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Enhancing user experience in public electric vehicle charging

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ZEV ALLIANCE

The International Zero-Emission Vehicle Alliance is a network of leading national and sub-national governments demonstrating their deep commitment to accelerating the transition to zero-emission vehicles within their markets and globally. Its members include Austria, Baden-Württemberg, British Columbia, California, Canada, Chile, Connecticut, Costa Rica, Germany, Maryland, Massachusetts, the Netherlands, New Jersey, New York, New Zealand, Norway, Oregon, Québec, Rhode Island, Switzerland, the United Kingdom, Vermont, and Washington. The members collaborate through discussion of challenges, lessons learned, and opportunities; hosting events with governments and the private sector; and commissioning research on the most pressing issues in the ZEV transition.

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Executive summary

Many jurisdictions are planning to transition to full electric vehicle (EV) sales, with the European Union (EU) and Canada fully phasing in the sales of new zero-emission vehicles (ZEVs) by 2035. Similarly, in the United States (U.S), California has adopted a 100% EV sales target by 2035, a goal that several other U.S. states have also committed to achieving. Meeting the charging needs of the growing number of EVs on the road will require an increase in the quantity of publicly accessible chargers as well as improvements to their ease of use. This report assesses the existing public charging infrastructure networks for electric passenger cars in Canada, Europe, and the United States, focusing on three key factors: availability, reliability, and interoperability.

Availability

Ensuring widespread public charging availability involves making chargers available where people live and spend time, such as at home, workplaces, and shopping and leisure locations. Our analysis identified disparities in access to public charging infrastructure in Canada, Europe, and the United States. At the EU Member State level, public charger deployment was found to be strongly correlated with average household income. This correlation between income and public charger deployment was found to be stronger than the correlation between income and new EV registrations. This pattern was less pronounced in the United States; though some U.S. areas with relatively higher income were found to have access to more chargers than areas with relatively lower income, we found multiple U.S. states with no correlation between public charging deployment and income or income and EV adoption. Additionally, our analysis found that areas in Canada with higher unemployment rates tended to have lower access to public chargers. Beyond socioeconomic factors, our research also found disparities in access to and satisfaction with public charging among specific user groups, such as women.

Governments have taken various actions to address these disparities. Harmonization of legislation and guidelines can ensure inclusive planning for charging infrastructure. For example, some have sought to provide a uniform approach to accessibility at the market level to help to prevent a patchwork of regional regulations and guidelines and interpretation differences between stakeholders. Incentive programs and legislation have been implemented to prevent charging deserts by providing targeted subsidies to areas undersupplied in terms of EV chargers. Targets or mandates for minimum charging deployment along highways have also been established, and proactive planning efforts have been undertaken to deploy charging in specific areas to reduce disparities in access. Some governments also perform regular assessments to ensure public charging is being deployed equitably.

Reliability

Reliable charging infrastructure means that users can trust chargers to function correctly. Unreliable public charging can be a significant barrier to the widespread adoption of electric vehicles. While early adopters might be more willing to tolerate occasional issues with public charging stations, growing reliance on these chargers for daily commuting and longer journeys has underlined the need for more dependable charging infrastructure. To address this, several jurisdictions have developed minimum uptime or successful charge rate requirements, with potential penalties levied for non-compliance. Other options include setting and enforcing robust hardware, software, and charging deployment standards and certification programs with stringent reliability benchmarks. Some governments have also taken steps to ensure data transparency by mandating that charging network operators provide real-time data on charger availability and functionality through open APIs. Lastly, incentives like tax breaks or rebates have been offered for the installation and maintenance of chargers to meet uptime requirements.

Interoperability

Interoperability refers to compatibility between the vehicle, the user, and the charger. Users can encounter hardware incompatibilities, such as mismatched connectors, or software issues, such as the inability to make ad hoc payments. The cooperation of many stakeholders and communication layers is needed to make a charging session successful.

The European Union has achieved significant harmonization of connector types, with over 95% of alternating current chargers supporting Type 2 connectors and over 80% of direct current chargers supporting CCS2 connectors. The U.S. and Canadian markets are more fragmented, but drivers are on track to benefit from a fully integrated hardware system with the adoption of the J3400 connector standard (the North America Charging Standard [NACS], formerly Tesla). However, during this transition, promoting backward compatibility for existing vehicle models incompatible with NACS can ensure drivers are still able to charge their vehicles.

In Europe, the United States, and Canada, software interoperability levels vary across communication interfaces within the public charging ecosystem; even in areas where certain protocols have achieved widespread adoption, protocol implementation can differ, leading to interoperability barriers. There are ongoing efforts to advance harmonization and convergence of communication standards, including through policy support, but a unified approach and agreement across stakeholders on common protocols is still lacking. At the same time, recent EU and U.S. regulations have tackled constraints regarding payment options, such as eliminating membership requirements to use chargers, to improve the driver experience.

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Introduction

In the European Union, the number of publicly accessible chargers has grown substantially, increasing from 320,000 at the end of 2021 to close to 800,000 as of mid-2024.[1] The number of public chargers in the United States and Canada has also increased, reaching 220,000 as of January 2024.[2] This growth represents a critical step towards supporting the widespread adoption of electric vehicles (EVs). However, along with an increased quantity of chargers, public charging needs to be user-friendly to effectively meet the demands of EV users.

Three key factors determine whether a charging network is easy to use and can meet the demands of EV drivers. The first is availability, or whether chargers are available where people live and spend time, such as at home or in shopping centers, workplaces, and leisure locations. Availability also considers whether all EV users can locate and utilize charging stations regardless of socioeconomic classes or user group. The second key factor is reliability. Deploying a vast charging infrastructure network is insufficient if users cannot be assured that chargers will function correctly. Lastly, access to a functioning charger must be complemented by interoperability between the vehicle, the method of payment, and the charger. Hardware incompatibilities, such as mismatched connectors, or software issues, such as the inability to make ad hoc payments, can prevent users from charging. A seamless and interoperable charging experience is crucial for fostering confidence among EV users.

This paper assesses how selected jurisdictions in Europe, Canada, and the United States are performing concerning charging accessibility, reliability, and interoperability, and discusses policies to improve public charging deployment. The following sections explore each of these factors by addressing the following questions:

1. Availability: Can any EV driver confidently expect to find a charger where and when needed, be able to safely access it, and understand the charging process?

2. Reliability: Can any EV driver confidently rely on public chargers, how has reliability evolved, and what level of reliability can be achieved?

3. Interoperability: Can EV drivers seamlessly travel throughout jurisdictions, or do they have to worry about not being able to recharge because of payment options, membership requirements, or hardware or software standards?

The following sections address these questions with data-driven analyses and discuss possible policy solutions to the identified challenges. A summary is provided at the end of each section.

Availability

The availability of public charging infrastructure plays a pivotal role in ensuring the use of EVs is convenient for drivers. Public charging availability can be broadly measured in terms of whether charging infrastructure is in the vicinity of where people live, shop, work, and need to travel, as well as whether chargers fulfill the needs of various user groups and can be accessed safely and conveniently. Ensuring that public charging is deployed evenly, without bias toward certain groups, is crucial to ensuring that everyone may reap the benefits of vehicle electrification.

This section is guided by the following question: *Can any EV driver, regardless of income level, employment status, and race, confidently expect to find a charger where and when needed,* *access it safely, and understand the charging process?* To answer this, this section presents a quantitative analysis of public charging infrastructure deployment and its correlation with income, unemployment, and the share of people of color within the overall population. It also suggests policy actions to address geographic gaps in charging deployment. Moreover, this section highlights the importance of addressing the needs of diverse user groups and of establishing a clear, easy-to-understand process for charging.

Public charging infrastructure deployment and its correlation with income, unemployment, and share of people of color within the overall population

Income, unemployment, and share of the population made up of people of color were chosen as metrics because they all reflect equity in EV charging. Equitable public charging deployment is defined here as the planning and deployment of public chargers without bias towards groups of people with certain socioeconomic backgrounds. We acknowledge that many other factors can influence the geographic coverage of public charging infrastructure outside of these metrics. The following sub-sections thus do not intend to demonstrate a causal relationship, but rather raise awareness among policymakers about the equity implications of charging infrastructure deployment and the need to account for these implications in planning and monitoring.

In this section, public charger deployment refers to public installed power output (in MW) per million population instead of the number of chargers, to account for the differences in power output between alternating current (AC) and direct current (DC) chargers. Because a DC charger has a higher power output than an AC charger, it can charge cars faster and accommodate more vehicles per day.[3] Our analysis uses population as a proxy for the number of cars in an area; because areas with higher population generally have more car activity, it can be assumed that these areas will need more charging infrastructure in the long term. Population data were obtained from Eurostat for Europe, the U.S. Census Bureau for the United States, and Statistics Canada.[4] Public charger deployment data for the three regions were sourced from Eco-Movement.

Correlation analyses were conducted between public charger deployment and household income for Canada, the European Union, and the United States, as well as between public charger deployment and unemployment rate for Canada and the United States. Additionally, a correlation analysis was performed between public charger deployment and the share of people of color in the overall population for the United States. Income data were obtained from the Canada Mortgage and Housing Corporation, Eurostat, and the U.S. Census Bureau.[5] Unemployment data were obtained from Statistics Canada and the U.S. Census Bureau.[6] Information on the share of the population composed of people of color was obtained from the U.S. Census Bureau.[7] All data used in the analyses were for 2023, with the exception of income data for Canada and the European Union, which were for 2021 and 2022, respectively, as these were the most recent data available.

The Pearson correlation coefficient (ρ) is used to assess the strength and direction of any correlations. The Pearson coefficient is always between -1 and +1. Positive coefficient values indicate that the variables change in the same direction, while negative values indicate that they change in opposite directions. A coefficient value close to +1 or -1 indicates a strong linear correlation, meaning that an increase (or decrease) in one variable is mirrored by a corresponding change in the other variable. In contrast, a coefficient value close to 0 means that the correlation is weak.

For statistically relevant correlations, further analysis was performed (when data were available) to assess whether the correlation was direct between public charger deployment and each of the selected metrics or more indirect due to EV adoption. Indeed, average household income, unemployment, and share of people of color in the overall population have been found to be often correlated with EV adoption and, as a result, correlated with public installed power output.[8] These additional correlation analyses were based on new EV registration data for 2023, sourced from energyrates.ca for Canada and from ICCT reports for the European Union and the United States.[9]

Because correlations at different geographic levels cannot be directly compared, analyses were performed at the national and state level using EU Member States, U.S. states, and Canadian provinces, and at the local level using NUTS 3 regions in the European Union,[10] counties in the United States, and divisions in Canada. These levels were chosen due to data availability.

National-level analysis

The national-level correlation coefficient results are shown in Table 1. The cells are highlighted in red when the correlation between two variables was deemed very strong ($|\rho| \geq 0.8$), in orange for strong correlations ($0.6 \leq |\rho| \leq 0.8$), and in yellow for fair correlations ($0.3 \leq |\rho| \leq 0.6$).[11]

Table 1. Relative strength of the correlation between public charging infrastructure deployment and selected metrics according to the Pearson coefficient

Geography	Level	Sample size	Pearson coefficient		
			Mean household income	Unemployment	Share of people of color
European Union	Member State	27	0.817	0.085	
Canada	Province	10	0.092	-0.482	
United States	State	50	0.463	0.080	0.091

Note: Public charger deployment is measured as public installed power output per million population.

The results showed a strong correlation between charger deployment and average household income at the EU Member State level, a fair correlation between charger deployment and unemployment at the Canadian province level, and a fair correlation between charger deployment and mean household income at the U.S. state level. This means that public charger deployment in the European Union and the United States is generally lower in areas with relatively lower average income per household, and vice versa. Similarly, in Canada, public charger deployment is generally lower in areas with higher unemployment rates, and vice versa.

European Union: Income

The first case study focuses on the correlation between average household income and public installed power output in the European Union. As shown in Table 1, the correlation between these two variables was deemed very strong ($\rho \geq 0.8$). This means that Member States with a relatively higher average household income also have a higher public installed power output per million population. Figure A1 in the appendix shows the public installed power output per million population as a function of the average household income for each of the 27 EU Member States.

One could assume that average household income is first correlated with EV adoption and, as a result, also correlated with public installed power output. To assess this, we analyzed the strength of the correlation between public charger deployment and two metrics of EV adoption—sales shares of all new EVs (including both battery electric vehicles [BEVs] and plug-in hybrid electric vehicles [PHEVs]) and of only BEVs—and between income and new EV and BEV sales shares. The strength of the correlations is shown in Table 2, with the cells representing the Pearson coefficient of the correlation between the metrics.

Table 2. Relative strength of the correlations between public charging deployment and new BEV and EV sales shares with income in the European Union

Pearson coefficients	Public charger deployment	2023 new BEV sales share	2023 new EV sales share	Average household income
Public charger deployment	1	0.854	0.751	0.817
2023 new BEV sales share	0.854	1		0.724
2023 new EV sales share	0.751		1	0.599

Average household income was more strongly correlated with public charger deployment (the red cell at top right) than with new EV and BEV sales shares (the orange cells below). This means that households in Member States with relatively higher average household incomes have even more access to public chargers than to EVs. In other words, the analysis implies that income impacts public charger deployment more than it affects EV adoption. That said, both correlations were relatively strong, making it difficult to draw a clear conclusion. Furthermore, regarding the correlation between income and new EV sales, new vehicle buyers are not representative of the population as a whole and a strong positive correlation between new vehicle sales and income is also found in the internal combustion engine (ICE)-powered vehicle market.[12]

Canada: Unemployment rate

For Canada, we analyzed the correlation between public chargers deployed and unemployment. As indicated by the negative coefficient in Table 1 (-0.482), we found a fair negative correlation, meaning that people in provinces with higher unemployment rates are relatively less likely to have access to public chargers in their vicinity. However, the sample size was small, with only 10 provinces, and the removal of one outlier (Newfoundland, with 10% unemployment in 2023) caused the Pearson coefficient to drop to -0.19, implying no correlation. A graph representing public installed power output per million population as a function of the unemployment rate for 2023 for each Canadian province is provided in Figure A2 in the appendix.

Beyond the correlation between unemployment and public charger deployment, we analyzed the correlation with the new EV registration share for 2023.[13] The relative strength of the correlations is shown in Table 3, which includes the outlier province of Newfoundland.

Table 3. Relative strength of the correlations between public charging deployment and new EV registrations with unemployment rate in Canada at the provincial level (including outlier data)

Pearson coefficients	Public charger deployment	2023 new EV registration share	Unemployment rate
Public charger deployment	1	0.745	-0.482
2023 new EV registrations share	0.745	1	-0.400

The strongest correlation was between the new EV registration share and public charging deployment. Meanwhile, the correlation between unemployment and public charging deployment was slightly stronger than the one between unemployment and the new EV registration share. However, as noted above, removing the outlier resulted in a coefficient between charger deployment and unemployment of -0.19, implying no correlation, while the coefficient between unemployment and new EV registrations share dropped by less, to -0.352.

United States: Income

Table 1 shows that the correlation between average household income and public charging deployment in the United States was fair, with a correlation coefficient of 0.463. We further assessed whether this correlation was due to EV adoption. The strength of the correlations is shown in Table 4, with the cells representing the Pearson coefficient of the correlation between the metrics.

Table 4. Relative strength of the correlations between public charging deployment and new EV registrations with income in the United States at the state level

Pearson coefficients	Public charger deployment	2023 new EV sales share	2023 new BEV sales share	Average household income
Public charger deployment	1	0.705		0.463
2023 new EV sale share	0.705	1		0.720
2023 new BEV sales share	0.734		1	0.755

While the strongest correlation was found between the new BEV sales share and average household income, we note that this does not hold at the local level, as described in the next section. This highlights the work done by some U.S. states to make BEVs more affordable.[13] Further, correlation between new vehicle sales and income is not specific to EVs and can also be seen in the ICE market. In addition, as noted above, new car buyers are not representative of the population at large.

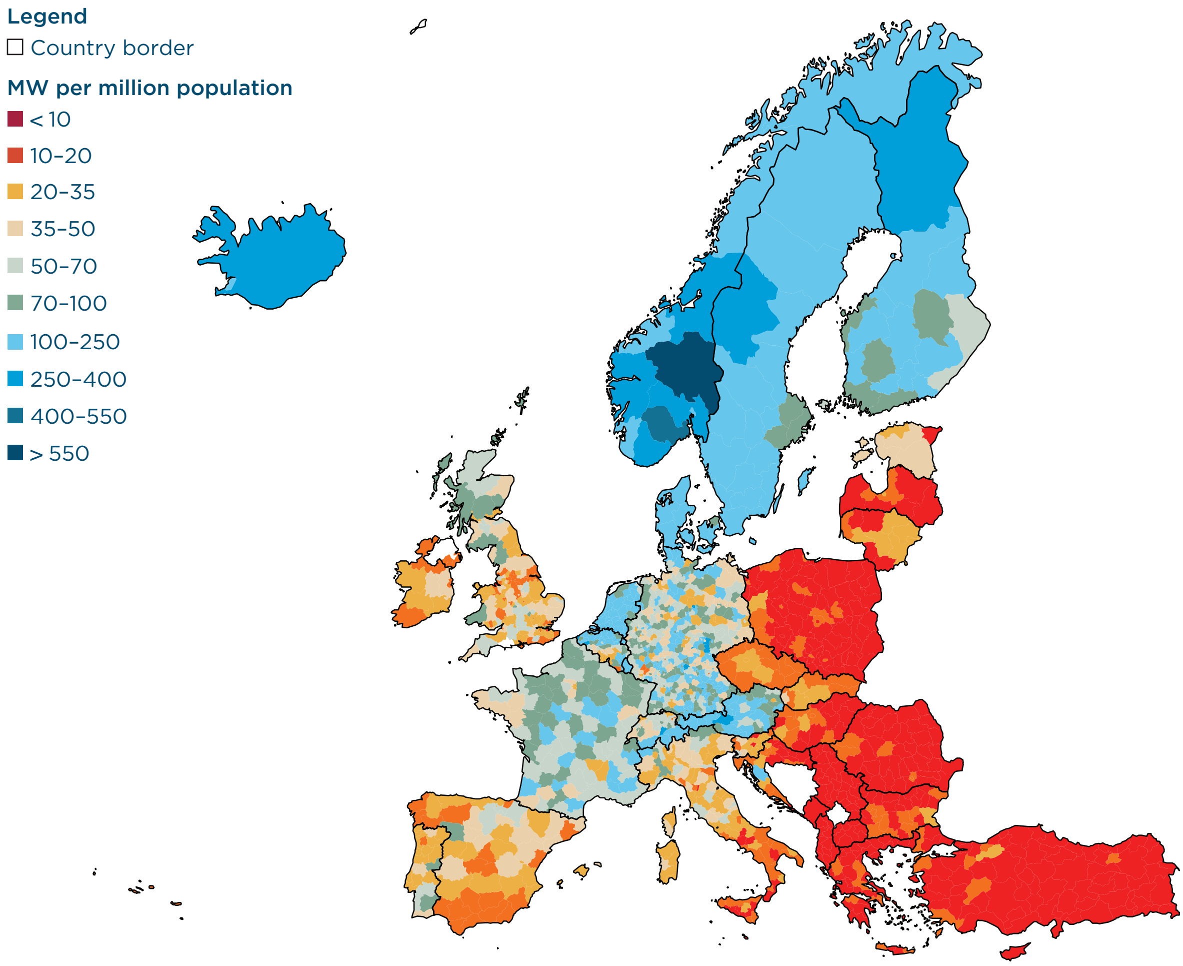
Local-level analysis

This section presents information on charger availability at the local level in Canada, the European Union, and the United States, and assesses the correlations between public charger deployment and income, unemployment, and share of people of color in the overall population.

Availability by area

Figure 1 and Figure 2 show the public installed power output per million population at the NUTS 3 level in Europe, county level in the United States, and division level in Canada. For reference, Europe has an average of 52 MW of charging power installed per million population and the United States and Canada have an average of 23 MW per million population.

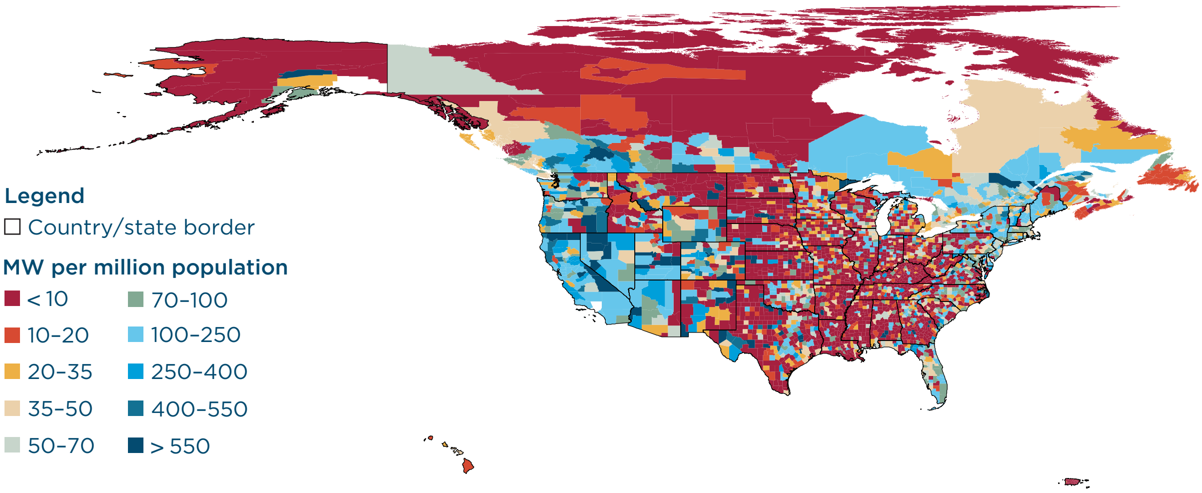
Figure 1. Public installed power output, in MW per million population, for NUTS 3 regions in Europe



Data source: Eco-Movement

As shown in Figure 1, there is a clear difference in terms of public charging deployment between Northern, Southern, Western, and Eastern Europe. As an example, while Norway has, on average, 384 MW of charging power installed per million population, Germany has 104 MW and Poland 10 MW. Consistent with the high Pearson coefficient discussed above, this correlates with European disparities in terms of income per household.[14] In 2022 (the last year for which data are available), Norway had a median equivalized disposable income of €27,893 compared with €23,197 for Germany and €14,906 for Poland. This pattern of public installed power output is also correlated with the EV adoption rate, as Norway had a new EV sales share of 82% in 2023 compared with 18% in Germany and 4% in Poland.[15]

Figure 2. Public installed power output, in MW per million population, at the county (United States) and division (Canada) levels



Data source: Eco-Movement

Contrary to Europe, variations in installed power output per population in U.S. counties and Canadian divisions have less of a geographic component. For instance, although California, on the west coast, is a leader in terms of county-level coverage, we also see counties in central states with blue shades, indicating high installed power output. Indeed, several leading counties are in states with overall a lower installed power output per million population. For example, in South Dakota, most counties have relatively low installed power output per million population, but the western county of Pennington—home to Rapid City, the state's second most populous city—has levels similar to cities in California.

Correlations

Table 5 shows the correlations between public charging deployment as of the end of 2023 and income, unemployment, and share of people of color for German NUTS 3 regions, Canadian provinces, and U.S. states. (NUTS 3 regions are differentiated by urban areas, suburban areas, and rural areas.) The cells are highlighted in yellow if $0.3 \leq |\rho| \leq 0.6$, meaning there is a fair correlation. In this case, no correlation coefficient had an absolute value greater than 0.6, so there was no strong or very strong correlation between the metrics.

Table 5. Relative strength of the correlation between public charging infrastructure deployment and selected metrics by region

Pearson coefficient						
Geography		Level	Sample size	Mean household income	Unemployment	Share of people of color
Germany	All	NUTS 3	401	0.178		
	Urban areas	NUTS 3	95	0.221		
	Suburban areas	NUTS 3	196	0.229		
	Rural areas	NUTS 3	110	0.244		
Canada		Division	293		-0.212	
United States	California	County	58	-0.211	-0.187	-0.220
	Connecticut	County	8	0.296	0.290	0.598
	Maryland	County	23	-0.032	-0.105	-0.410
	Massachusetts	County	14	-0.277	-0.500	-0.341
	New Jersey	County	21	-0.075	-0.016	-0.142
	New York	County	62	-0.101	-0.185	-0.264
	Oregon	County	36	-0.265	-0.104	0.101
	Rhode Island	County	5	-0.146	-0.114	-0.287
	Vermont	County	14	-0.068	-0.175	-0.072
	Washington	County	39	-0.084	0.076	0.230

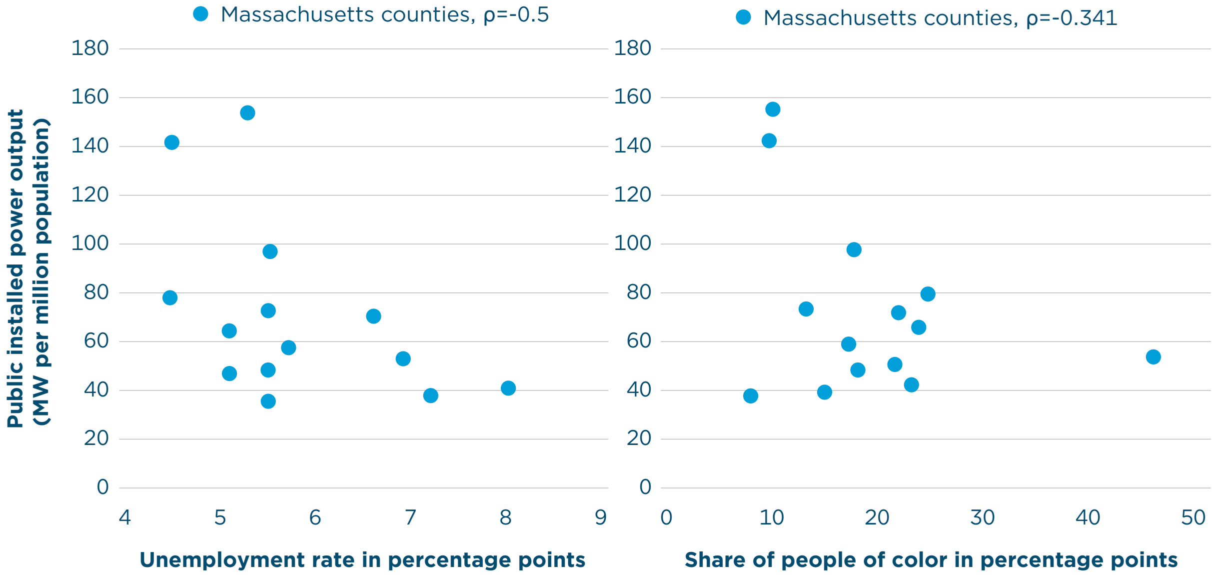
Note: Public charger deployment refers to public installed power output per million population.

The table shows that there were very few relevant correlations at the local level. However, in Massachusetts, a fair correlation was observed between charger deployment and both unemployment and the share of people of color in the overall population. In addition, although our analysis found no correlation between income and charger deployment in Germany, there were interesting outliers to highlight. These are discussed in more detail below.

Massachusetts: Unemployment and population share of people of color

Figure 3 shows the public installed power output per million population as a function of the unemployment rate (left) and share of people of color (right) in Massachusetts in 2022, the latest year for which data are available. In both cases, we observed a fair negative correlation ($0.3 \leq |\rho| \leq 0.6$). This means that areas with a higher share of people of color in the population or a higher share of unemployment tended to have less charging infrastructure deployed.

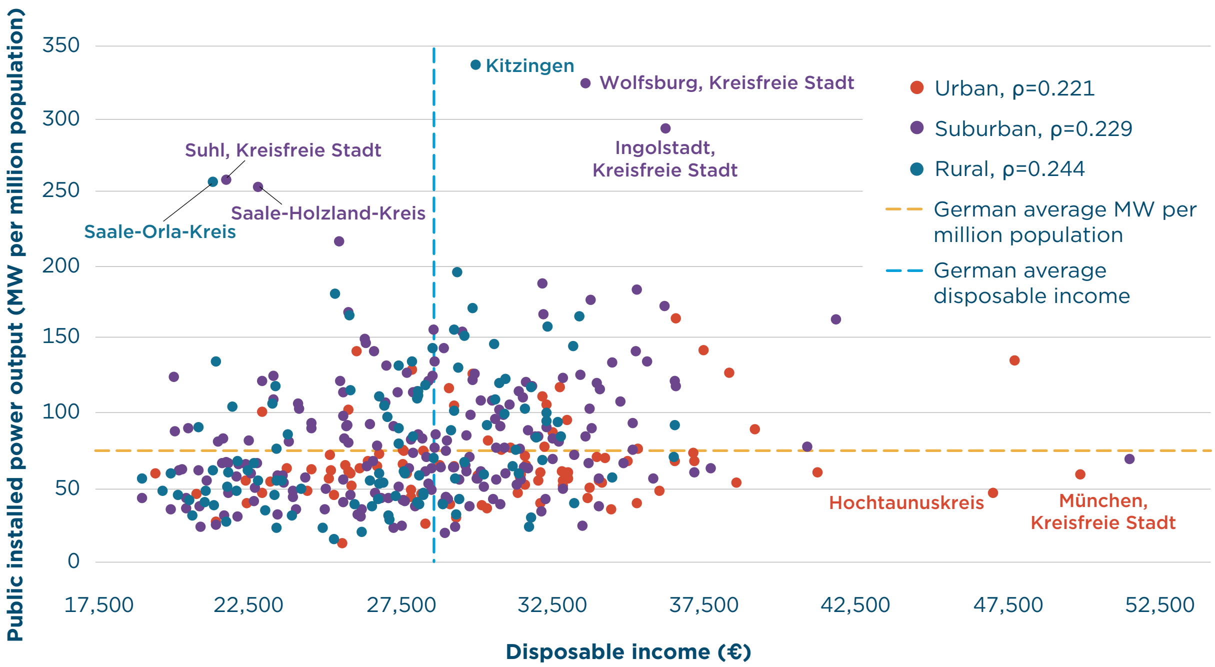
Figure 3. Public installed power output per million population as a function of unemployment rate (left) and share of people of color (right) in Massachusetts



Germany: Income

As shown in Table 2, we found no correlation between public charger deployment and income at the NUTS 3 level in Germany. This means that public chargers seem to be deployed in areas regardless of income level. Figure 4 shows the correlation between the public charging power output installed per million inhabitants and disposable income (that is, income remaining after deduction of taxes and social security charges).[16] The average MW per million population and average disposable income are also shown for comparison. Selected outlier regions are labeled.

Figure 4. Public installed power output in MW per million population as a function of disposable income in Germany



Note: One circle represents one NUTS 3 area.

The outliers on the upper left (corresponding to relatively low disposable income but high installed power output per million population) are suburban and rural areas, while the outliers on the bottom right (relatively high disposable income but low installed power output per million population) are urban areas. This could reflect urban areas being more densely populated and therefore having a lower amount of installed power output per million population.

Two observations can be made regarding the outliers. First, the three NUTS 3 regions clustered in the upper left are all located in the state of Thüringen. Second, three of the outliers are home to auto manufacturer headquarters: Ingolstadt (Audi), Wolfsburg (Volkswagen), and Munich (BMW). While Munich is a large city with a robust economy outside of the BMW facility, Ingolstadt and Wolfsburg are relatively smaller cities more reliant on the automotive firms.

The analyses above found that charging deployment varies from region to region, even in leading ZEV markets, and that the relationship between charging infrastructure development and socioeconomic metrics—income, unemployment, and the share of people of color in the population—varies across markets. At the national level, one or more of these metrics are often correlated with public charging deployment. These correlations are less pronounced at the local level, but deployment is still uneven. In the next section, we discuss how governments can use targeted policies to promote the deployment of charging infrastructure that serves the needs of current and future EV drivers regardless of these socioeconomic factors.

Policies to foster an equitable charging infrastructure distribution

Policies at the state level in California, at the national level in Austria, the Netherlands, and the United States, and at the regional level in the European Union provide examples of targeted approaches to promoting equity in charging infrastructure deployment.

California Senate Bill 1000, approved in 2018, requires the California Energy Commission to assess whether charging infrastructure has been deployed equitably throughout the state.[17] A 2022 Commission report, for instance, assessed the drive time to the closest DC fast charging station for various income groups and geographies (rural versus urban) throughout California. The result of this assessment influenced investments from the state's Clean Transportation Program, which invests in innovative zero-emission transportation and fuel technologies.

Austria's LADIN funding program aims to build the fast charging network in "undersupplied areas," defined as those further than 7 km from existing fast charging infrastructure or those designated as settlement, industrial, or agricultural areas.[18] The funding covers up to 60% of the investment costs for charger installations (which is higher than the government's general public charger funding program), including upstream investments such as transformers.[19] In the Netherlands, the government has allocated €90 million to support the establishment of at least one public charging station in every 500 meter by 500 meter area with 125 households or more.[20]

The United States and the European Union have implemented policies to promote widespread charging access and avoid charging deserts. The U.S. National Electric Vehicle Infrastructure (NEVI) program provides funding for charging infrastructure along designated Alternative Fuel Corridors and encourages locating DC charging stations every 50 miles. Meanwhile, the EU Alternative Fuel Infrastructure Regulation (AFIR) mandates a maximum distance of 60 km between DC charging stations along highways.[21]

A previous ICCT analysis showed the benefit of adopting different public charging infrastructure deployment strategies depending on the EV adoption phase to ensure drivers have access to public chargers.[22] The analysis suggested that a demand-driven strategy, in which chargers are deployed where there is EV driver demand, can be balanced with a planning-oriented strategy, in which jurisdictions foster wider public charging coverage to prepare for future demand.

Accessibility

Women

According to a 2024 European Commission analysis of 12 EU countries, only 22% of BEV drivers were women, compared with 53% of non-BEV drivers.[23] Recent surveys focusing on EV charging infrastructure have also highlighted gender disparities in attitudes about public charging. A UK government survey, for instance, found that 55% of women, compared with 70% of men, felt generally "very safe" when using public charging stations.[24] Respondents giving lower ratings cited the location of charge points in isolated or dark areas, insufficient lighting when having to charge at night, concerns about leaving the cable exposed while charging, and concerns about potential theft of the vehicle. Another survey of 4,000 individuals found that only 43% of women felt safe using public chargers, compared with 53% of men.[25] A survey of 1,000 individuals in Canada and the United States also emphasized security concerns among women, indicating a need for EV charging environments that are safe and accessible for all.[26] In this survey, 30% of Canadian women and 43% of U.S. women expressed safety concerns regarding public EV charging infrastructure. These studies and surveys imply action is needed in three areas to address gender disparities in charging: safety, deployment planning, and awareness.

Charging station providers could prioritize safety by ensuring stations are well lit and equipped with emergency buttons to enable vehicles to be quickly disconnected. In addition, having staff at the facility, akin to traditional petrol stations, could also improve safety. Horizontal charging pole designs, as seen with companies like Flo, could also enhance visibility and security.[27] Further, more overnight charging options could be placed in residential areas to minimize the distance an EV driver must travel home from the charging station to avoid long walks at night.

A 2016 study by CIVITAS found that, compared with men, women made shorter, more frequent trips with multiple stops.[28] The study also found that women's trips were more likely to be related to caregiving and other domestic roles: around 45% and 44% of women's trips in Italy and Germany, respectively, pertained to family responsibilities, compared with 30% (Italy) and 35% (Germany) for men. To cater to these needs, charging infrastructure could be extended to locations such as healthcare facilities and schools. More comprehensive data collection on women's traveling and charging patterns and greater representation of women in transport planning could result in more effective policies to address gender disparities in charging.[29]

Providing information on where chargers are located and how long it may take to charge could also help address the concerns of women related to EV charging. A 2023 study found that 49% of women reported being worried about not being able to recharge when needed compared with 39% of men.[30] When asked about EV ownership concerns, 43% of women agreed that they were worried about charging times compared with just 35% of men.

Many charging infrastructure operators, such as Pod Point, Osprey Charging Network, and Fastned, have advocated for safety standards and urged governments to incorporate such regulations into legislation.[31] Governments could also add safety and access requirements to existing charging infrastructure regulations, such as the European Union's AFIR and the United Kingdom's Public Charge Point Regulations. Some existing incentive programs do target locations traditionally more often visited by women. For example, in early 2024, the UK government introduced new grants for the installation of EV charge points at educational institutions and nurseries, among other locations, covering up to 75% of related costs.[32]

People with disabilities

Ensuring equitable charging access also means considering the specific needs of people with disabilities. Some governments have taken steps in this regard. Reports published by the U.S. Access Board, a federal agency responsible for the development of accessibility guidelines and standards, and the German agency NOW GmbH, a federally-owned company that implements and coordinates electromobility funding programs, recommend that a certain number of charging stations have minimum parking area requirements.[33] California has implemented regulations requiring a certain number of chargers be "van accessible," "standard accessible," or "ambulatory" depending on the total number of chargers at the facility.[34] For example, for a facility with 26 to 50 EV chargers, at least one must be ambulatory accessible.

Other recommendations in the U.S. Access Board and NOW GmbH reports include ensuring adequate space to enter, exit, and move around the vehicle and locating charging near building entrances. In addition, ensuring devices like the charging cable are not too heavy to be carried, which can be achieved through the installation of a motorized cable management system, can help overcome physical barriers to charging. NOW GmbH's guide also highlights the need to have functionalities within charging applications for people with disabilities, rather than requiring them to download separate applications to receive assistance. Table A1 in the appendix provides a list of additional resources related to public charging accessibility for people with disabilities.

Charging process

Because charging an EV differs from the familiar refueling process of ICE vehicles, a clear and easily understood charging process could ease the concerns of new drivers and improve the user experience. Drivers who are yet to join the EV transition may have less patience than early adopters and require that charging be clear, convenient, and easy. As an example, a 2024 study from J.D. Power highlighted a decline in customer-reported public charging satisfaction.[35]

Effectively informing drivers about the EV charging process is a prerequisite for accelerating EV adoption. Switching from refueling an ICE to recharging an EV involves getting familiar with a new technology; one of the first things EV drivers need to know is which chargers they can use based on their vehicle's connector and power acceptance rate to avoid charging frustrations. A French survey revealed that 47% of EV owners did not know the power acceptance rate of their vehicle.[36] Drivers must also familiarize themselves with methods for charging payment, which is often done through a charge point operator (CPO)'s digital app. CPOs could provide easy-to-understand user guides for charging to provide clarity regarding the process for new drivers.

New technologies are also under development that could ease the charging process. As of early 2024, recharging an EV required drivers to identify themselves through membership cards or charging apps and then pay with a credit card through the app or an online platform. To reduce the number of steps required to charge an EV, a "Plug & Charge" model is being developed in Europe. As defined by charging industry association CharIN, Plug & Charge (P&C) allows automated communication and billing processes between the EV and the charging station without any need for external identification.[37] Instead, EV drivers would be able to park in front of the charger, plug in their vehicle, and then leave when they are done recharging. As of the end of 2023, a contract with a mobility service provider (MSP) was required to enable P&C.[38] However, it appears technically feasible to store credit card details in EVs, similar to how MSP contract certificates are handled, to allow for ad hoc payments at chargers with P&C capability.[39]

Conclusion

Equitable deployment of public charging infrastructure, addressing the needs of diverse user groups, and ensuring a clear charging process can help ensure an equitable EV transition. At present, significant disparities exist in public charging infrastructure deployment in Europe, the United States, and Canada. Several policy interventions could help to ensure charging is available to all EV users.

Harmonization: A lack of uniform guidelines can complicate user experiences and present challenges for businesses, as approaches and guidelines can vary across countries and regions. A uniform approach to accessibility at the market level would prevent a patchwork of regional regulations and guidelines as well as interpretation differences between stakeholders. Among other actions, the issuance of governmental guidelines could help align market players.

Minimum deployment requirement: A maximum distance between two charging stations along highways, as encouraged in the U.S. NEVI program and mandated in the EU AFIR, can prevent charging deserts. Tender processes can also help to ensure widespread charger availability. Moreover, programs to foster new public overnight AC charging in residential areas can maximize the economic benefits of switching to an EV and encourage further adoption.

Incentive programs: Targeted incentive programs can foster equitable public charging deployment. For example, the LADIN charging infrastructure funding program in Austria aims to build fast charging networks in undersupplied areas to reduce inequalities in charger access.

Inclusive planning: Public charging infrastructure can be designed to consider the needs of drivers regardless of socioeconomic background and address the concerns of women, people with disabilities, and people with minimal knowledge of EV charging. Charging infrastructure that is widely available, accessible, and easy to use can ensure all EV drivers are able to charge.

Reporting and follow-up actions: Ensuring public charging infrastructure can be accessed by everyone requires continuous monitoring and adjustment. To this end, Senate Bill 1000 in California requires the California Energy Commission to assess whether charging infrastructure has been equitably deployed throughout the state and take action if this is not the case.

Reliability

Unreliable public charging infrastructure can be a significant barrier to the mass adoption of EVs. Growing reliance on these chargers for daily commuting and longer journeys has highlighted the need for more dependable charging infrastructure. This section thus aims to address the following questions: *Can any EV driver confidently rely on public chargers? How has reliability evolved? What level of reliability can be achieved?*

Several studies have shown that the reliability of public chargers (meaning chargers are available and functioning properly) is a major concern for users across the United States, Europe, and China. As shown in Table 6, studies have found significant variations between markets in the reliability of public chargers. For example, in France (as of 2021–2022) and the San Francisco Bay Area (as of 2023), researchers found that roughly 1 in 4 public chargers were unavailable at the time of testing, while studies in 2022 and 2023 found that 1 in 5 visits to public chargers in the United States resulted in no charge. Additionally, in 2022, 6% of public chargers in the United Kingdom were found to be out of service at any time, and a consumer survey in China found that 60% of respondents often encountered damaged or malfunctioning chargers.

Table 6. Studies on public charging reliability

Author/study	Country	Year	Results
AFIREV[a]	France	2021 and 2022	76% of chargers were available at any one time in 2022, up from 74% in 2021
J.D. Power[b]	United States	2023	20% of visits across the United States resulted in no charge, same as the previous year; 25% of people reported unreliable public charging in California
Rempel et al.[c]	United States	2023	72.5% of public DC fast chargers in the San Francisco Bay Area were functional at the time of testing
Zapmap[d]	United Kingdom	2022	65% of respondents named reliability as their top concern; 94% of chargers were functioning at any point
Boston Consulting Group[e]	United States, Europe, China	2022	73.6% of respondents named reliability as their top issue
China Consumers Association[f]	China	2022	60% of respondents encountered damaged or malfunctioning chargers; 35.8% of respondents reported the number of chargers available was not sufficient

[a] Association Française pour l'Itinérance de la Recharge Électrique des Véhicules (AFIREV), Observatoire de la Qualité des Services de Recharge Électrique Accessibles au Public, 3éme Edition [Observatory of the Quality of Electric Charging Services Accessible to the Public, 3rd Edition] (2023), https://www.observatoire-recharge-afirev.fr/wp-content/uploads/2023/06/ObsAFIREV2023_RapportDetaille_Final.pdf.

[b] JD Power, "Electric Vehicle Experience (EVX) Public Charging," https://www.jdpower.com/business/electric-vehicle-experience-evx-public-charging-study, August 26, 2023.

[c] David Rempel et al., "Reliability of Open Public Electric Vehicle Direct Current Fast Chargers," SSRN (2022): https://doi.org/10.2139/ssrn.4077554.

[d] Zapmap. "EV Charging in 2022: What We Said and What Actually Happened," December 23, 2022, https://www.zap-map.com/news/ev-charging-2022-what-happened.

[e] Markus Hagenmaier et al., "What Electric Vehicle Owners Really Want from Charging Networks," Boston Consulting Group, January 17, 2023, https://www.bcg.com/publications/2023/what-ev-drivers-expect-from-charging-stations-for-electric-cars.

[f] 119IT, "中国消费者协会：新能源电动汽车消费与公共充电桩使用情况调查报告 [China Consumers Association: Survey Report on New Energy Electric Vehicle Consumption and Public Charging Pile Usage], March 20, 2023, https://www.199it.com/archives/1571212.html.

Types of malfunctions found to contribute to public charger unreliability in the San Francisco Bay Area include blank, non-responsive screens, connection errors, payment system failures, and charging initiation failures.[40] According to charging network operator Electrify America, hardware failures, a lack of vehicle interoperability, global supply chain disruptions, service repairs, network IT management system issues, and payment system failures constitute six key causes of DC fast charging unreliability in the United States.[41] Improving public awareness of tariffs, the quality of published data, and the protection of charging equipment against weather events are key to improving public charging reliability in France, according to an AFIREV study.[42]

Evolution of policies for improving public chargers' reliability

Balancing the need for a robust charging network with the interests of private charging operators is crucial when regulating the reliability of public chargers. Some jurisdictions have begun implementing standards to improve public charger reliability while providing public funding to share the burden of financing the replacement and repair of broken chargers, as shown in Table 7. Measures include regulations on uptime (the percentage of time a charging station is available and in operation) or successful charge rate requirements (referring to the ability to begin and complete a charging session) implemented through monitoring and reporting of response times. Other government actions include measures to increase data transparency and accessibility, increased funding for infrastructure, and incentives to marshal private sector investment.[43]

However, enforcing public charging reliability can be challenging, as it requires regular audits, monitoring, and penalties for non-compliance. Indeed, the charging operator's software-reported uptime can be much higher than the uptime experienced by drivers while attempting to charge an EV. For instance, a 2023 study of over 4,800 charging stations in the United States found that the true uptime (84%) of EV chargers was considerably lower than the reported uptime (92%), with 26.3% of charging attempts failing even when the station was reported as online.[44] Standardized metrics and regulatory oversight can ensure reporting consistency regarding the reliability and performance of EV charging stations.

Table 7. Regulations addressing public charging reliability

Jurisdiction	Uptime requirement	Successful charge attempt rate
California	97% for state- or rate-funded chargers	90% for state-funded chargers
Netherlands	99% for public chargers	Not specified
New Zealand	95% for publicly funded chargers	Not specified
United States	97% for publicly funded chargers	Not specified
United Kingdom	99% for average across network	Not specified

Note: A high uptime rate indicates that chargers are generally available for use, while a high successful charge attempt rate suggests that charging sessions are typically successful.

In February 2023, the United States released new standards to improve the reliability of public chargers.[45] The standards require that all publicly funded chargers be functional 97% of the time and have consistent plug types, power levels, and a minimum number of chargers capable of fast charging. Additionally, the standards require that information on charger locations, price, availability, and accessibility be publicly available on mapping applications. The requirements apply to federally funded chargers under the NEVI program, and 10% of funding under NEVI in fiscal year 2023–2025 is set aside for enhancing public charger reliability and accessibility.[46] As of January 2024, the government had awarded $150 million to 20 states for the repair and replacement of almost 4,500 broken or faulty chargers.[47]

California has introduced new regulations at the state level to enhance the reliability and accessibility of charging stations, particularly for low-income communities.[48] As of January 2024, all state- and ratepayer-funded chargers were required to maintain a 97% operational uptime for 6 years, taking into account factors like weather and vandalism. From January 2026 onwards, these chargers will be required to satisfy a 90% successful charge attempt rate. To further improve reliability, real-time data on charger availability, accessibility, downtime incidents and response times, and pricing are required to be shared with third-party apps, making it easier for EV drivers to locate functional chargers. The California Energy Commission will use this information to monitor charging network performance and identify areas needing improvement.

The United Kingdom's 2023 Public Charge Point Regulations include, among other provisions, a 99% uptime requirement for rapid chargers (of 50 kW and above), measured as an average across each charging network operators' rapid network in a year, starting in November 2024. Charging network operators must report their reliability data annually to the Department of Transport. The data will be measured through the Open Charge Point Interface (OCPI) protocol to ensure standardized reporting and transparency. Information about reliability compliance must be published on the operator's website, helping EV drivers to make informed decisions about where to charge. The regulation also aims to improve consumer experience through contactless payment options for all new charge points (of 8 kW and above) and existing rapid chargers (of 50 kW or above). Consumers will be able to compare prices across different public charge point networks, as charge operators are required to display the total price for charging an EV at or near the charge point. For operators who do not comply with these aspects of the regulation, the penalty may be as high as £10,000 per charge point. The Office for Zero Emission Vehicles has the authority to determine the actual penalty based on the severity of the violation and may issue compliance notices before imposing a financial penalty to give operators a chance to rectify the issue.

Conclusion

Setting minimum reliability standards for public charging stations could help ensure a consistent and dependable charging experience. Determining the appropriate level of reliability to target requires careful consideration of technological feasibility, industry best practices, and the needs of consumers and businesses. Several policy options could be considered as part of a reliability standard.

Minimum uptime requirements: Governments could introduce laws mandating a reasonable uptime requirement or successful charge attempt rate for all public chargers. The 99% average uptime requirement for rapid chargers in the United Kingdom is an example of this approach. Penalties can be levied for non-compliance and response times when an issue occurs.

Certification and standards: Governments can also set and enforce robust charging standards and certification programs with stringent reliability benchmarks for public chargers. The standards could address the technical competence of chargers, including communication protocols, component durability, and data logging capabilities. This would enable only chargers meeting these comprehensive standards to be permitted for public installation, ensuring a consistent and dependable charging experience for EV drivers.

Data transparency: Governments could mandate that charging network operators provide real-time data on charger availability and functionality through open APIs, as has been done for chargers funded by the NEVI program in the United States. This would allow third-party apps and services to integrate the information and help EV drivers plan their trips and avoid unreliable or out-of-service chargers.

Incentives: Governments and charging network operators could offer financial incentives, such as tax breaks and rebates, to encourage the installation and maintenance of reliable chargers. Connecting incentives and permits for charging station installation and operation, as has been done in California, could yield high reliability rates.

Interoperability

Interoperability is the capacity of multiple systems and products to work together without restrictions or special efforts from the end user. In an interoperable public charging network, any EV can be charged at any charging station regardless of the EV model or the charger network, just as conventional vehicle drivers refuel at gas stations. That is, EV drivers can rely on a cohesive infrastructure across jurisdictions, without encountering hardware or software compatibility barriers or restrictions regarding standard payment methods.

The guiding question for this section is thus: *Can EV drivers recharge at public charging stations throughout Canada, Europe, and the United States without encountering hardware or software incompatibility?* To answer this, this section explores hardware and software interoperability trends in the Canadian, European, and U.S. public charging ecosystems.[49]

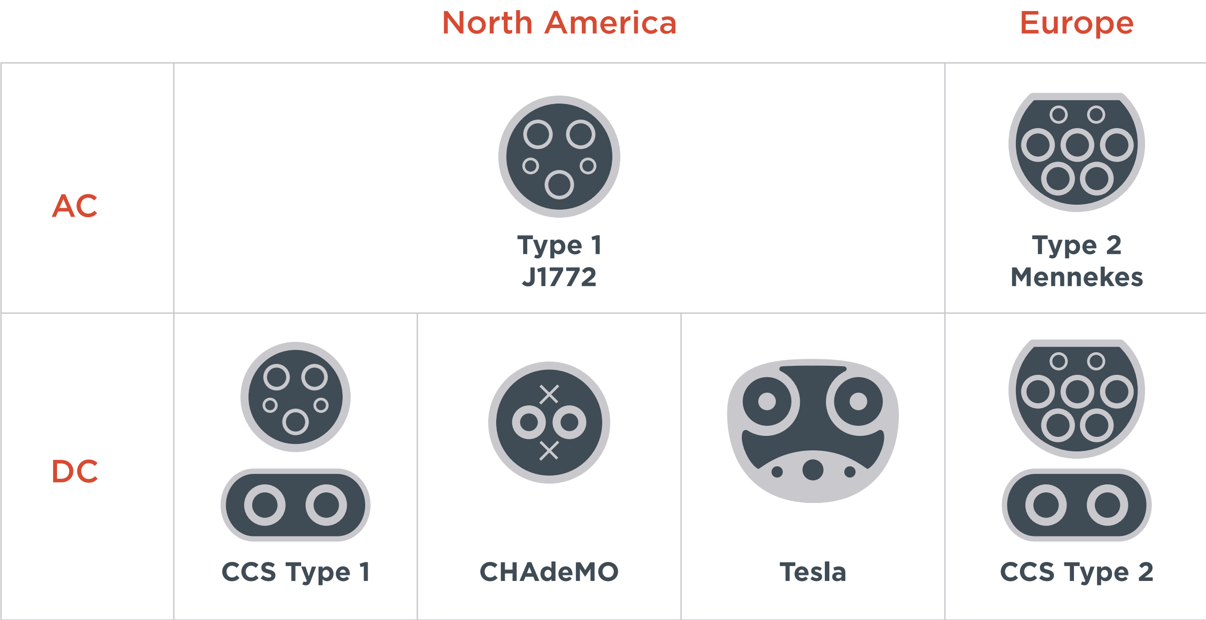
Hardware interoperability

Physical vehicle-to-charger interoperability, also known as hardware interoperability, depends on compatible, standardized connector types. Regulations concerning connector types vary by market, with certain jurisdictions imposing a single standard and others tolerating multiple standards.[50]

Figure 5 provides an overview of different connector standards used for AC and DC charging in the European Union and North America. The European Union takes a hybrid approach, mandating Type 2 connectors for public AC chargers and Combined Charging System (CCS) Combo 2 (CCS2) connectors for DC chargers as minimum requirements, while still allowing for the installation of additional connector types. In contrast, there are no nationwide connector requirements for public chargers in Canada and the United States. However, recent major public funding programs focused on charging infrastructure in these two countries require Type 1 (AC charging) and CCS1 (DC charging) connectors.[51]

In this way, Europe, Canada, and the United States have initiated transitions towards greater harmonization of connector types across their charging networks, although they are at different stages of implementation. Europe is at an advanced stage of a transition from CHAdeMO to CCS2 for DC charging,[52] while in Canada and the United States, the emerging standard developed by Tesla (the North America Charging Standard [NACS]), could phase out Type 1 J17712 and CCS1 standards in the coming years.

Figure 5. Common AC and DC connector types in Europe, the United States, and Canada



Note: Adapted from Pettigrew, *Strategies for Setting a National Electric Vehicle Charger Standard.*

This section examines market shares of public charger connector types in Europe (in 2022–2024) and Canada and the United States (in 2024). It then summarizes relevant hardware interoperability policies in the European Union, Canada, and the United States. Details on the connectors' technical capabilities can be found in a previous ICCT publication.[53]

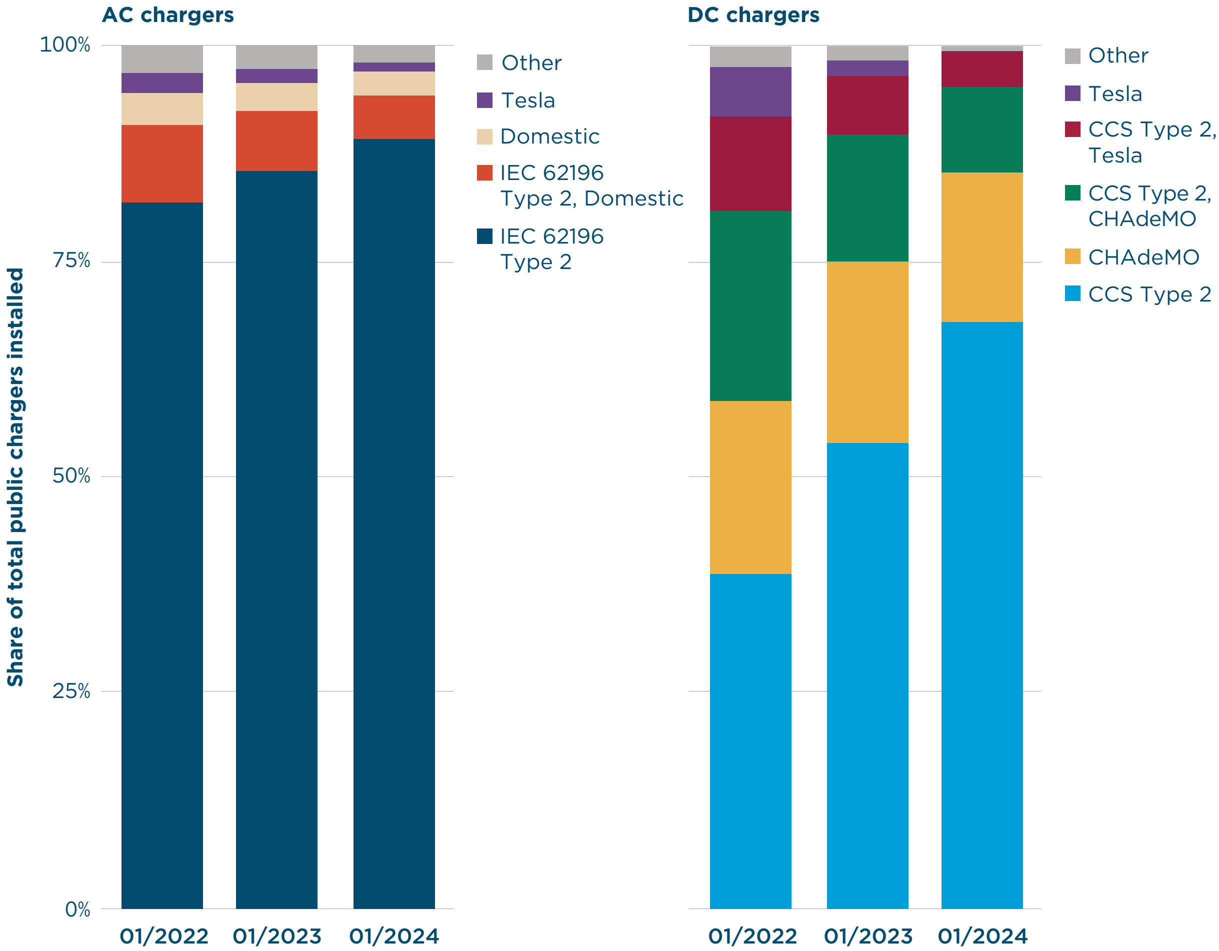
Connector type shares

Europe

Figure 6 illustrates the evolution of available connector type combinations in AC and DC public chargers installed in Europe from 2022 to 2024. A growing share of AC chargers featuring Type 2 connectors can be observed, with Type 2 penetration exceeding 95% as of January 2024. Domestic connectors continue to account for a significant but declining share of AC chargers and are primarily found in combination with Type 2 connectors.[54] Domestic ports are particularly common in Austria, France, and Norway (see Figure A3 in the appendix). Tesla initially deployed modified Type 2 connectors with AC and DC charging capability in Europe before switching to CCS technology in 2019 to align with EU regulations. These Tesla-specific connectors were found in about 1% of AC chargers as of January 2024. All vehicle models sold in Europe, including CHAdeMO-equipped and Tesla models, rely on Type 2 for AC charging.[55]

European DC infrastructure is more diverse than AC infrastructure in terms of connector types. However, CCS2 has gained market share over the past several years and was deployed in around 82% of DC chargers as of January 2024, up from 72% in 2022. CHAdeMO is still available at about 28% of DC chargers, down from around 43% as of January 2022. Figure 6 suggests that it is no longer customary to equip CCS2 chargers with additional CHAdeMO connectors. In the United Kingdom, however, CHAdeMO is still available at half of DC chargers (see Figure A4 in the appendix). Further, Figure 6 shows that all pre-2019 Tesla stations in operation as of January 2024 had been retrofitted with dual-cable posts to accommodate CCS2 connectors in addition to Tesla's DC Type 2 ports.[56]

Figure 6. Shares of total public chargers installed by combination of available connector types and date in Europe for AC chargers (left) and DC chargers (right)



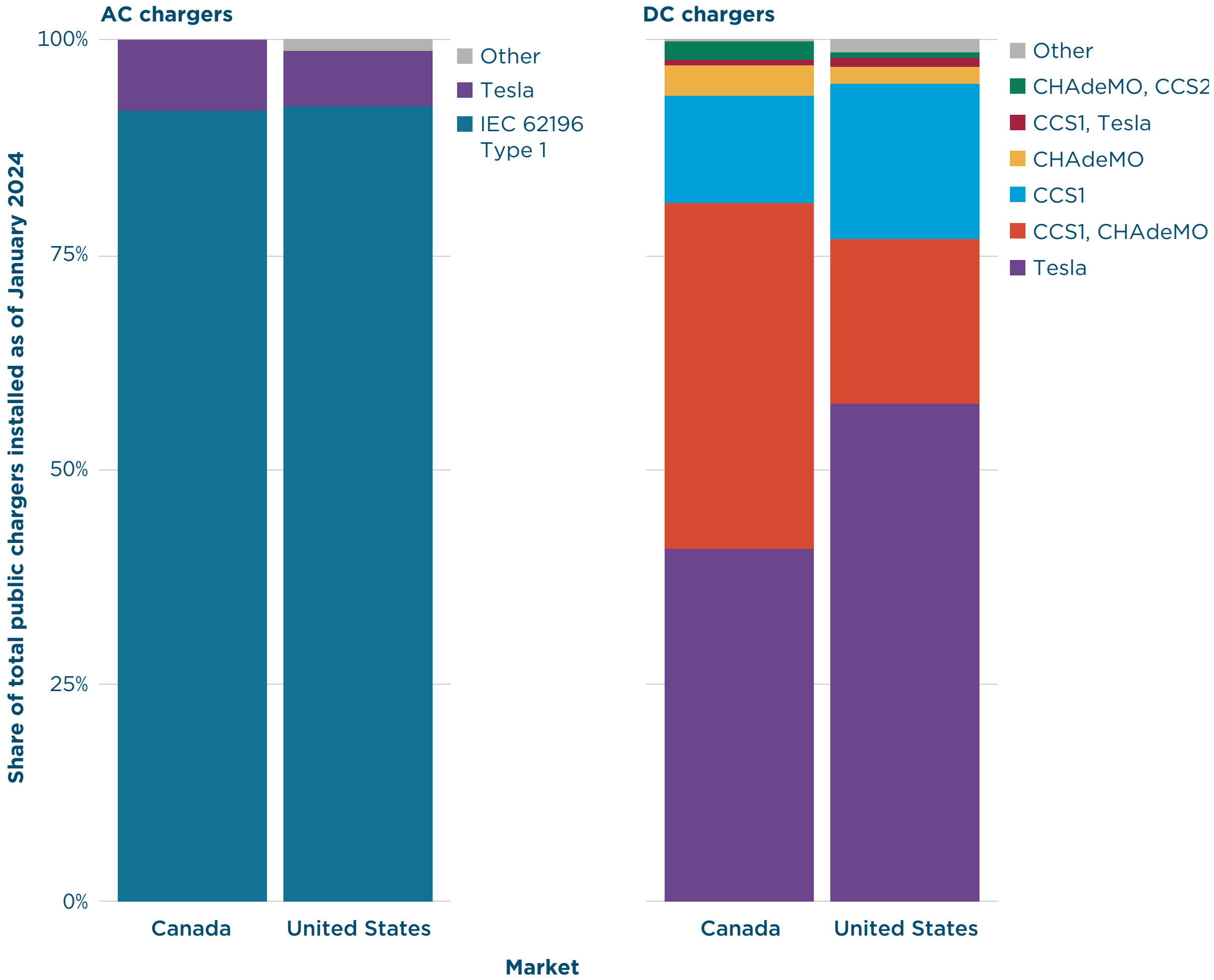
Data source: Eco-Movement

United States and Canada

In the United States and Canada, for AC charging, virtually all EV manufacturers except Tesla use Type 1 connectors, a single-phase plug standard maintained by the Society of Automobile Engineers (SAE) International. Type 1 connectors, also known as SAE J1772, use the same communication protocol as Type 2 connectors. As of January 2024, Type 1 connectors were available at about 92% of public AC chargers installed in both Canada and the United States (see Figure 8). The remainder were mainly equipped with Tesla connectors.

Regarding DC connector standards, the U.S. and Canadian markets are more fragmented than the European market, as regulators in these countries have not mandated a specific connector standard nor compelled the integration of proprietary connectors into the public charging network.[57] As illustrated in Figure 7, three DC connector types currently coexist in the U.S. and Canadian public DC charging networks: CCS1, Tesla, and CHAdeMO. In the United States, as of January 2024, Tesla connectors led with a DC charger share of about 58%, followed by CCS1 and CHAdeMO with shares of 38% and 20%, respectively. However, CHAdeMO-only chargers are rare, comprising just about 2% of all DC chargers. Instead, most chargers with CHAdeMO connectors also include CCS1 connectors. In Canada, the market is more balanced, with each of the three connector types featured in approximately 40%–50% of public DC chargers as of January 2024. As in the United States, CHAdeMO connectors in Canada are typically paired with CCS1 connectors, with only about 3% of DC chargers featuring CHAdeMO connectors exclusively. Currently, all non-Tesla EV models sold in the United States and Canada are equipped with CCS1 connectors except the Nissan Leaf and Mitsubishi Outlander, which use CHAdeMO.[58]

Figure 7. Shares of total public chargers installed by combination of available connector types in Canada and the United States as of January 2024 for AC chargers (left) and DC chargers (right)



Data source: Eco-Movement.

Policies for improving public chargers' hardware interoperability

Europe

In the European Union, connector types deployed at public chargers have been regulated since the enactment of Directive 2014/94/EU (the Alternative Fuels Infrastructure Directive, AFID) in 2014, which required all AC and DC charging points deployed or renewed from November 2017 to be equipped, at a minimum, with Type 2 and CCS2 connectors. The provision of additional connector types beyond Type 2 and CCS2 is likely related to the fact that, when the AFID was drafted, CHAdeMO was popular among top-selling EV models with DC charging capability (e.g., the Nissan Leaf, Kia Soul, and Peugeot iOn).[59] In 2023, the AFID was revamped as part of the AFIR, which retained the connector requirements adopted in 2014. In the United Kingdom, connector types available at public chargers are not regulated.

The Type 2/CCS2 mandate, which had the endorsement of European carmakers, has been pivotal in shaping hardware interoperability in European charging infrastructure.[60] Since 2014, the charger network has gradually coalesced around the Type 2 and CCS2 standards, as seen in Figure 6. Accommodating the needs of existing CHAdeMO drivers has been a key element of this transition. Due to CHAdeMO's lack of compatibility with CCS because of their different communication protocols, it became market practice after AFID's enactment to equip public DC chargers with both connector types and the EU funded dual-cable DC charging infrastructure along the Trans-European Transport Network (TEN-T).[61] The French transposition of the AFID required CHAdeMO connectors in public DC charging stations, a mandate that was in force from 2017 to 2021.[62] After the enactment of the AFID, CHAdeMO carmakers gradually shifted to CCS2 inlets, with the 2022 Nissan Leaf being the last CHAdeMO model to come to the European market.[63]

The shift away from CHAdeMO connectors and towards harmonization around Type 2/CCS2 has been a decade-long process sparked by CHAdeMO's lack of compatibility with CCS and limited regulatory intervention beyond the French mandate. Today's CHAdeMO-only chargers (17% of public DC chargers) are expected to be replaced with CCS2 chargers within 3 to 5 years, considering that pre-2017 EU charging points are required to include CCS2 connectors upon renewal and assuming a charger useful life of 8 to 10 years.[64]

United States and Canada

The experience in the European Union offers insights for the U.S. and Canadian markets, which are currently divided between multiple possible standards. The widespread adoption of Type 1 connectors in AC charging infrastructure across the United States and Canada, as seen in Figure 8, has been mainly driven by California's requirement of Type 1 connectors (in their second version) in model year 2010 and later vehicles.[65]

In the United States, the NEVI Program, which provides funds for charging infrastructure deployment across the country, requires each funded DC charger to have at least one CCS1 connector while allowing other additional connector types if they are non-proprietary.[66] While NEVI does not mandate that every public charger in the United States adhere to these requirements, the substantial funding provided under the program is anticipated to shape the default practices adopted by the EV industry, including the design of charging stations. In addition, the California Advanced Clean Cars II regulations require new EVs to be equipped with CCS1 inlets or an adapter starting in 2026.[67] Similar requirements to those of the NEVI program can be found in California's charger block grants.[68]

Canada's Zero Emission Vehicle Infrastructure Program, launched in 2019 to expand charging infrastructure in the country, does offer funding for the installation of proprietary connector types, which can represent up to 75% of the connectors installed at a single project site. The remaining 25% must be CCS1 in the case of DC chargers or Type 1 in the case of AC chargers.[69]

A major shift in Canadian and U.S. connector standards began in late 2022, when Tesla opened its connector design, renamed the NACS, to other manufacturers and charging service providers. The company maintained a network of primarily DC chargers exclusively for Tesla drivers using its proprietary connector standard that supports both single-phase AC and DC charging until 2024, when they started granting access to their chargers to select carmakers. Shortly after Tesla's 2022 announcement, SAE International started the NACS standardization process as J3400 to enable its integration throughout the EV industry. All automakers have committed to equipping their EV models with NACS inlets as early as model year 2025. In addition, CPOs have announced plans to add NACS alongside CCS1 in future stations and to gradually retrofit their existing stations, most likely by replacing CHAdeMO and duplicated CCS1 connectors with NACS connectors.[70]

As part of the transition, car manufacturers are entering agreements with Tesla to provide their drivers with a portable NACS-to-CCS1 adapter.[71] At select charging stations, Tesla provides fixed NACS-to-CCS1 adapters, known as Magic Docks, but these are not expected to become widely available.[72] As can be seen in Figure 8, only about 1% of U.S. DC chargers featured both Tesla and CCS1 connectors as of January 2024, while in Canada the share was negligible.

In light of the industry shift towards NACS, the federal and California governments have signaled plans to update the minimum requirements for publicly funded chargers, but the details are not yet known.[73] In parallel, starting with Texas in 2023, several U.S. states have announced that they will or may require both CCS1 and NACS connector types on their NEVI-funded charging networks.[74] To meet current NEVI CCS1 requirements, it is sufficient to equip chargers with certified built-in NACS-to-CCS1 adapters, as opposed to a two-cable solution. Such adapters were expected to become available in the market in 2024.[75]

EV industry plans for widespread adoption of the NACS J3400 standard will also impact AC infrastructure. If car manufacturers equip future EV models with J3400 inlets, Type 1 connectors, featured in 90% of AC chargers as of January 2024, would be gradually phased out; existing Type 1 chargers would serve current and older models as well as future EV NACS models when retrofitted with adapters. Similarly, Type 1 vehicles on the road today could access NACS infrastructure by means of adapters or carry-along cables. Different adapters are required for AC and DC charging at NACS chargers, despite the single vehicle inlet.

Compared with the CCS2 transition in Europe, the switch to NACS has the advantage that Type 1/CCS1 and J3400 share communication standards (unlike CHAdeMO), so it is possible to make use of fixed or portable adapters to accommodate the mix of connector types during the transition. However, cumulative EV sales in the United States were at roughly 4.8 million in 2023, well above the 0.2 million EVs that were sold in Europe by 2014, when CCS2 was adopted as the standard for public DC chargers, initiating the phase-out of CHAdeMO. Canada and the United States are thus facing a transition of much greater magnitude.[76] At the same time, the high share of Tesla models among cumulative U.S. EV sales, estimated at 50%, and the widespread support that the industry has so far given to NACS work in its favor.[77]

Software interoperability

Benefits of software interoperability

Software interoperability refers to the ability of software components within the public charging ecosystem—including vehicles, charging stations, and charging networks—to communicate with each other across vendors and jurisdictions. Interoperability is crucial for enabling contract-based authentication, payment processing, and related services. In addition, software interoperability is key to enabling the implementation of emerging technologies and processes such as Plug & Charge, discussed above, and smart charging, which optimizes the charging process to balance energy demand, enhance grid stability, and minimize costs.

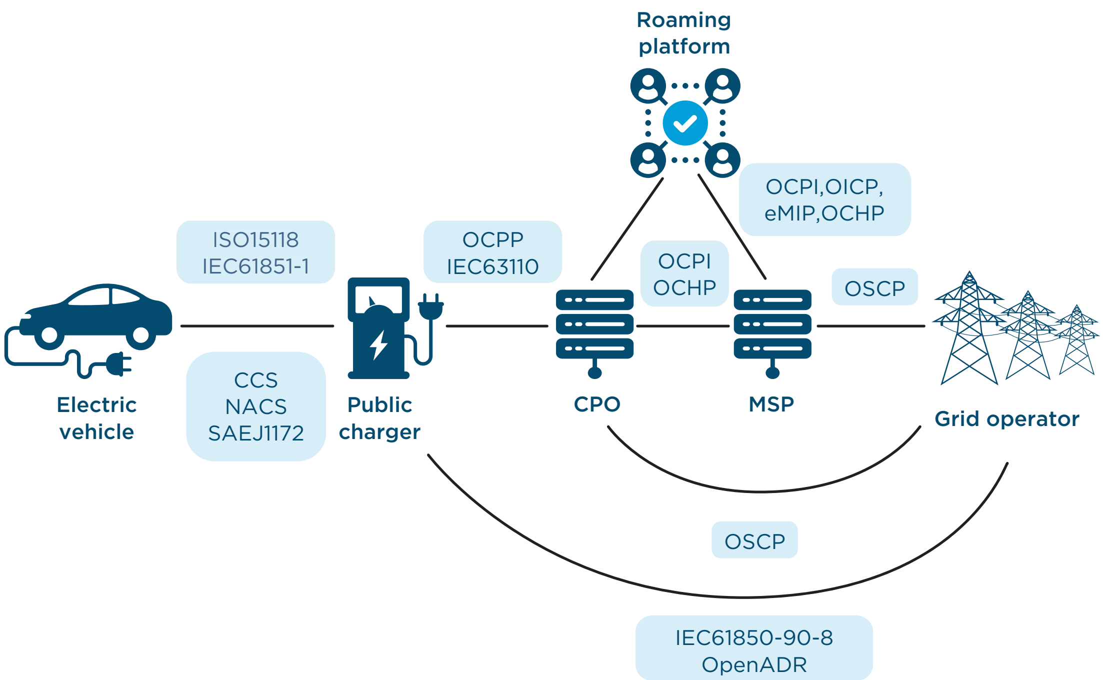
Software interoperability allows CPOs and MSPs to enter into e-roaming agreements, which give drivers access to charging stations operated by various providers using a single authentication method and consistent payment options, regardless of the user's subscription status. E-roaming thus eliminates the need for users to carry multiple charging cards or use various mobile applications. These agreements may be developed directly between companies or indirectly using roaming platforms such as Gireve, Hubject, or e-clearing.net as intermediaries.

Software interoperability also enables real-time data sharing across services. Consumers may thus access charging process details and real-time information about charging stations, including location, availability, pricing, and payment options, via a single platform for different networks. For companies, some of the benefits of software interoperability include seamless and flexible integration with the grid and different charging networks, higher utilization rates, and collaboration on common technology challenges such as implementation of safety standards.

The role of communication protocols

Communication protocols are the basis for software interoperability. These are agreed-upon sets of rules and conventions that govern the exchange of information between different software systems, ensuring the data transmission's reliability, security, and performance. Currently, there are roughly 20 protocols and standards at various stages of development involved in the European, Canadian, and U.S. public charging ecosystems (see Figure 8).

Figure 8. Overview of select communication protocols within the public charging infrastructure ecosystem



Source: Adapted from Paul Klapwijk and Lonneke Driessen, EV Related Protocol Study (ElaadNL, May 31, 2017), https://www.researchgate.net/publication/317265159_EV_Related_Protocol_Study.

From a technical standpoint, achieving broad software interoperability essentially requires the following three elements: (1) the development of open-source standardized communication protocols and their consistent implementation across the charging ecosystem; (2) the creation of certification programs to verify that a product's protocol implementation is consistent with the protocol specification; and (3) collaborative testing to ensure that systems using the same protocol can work together.[78]

The development and widespread implementation of open-source standardized communication protocols is challenging, as it involves stakeholders reaching some degree of consensus on common communication protocols while balancing standardization and innovation. In this context, sustained industry-wide collaboration and coordination are crucial, while regulators may intervene to steer harmonization and convergence of standards.[79] Examples of such policy interventions include mandates for conformance (or certification) with specific protocols, funding for testing and certification facilities, and funding for knowledge transfer venues.

Software interoperability policies in Europe, the United States, and Canada

In Europe, the United States, and Canada, several public and private initiatives are working on promoting software interoperability (e.g., evRoaming4EU, CharIn, and EV-Smart Grid Interoperability Centers), but the EV industry has not yet adopted a comprehensive approach. In some areas of the public charging ecosystem, several incompatible protocols coexist, such as those used for communication across charging networks. De facto standards have emerged in other areas, such as the Open Charge Point Protocol (OCPP), an open communication protocol used by CPOs to manage charging points. In practice, however, protocol implementation often deviates from the protocol specifications, leading to interoperability issues. In addition, companies often do not certify implementation and there is a lack of testing harmonization.[80]

These software interoperability limitations negatively impact user experience and, accordingly, EV adoption. Recent studies show that EV drivers do not have easy access to complete information on charger location, charger availability, or pricing.[81] Also, limitations regarding e-roaming mean that users need to subscribe to multiple MSPs or rely on ad hoc charging, whose prices are often unknown beforehand, to access a larger network.[82]

Legislators have recognized a need for increased regulatory support to harmonize communication protocols to improve user experience, create certainty in the market, and pave the way for electric grid integration. Table 8 provides a non-exhaustive summary of regulatory actions taken recently in Europe and the United States. (In Canada, interoperability requirements for publicly funded chargers are so far limited to connector types.) These interventions, when mandating a specific protocol, have focused on those areas where a significant portion of the industry has coalesced around a certain protocol, as in the case of connector type requirements. Ensuring access to public chargers without subscription and tackling barriers related to payment options have been other top priorities.

Table 8. Examples of software interoperability regulations in key areas of the public charging ecosystem in Europe and the United States

Area of interoperability	Europe	United States
EV-to-charger	AFIR requires public charging built after April 2024 or renovated after October 2024 to support smart charging and communication standards to support smart and bidirectional charging. All public chargers should be "digitally-connected" after October 2024.[a] While there is no specific standard requirement in AFIR, there is wide support for an ISO 15118 mandate among members of the Sustainable Transport Forum (STF), a group of experts established by the European Commission.[b]	NEVI requires DC chargers to conform to ISO 15118-3 and have hardware capable of implementing ISO 15118-2 and ISO 15118-20. By March 2024, chargers must conform to ISO 15118-2 and be capable of supporting P&C. Conformance testing for charger software and hardware should follow ISO 15118-4 and ISO 15118-5, respectively. In California, CALeVIP requires conformance to ISO 15118-3.[c]
Charger-to-charger network (CPO)	No standard requirement in AFIR, but STF encourages the use of OCPP as a de-facto standard until an international standard becomes available.[d]	NEVI requires DC chargers to conform to OCPP 1.6 or higher and, from March 2024 onward, OCPP 2.0.1. In California, CALeVIP requires OCPP certification, while certification to OCPP 2.0.1 will be required by January 2025.[e]
Charging network (CPO)-to-MSP or e-roaming platform	No standard requirement in AFIR but STF encourages the use of free open-source non-proprietary protocols.[f]	NEVI requires charging networks to be capable of communicating with other charging networks in accordance with OCPI 2.2.1 from March 2024 onward. CPOs are not required to develop roaming agreements. In California, requirements similar to those of NEVI apply to all Level 2 and DC chargers installed.[g]
Payment methods	AFIR requires ad-hoc payment at all public chargers and, from April 2024, at least one widely used electronic payment instrument should be available. For > 50 kW chargers, contactless payment car readers are required.	NEVI requires a contactless payment method that accepts major credit and debit cards. Payment via toll-free phone or SMS is required as a back-up option. Funded chargers must not require a subscription or membership. In California, requirements similar to those of NEVI apply to all public chargers installed.

[a] As defined in AFIR, digitally-connected chargers "can send and receive information in real time, communicate bi-directionally with the electricity grid and the electric vehicle, and that can be remotely monitored and controlled, including in order to start and stop the recharging session and to measure electricity flows."

[b] ISO 15118 is a set of standards that specifies the digital communication protocol between the software controlling the vehicle and the charger. ISO 15118-2 enables smart charging and P&C, while the extension ISO 15118-20 adds bidirectional power transfer, required for vehicle-to-grid applications, and easier handling of multiple MSP contract certificates, among others. CCS and J3400 connector standards support ISO 15118. See Severin Sylla, Adrian Ostermann, and Jeremias Hawran, "Standardization Landscape for Electromobility," FfE, January 12, 2023, https://www.ffe.de/en/publications/normenlandschaft_fuer_die_elektromobilitaet/.

[c] CALeVIP, "CALeVIP Eligible Equipment."

[d] An international standard has been developed by IEC for charger-to-CPO communication (IEC 63110). However, given the widespread adoption of OCPP, a partnership has been established between IEC and Open Charge Alliance (which maintains OCPP) to have OCPP published as an IEC standard.

[e] "OCPP Certification Process," CALeVIP, accessed July 15, 2024, https://calevip.org/ocpp-certification-process.

[f] Directorate-General for Mobility and Transport (European Commission), "Mapping of the Discussion."

[g] "Electric Vehicle Supply Equipment Standards Regulation Background and FAQs," California Air Resources Board, accessed July 15, 2024, https://ww2.arb.ca.gov/resources/documents/electric-vehicle-supply-equipment-standards-regulation-background-and-faqs.

In the European Union, AFIR does not include detailed technical requirements for software interoperability but rather foresees the adoption of delegated acts to develop the requirements. The preparation of these pieces of secondary legislation strongly relies on the support of expert groups such as the STF.[83] Conversely, in the United States, charging infrastructure funded by the NEVI program is required to implement certain standards where it was deemed that the market is mature enough for a single protocol. For example, choosing a single standard for CPO-to-utility communication in the United States has, to date, been regarded as premature.

In Europe, the Netherlands stands out as an interoperability pioneer. Knowledge-sharing institutions with public and private partners like ElaadNL (established in 2009) and the National Charging Infrastructure Knowledge Platform (established in 2014) work to support the development of open protocols. These institutions also conduct interoperability tests and carry out research on smart charging.[84] The country released Smart Charging Requirements in 2021 to compel the deployment of chargers with smart charging capability.[85]

Conclusion

Regarding charger connector standards, European AC infrastructure is highly aligned with AFIR requirements and well on track to full hardware interoperability. For DC infrastructure, over 80% of chargers already support CCS2 and the share is expected to increase further with CHAdeMO chargers being slowly phased out. CHAdeMO drivers cannot rely on certified adapters to access the growing CCS2 infrastructure, but about 28% of DC chargers still support CHAdeMO due to years of dual-connector deployments.

While there are differences in how hardware and software interoperability are regulated in the European Union and North America, there has been clear alignment in both regions:

Hardware interoperability: In the United States and Canada, the DC charging network is more fragmented than in Europe, but drivers stand to benefit from fully interoperable hardware if J3400 (NACS) is implemented as the single connector standard for AC and DC charging across the EV industry after a phase-in period. In addition, non-Tesla drivers are anticipated to gain access to Tesla's fast chargers, which currently account for roughly 40% and 50% of DC chargers installed in Canada and the United States, respectively. During this transition, it is essential to ensure backward compatibility for existing models incompatible with NACS. The preferred adapter and retrofit options to tackle CCS1 and NACS interoperability issues have not yet been clarified by industry and regulators, but the alignment of NACS and CCS1 communication protocols is expected to allow for a smoother transition than in the case of CHAdeMO.

Software interoperability: In Europe, Canada, and the United States, software interoperability varies across communication interfaces within the public charging ecosystem and, even in those areas where certain protocols have achieved widespread adoption, protocol implementation often differs from the protocol specifications, leading to interoperability barriers. There are ongoing efforts to advance harmonization of communication standards, including increasing policy support, but a unified approach and agreement across stakeholders on common protocols is still lacking. At the same time, recent EU and U.S. regulations have tackled constraints regarding payment options, such as eliminating membership requirements to use chargers, which is pivotal to improving the driver experience.

Conclusions

This report identified options for enhancing user experience in public EV charging networks through a data-driven policy approach, focusing on three key factors: availability, reliability, and interoperability. The following conclusions flow from the analysis:

There are significant geographic disparities in public charging infrastructure deployment in Europe, Canada, and the United States. These disparities are sometimes, but not always, correlated with income, unemployment rate, and share of people of color in the overall population. Northern and Western Europe have up to 6 times more public installed power output per million population than Southern and Eastern Europe. The analysis showed that European Union Member States with high average household income not only have higher access to public chargers, but also that the correlation between public charger deployment and household income is stronger than the correlation between income and EV adoption. This means that at the EU Member State level, income tends to have a slightly greater impact on public charger deployment than on EV adoption. In Canada and the United States, the disparities are less strong. While Canadian provinces with higher unemployment tend to have fewer public chargers deployed and lower EV registration shares, this is not the case for the United States. Meanwhile, in a few U.S. states like Massachusetts, areas with a higher share of people of color in the population have slightly less charging infrastructure deployed.

Governments have adopted various policies to target disparities in public charging deployment. For example, California Senate Bill 1000 required that the California Energy Commission conduct an analysis of inequities in public charging deployment. The results of this analysis were used to direct Clean Transportation Program investments in public charging. Other jurisdictions have adopted legislation and funding programs to foster widespread deployment and target undersupplied areas, as was done with the LADIN program in Austria, or by funding or mandating the installation of DC chargers along highways, as was done with the NEVI program in the United States or AFIR in Europe. Policymakers can also consider public charging deployment in areas without widespread residential charging to encourage EV adoption by those without access to private charging.

Governments are implementing uptime and successful charge rate requirements to improve public charging network reliability. Studies reveal substantial variations in charger availability and functionality, with issues ranging from unresponsive screens to payment failures. As public charging unreliability remains a significant barrier to widespread EV adoption, and as reliance on these chargers grows, the need for dependable infrastructure becomes more pressing. To address this barrier, governments are implementing a range of policies such as uptime requirements, successful charge attempt rates, reporting obligations, data transparency measures, and incentives like tax breaks or rebates for meeting uptime requirements. The United States has set a minimum uptime requirement (of 97%) for chargers funded under the NEVI Program, and California has adopted similar regulations in addition to requiring a 90% successful charge attempt rate. In comparison, the United Kingdom has introduced comprehensive regulations mandating a 99% uptime for rapid chargers (with penalties for non-compliance), annual reliability reporting for all charging operators, and contactless payment and price transparency measures to enhance the consumer experience.

Fostering broad interoperability through connector standards can ensure drivers have access to the charging network, regardless of the vehicle model. A 2014 EU directive requiring all AC and DC charging points deployed or renewed from November 2017 to be at least equipped with connectors of Type 2 and CCS2 has proven successful in driving the harmonization of public chargers. While there is no such harmonization in the United States and Canada as of 2024, mandating that new EVs be equipped with NACS inlets instead of CCS1 from model year 2026 through California's Advanced Clean Car II regulations, and establishing NACS as the sole minimum requirement for NEVI-funded chargers after a phase-in period, could support the transition by creating certainty for both the industry and consumers. During the interim period when CCS1 vehicles are still being sold, CCS1 connectors would still be required, but this requirement could be met with attached adapters to minimize costs. In addition, all automakers in the United States and Canada have committed to equipping their EV models with NACS inlets as early as model year 2025.

Realizing broad software interoperability in the public charging ecosystem via open communication protocols requires close collaboration among stakeholders. In the United States, chargers funded by programs in California and by the federal NEVI program are required to use specific communication protocols, while in the European Union, similar requirements could be adopted in the near future by means of delegated acts under AFIR. In this context, industry coordination via expert groups such as the EU's Sustainable Transport Forum plays a key role in advancing harmonization. In parallel, governments could consider aligning their software interoperability requirements as much as possible, as divergent requirements will increase the cost and complexity associated with compliance.

Appendix

This appendix contains additional information related to the charger availability and interoperability sections of this paper.

Figures A1 and A2 show public charging deployment as a function of average household income for each EU Member State and as a function of unemployment share for each Canadian province.

Figure A1. Public installed power output (MW) per million population as a function of average household income for each of the 27 EU Member States

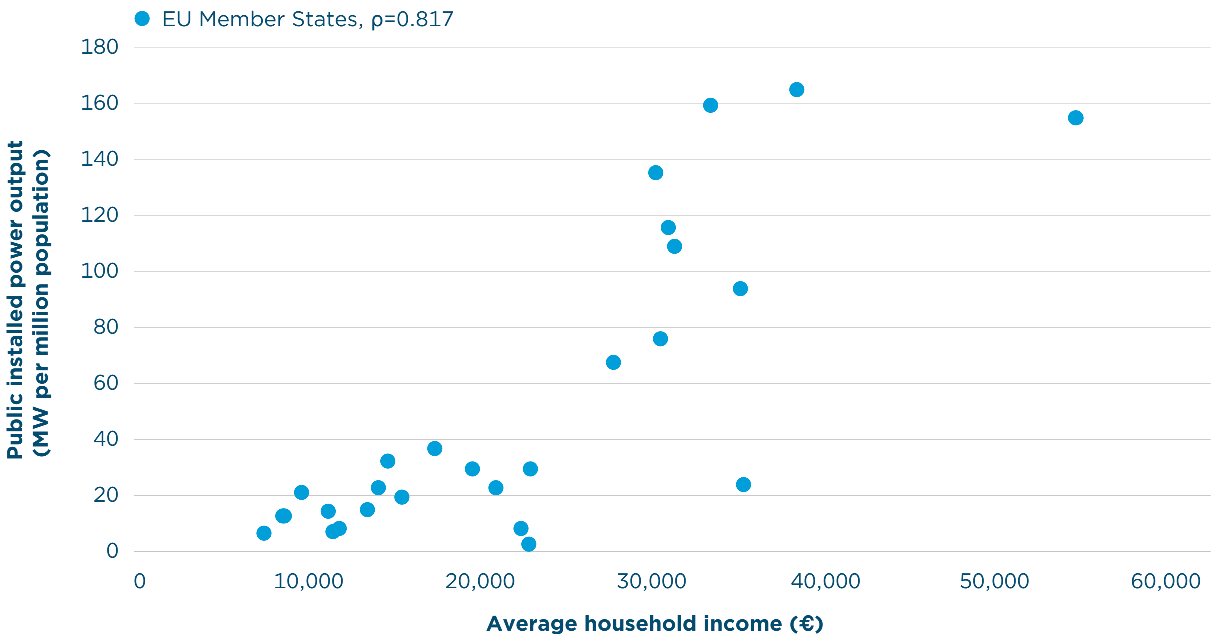


Figure A2. Public installed power output (MW) per million population in Canada as a function of unemployment rate; one circle represents one province

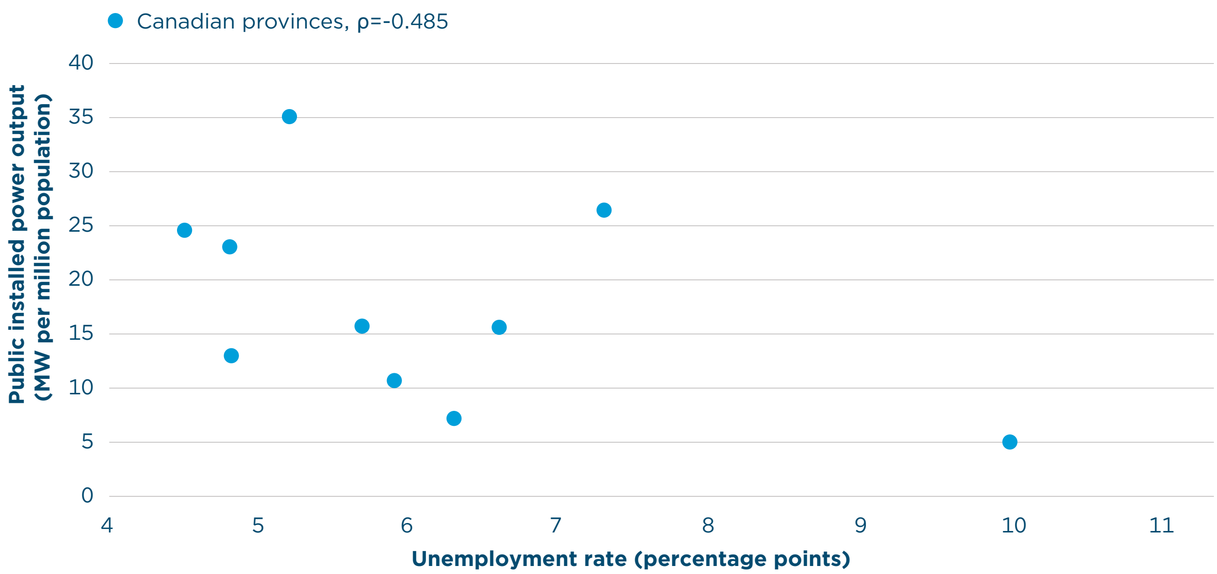


Table A1 provides a list of resources, including guidelines and legislation, regarding charging infrastructure deployment for people with disabilities.

Table A1. Guidelines and legislation regarding charging infrastructure deployment for people with disabilities

Document type	Market	Author	Details
Guidelines	Germany[a]	NOW	This guideline on barrier-free charging can support institutions to set up regulations and tendering processes and aid manufacturers and CPOs. This document has also been transferred to the German Institute for Standardization.
Legislation	United Kingdom[b]	UK government	Publicly Accessible Specification (PAS) 1899 covers accessible electric vehicle charge points for those with diverse accessibility needs.
Guidelines	Sweden[c]	Swedish government	These guidelines provide practical advice on designing inclusive charging stations.
Guidelines	Ireland[d]	Irish government	These draft Universal Design Guidelines for Electric Vehicle Infrastructure aim to ensure that electric vehicle charging stations are accessible to everyone. They cover various aspects, such as the design of the charging station, accessibility of the site, and the provision of information to users before, during, and after charging sessions.
Legislation	California, United States[e]	California Building Standards Commission	In California, public facilities must install handicap-accessible EV charging stations when installing new or additional stations. This document specifies minimum accessible EV charging station installation requirements.
Guideline/ position paper	Europe[f]	AVERE	In this position paper, AVERE provides recommendations on the accessibility of charging infrastructure and suggests a standardized pan-European approach to requirements related to accessibility by persons with reduced mobility.

[a] Nationale Leitstelle Ladeinfrastruktur and Bundnisministerium für Digitales und Verkehr, "Einfach laden ohne Hindernisse" [Simple Charging Without Obstacles], 2023, https://nationale-leitstelle.de/wp-content/uploads/2023/04/Leitfaden_barrierefreie_Ladeinfrastruktur.pdf.

[b] "Electric Vehicles Accessible Charging Specification - PAS 1899," BSI, 2022, https://www.bsigroup.com/en-GB/insights-and-media/insights/brochures/pas-1899-electric-vehicles-accessible-charging-specification/.

[c] Moa Breivik and Johan Lagrelius, "Accessible Charging Stations: Practical Advice on Designing Inclusive Charging Stations," accessed July 5, 2024, http://www.escif.org/wp-content/uploads/2022/11/Manual_Sweden_E.pdf.

[d] Government of Ireland, "Electric Vehicle Charging Infrastructure Universal Design Guidelines," June 2023, https://assets.gov.ie/262289/13716b9a-a09f-4ced-87f1-41fc3e6d92c1.pdf.

[e] U.S. Department of Energy, Alternative Fuels Data Center, "Mandatory Electric Vehicle (EV) Charging Station Building Standards."

[f] AVERE, Charging for All - A Vision for an Accessible European Charging Infrastructure, February 2024, https://www.avere.org/blogpages/policy-details/2024/02/27/Position-Paper-Charging-for-All-A-Vision-for-an-Accessible-European-Charging-Infrastructure.

Figures A3–A6 provide information on connector types in Europe, Canada, and the United States.

Figure A3. Shares of total public AC charging installed in Europe and select countries by available connector type and date

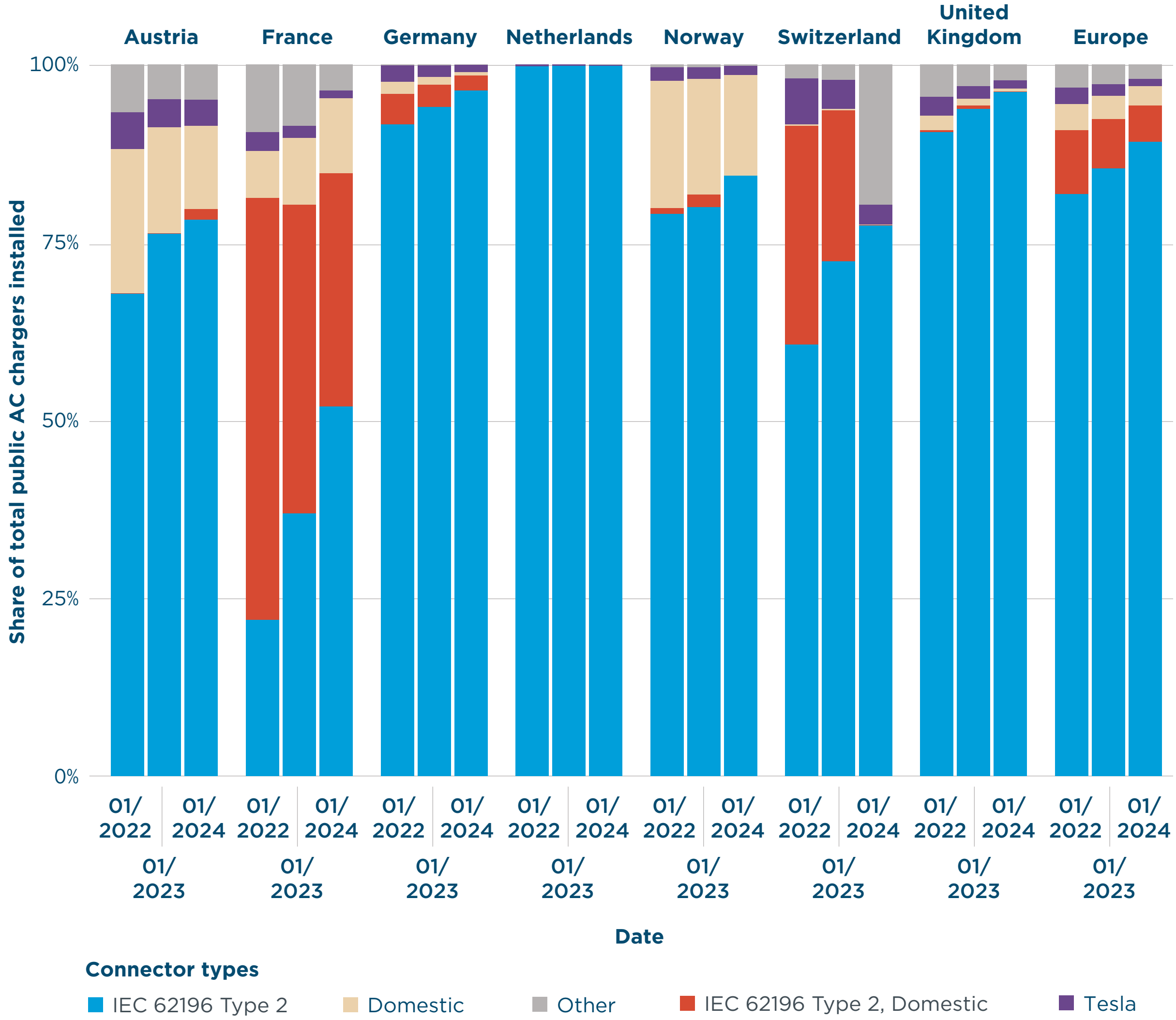


Figure A4. Shares of total public DC charging installed in Europe and select countries by available connector type and date

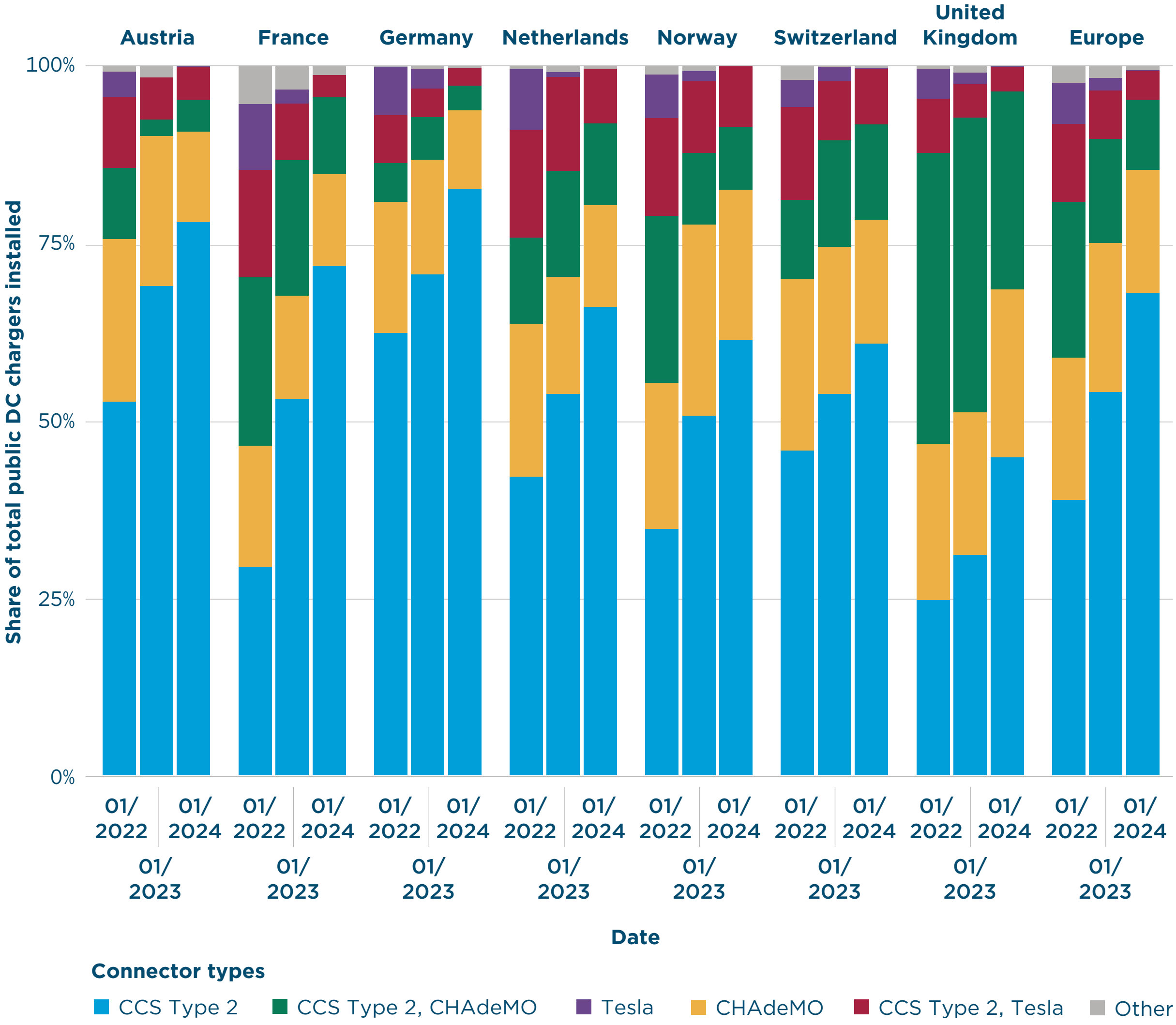


Figure A5. Shares of total public AC charging installed in Canada, the United States, and select states and provinces by available connector type

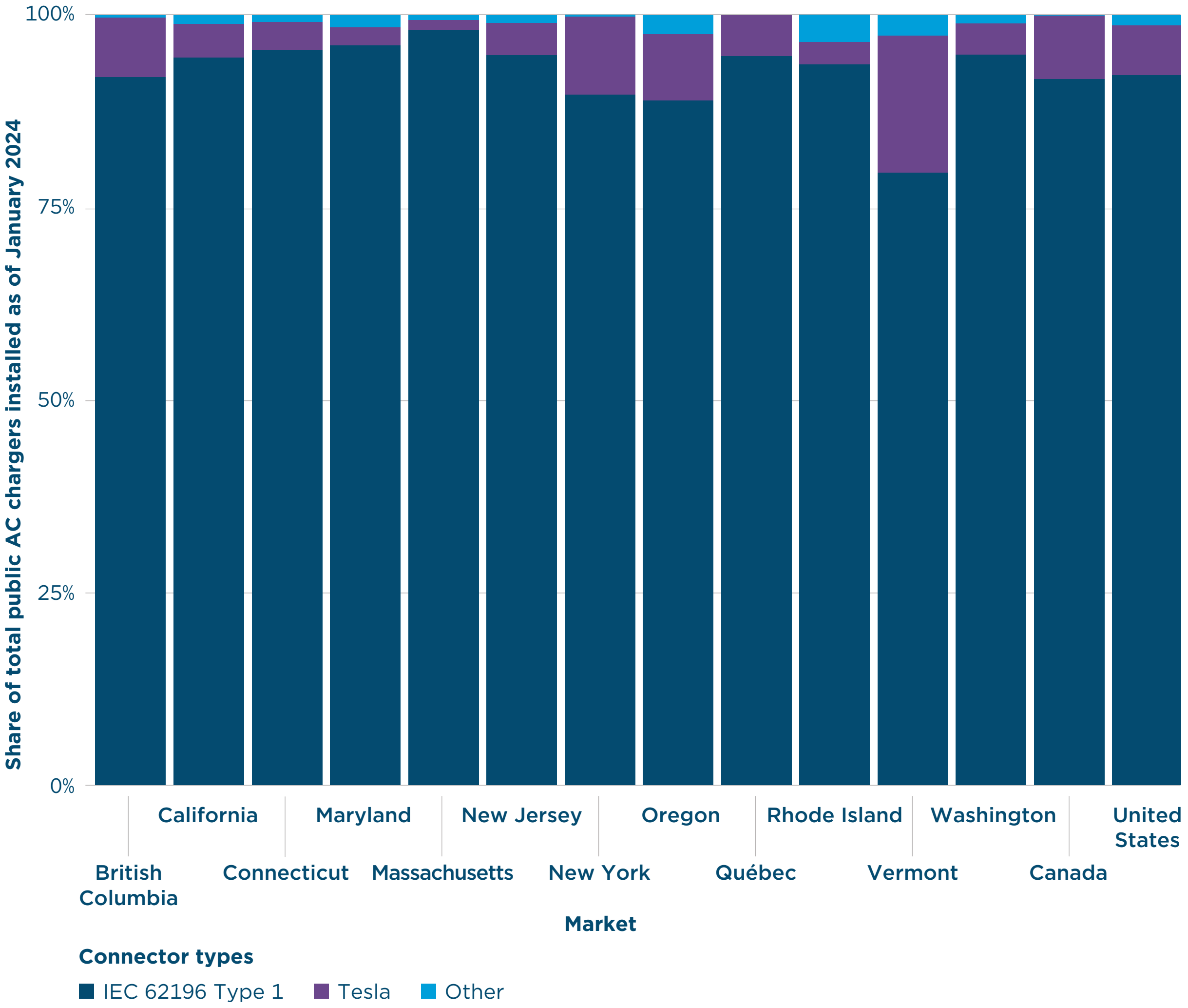
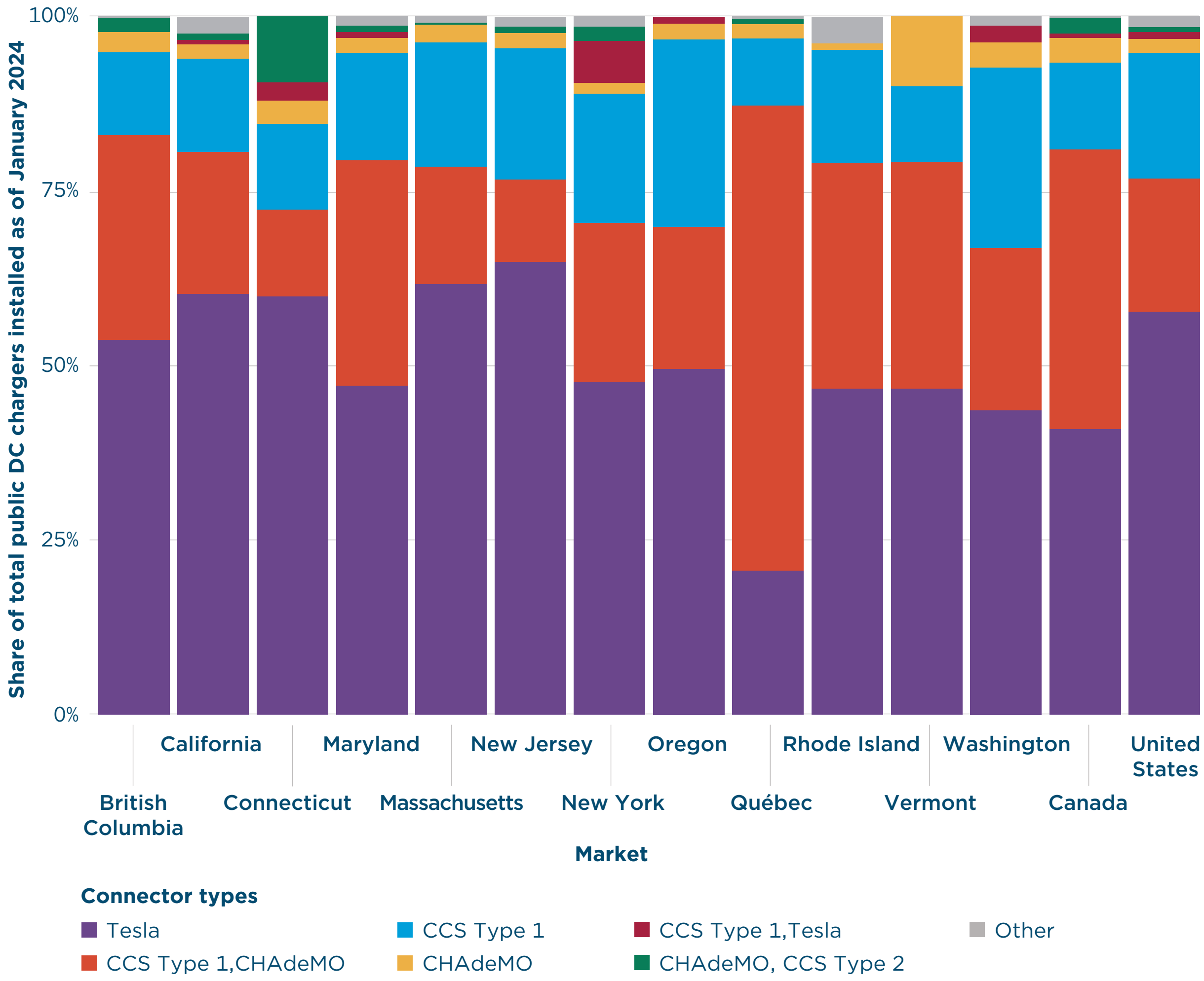


Figure A6. Shares of public DC charging installed in Canada, the United States, and select states and provinces by available connector type



Endnotes

1 Publicly accessible chargers include those available to everyone at all hours as well as semi-public chargers, which have some conditions for use (e.g., chargers in a supermarket parking lot with access only to store customers).
2 Data sourced from Eco-Movement, https://www.eco-movement.com. Historical data are only available for Europe.
3 Nevertheless, while DC chargers can accommodate more charging sessions per day, it does not always make sense to prioritize deployment of public DC chargers. A balance between AC and DC chargers may be optimal based on parking patterns (e.g., short- vs. long-term parking), financial considerations, land availability, and other factors.
4 "Population and Population Change Statistics," Eurostat, July 6, 2024, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Population_and_population_change_statistics#Population_change_at_national_level; "Population," U.S. Census Bureau, accessed July 2024, https://www.census.gov/topics/population.html; "Population Estimates, Quarterly," Statistics Canada, September 25, 2024, https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1710000901.
5 "Canada — Household Income - Average and Median ($)," Canada Mortgage and Housing Corporation, accessed August 13, 2024, https://www03.cmhc-schl.gc.ca/hmip-pimh/en/TableMapChart/TableMatchingCriteria?GeographyType=Country&GeographyId=1&CategoryLevel1=Population%2C%20Households%20and%20Housing%20Stock&CategoryLevel2=Household%20Income&ColumnField=HouseholdIncomeRange&RowField=Province&SearchTags%5B0%5D.Key=Households&SearchTags%5B0%5D.Value=Number&SearchTags%5B1%5D.Key=Statistics&SearchTags%5B1%5D.Value=AverageAndMedian; "Income Inequality Across the EU," Eurostat,November 3, 2023, https://ec.europa.eu/eurostat/web/products-eurostat-news/w/DDN-20231103-1; "Income," U.S. Census Bureau, accessed August 13, 2024, https://www.census.gov/topics/income-poverty/income.html.
6 "Labour Force Characteristics by Sex and Detailed Age Group, Annual," Statistics Canada, April 17, 2019, https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1410032701; "Employment," U.S. Census Bureau, accessed August 13, 2024, https://www.census.gov/topics/employment.html.
7 "Race," U.S. Census Bureau, accessed August 13, 2024, https://www.census.gov/topics/population/race.html.
8 Sandra Wappelhorst et al., *ICCT-Monitor 2023: Ist Der Übergang von Verbrenner- Zu Elektro-Pkw Sozial Gerecht?* (International Council on Clean Transportation, December 13, 2023), https://theicct.org/publication/icct-monitor-2023-ist-ubergang-von-verbrenner-elektro-pkw-sozial-gerecht-dec23/; Nadia Lopez and Yee Erica, "Who Buys Electric Cars in California — and Who Doesn't?," *CalMatters*, March 22, 2023, http://calmatters.org/environment/2023/03/california-electric-cars-demographics/.
9 Nicholas Mah, "Canada Electric Vehicle (EV) Statistics: EV Industry Data," EnergyRates.ca, October 19, 2023, https://energyrates.ca/canada-electric-vehicle-ev-statistics-ev-industry-data/; Michelle Monteforte et al., E*uropean Market Monitor Quarterly European Car and Van Market and Charging Infrastructure Development: January–December 2023* (International Council on Clean Transportation, 2024), https://theicct.org/publication/eu-car-and-van-market-development-quarterly-december23-mar24/; Anh Bui and Peter Slowik, *Electric Vehicle Market and Policy Developments in U.S. States, 2023* (International Council on Clean Transportation, 2024), https://theicct.org/publication/ev-ldv-us-major-markets-monitor-2023-june24/.
10 The nomenclature of territorial units for statistics (NUTS, from the French *nomenclature des unités territoriales statistiques*) is a geographical nomenclature subdividing the economic territory of the European Union into three regions at three different levels: Nuts 1, 2, and 3, moving from larger to smaller territorial units.
11 "Pearson Correlation," ScienceDirect, accessed August 13, 2024, https://www.sciencedirect.com/topics/computer-science/pearson-correlation#:~:text=content%20were%20calculated.-,The%20Pearson%20correlation%20measures%20the%20strength%20of%20the%20linear%20relationship,meaning%20a%20total%20positive%20correlation.
12 Peter Slowik, *Expanding Zero-Emission Mobility Equity and Access* [Workshop report] (ZEV Alliance, 2019), https://www.zevalliance.org/wp-content/uploads/2019/12/ZEV_access_workshop_report-_fv.pdf.
13 Peter Slowik, *Expanding Zero-Emission Mobility Equity and Access*.
14 Eurostat, "Income Inequality Across the EU."
15 Monteforte et al., *European Market Monitor*.
16 "Einkommen (Kreise)" [Income (Districts)], Statistische Ämter des Bundes und der Länder, accessed July 12, 2024, https://www.statistikportal.de/de/vgrdl/ergebnisse-kreisebene/einkommen-kreise.
17 "Electric Vehicle Infrastructure Deployment Assessment – SB 1000," California Energy Commission, 2022, https://www.energy.ca.gov/programs-and-topics/programs/clean-transportation-program/electric-vehicle-infrastructure.
18 AustriaTech, "Förderprogramm LADIN" [LADIN Funding Program], January 24, 2024, https://www.austriatech.at//de/foerderprogramm-ladin/.
19 FFG, "LADIN – Ladeinfrastruktur" [LADIN – Charging Infrastructure], accessed July 5, 2024, https://www.ffg.at/LADIN.
20 NOS, "Grote verschillen in beschikbaarheid elektrische laadpalen" [Large Differences in Availability of Charging Stations], April 27, 2023, https://nos.nl/artikel/2472991-grote-verschillen-in-beschikbaarheid-elektrische-laadpalen.
21 Marie Rajon Bernard, *European Union Alternative Fuel Infrastructure Regulation (AFIR)* (International Council on Clean Transportation, April 26, 2023), https://theicct.org/publication/afir-eu-april2023/; Alternative Fuels Data Center, "National Electric Vehicle Infrastructure (NEVI) Formula Program," accessed August 13, 2024, https://afdc.energy.gov/laws/12744.
22 Marie Rajon Bernard and Dale Hall, *Efficient Planning and Implementation of Public Chargers: Lessons Learned from European Cities* (International Council on Clean Transportation, February 2, 2021), https://theicct.org/publication/efficient-planning-and-implementation-of-public-chargers-lessons-learned-from-european-cities/.
23 European Commission, *Consumer Monitor 2023 European Alternative Fuels Observatory EU Aggregated Report* (June 2024), https://alternative-fuels-observatory.ec.europa.eu/system/files/documents/2024-06/EU%20Aggregated%20Report%202023_0.pdf
24 Britainthinks and UK Department for Transport, *Electric Vehicle Charging Research: Survey with Electric Vehicle Drivers* (April 2022), https://assets.publishing.service.gov.uk/media/628f5603d3bf7f037097bd73/dft-ev-driver-survey-summary-report.pdf.
25 Liam McLoughlin, "Mind the EV Charging Gap: Women Excluded from EV Transition," Electric Vehicle Charging & Infrastructure, June 9, 2023, https://www.evcandi.com/feature/mind-ev-charging-gap-women-excluded-ev-transition.
26 Geotab, "Study Reveals Safety Concerns May Be Hindering EV Adoption by Women," press release, October 24, 2023, https://www.geotab.com/press-release/ev-adoption-study/.
27 Gemma Trigueros, "Public EV Charging: Are Women's Voices Being Included?," Flo, February 23, 2023, https://www.flo.com/insights/public-ev-charging-are-womens-voices-being-included/.

28 CIVITAS, *Gender Equality and Mobility: Mind the Gap!* (2016), https://civitas.eu/sites/default/files/civ_pol-an2_m_web.pdf.
29 CIVITAS, *Gender Equality and Mobility*.
30 McLoughlin, “Mind the EV Charging Gap.”
31 “Setting the Industry Standard for Public EV Charging,” Charge Safe, accessed October 7, 2024, https://www.chargesafe.uk.
32 UK Government, “Rollout of Electric Vehicle Chargepoints to Be Accelerated,” February 5, 2024, https://www.gov.uk/government/news/rollout-of-electric-vehicle-chargepoints-to-be-accelerated.
33 U.S. Access Board, “Design Recommendations for Accessible Electric Vehicle Charging Stations,” last modified July 17, 2023, https://www.access-board.gov/tad/ev/; NOW GmbH, “New ‘Easy Charging without Barriers’ Guideline Highlights How to Make Charging Infrastructure Barrier-Free” (blog), April 19, 2023, https://www.now-gmbh.de/en/news/pressreleases/new-easy-charging-without-bariers-guideline-highlights-how-to-make-charging-infrastructure-barrier-free/.
34 “Mandatory Electric Vehicle (EV) Charging Station Building Standards,” U.S. Department of Energy, Alternative Fuels Data Center, September 16, 2022, https://afdc.energy.gov/laws/11068.
35 J.D. Power, “2024 U.S. Electric Vehicle Experience (EVX) Ownership Study,” February 27, 2024, https://www.jdpower.com/business/press-releases/2024-us-electric-vehicle-experience-evx-ownership-study.
36 Enedis, “Utilisation et Recharge : Enquête Comportementale Auprès des Utilisateurs de Véhicules Électriques” [Utilization and Recharge: Behavior Survey on Electric Vehicle Users], September 2023, https://www.enedis.fr/sites/default/files/documents/pdf/utilisation-et-recharge-enquete-comportementale-aupres-des-utilisateurs-de-vehicules-electriques-septembre-2023.pdf?VersionId=Flhy.j8znKVUAXiTXJZG_pGAe8NNGkd5#:~:text=En%20particulier%2C%20une%20forte%20progression,%2C%20contre%2030%20%25%20de%20locataires.
37 “Plug & Charge,” CharIN, accessed July 5, 2024, https://www.charin.global/technology/plug-charge/.
38 An MSP offers EV drivers a range of services related to charging, including providing charging passes, apps for locating and navigating charging stations, and managing the roaming network, billing, and customer service.
39 Monopolkommission, “Energie 2023: Mit Wettbewerb Aus Der Energiekrise” [Energy 2023: Out of the Energy Crisis through Competititon], accessed August 13, 2024, https://www.monopolkommission.de/images/PDF/SG/9sg_energie_volltext.pdf.
40 Rempel et al., *Reliability of Open Public Electric Vehicle Direct Current Fast Chargers*.
41 Marie Rajon Bernard, *Improving Public Charging Infrastructure Reliability* (International Council on Clean Transportation, 2023), https://theicct.org/publication/public-charging-reliability-mar23/.
42 AFIREV, *Observatoire de la Qualité*.
43 Rajon Bernard, *Improving Public Charging Infrastructure Reliability*.
44 ChargerHelp. *ChargerHelp Annual Reliability Report: The State of EV Charging and the Driver Experience (2024)*, https://www.chargerhelp.com/2024-annual-reliability-report
45 The White House, “FACT SHEET: Biden-Harris Administration Announces New Standards and Major Progress for a Made-in-America National Network of Electric Vehicle Chargers,” press release, February 15, 2023, https://www.whitehouse.gov/briefing-room/statements-releases/2023/02/15/fact-sheet-biden-harris-administration-announces-new-standards-and-major-progress-for-a-made-in-america-national-network-of-electric-vehicle-chargers/
46 U.S. Department of Transportation, Electric Vehicle Charger Reliability and Accessibility Accelerator, last modified August 15, 2024, https://www.fhwa.dot.gov/environment/nevi/evc_raa/.
47 U.S. Department of Transportation and Federal Highway Administration, “Biden-Haris Administration Announces Grants to Upgrade Almost 4,500 Public Electric Vehicle Chargers,” press release, January 18, 2024, https://highways.dot.gov/newsroom/biden-harris-administration-announces-grants-upgrade-almost-4500-public-electric-vehicle.
48 California Energy Commission, *Tracking and Improving Reliability of California’s Electric Vehicle Chargers* (2023), https://www.energy.ca.gov/publications/2023/tracking-and-improving-reliability-californias-electric-vehicle-chargers#:~:text=Require%20reliability%20record%20keeping%20and,uptime%20standard%20for%20six%20years.
49 In this section, unless otherwise stated, charging infrastructure data for Europe cover public and semi-public chargers installed in the 27 EU Member States plus the United Kingdom and the four European Free Trade Association countries (Iceland, Liechtenstein, Norway, and Switzerland). Data for the United States and Canada also cover public and semi-public chargers. All data are sourced from Eco-Movement.
50 Samantha Pettigrew, *Strategies for Setting a National Electric Vehicle Charger Standard: Relevant Factors and the Case of Chile* (International Council on Clean Transportation, January 9, 2023), https://theicct.org/publication/lat-am-evs-choose-charger-std-chile-jan23/.
51 Type 1, Type 2, CCS1, and CC2 connectors are described in the International Electrotechnical Commission (IEC) series of standards IEC 62196.
52 CHAdeMO is a DC connector type introduced in Europe by Japanese manufacturers before the emergence of CCS. As opposed to CCS technology, CHAdeMO vehicle models feature separate inlets for AC and DC charging.
53 Pettigrew, *Strategies for Setting a National Electric Vehicle Charger Standard*.
54 The term “domestic connector” groups all connector types that are typically used in domestic appliances, including types A to G.
55 Pettigrew, *Strategies for Setting a National Electric Vehicle Charger Standard*.
56 Tesla, “Supercharger Support,” accessed July 12, 2024, https://www.tesla.com/en_EU/support/charging/supercharger.
57 Pettigrew, *Strategies for Setting a National Electric Vehicle Charger Standard*.
58 “The Different North American EV Charging Connector Types,” Enel X, January 3, 2024. https://www.enelxway.com/us/en/resources/blog/ev-charging-connector-types
59 European Court of Auditors, *Infrastructure for Charging Electric Vehicles: More Charging Stations but Uneven Deployment Makes Travel the EU Complicated* (2021), https://www.eca.europa.eu/lists/ecadocuments/sr21_05/sr_electrical_charging_infrastructure_en.pdf.
60 European Automobile Manufacturers’ Association, *ACEA Position and Recommendations for the Standardization of the Charging of Electrically Chargeable Vehicles* (March 2, 2011), https://www.acea.auto/files/charging_20110511.pdf.
61 Modern connector types incorporate communication protocols to allow the exchange of information between vehicle and charger; Tomoko Blech and Natalia Kozdra, “Fast Chargers for All: Multistandard Charger Deployment and Usage in Europe” (paper presentation, EVS29 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, Montréal, Québec, Canada, June 19–22, 2016), https://www.chademo.com/wp2016/wp-content/uploads/2016/07/EVS_CHAdeMO_Multi-standard_charger_usage.pdf; “Recharging Systems,” European Alternative Fuels Observatory, accessed July 12, 2024, https://alternative-fuels-observatory.ec.europa.eu/general-information/recharging-systems.

62 Décret N° 2021-546 Du 4 Mai 2021 Portant Modification Du Décret N° 2017-26 Du 12 Janvier 2017 Relatif Aux Infrastructures de Recharge Pour Véhicules Électriques et Portant Diverses Mesures de Transposition de La Directive 2014/94/UE Du Parlement Européen et Du Conseil Du 22 Octobre 2014 Sur Le Déploiement d'une Infrastructure Pour Carburants Alternatifs - Légifrance, Pub. L. No. 2021–546 (2021), https://www.legifrance.gouv.fr/loda/id/LEGIARTI000043475843/2021-05-06/.
63 Scooter Doll, "2022 Nissan LEAF Gets Cosmetic Updates But Is Still Clinging to Yesteryear's CHAdeMO Fast Charging," Electrek, February 23, 2022, https://electrek.co/2022/02/23/2022-nissan-leaf-gets-cosmetic-updates-but-is-still-clinging-to-yesteryears-chademo-fast-charging/.
64 Christopher Hecht, Jan Figgener, and Dirk Uwe Sauer, "Analysis of Electric Vehicle Charging Station Usage and Profitability in Germany Based on Empirical Data," *iScience* 25, no. 12 (December 22, 2022), https://doi.org/10.1016/j.isci.2022.105634.
65 The Society of Motor Manufacturers and Traders Limited, "Report on the Current Situation and Future Direction of Electric Vehicle Charger Standardisation," July 2010, https://www.smmt.co.uk/wp-content/uploads/SMMT-report-on-the-direction-of-EV-Charger-Standardisation-July-2010.pdf.
66 National Electric Vehicle Infrastructure Standards and Requirements, 88 FR 12724 (2023), https://www.federalregister.gov/documents/2023/02/28/2023-03500/national-electric-vehicle-infrastructure-standards-and-requirements.
67 Anh Bui, Dale Hall, and Stephanie Searle, *Advanced Clean Cars II: The next Phase of California's Zero-Emission Vehicle and Low-Emission Vehicle Regulations* (International Council on Clean Transportation, 2022), https://theicct.org/wp-content/uploads/2022/11/accii-zev-lez-reg-update-nov22.pdf.
68 "CALeVIP Eligible Equipment," CALeVIP, accessed July 13, 2024, https://calevip.org/calevip-eligible-equipment.
69 Natural Resources Canada, "Zero Emission Vehicle Infrastructure Program Funding for Owners and Operators of Charging and Refuelling Infrastructure" (March 24, 2023), https://natural-resources.canada.ca/energy-efficiency/transportation-alternative-fuels/zero-emission-vehicle-infrastructure-program/zero-emission-vehicle-infrastructure-program/25027.
70 Mark Kane, "CCS1 To Tesla NACS Charging Connector Transition: Everything We Know," InsideEVs, December 20, 2023, https://insideevs.com/reviews/672485/ccs1-tesla-nacs-charging-connector-transition-info/.
71 Jameson Dow, "Rivian Starts Shipping NACS Adapters for Tesla's Supercharger Network," Electrek, April 26, 2024, https://electrek.co/2024/04/26/rivian-starts-shipping-nacs-adapters-for-teslas-supercharger-network/.
72 Francesca Wahl, "Request for Information on the J3400 Connector and Potential Options for PerformanceBased Charging Standards," April 5, 2024, https://www.regulations.gov/comment/FHWA-2023-0054-0122.
73 "Request for Information on the J3400 Connector and Potential Options for Performance-Based Charging Standards," 89 FR 16081, March 6, 2024, https://www.federalregister.gov/documents/2024/03/06/2024-04750/request-for-information-on-the-j3400-connector-and-potential-options-for-performance-based-charging; Jeffrey Lu, "Statement on the North American Charging Standard - J3400," California Energy Commission, September 27, 2023.
74 "Tesla NACS Charger Adoption Tracker," EVStation, January 16, 2024, https://evstation.com/tesla-nacs-charger-adoption-tracker/.
75 "SAE J3400 Charging Connector," Joint Office of Energy and Transportation, accessed July 15, 2024, https://driveelectric.gov/charging-connector.
76 "Trends in Electric Cars," International Energy Agency, accessed July 15, 2024, https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-cars.
77 "Tesla Inc Sales Figures – US Market," Good Car Bad Car, accessed July 15, 2024, https://www.goodcarbadcar.net/tesla-inc-us-sales-figures/.
78 Jeffrey Lu, "Statement on Charging Interoperability (ADA)," California Energy Commission, November 14, 2023.
79 Mart van der Kam and Rudi Bekkers, "Mobility in the Smart Grid: Roaming Protocols for EV Charging," *IEEE Transactions on Smart Grid* 14, no. 1 (January 2023): 810–22, https://doi.org/10.1109/TSG.2022.3202608.
80 Lu, "Statement on Charging Interoperability (ADA)"; Directorate-General for Mobility and Transport (European Commission), "Mapping of the Discussion Concerning Standards and Protocols for Communication Exchange in the Electromobility Ecosystem," *EU Publications*, October 25, 2022, https://doi.org/10.2832/6763.
81 EVRoaming Foundation, "Issues and Solutions for Better Exchange and Understanding of EV Charging Tariffs," February 2024, https://evroaming.org/app/uploads/2024/03/EVRoaming-White-Paper-Tariffs-in-EV-charging-world-v1_21.pdf.
82 Carlo Mol et al., "Interoperability of E-Mobility Services - User Centric Charging Infrastructure," (HEV-TCP, June 2022), https://ieahev.org/wp-content/uploads/2022/07/IEA-TCP-HEV-Task39-Final-Report-ExCo55.pdf.
83 "Sub-Group on Governance and Standards for Communication Exchange in the Electromobility Ecosystem (RegEx E03321/6)," Directorate-General for Mobility and Transport (European Commission), accessed July 15, 2024, https://transport.ec.europa.eu/transport-themes/clean-transport/sustainable-transport-forum-stf/active-sub-groups/sub-group-governance-and-standards-communication-exchange-electromobility-ecosystem-regex-e033216_en.
84 "Interoperability," ElaadNL, accessed July 15, 2024, https://elaad.nl/en/topics/interoperability/.
85 Nationale Agenda Laadinfrastructuur Working Group Smart Charging, "Smart Charging Requirements (SCR)" (February 5, 2021), https://elaad.nl/wp-content/uploads/downloads/smart-charging-requirements-uk-1.pdf.

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