affect electric vehicles; model availability; automaker marketing and dealer activities (e.g., see Slowik & Lutsey, 2017); and other factors that are not analyzed here.

Although it is widely recognized that charging infrastructure will be required to expand the electric vehicle market, there is considerable uncertainty about the precise amount of public charging infrastructure needed to reach a given market size. As suggested by the successful early electric markets described above, there is no single global answer to this question. It is unlikely that any market has achieved the perfect balance of electric vehicles and charge points, and it would be difficult to know when this is the case. The electric vehicle market and the associated charging infrastructure will grow and coevolve. The rapid development of the technology means that the situation may be quite different in a few years. Furthermore, local conditions, the availability of private and workplace charging, and the mix of electric vehicle types could also strongly influence the appropriate level of public charging infrastructure deployment in various markets.

RATIO BETWEEN ELECTRIC VEHICLES AND PUBLIC CHARGE POINTS

The idea of a ratio between electric vehicles and public charge points is attractive to policymakers, as this ratio could inform targets for infrastructure buildout to support an electric vehicle market of a given size. Although our analysis shows the difficulties in developing international benchmarks or quantitative guidelines for charging infrastructure, several organizations have sought to do so, as shown in Table 6. These ratios help to reveal broad international trends, but it is not yet clear whether these ratios represent the correct benchmarks for future market development or how useful they might be for national or local decision-makers planning their charging infrastructure to match electric vehicle deployment. The estimates from the Electric Power Research Institute (EPRI) and the National Renewable Energy Laboratory (NREL) are based on detailed models of the evolution of the U.S. electric vehicle market. The International Energy Agency (IEA) Electric Vehicle Initiative's ratios are based on global averages in 2015 and 2016. The numbers from the California Energy Commission (CEC) and NREL are the California average values for a more detailed tool that estimates the future public charging on the basis of projected future electric vehicle deployment and several local factors.

Table 6. Indicated average electric vehicle/public charge point ratios.

Organization	Region	Electric vehicle/public charge point ratio	Source
European Council	European Union	10	European Parliament (2014)
NDRC	China	8 (pilot cities), 15 (other cities)	NDRC (2015)
IEA Electric Vehicle Initiative	Worldwide	8 (2015), 15 (2016)	EVI (2016, 2017)
EPRI	United States	7-14	Cooper & Schefter (2017); EPRI, 2014
NREL	United States	24	Wood et al. (2017)
CEC/NREL	California	27	CEC & NREL (2017)

On the basis of the data presented above, we provide an additional summary chart to explore what the local-level data reveal for public charging deployment trends. Figure 4 shows the distribution of electric vehicle sales among major metropolitan areas within the countries analyzed here (again, only for areas with at least 200,000 residents) according to their electric vehicle/charge point ratio. This distribution shows that within each country, there tend to be some groupings related to the relationship between electric vehicle sales and number of charge points. For example, the ratio in the Netherlands and China ranges from 0 to 10, whereas in the United Kingdom it generally ranges from 15 to 25. As shown above, this ratio can vary by a factor of 20—for example, from 1.5 (Rotterdam, Netherlands) to 33 (San Jose, United States). We also examined how this ratio has changed from 2014 to 2016 in select markets in the United States, Norway, Sweden, and Germany; in general, the same national relationships shown in Figure 2 and Figure 4 were consistent over this period. With the limited sample of multi-year data, we find no clear trend that would indicate that electric vehicle stock or public charging infrastructure tends to grow at a faster rate or that the ratios are shifting in any clear way.

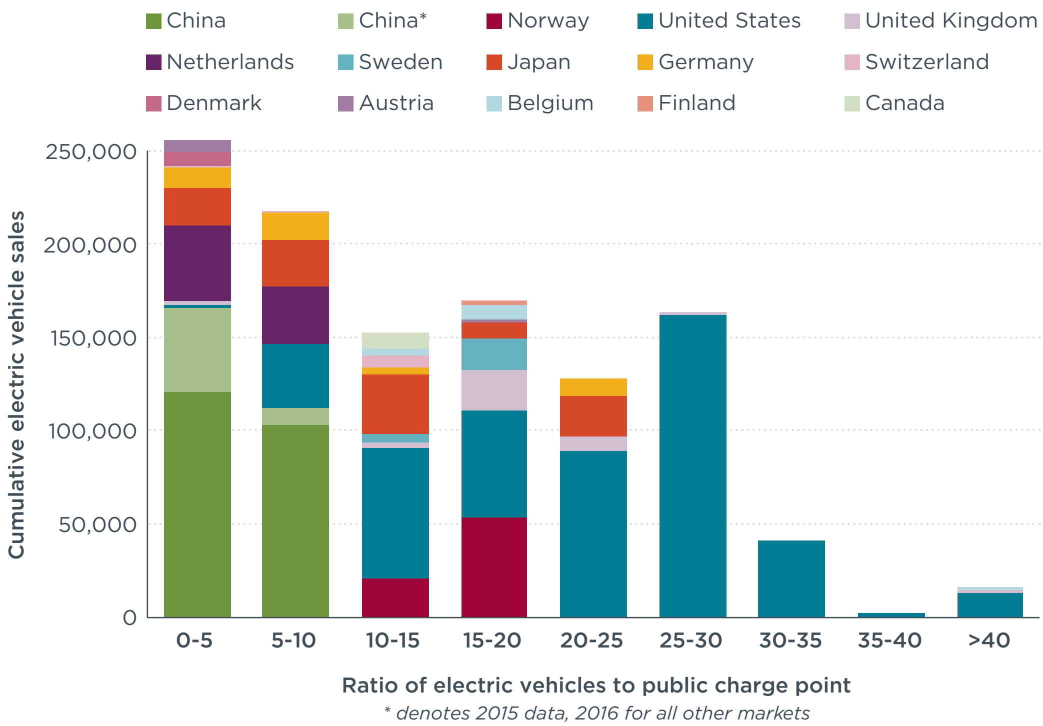

Figure 4. Distribution of cities by electric vehicle/public charge point ratio.

We note that this global comparison and the above statistical analysis of public charging infrastructure availability at the local level constitute a novel contribution to the research literature, and that there are a number of additions that could strengthen this type of research. First, our study only covers select countries with high electric vehicle uptake. Second, some of the data may be incomplete for particular local markets. Integration of privately held charging point data with the data compiled here might result in more accurate estimates and relationships. Third, we do not include workplace charging in this analysis, which may play a similar role in some circumstances. In most markets, there are very few data revealing the share of workplace charging. Finally, many additional factors influence electric vehicle uptake, such as model availability, income, fuel and electricity costs, and residential and workplace charging availability. Accounting for these variables in a statistical regression may lead to a more accurate estimate of the relationship between charge points and uptake. Certainly, this is a rich area for further research as the market evolves and more data become available.

V. ADDITIONAL TOPICS IN PUBLIC INFRASTRUCTURE PLANNING

STANDARDIZATION AND INTEROPERABILITY

Much of the early electric vehicle charging infrastructure was not systematically planned or optimally placed. Rather, in many cases it was developed in a relatively fragmented way, with different government and private-sector players deploying numerous types of infrastructure without necessarily holding a shared vision. Although standards for the physical plugs have been generally accepted (as described above), the back-end communications, payment, and power supply standards are less developed. In many markets, this means that an electric vehicle driver needs a variety of memberships, accounts, and cards to access all of the nominally publicly available infrastructure. This was not a problem for most early adopters of this technology, when almost all charging was done at home and many charging stations were free; however, it is likely to become an increasingly difficult issue as the market grows.

There have been several major efforts toward improving the user experience of charging infrastructure by promoting interoperability, both for drivers and for charging network operators. For electric vehicle drivers, interoperability, or "e-roaming," means that drivers can charge at any station with a single identification or payment method, and that all charging stations can communicate equally with vehicles. For this to work seamlessly, common standards for charging network operators must also be established so that usage data and payment information can be consolidated and directed to the correct accounts. Of particular interest is the experience of the Netherlands, a leading electric vehicle market with the highest number of charging stations per capita. Through careful planning and regulation, every public charging station (and many private stations) in the country can now be operated and paid for using a single radio-frequency identification card or key fob. This has made traveling with an electric vehicle in the Netherlands much easier and more affordable while also promoting competition in the electric vehicle charging industry.

Driver roaming is accomplished through the widespread adoption of open standards, including the Open Charge Point Protocol (OCPP) and Open Clearing House Protocol (OCHP), which allow for efficient communication between charging stations, the grid, and back-end offices to ensure interoperability in operation and payment. These protocols are now enforced through all public tenders in the Netherlands. ELaadNL, a consortium of grid operators formerly known as the ELaad Foundation, was largely responsible for the early development of these standards; the organization is also currently working on the Open Smart Charging Protocol (OSCP), which would allow coordinated smart charging across many stations.

While the Netherlands has led in this area, numerous projects in other countries are also trying to promote interoperability. Ladenetz, a government-sponsored collaboration among municipal utilities, universities, and private electric vehicle service equipment (EVSE) operators in Germany and the Netherlands, seeks to create a Europe-wide network of interoperable and user-friendly charging stations. Hubject, a company founded by BMW, Bosch, Siemens, and EnBW, has launched a service known as "intercharge" that incorporates e-roaming into more than 40,000 stations.

In the United States—where interoperability in the charging infrastructure sector is perhaps least developed—BMW, Nissan, ChargePoint, and EVgo founded the ROEV (Roaming for EV Charging) project to advance interoperability. California is currently working on implementing the Electric Vehicle Charging Open Access Act, which focuses on customer interaction with the EVSE. This act requires (1) publication of all station locations on the Alternative Fuels Data Center (AFDC) website; (2) disclosure of all fees before a charging event begins, including plug-in fees if not a member of the network; and (3) charge point accessibility to nonmembers of the network, including the ability to accept multiple forms of payment. Implementing these key features will enable broader access for consumers. Other states such as Washington and Massachusetts are also pursuing interoperability initiatives. These projects, as well as government support for interoperability and the use of open standards, could be important in the long-term growth of electric vehicle charging networks.

POWER SUPPLY AND GRID EFFECTS

Electric vehicle charging has the potential to use vast amounts of power, and although it currently does not pose any substantial risk to the grid, this is an issue that should be considered by authorities as the market grows. A frequently cited concern is the exacerbation of evening peak power demand, both on a local and regional level, due to many drivers plugging in after arriving home from work (Brandmayr et al., 2017; National Academy of Sciences, 2015). This could be compounded by increasing use of solar power, which may decline in output at the same time of day that charging demand spikes. Utilities could see some increased costs from this phenomenon. The Sacramento Municipal Utility District in California calculated costs of about $150 per vehicle at 5% fleet penetration using uncontrolled charging patterns. However, these issues may also be increasingly easy to work around as smart charging technology develops (Berkheimer et al., 2014). Many governments are engaged with working group activities, pilot projects, and policy processes to incorporate greater use of smart charging practices, including controlled charging and demand response (see, e.g., Hall & Lutsey, 2017). Even simpler solutions, such as using in-vehicle timers to take advantage of time-of-use rates, could help minimize stress on the electrical grid while also saving money for consumers.

Another area of concern in some areas is the effect of DC fast charging on local distribution infrastructure. These fast charging stations use very high amounts of power for short periods of time, meaning that more expensive upgrades will be needed with a relatively low use rate. This problem could intensify as technology improves: Four European automakers have announced plans to build a network of 400 charging stations capable of charging at 350 kW, more than three times the current industry standard (Herdlitschka & Sedlmayr, 2016). Electrify America will also build charging stations capable of 350 kW charging in the United States (Electrify America, 2017).

These usage patterns and the potential for infrastructure upgrades often cause charging sites to incur high demand charges, a component of electricity rates based on the highest capacity used. For fast charging stations, which use a lot of power but may be less frequently needed by drivers, demand charges can account for 90% of operating costs, which leads to higher rates for drivers (Fitzgerald & Nelder, 2017). Utilities, regulators, and research groups are developing alternative rate structures for workplace and public charging infrastructure, an important step in improving the commercial case for electric vehicle charging (see Fitzgerald & Nelder, 2017; O'Conner & Jacobs, 2017).

Because drivers expect fast charging to be available on demand, smart charging strategies are less practical than for Level 2 charging. However, there are a number of innovative solutions to minimize the grid effects of fast charging. For example, projects in the United Kingdom, Germany, British Columbia, Hawaii, and elsewhere have paired fast charging stations with stationary battery storage (sometimes second-life electric vehicle batteries) in order to mitigate grid impacts and coordinate with renewable energy output (Hall & Lutsey, 2017). Perhaps the most important practice for preventing negative effects for the grid, especially as the fast charging market continues to grow, is to coordinate closely with the utility to site fast chargers near adequate high-capacity electrical infrastructure. The California utility Pacific Gas & Electric has created a comprehensive guide and map tool enabling charging providers to identify which sites have sufficient grid capacity and driver demand (PG&E, 2017). Such coordination will be important for the growth of the electric vehicle charging infrastructure industry.

CHARGING INFRASTRUCTURE PLACEMENT

Ensuring that the electric vehicle charging network operates efficiently and meets driver expectations can be crucial in maintaining future investment and support. One critical step toward maximizing the return on investment is to place charging stations in optimal locations at a local level in order to maximize usage, avoid traffic and parking issues, and minimize stress on the power grid.

A number of studies and models have addressed this issue in depth, both in urban and regional contexts. Table 7 summarizes some of these studies, including their geographic focus, the type of data they include, and the considerations used in choosing locations. These methods, adapted for local context, enable governments and private-sector partners to create guidelines that will maximize the usefulness of infrastructure. Although these studies vary in their approach and the factors they consider, there are commonalities in their use of data from many partners, including municipal governments and utilities. This further emphasizes the need to coordinate efforts between multiple stakeholders when funding and deploying electric vehicle charging infrastructure.

Within a specific location, such as a parking lot, there are additional factors to consider in determining the final placement of charging infrastructure. For instance, it is smart to place the charging posts, where possible, in a position that is accessible to multiple cars at once. This could mean putting it in the middle of a parking lot, where up to six vehicles could use the post, rather than at the edge or a corner, where only two or three vehicles would be able to connect. These stations would ideally be handicapped-accessible, with any tripping hazards covered or removed. Additionally, placing charging stations near the entrance to buildings increases their visibility and their convenience for drivers. However, various additional complicating factors influence these decisions; a number of publications offer more detailed guidelines (see OREF & EVAS, 2016; Webb & Sears, 2017; NYSERDA, 2017).

Table 7. Studies on electric vehicle charging infrastructure placement optimization.

Region	Considerations	Data sources	Citation
Bolzano and South Tyrol, Italy	Parking, transit, power supply	City and provincial GIS data	Harrison & Thiel (2017)
Boston, United States	Parking, driver discomfort, cost	Cell phone location data	Vazifeh et al. (2015)
Beijing, China	Parking, traffic impacts, power supply	Taxi fleet data	Hua et al. (2014)
California, United States	Regional traffic, cost	Travel surveys, past charger utilization	Ji et al. (2014)
Liege, Belgium	Commute patterns, transit, business locations	City and provincial GIS data	Wirges (2016)
Singapore	Traffic impacts, vehicle range	City and national traffic and GIS data	Xiong et al. (2015)
Chicago and South Bend, United States	Energy consumption, cost, parking	Census data, public map data	Yi & Bauer (2016)

COSTS OF ELECTRIC VEHICLE CHARGING INFRASTRUCTURE

Electric vehicle charging infrastructure has seen substantial cost declines over the past several years due to new technological innovation and larger production scale, as with electric vehicle production. For example, since 2009, the city of Amsterdam has seen the costs of their curbside charging stations fall from approximately €12,000 to €2,000 per station. Nonetheless, charging infrastructure also typically requires substantial installation costs and can also incur additional costs for land procurement, administration, and maintenance.

Figure 5 illustrates the approximate per-station costs of a number of major government programs to fund charging infrastructure, including administrative, installation, and siting costs. As seen in the figure, total costs per Level 2 station range from $5,000 to $15,000, whereas each DC fast charging station can cost $40,000 to $100,000. These wide ranges of values depend on the type of charging station (including its networking capabilities), the setting (urban versus rural, mounted on walls or on posts), and the administrative details of the program.

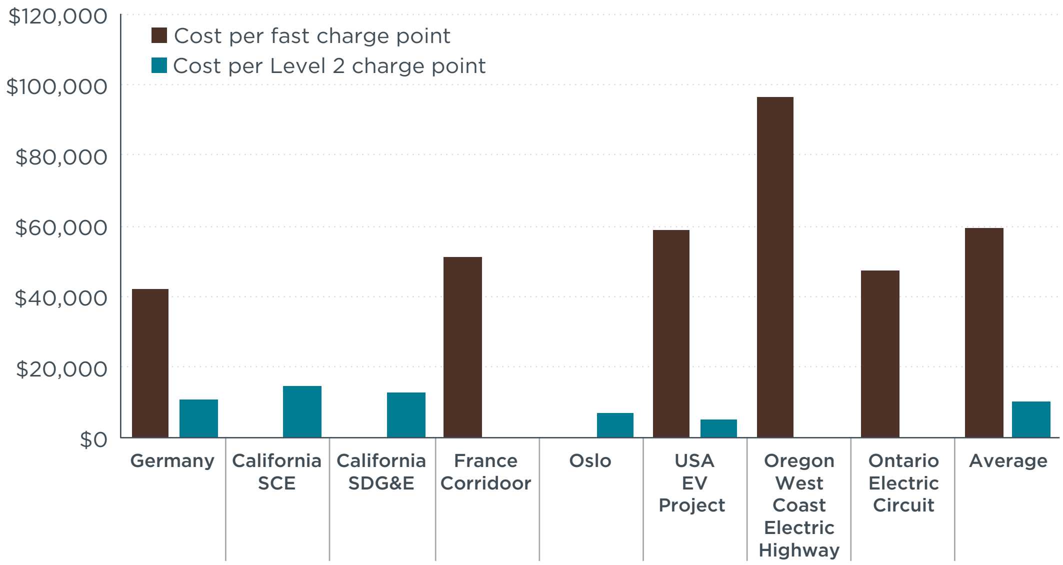

Figure 5. Approximate program-level costs of Level 2 and DC fast charging stations from selected major government charging infrastructure programs.

There are a number of ways to reduce the costs of charging infrastructure construction. Using stations with two connectors rather than one can greatly reduce the cost per outlet. Given sufficient demand, constructing multiple stations in the same area can reduce installation costs and save on the back-end electrical infrastructure. Wall-mounted charging stations typically cost much less than freestanding charging stations. Consulting with utilities beforehand to select sites with sufficient nearby electrical capacity can substantially reduce installation costs, especially for DC fast charging stations or for multi-unit installations. In the future, building codes requiring supporting electrical infrastructure in new buildings will substantially reduce the total costs of installing residential, workplace, and public charging stations.

Governments can also select more basic charging station units to save on costs, but this may increase the risk of stations becoming obsolete or incurring higher costs in the long run. Charging stations with lower power output tend to cost less but are better suited for workplace and residential charging than for situations when drivers are parked for only a few hours. Additionally, although non-networked charging stations (those that cannot communicate with a central server and therefore typically only allow free electricity) are usually cheaper upfront, they do not allow recovery of costs through electricity sales. Furthermore, a greater number of stations may be needed in the long term if drivers gravitate toward free public charging instead of charging at home. Additionally, non-networked chargers will not be able to support variable rates or smart charging programs that could be increasingly useful as the market develops. For these reasons, networked Level 2 stations may have a lower amortized cost than non-networked (free) stations (Webb & Sears, 2017). One compromise is to offer a range of charging power and payment options at areas where many charging stations are needed, from free Level 1 to increasingly expensive Level 2 or even DC fast stations. This allows drivers to select the charging power that best matches their vehicle and travel patterns while paying for the electrical capacity they use, and allowing site hosts to offer more stations and save money.

BUSINESS CASES FOR PUBLIC CHARGING

Governments have largely funded early electric vehicle charging infrastructure in order to advance low-emission transportation, often without an expectation of making back the investment or turning a profit. As the market grows and begins to reach mainstream customers, there is increasing interest in a transition to commercially sustainable charging infrastructure. With this in mind, there are a few promising business models based on electricity sales, increased retail sales, advertising revenue, and automaker-funded stations. Some options are briefly described here, although we emphasize that they are not mutually exclusive.

Perhaps the simplest business model for public charging infrastructure is to sell electricity with a sufficient markup to recover the cost of the charging infrastructure. The limitations of this model are clear: If electricity costs approach the costs of gasoline (on a per-kilometer basis), electric vehicles become less financially attractive and PHEV drivers are more likely to operate on gasoline. Furthermore, even a slight markup in electricity price makes it cheaper for drivers to charge at home if infrastructure is available. The wide-scale viability of an electricity price–based business model depends on the relative cost per mile of driving with electricity versus gasoline. When gasoline costs about $3 per gallon, as is typical in California, electricity cannot cost more than $0.22 per kWh and still be cheaper than driving purely with gasoline in a PHEV. However, when gasoline costs approximately $6 per gallon (€1.414 per liter, comparable to prices in Western Europe), electricity priced at $0.44 per kWh would be cheaper than driving with gasoline in the same vehicle. This basic, illustrative calculation is for the 2016 Chevrolet Volt, achieving 42 miles per gallon (5.6 L/100 km) on gasoline versus 0.32 kWh per mile (0.2 kWh/km) in electricity consumption. This cost-per-mile equivalence implies that this business model is much better suited for European markets and other regions with higher fuel prices than in the United States. Indeed, the curbside charging stations in Amsterdam, where the electricity price is regulated to be cheaper on a per-mile basis than gasoline, are beginning to make a profit through electricity sales alone.

Another option is to base the business case on increased retail sales. Because public electric vehicle charging requires significant time and a new stop on a trip, charging stations may represent a way for retailers to attract new customers and increase sales. This represents an important business model for private-sector charging infrastructure deployment by defraying charging station costs through increased sales at commercial site hosts. There is some early evidence that this approach can be successful. After installing Level 2 charging stations at one of its California locations, a major U.S. retailer found that dwell time for customers using the charging stations was 50 minutes longer than average, a 257% increase (ChargePoint, 2015). This led to an estimated $56,000 in additional sales over 9 months, and the retailer is now installing charging stations at additional locations. Similarly, another study in California found that when electric vehicle drivers stopped to charge at a fast charging station next to a retailer, 50% of drivers shopped during the charging, and among those shopping, the average expenditure was about $18 (Nicholas & Tal, 2017). As the market continues to grow, greater use of this model may benefit drivers and businesses alike.

Advertising revenues are another option on which to base a charging station business model. Gasoline stations already have increasingly integrated advertisements on pumps and signage; electric vehicle charging stations could offer a similar opportunity for advertising, which could generate revenue to offset initial costs. Such an idea is most appropriate for high-traffic, high-visibility locations such as malls, restaurants, and busy highway rest areas. California-based Volta Charging is pursuing this business model, providing free Level 2 charging at high-traffic retail locations in several U.S. cities, paid for by advertising revenue from large video screens attached to each station. In some cases, advertising revenue may not completely offset the initial installation costs but could be integrated with other tactics to form a profitable business case.

Automobile manufacturers could also fund charging stations by integrating their overall electric vehicle deployment and infrastructure into their unique customer proposition. As discussed in the introduction, charging infrastructure is seen as a key driver of electric vehicle uptake. Therefore, to fuel future sales of their electric vehicles, automakers have an interest in creating a robust charging infrastructure network. The most obvious example of this is Tesla's proprietary Supercharger network, consisting of 5,043 charge points at 790 locations, 2,636 of those in North America (as of December 31, 2016) (Golson, 2017). In addition, Tesla communicates to owners via text message when new Supercharger stations come on line. However, many other automakers are helping to fund more open charging networks. BMW, Ford, and Nissan all provide subscriptions to EVgo, a major U.S. fast-charging network, and are helping to fund the expansion of that network. In Europe, BMW, Daimler, Ford, and Volkswagen Group (including Audi and Porsche) have announced a joint venture to construct a network of ultrafast charging stations across Europe, beginning with 400 sites in 2017 (Herdlitschka & Sedlmayr, 2016). This automaker investment signals a commitment to the technology and an understanding of the relationship between charging infrastructure and vehicle sales, and could be an important contribution to the private-sector charging infrastructure industry.

VI. HOME AND WORKPLACE CHARGING INFRASTRUCTURE

Although this report primarily focuses on public charging infrastructure, we recognize that private charging, both at home and at the workplace, represents the majority of electric vehicle charging. This section highlights some emerging best practices by governments to support home and workplace charging infrastructure.

HOME CHARGING INFRASTRUCTURE PROGRAMS

Among early adopters, the vast majority of charging events have been carried out with private home charging infrastructure (see, e.g., Figenbaum & Kolbenstvedt, 2016; Idaho National Laboratory, 2015). In general, private home charging has not been a major barrier, as most vehicles come with Level 1 or Level 2 charging equipment. However, purchasing and installing more advanced Level 2 stations with higher charging power and features such as internet connectivity or timers can add additional costs for electric vehicle drivers. As longer-range BEVs become more available, Level 1 charging could be insufficient for many drivers; therefore, affordable and convenient Level 2 home charging would be increasingly important.

A number of governments operate programs to defray the added costs of charging infrastructure. The United Kingdom's Office for Low Emission Vehicles will pay up to 75% of the hardware and installation costs (up to £500) for a hardwired Level 2 station (OLEV, 2016c). Likewise, Québec offers up to $600 CAD for the cost and installation of a 240 V station (Gouvernement du Québec, 2012). In the United States, a number of states offer similar rebates or incentives, such as Washington, D.C. ($1,000), Oklahoma (75%), Delaware (50%), Maryland (40%), Louisiana (36%), and Oregon (25%) (ChargePoint, 2017a). Utilities in some parts of the United States also offer incentives, up to several hundred dollars, for home charging stations, indicating the growing role of utilities in expanding the electric vehicle market (Salisbury & Toor, 2016). Consistent incentives for higher-capacity home charging stations may help to make electric vehicles more accessible and increase the viability of long-range vehicles in the future.

BUILDING CODE REGULATIONS

Electric vehicle charging infrastructure requires robust electrical wiring and safety equipment beyond what is included in most construction. Retrofitting existing wiring to accommodate the high power consumption of electric vehicle charging equipment can greatly increase the cost of installation; conversely, pre-installing the necessary electrical infrastructure for charging equipment is relatively inexpensive. A number of governments at various levels have crafted regulations to promote charging infrastructure, especially through mandating "make-ready" infrastructure in buildings.

One pioneering use of building requirements to promote electric vehicles was California's Green Building Standards Code, which required in 2015 that 3% of all parking spaces in commercial buildings include make-ready infrastructure for charging stations (including dedicated panel and circuit capacity) (CARB, 2015). This regulation has since been expanded to include more parking spaces and higher-powered charging infrastructure. In some cities, standards are more progressive. In Los Angeles, for example, all single-family homes require a dedicated 240 V outlet and circuit capacity for a Level 2 charger, and there are additional requirements for make-ready infrastructure in multi-unit residential and commercial buildings.

Similar regulations have also been implemented in Europe. A new European Union directive is set to require an electric vehicle charging point in every new or refurbished home beginning in 2019 (Hyundai Motor Europe, 2016). The city of London now requires electric vehicle charge points at 20% of parking spaces in all new developments, as well as make-ready infrastructure for an additional 20% of spaces (Greater London Authority, 2016). The government of Germany is considering new policies mandating charge points or make-ready infrastructure in all new buildings, as well as policies to streamline the construction of charging stations in existing buildings (Harendt & Mayer, 2015). Similar policies may help to boost electric vehicle uptake and driver satisfaction in these quickly growing markets.

MULTI-UNIT DWELLINGS

Early adopters of electric vehicles have tended to be relatively wealthy drivers living in single-family homes with private garages. However, as the market grows and expands to more diverse clientele, charging infrastructure will adapt. One of the most pressing questions is how to address multi-unit dwellings, where residents frequently do not have dedicated parking spots, instead parking in a shared garage or on the street. As such, many residents cannot access a dedicated residential charge point.

A number of cities and countries have created programs specifically targeting drivers in multi-unit dwellings and others without access to off-street parking. One potential solution is to simply build public curbside charging stations in the areas where the potential demand is relatively high, a model followed by Amsterdam and other cities in the Netherlands. The United Kingdom also operates a curbside charging station program. A few cities in North America, including Philadelphia, Los Angeles, Berkeley, and Montreal, operate similar programs, but they are temporary pilots (Berkeley Office of Energy and Sustainable Development, 2017; CBC News, 2015; Glovas, 2015; LADWP, 2017).

Governments can also work with residents and property owners to install charging infrastructure in shared parking facilities and promote consumer awareness in multi-unit dwellings. California has created the emPower the People program, which assists residents in advocating for charging infrastructure in multi-unit dwellings, and also provides materials to property owners to reduce the costs and clarify the benefits of adding charging infrastructure in their buildings (California Plug-In Electric Vehicle Collaborative, 2017). Nonetheless, the costs of installing stations in multi-unit dwellings can be high: A recent study in California estimated average installation costs of $5,400 per Level 2 charge point, more than three times the average cost for installation in a single-family home (Turek et al., 2017).

There is growing recognition of the challenges in this field, and some governments may be interested in making substantial financial investments in this area. The government of France, for example, subsidizes 50% of the costs (up to €1,300) for shared stations in multi-unit residential buildings through the ADVENIR program, with a goal to fund 5,700 charge points (AVERE-France, 2016). Although broader funding programs in other countries (such as OLEV’s Homecharge scheme in the United Kingdom) may be used to install charge points in multi-unit dwellings in some cases, dedicated funding such as this may help to increase awareness and create stronger business cases for multi-unit dwellings.

Electric utilities may also be a major actor in this field, especially when they are able to use ratepayer money for infrastructure investments. California's three major utilities have each announced plans to deploy thousands of charging stations in the state; in each case, multi-unit dwellings are a major focus (CPUC, 2017). Regulators in the northeastern United States are currently working with utilities to accelerate charging infrastructure construction in that region, including in multi-unit dwellings. Although much work is required to make electric vehicles advantageous for all electricity sector stakeholders, these electric companies could be crucial to expanding the electric vehicle market for drivers living in multi-unit dwellings.

WORKPLACE CHARGING

In many markets, dedicated workplace charging infrastructure for employees plays a role in the charging ecosystem. Workplace charging can serve as the primary charging opportunity for drivers without a dedicated home charge point, allowing increased flexibility for drivers who commute with their electric vehicle and more all-electric miles for those who drive PHEVs. Several governments have created schemes to support workplace charging infrastructure, as summarized below.

In the United States, the Department of Energy operated the Workplace Charging Challenge from 2013 to 2017 to promote and track workplace charging infrastructure deployment, with the goal of achieving a factor of 10 increase in the number of workplaces offering charging by 2018. As of late 2016, the 757 partner workplaces of the Challenge had installed more than 7,000 Level 2 and Level 1 stations, as well as 136 fast charging stations (U.S. DOE, 2017b). At a regional level, the metropolitan areas of San Jose (with approximately 1,700 charge points), Detroit, San Francisco, and Portland, Oregon, have the most workplace charging infrastructure registered through this program (Heywood & Olexsak, 2017). Only a few cities (including San Jose, Detroit, and Raleigh, North Carolina) have more workplace charging than public charging, although these stations are likely to be highly clustered, and many other workplaces may provide charging points without participating in this program. For example, a major U.S. charging network provider, ChargePoint, estimates that approximately 40% of their charge points are at private workplace locations, totaling almost 14,000 points in their network alone (Alternative Fuels Data Center, 2017; ChargePoint, 2017b).

Noting the caveats above about the limited data on workplace charging, we present data on workplace charging and public charging data in Figure 6 for the 15 major U.S. metropolitan areas with the highest shares of new vehicles that were electric in 2016. The chart includes public charging as above, with workplace charging reported through U.S. DOE's Workplace Charging Challenge; both are reported in terms of charge points per million residents to better compare markets of different sizes. As shown, there is an approximate alignment with the markets with high electric vehicle uptake and relatively high public-plus-workplace charging availability. The three markets with the highest workplace charging per capita—San Jose, Detroit, and San Francisco—are shown.

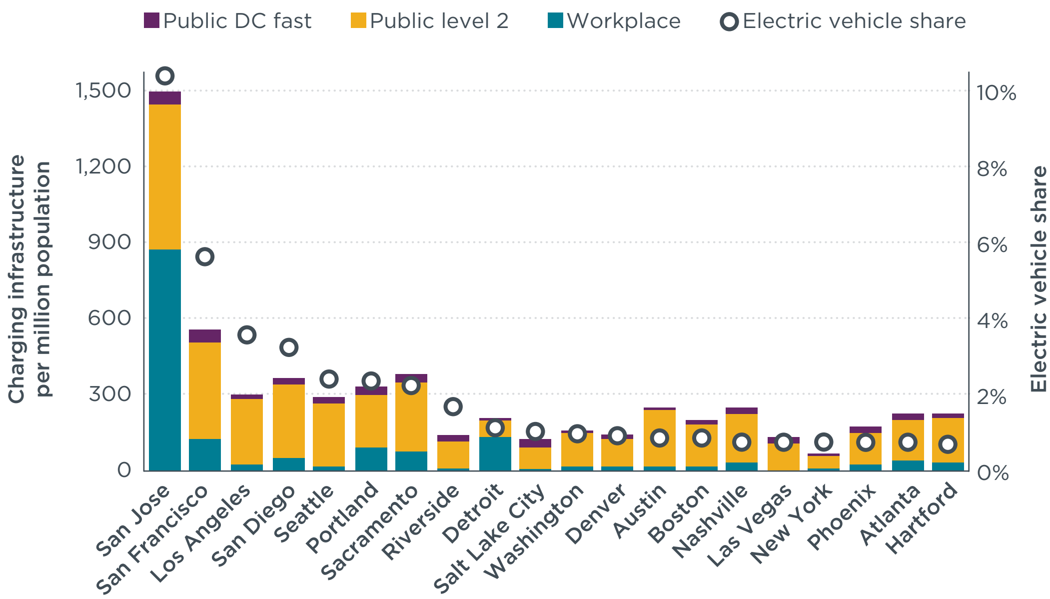

Figure 6. Public and workplace charging per million population and electric vehicle sales share for the 15 major U.S. metropolitan areas with the highest electric vehicle uptake.

A number of other jurisdictions have also created programs to accelerate employer charging installations. The province of Québec's Branché au Travail program funds 50% of the costs, up to $5,000 CAD per station, for businesses and municipalities offering free charging to their employees (Gouvernement du Québec, 2017). The Massachusetts Electric Vehicle Incentive Program offers grants for workplace charging that provide 50% of the funding (up to $25,000) for hardware costs to employers installing Level 1 and Level 2 stations (EEA, 2017). The United Kingdom's OLEV has launched the Workplace Charging Scheme, which provides rebates up to £300 per charge point for up to 20 charge points, to defray initial purchase and installation costs for organizations providing off-street employee or fleet charging (OLEV, 2016b). France's ADVENIR program funds workplace and public charging on company property, with a goal of installing 6,300 such charge points through 2018. The program will cover 40% of the costs per charge point, up to €1,000 for employee and fleet stations and €1,500 for public stations (AVERE-France, 2016). The Norwegian EV Association works with businesses to build charging infrastructure for employees and customers, and has created a comprehensive guide on regulations, costs, pricing, siting, and more. In the past, tenders from Enova have funded workplace charging infrastructure (Norsk Elbilforening, 2017).

As the electric vehicle market continues to grow, workplace charging may further grow in importance. Because cars charging at a workplace tend to be plugged in for many hours during the middle of the day, it is an ideal setting for smart charging programs and could further the integration between electric vehicles and daytime renewable energy (especially solar). Research has shown that people are 20 times as likely to buy an electric vehicle if there is access to charging infrastructure at their workplace (Olexsak, 2014). An electric vehicle owner who lives in an apartment that does not offer overnight charging could consequently be especially interested in workplace charging. However, when creating funding programs or awareness campaigns to promote workplace charging availability, governments may consider data reporting requirements in order to identify further trends and best practices in this important field.

VII. DISCUSSION

As with the electric vehicle industry as a whole, charging infrastructure technology is changing quickly. New developments such as superfast and inductive charging are making their way out of laboratories and could further change the industry. This report provides a snapshot of the state of public charging infrastructure deployment as of late 2016, highlighting prominent actions and progress in the major electric vehicle markets in Asia, Europe, and North America.

FINDINGS

On the basis of our analysis of major electric vehicle markets that make up about 90% of global electric vehicle sales, we find that the availability of public charging is generally linked with electric vehicle uptake. As illustrated in Figure 7, national vehicle markets with higher electric vehicle uptake tend to have more publicly available charging infrastructure. The basic national statistics in the figure indicate the need to build charging stations to help meet charging demand and increase electric vehicle consumer confidence as the market develops. The general market statistics also show that there are underlying differences among countries that are worthy of much deeper investigation.

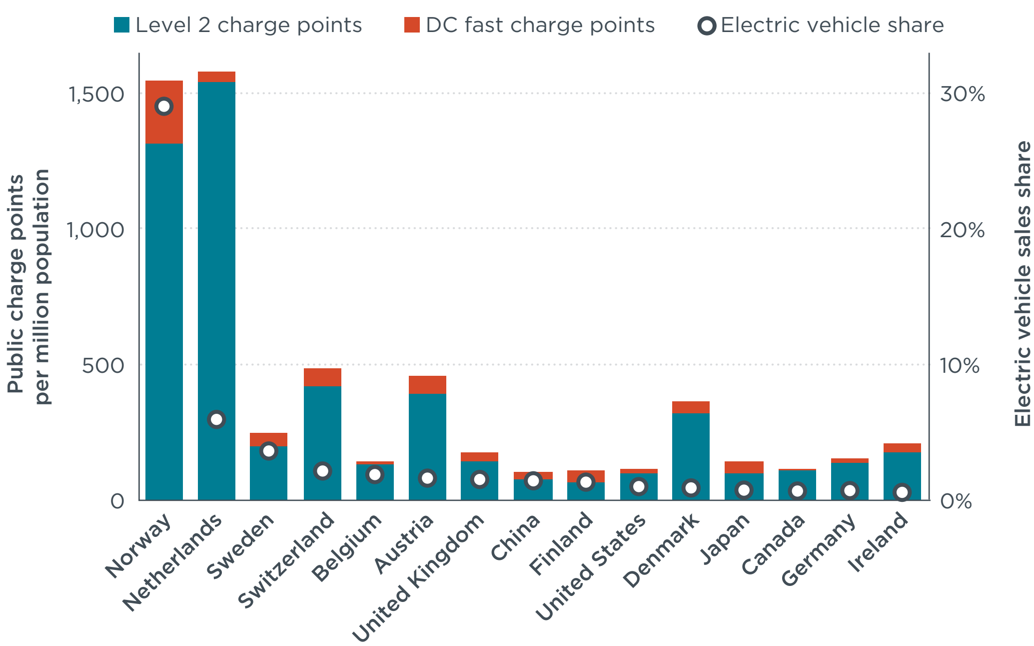

Figure 7. 2016 electric vehicle sales shares and public charge points per million population in major national markets.

The variation across national markets led us to analyze the differing local charging infrastructure characteristics and underlying factors that were emerging through 2016. When analyzing local-level data, we find that different patterns emerge among the top global electric vehicle markets. Figure 8 compiles several of the results from this paper's analysis to depict electric vehicle uptake and the relative availability of public charging infrastructure. The figure shows the major metropolitan areas with the highest electric vehicle shares in Norway, China, the Netherlands, California, and Sweden in 2016. When local-level uptake and charging infrastructure data were unavailable for 2016, China data are from 2015 as marked. These markets represent the highest electric vehicle shares among major metropolitan areas around the world, with electric vehicle shares ranging from 3% in Gothenburg, Sweden, to 36% in Bergen, Norway. To give a sense of the scale of these markets, cumulative electric vehicle sales in Oslo, Shanghai, Beijing, San Francisco, and Los Angeles each number more than 50,000.

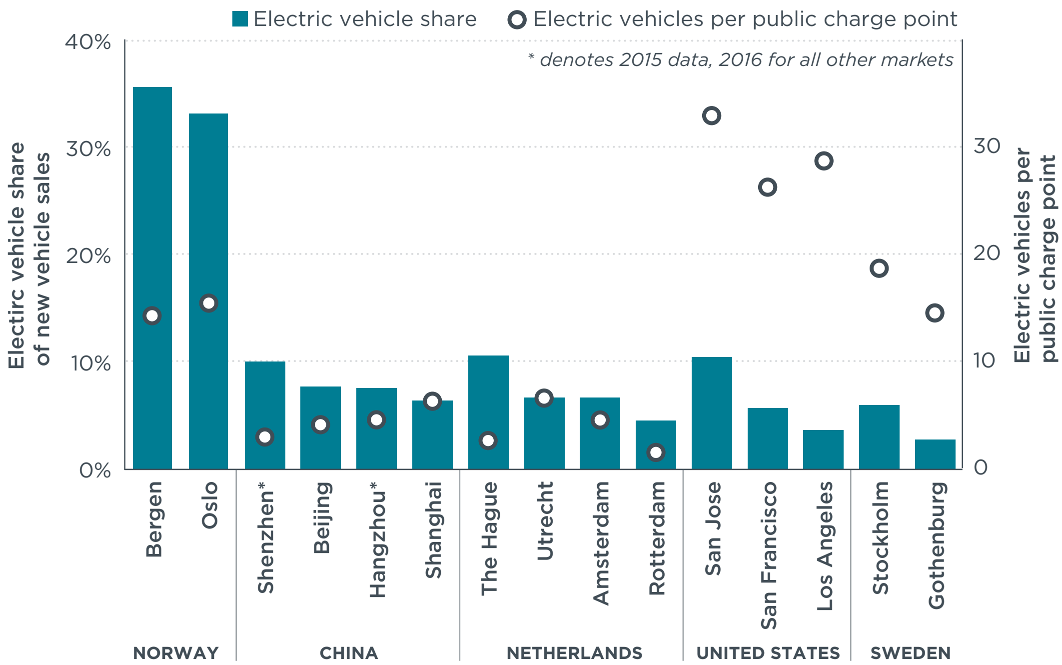

Figure 8. Electric vehicle sales share and public charge points per electric vehicle in selected leading markets.

This local-level analysis reaffirms that the electric vehicle charging ecosystem is evolving differently in the various markets. By selecting major metropolitan areas within the most prominent national electric vehicle markets, we get a glimpse of the emerging patterns of charge points per electric vehicle. In Norway, the electric vehicle share has been highest, and there is one public charge point per 14 to 17 electric vehicles. The major China markets more typically have 3 to 6 electric vehicles per charger, and they also tend to have 30 to 40% of their charging as DC fast charging, whereas most other markets are below 15% DC fast. In the Netherlands, where private parking and charging are less common, 2 to 7 electric vehicles per public charger is more typical. Electric vehicle owners in California more frequently have access to home charging in their private garages or to charging at their workplaces, and there is roughly one public charger per 25 to 30 electric vehicles. In addition, we find that the various electric vehicle markets have greatly differing mixes of public fast charging, workplace charging, and supporting policies to help encourage the charging market.

CONCLUSIONS

These findings do not permit definitive, universal conclusions about such a quickly moving industry with so many differences across the various markets. However, we do offer several high-level conclusions about the status of charging infrastructure and exemplary practices that help point toward the path forward.

Charging infrastructure availability varies dramatically at a local level, and there is no universal benchmark for the amount of charging infrastructure required. Although national-level numbers of charge points allow easy comparisons across markets, these statistics hide the high level of variation among regions and cities within a single country. Moreover, characteristics such as the balance between regular and fast charging can also vary widely within a single country. Certain regions and metropolitan areas typically lead in both electric vehicle uptake and charging infrastructure availability. We identify an average of one charge point for every 7 electric vehicles, with about one in every five charge points a DC fast charger. However, as shown in Figure 8, the electric vehicle/charge point ratio varies by a factor of 10 even among the leading global markets. This variability may stem from the varied roles of public charging in different city contexts. For example, in the Netherlands cases, public charging appears to effectively take a role that is more like that of residential or workplace chargers elsewhere. In other cases, more often in California, public charging supplements home and workplace charging. The clear broader conclusion from all these developments is that as the global electric vehicle market grows—likely by at least an order of magnitude by 2025—so too will the need for much more public charging infrastructure.

Although we find that public charging infrastructure is a key to growing the electric vehicle market, there is no universally accepted benchmark or global threshold for the extent of charging required. This work corroborates other research that indicates the importance of developing charging infrastructure in unison with electric vehicle deployment. In our analysis, both standard and DC fast charging infrastructure are statistically linked to electric vehicle uptake, as are consumer purchase incentives and factors such as population density and the prevalence of multi-unit dwellings. The leading electric vehicle markets of Norway and the Netherlands have more than 10 times as many public charge points per capita as average markets, and leading markets such as California and China had 3 to 5 times the average. However, there is also significant unexplained variability in our statistical analysis that goes beyond charging infrastructure availability. As routinely indicated in other studies, consumer incentives, vehicle policy, and consumer awareness campaigns are also key components of electric vehicle market development. Although there is no single ideal global ratio or benchmark for charging, comparisons of similar markets still offer an instructive way to understand where and how charging is relatively insufficient. Lagging electric markets can strive toward the leading benchmarks of comparable cities, while top markets continue to set new benchmarks as the market and its charging infrastructure coevolve.

Multifaceted and collaborative approaches have been most successful in promoting early charging infrastructure buildout. Governments at the local, regional, and national levels around the world have used varied strategies to promote public and private charging infrastructure. In leading markets, programs have engaged many stakeholders through integration of driver feedback on charger deployment, implementation of smart charging systems, distribution of funding to local governments, creation of public-private partnerships, and consultation with utilities to minimize grid impacts and limit costs. To address changing needs in this growing market, leading governments have created and provided consistent funding for separate programs to target several difficult market segments, such as curbside charging stations, multi-unit dwellings, and intercity fast charging stations. In all cases, it is important to make programs transparent and easily accessible for electric vehicle owners and industry stakeholders.

OPPORTUNITIES AHEAD

Despite this government support and falling costs, there are still a number of challenges to the further development of global electric vehicle charging networks. Charging infrastructure still suffers from fragmentation, inconsistent data availability, and a lack of consistent standards in most markets. Open standards for vehicle–charge point communication and payment may mitigate these issues by enabling interoperability between charging networks, increasing innovation and competition, and reducing costs to drivers. Led by successful efforts in the Netherlands, a number of public and private efforts promote these open standards and a more robust market. Governments may wish to mandate data collection and the use of open standards for publicly funded projects, an approach adopted in several programs. The success of such initiatives will be increasingly important as the market grows and smart charging develops.

This study also raises additional questions for future research. The analysis focuses on public charging, but more research into home, workplace, and fast charging availability is needed to create a fuller understanding of the complex charging ecosystem. Because each charging type lessens the need for the others to an extent, a clearer relationship between electric vehicle stock and charge points may emerge when all types of charging are considered. As the market develops, the need for public and other charging types will shift with vehicle technology (e.g., longer-range electric vehicles) in uncertain ways. As the electricity sector embraces more intermittent renewables, the location and timing of charging could shift from the home overnight charging paradigm to daytime public and workplace charging. Another important area for deeper analysis is how the right amount, types, and locations of charging can encourage PHEV drivers to use electricity for a greater proportion of their driving. Going forward, another key question is how to ensure that the cost of public electric vehicle charging remains competitive with the comparable per-kilometer cost of conventional internal-combustion vehicles.

Electric vehicle charging infrastructure, as indicated above, will need to grow with electric vehicle deployment. Global electric vehicle growth has averaged more than 50% annual growth per year from 2013 to 2016. Taking into account the various technology improvements, battery cost reductions, auto industry announcements, and policy developments that are under way, this growth appears likely to persist for years to come. With regulatory policies that require greater electric vehicles sales nationally, reinforced with preferential access for electric vehicles locally, the annual growth could be even higher. This means that electric vehicles on the world's roads could increase from 2 million in early 2017 to well over 10 times that number by 2025 (see Lutsey, 2015). Our work assesses the level of public charging infrastructure, on a per-capita and per–electric vehicle basis, that has enabled the initial leading markets to emerge. To aid in the transition, lagging markets will have to strive toward today's leading charging infrastructure benchmarks for comparable cities. Top markets will continue to set new benchmarks as the electric vehicle charging infrastructure evolves.

The expansion of charging infrastructure networks will create many opportunities. Governments can catalyze these markets with policy, share in the initial infrastructure investments, and pave the way for business cases to improve and eventually thrive. Electric power utilities in many regions could especially play a key role as they seek mutual benefits for the broader network and the electric vehicle market (see Hall & Lutsey, 2017). As with the broader electric vehicle market, charging infrastructure is changing quickly, causing further challenges beyond responding to the growth in charging. It is important that governments and the private sector coordinate their deployment activities to ensure that convenient, affordable, and reliable public charging infrastructure is available to all electric vehicle drivers. There is still much more work to do, but cities, national governments, public utilities, and the private sector are making great strides toward developing a robust charging infrastructure network, setting the foundation for the transition to electric mobility.

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ANNEX

Table A-1. Sources and local level of charging infrastructure data in selected markets.

Country or region	Lowest level of analysis	Number of metropolitan areas	Sources
Austria	Bezirk	3	E-tankstellen-finder, 2017; LEMnet, 2017
Belgium	Arrondissement	5	Open Charge Map, 2017
China	Prefecture-level city	11	EVCIPA, 2017; ICCT project for EV100, personal communication, April 13, 2017; Yurui, 2017
Denmark	Province	4	LEMnet, 2017; Open Charge Map, 2017
Finland	Region	3	Nobil, 2017; Open Charge Map, 2017
Germany	Kreis	65	LEMnet, 2017; Open Charge Map, 2017; YellowMap AG/ADAC e. V. München, 2017
Japan	Prefecture	13	Nippon Charge Service, 2017
Netherlands	COROP region	9	Netherlands Enterprise Agency, personal communication, February 2, 2017
Norway	County	3	Nobil, 2017
Québec	Region	2	Electric Circuit, 2017; Tesla, 2017
Sweden	County	5	Nobil, 2017
Switzerland	Canton	5	LEMnet, 2017; Open Charge Map, 2017
United Kingdom	District	24	OLEV, 2017; Open Charge Map, 2017
United States	County	277	U.S. DOE, 2017a

Table A-2. List of metropolitan area definitions used in analysis.

Country or region	Definition of metropolitan area	Source
China	City (市)	China Central Government
Europe	Metropolitan region	European Commission
Japan	Major metropolitan area and metropolitan area	Statistics Japan
Québec	Administrative regions (2 selected)	Government of Québec
United States	Census bureau statistical area	U.S. Census Bureau

Table A-3. Summary of three multiple linear regressions for electric vehicle uptake.

	Independent variable	Coefficient	Standard Error	t Stat	*P* value	Beta
Electric vehicle share	Incentive (weighted BEV/PHEV)	0.0000059	0.0000003	18.01	0.00000	0.618
	DC fast charge points per million population	0.0004200	0.0000400	10.87	0.00000	0.319
	Level 2 charge points per million population	0.0000300	0.0000031	9.77	0.00000	0.289
	Percent of households in multi-unit dwellings	0.0297600	0.0057000	5.22	0.00000	0.169
	Population density (residents per km^2)	0.0000073	0.0000015	4.76	0.00000	0.128
Battery electric vehicle share	Incentive (BEV)	0.0000036	0.0000003	13.55	0.00000	0.569
	DC fast charge points per million population	0.0003400	0.0000300	11.71	0.00000	0.428
	Percent of households in multi-unit dwellings	0.0180600	0.0042400	4.26	0.00003	0.174
	Level 2 charge points per million population	0.0000063	0.0000023	2.74	0.00640	0.101
Plug-in electric vehicle share	Level 2 charge points per million population	0.0000300	0.0000014	19.08	0.00000	0.547
	Incentive (PHEV)	0.0000015	0.0000001	15.43	0.00000	0.424
	DC fast charge points per million population	0.0001200	0.0000200	6.81	0.00000	0.194
	Population density (residents per km^2)	0.0000042	0.0000007	5.86	0.00000	0.156