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Electric vehicle charging network in Europe: An accessibility and deployment trends analysis

Giacomo Falchetta [a,b], Michel Noussan [a,*]

[a] Fondazione Eni Enrico Mattei, Milan, Italy
[b] Free University of Bozen-Bolzano, Bolzano, Italy

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ABSTRACT

If coupled with a low-carbon electricity mix, electric vehicles (EVs) can represent an important technology for transport decarbonization and local pollutants abatement. Yet, to ensure large-scale EVs adoption, an adequate charging stations network must be developed. This paper provides the first comprehensive bottom-up analysis of the EV charging network in Europe. Combining a crowd-sourced database of charging stations with accessibility data and algorithms, we produce maps of the travel time to the most accessible EV charging station across Europe, we evaluate the charging points density and the number of active operators in different areas. We find that although recent years have witnessed a notable expansion of the EV charging network, stark inequalities persist across and within countries, both in terms of accessibility and of the charging points available to users. Our results allow for a better understanding of some of the key challenges ahead for ensuring mass EVs adoption throughout Europe and thus potentially reducing the environmental impact of the transport sector.

1. Introduction

The decarbonization strategies developed by the European Union and by different European countries are fostering the development of different technologies, including electric vehicles (EVs) (Wappelhorst et al., 2020; Usmani and Rösler, 2015). When coupled to low-carbon electricity generation, they represent a potential solution to decrease the current heavy dependence of transport from oil and gas products. Together with China and the United States, Europe represents one of the world's largest markets for EVs, with year-on-year significant growths of sales. However, in most countries EVs remain a marginal share of the total car market, due to a number of barriers, including higher investment cost, range anxiety and limited charging infrastructure in place. As of 2018, battery electric vehicles (BEVs) represented only 0.2% of the passenger cars stock in the EU (ACEA, 2020c), although in Norway this share reached 7.2%. Yet, BEV sales are continuously increasing, and they reached 4.1% of total passenger car sales in the EU in the first three quarters of 2020 (ACEA, 2020b).

In last years these barriers are in fact showing continuous improvements. Investment costs are decreasing thanks to a more intense competition between manufacturers, the increase of EV models available in the market, as well as national incentives in several countries (Santarromana et al., 2020) (including China (Ma et al., 2019), the US (Wee et al., 2018), Australia (Gong et al., 2020) and many European countries (Santos and Davies, 2020)). Range anxiety is decreasing, as the improvement of battery size and performance (Feng and Magee, 2020) is pushing most EVs towards a full-charge range comparable with those of traditional fossil-fueled cars. Finally, the deployment of charging infrastructure, which is a key aspect in the support of a wide use of EVs, is gradually improving thanks to both public and private investments (Zhang et al., 2018).

* Correspondence to: Fondazione Eni Enrico Mattei, c.so Magenta, 63, 20123 Milan, Italy.
E-mail address: michel.noussan@feem.it (M. Noussan).

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Publicly accessible EV charging infrastructure represents a key step in the chicken-and-egg problem of the EV market (Shi et al., 2020), especially in dense cities where the availability of household charging often remains limited. In the early development of the market, the low penetration of EVs is a strong barrier for private companies that want to invest in EV charging. Thus, an initial involvement of public funding may be needed to foster the deployment of publicly accessible charging for EV users. Additionally, public charging is complementary to household and work EV charging, which usually benefits from lower electricity cost and exploits the many hours in which cars are usually not in use. Nevertheless, in the coming years the share of public charging is expected to rise, due to the higher deployment of EV cars in middle- and low-income households that may not have access to home charging, especially in urban areas (Engel et al., 2018).

As detailed in Section 2 below, a rich literature stream has engaged with the role of the EV charging network for EV adoption, as well as with the development of approaches to optimize the deployment of the EV charging network according to different objectives and constraints. Nonetheless, the lack of analyses of the actual development of EV charging infrastructure, especially with the aim of comparing its evolution in different countries, is witnessed. The few empirical assessments based on GIS data modeling are limited to the United States (Wood et al., 2017; Nicholas et al., 2019) and the state of California (Chen, 2017; Hsu, 2019).

This paper aims at filling this gap by a detailed spatial analysis of the availability of EV charging stations with a focus on European countries and in comparison with the population and vehicles distribution in different regions. The novelty of our work comes from the comparative assessment across countries as well as within each country, the evaluation of the temporal evolution of EV charging accessibility, the highly granular spatial data processing, and the collation of accessibility data with EV fleet and other transport data. While most of the literature is based on top-down country-level data, our approach is a bottom-up analysis based on the available information of single charging points, allowing to provide insights at different spatial levels. In addition, the analysis pays explicit attention to the energy dimension of EV charging stations, thus combining accessibility with charging power (and therefore charging speed) information.

The remainder of the paper is organized as follows. Section 2 provides an overview on the current literature on the topic, Section 3 describes the methodology adopted in detail, with reference to the input data sources, their elaboration and the spatial analysis conducted. Section 4 illustrates the main results of this work, which are further discussed in Section 5. The main conclusions, together with some policy recommendations, are presented in Section 6.

2. Literature review

2.1. EV charging infrastructure and EV vehicles adoption

The complex role of EV charging infrastructure in supporting the development of the EV market is a topic that has been addressed in different literature contributions. However, most studies are based on top-down country-level data, which are unable to provide the level of geographical detail that can be reached with a bottom-up approach.

The most complete review on EV charging deployment in Europe is offered by Tsakalidis et al. (2019). The paper presents useful insights, including the different ratios of charging points per vehicle across countries, and some information on the percentage of high-power charging points. Still, the paper is based on country-level data and it is thus unable to provide information with higher level of geographical detail and beyond average figures per each country. Additionally, data refers to 2017, and last years show noticeable differences in such a fast-growing market.

Other useful figures comparing country data in Europe are provided by Transport & Environment (2018). This report highlights the strong divide between some Northern-Europe countries, which show advanced levels of EVs adoption, and the rest of the continent. The report confirms the strong role of publicly accessible EV charging in the early phases of the EV market, while it is expected that in the future households and work charging will take the lead, and customers will use public charging merely for fast charging needs. However, other studies highlight that in some contexts public charging will be crucial to support a wider deployment of EVs in middle- and lower-income households without home-charging options in urban areas (Engel et al., 2018).

A broader view comparing a selection of world countries leads to the conclusion that wide differences in the framework conditions exist (Funke et al., 2019). Thus, findings from literature for specific countries can only be transferred to other countries to a limited extent. The paper analyzes a group of countries to underline the importance of public charging, especially in densely populated urban environments, where home or work charging options are limited. Finally, it concludes that the ratio between EVs and charging points cannot be used alone as a reliable indicator to assess the effectiveness of the charging network, since many other aspects are of relevance in specific contexts.

Other works have found evidence of the importance of public charging in specific countries. Illmann and Kluge (2020) have investigated the effect of the availability of public EV charging infrastructure in the consumers' willingness to buy an EV. Their results, based on an analysis on 5 years of German data, find evidence of a positive long-run relationship, as well as of a causal link, but on a rather low scale. Ma and Fan (2020) found instead that the number of EV charging points had a significant impact on battery electric vehicle sales in China, with a higher effect for direct current charging. Moreover, their results suggest that the most effective policy for the increase of EV sales is the reduction of the electricity rates, while financial help for the investment in charging infrastructure has proven to be ineffective. Greene et al. (2020) present a California-based study focusing on the economic value of the EV charging infrastructure, based on estimate functions of willingness to pay of final customers. Their estimates indicate that publicly accessible EV charging infrastructure creates substantial value for current and potential future owners of BEVs, by reducing range anxiety and increasing their attractiveness.

An opposite outcome is reported by Miele et al. (2020), whose study, focused on Canada, shows that EV charging deployment plays a marginal role in increasing the market share of electric cars. Indeed, other policies and measures show higher effectiveness in supporting the increase of EV adoption rates. The fact that these results are in contrast with other studies further stresses the importance of context-specific enablers and barriers, including population density, building types, drivers' behaviors and charging preferences. Additional elements on the balance between different policies are provided by Fang et al. (2020), who analyze the role of charging infrastructure by means of an evolutionary game model in a small-world network. They highlight the advantages of the balanced dynamic subsidy and taxation policies on the promotion of electric charging infrastructures. Their findings also suggest that the investment is not the main barrier for the deployment of charging stations, since the penetration level of EVs and the charging prices represent the main driving forces.

2.2. EV charging infrastructure allocation

Another recent stream of literature has engaged with the assessment of the positioning of EV charging infrastructure in relation to the current and future potential demand. These studies have developed geographically-explicit algorithms with an array of objective functions to optimize the allocation of charging stations.

As highlighted in Lam et al. (2014), the EV charging station placement problem requires that not only the charging network is pervasive enough such that an EV can easily access a charging station within its driving range, but also widely spread so that EVs can compete to displace internal consumption engine (ICE) vehicles. According to the authors, the optimal solution method is problem-specific. For instance, Shahraki et al. (2015), Brooker and Qin (2015), Dong et al. (2014) developed empirical EV charging station allocation models based on real world travel data at different scales. Interestingly, Shahraki et al. (2015) compare their optimal allocation estimates with the real location of currently installed stations, which they show being strongly sub-optimal based on real driving patterns from taxis. While these results may stem from the allocation of charging stations being a political decision or stemming from multiple independent decisions of different operators, it highlights the importance of examining accessibility to charging stations *ex-ante* from a public policy perspective, namely before planning and installing new charging stations.

Expansions to the optimal allocation problem include the work from Xu et al. (2017), who developed an EV charging station optimization approach which simultaneously optimizes the charging mode. Namely, three alternatives including charging at home or at company premise, normal charging at public charging stations and fast charging at public charging stations are considered. The study sheds light on the importance of differentiating between charging point power, namely charging speed, based on the distribution of the demand for EV charging and the prevalent user type at each location. Similar considerations are made in Philipsen et al. (2016), Sadeghi-Barzani et al. (2014), who evaluated the demand and supply potential for fast charging stations based on user criteria and electric infrastructure availability. A detailed GIS-based methodology is proposed in the European Commission JRC report by Gkatzoflias et al. (2016), who assess the optimal locations of EV charging stations in a city network (urban road network) and in a regional or national network (rural roads and highways). The approach builds on road network and population data to approximate demand density and precise infrastructure allocation patterns.

Other advances in the optimization problem formulation include Alhazmi et al. (2017), who modeled the *Trip Success Ratio* technique to measure the quality of charging station network from drivers accessibility perspective. Namely, they evaluated the positioning of charging stations in terms of the share of EV trips that can be completed successfully conditional on the electrical energy remaining in the EV's battery being sufficient to reach the destination. A similar approach was followed by He et al. (2018), who considered different EV driving ranges in their optimization approach. Andrenacci et al. (2016), He et al. (2015) carried out EV positioning optimization assessment specifically for metropolitan areas and the urban road network, which displays own challenges such as congestion. This results suggest the necessity of differentiating between urban and intercity journeys when evaluating EV charging network deployment.

Further studies have focused on the need of fast-charging systems to support car travel in highways. Jochem et al. (2019) present a methodology applied to a set of European countries to estimate the minimum required number of fast-charging stations located along highways based on a comprehensive dataset of vehicle flows over the network. The paper also highlights the expected positive profitability of a well-planned network of fast-charging stations. The profitability may also be improved by including an additional stationary storage, thanks to the possibility of decreasing grid connection costs and adding revenues from intra-day electricity trade (Funke et al., 2020). Some models have also been proposed to estimate the optimal location of fast-charging stations without the need of detailed input data of origins and destinations, such as the one proposed by Csiszár et al. (2020) and validated on a case study in Hungary.

Another crucial aspect is the role of the EV charging points deployment in facilitating daily travel needs of electric vehicle users. With regards to this issue, Gnann et al. (2018) analyzed real-world fast charging data from Sweden and Norway to calibrate a model for evaluating future fast charging point needs. They find that the ratio of EVs to public fast charging points is close to one fast charging point per 1,000 vehicles for high power rates of 150 kW, with little price surplus per charging point compared to alternative fuels. This finding is explained by the diminishing returns of charging infrastructure placement identified in Kontou et al. (2019), who observed the existence of a positive but marginally decreasing relationship of electric vehicle charging coverage (the share of area with public chargers installed) and charging opportunity (the drivers probability of accessing a public charger).

An additional interesting perspective is offered by a set of studies (Sun et al., 2020; Arias et al., 2017; Zhang and Chen, 2020) analyzing the interplay between the EV charging network and power network, such as current grid limitations and future capacity expansion needs. This is a crucial advance when compared to the previously reported pure transport demand-driven EV charging network deployment studies. In particular, Sun et al. (2020) introduce a transport-energy approach that is able to capture the interactions among battery electric vehicles' (BEVs) route choices, charging plans, and the prices of electricity. Their modeling framework aims at minimizing the total social cost, comprehensive of both the charging and the power networks. Arias et al. (2017) propose a time-spatial EV charging-power demand forecast model in urban areas. They adopt a scenario-based approach evaluating different fast-charging rates and EV charging patterns while also accounting for traffic with real world data from Seoul, South Korea. Another case study is formulated in Zhang and Chen (2020), who develop a model of smart charging management for shared autonomous electric vehicle fleets and test it on the Puget Sound region (Washington, United States). They simulate a smart charging scheme to shift the electricity load burden away from the evening hours, which already represent the demand peak time of the day. They find that EVs – and in particular those with larger battery sizes – are responsive to low-electricity cost charging opportunities. Thus, the authors argue that a smart charging scheme has significant potential to reduce total energy related costs, namely both electricity and charging infrastructure.

Overall, the empirical research works screened provide interesting insights on country-based figures, but we found a lack of bottom-up empirical analyses that exploit the available information on the location of charging points. While such data could have some limitations, as we discuss in detail in the following sections, they have the significant advantage of providing figures that go beyond the average values per country, by representing also the huge differences that occur within countries. A sound understanding of the status quo is deemed necessary to better plan the next generation of EV charging infrastructure and support large-scale EV adoption.

3. Materials and methods

3.1. EV charging database

The analysis presented in this work is based on the data extracted from a global public registry of electric vehicle charging locations (Open Charge Map, 2020). Open Charge Map (OCM) is a non-commercial, non-profit, electric vehicle data service that has been developed and operated by volunteers, and which is hosted and supported by a community of businesses, charities, developers and interested parties around the world. Its main aim is to provide a reliable reference for charging equipment location information, by cooperating with other data providers to avoid the proliferation of independent conflicting charging location databases. As of November, 2020, the database includes almost 130,000 EV charging stations worldwide. All the stations considered in the current study are reported in Fig. A.1, classified by their power tier.

Open Charge Map represents the most complete open global dataset of EV charging stations currently available. Yet, being developed by a number of volunteers, it may not include all the available charging points. In addition, there may be a time lag between the date of operation of a new station and its recording in the database, but also between a station having a technical issue and being reported. A comparison with data for EU countries from another source, based on commercial data (ACEA, 2020b), shows that the total number of EV charging points registered in OCM is around 25% lower than the figures provided by the other source (which may also be due to the aforementioned time lag), albeit with significant differences across countries. Thus, the results of this paper should be interpreted under the light of this potential source of bias, which represent an intrinsic limitation of crowd-sourced data. Nonetheless, it is also important to remark that without an official and standardized international database of EV charging points, the accuracy of other data sources (e.g. ACEA, 2020b) is not exempt from issues. But, given the lack of access to these data, we cannot verify this hypothesis.

The data that are used in this manuscript has been extracted as of November 30th 2020, by using the dedicated application programming interface (API) filtering the results on 29 European countries. Each record represents a charging station, and it includes:

- geographical information: country, latitude and longitude;
- the date of creation and last update of the information;
- the status type of the station (operational, planned or dismissed);
- the usage type of the station (open to the public or private, i.e. restricted to customers or workers);
- technical parameters including the current type (alternate or direct) and the nominal power of the charging point:
- the number of charging points that are available for each station;
- an identification number representing the operator of the station;
- additional information on the pricing scheme.

These parameters have been used to develop all the analyses presented in this paper, and they are a subset of all the available information, which include additional aspects that are not relevant for this work.

For the purpose of this work, the stations that are considered are all those represented as "Operational". In some cases, records were registered in the database without any information on the station status (in particular for some countries, including Norway, Sweden and the Netherlands). We nonetheless decided to consider those stations as operational, also after comparing country-level data with other sources (ACEA, 2020b).

In the cases in which an installation year has been reported, we considered the date provided in the field "Date Created", which refers to the date of creation of the record. This may lead to some inaccuracies, since this date actually represents the moment in which the station has been added to the database, which may be later than the real date of installation of the station. Unfortunately, there is no additional information, and thus this is the most reliable data available. Still, in our work the chronological analysis is limited to annual time steps, and thus we believe that this approximation remains within acceptable tolerance intervals.

We use data described above to present a number of descriptive statistics on the evolution of the infrastructure in European countries, with the aim of comparing the accessibility of citizens to EV charging stations. Some additional aggregations have been performed to highlight the most significant patterns in the charts and maps that we present.

With reference to the speed of the charging points, we consider the following categories, based on the common classifications in international studies:

- slow charging: lower or equal to 10 kW (alternate current);
- normal charging: higher than 10 kW and up to 22 kW (alternate current);
- fast charging: higher than 22 kW and up to 50 kW (alternate or direct current);
- ultra-fast charging: higher than 50 kW (direct current).

It must be remarked that each charging speed category tends also to be related to different uses and applications. While fast charging and ultra-fast charging are generally devoted to long trips, often in highways, slow and normal charging may be used mostly for occasional charging (e.g. during shopping or other daily activities) or for EV users that do not have access to charging infrastructure at home or at their workplace. To account for these differences, for most of the results in our analysis an differentiation by power tier is provided.

3.2. Additional data sources

Accessibility is estimated following procedures, code, and data described in Weiss et al. (2018, 2020). The approach is based on a high-resolution (1 km) friction raster layer, where each pixel expresses a nominal overall speed of travel, namely the land travel time required to traverse it (in minutes/meter). The layer is calculated based on local landscape characteristics (e.g. land cover, slope), transportation infrastructure (e.g. roads) and additional constraints. In our analysis we adopt the 2019 motorized transport friction layer from (Weiss et al., 2020), which is based on the OpenStreetMap and Google Roads datasets and includes the median speed limit value for each road type in each country.

For summarizing accessibility statistics and maps into administrative boundaries, we refer to the official *Nomenclature of territorial units for statistics* (NUTS) shapefiles from Eurostat for year 2021 (retrieved at https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/nuts).

To calculate population-weighted maps and empirical cumulative distribution curves (ECD curves), we adopt the GHS-POP gridded (residential) population product produced by the European Commission Joint Research Center (Schiavina et al., 2019) for year 2015 disaggregated from census or administrative units, informed by the distribution and density of built-up as mapped in the Global Human Settlement Layer (GHSL) global layer.

NUTS-2 level data on vehicle stocks (i.e. the motorization rates) (indicator *tran_r_vehst*) and the (un)employment rates (indicator *8Ao35GH6BEciDJu29SrLbw*) – used to calculate the working population – are extracted from the Eurostat database for the most recent years available for each administrative unit.

Data on EV sales are retrieved by ACEA, the European Automobile Manufacturers' Association, which publishes quarterly data on alternative fuel vehicle (AFV) registrations (ACEA, 2020a). The data used in this paper are annual-aggregated data for the 27 European countries that are available in the dataset. The data spans from 2013 to 2019, while 2020 is providing data on the first three quarters. For most countries, sales data are available for both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEV). Unfortunately, additional information on the total EV stock at a country basis is not available, but given the fact that EV sales were quite limited in 2013 (at EU level BEV sales increased twelve-fold from 2013 to 2019, and PHEV sales six-fold in the same interval), we believe that the cumulative sales are a good approximation of the actual fleet, especially in the most recent years.

3.3. Spatial analysis of accessibility

The steps adopted in the spatial analysis of EV charging station accessibility are summarized in Fig. 1.

The EV charging station database is processed together with the friction layer using a cumulative cost GIS algorithm in Google Earth Engine (Gorelick et al., 2017). The process follows the analysis of Weiss et al. (2020) and is based on the Dijkstra's least-cost-path algorithm (Dijkstra et al., 1959). The process generates a raster layer of the travel time (in minutes) to the most accessible charging station at each location in Europe. Note that due to consideration of transportation infrastructure patterns encapsulated in the friction layer, the most accessible charging station need not be the closest in terms of Euclidean distance. The process is replicated several times on year and charging station tier and mode slices of the charging station database to evaluate different dimensions and the temporal evolution in accessibility.

Accessibility statistics are then processed in the R scientific computing environment using the *raster* (Hijmans and van Etten, 2016), *sf* (Pebesma, 2018), and *tidyverse* (Wickham et al., 2019) packages suite. In particular, we calculate (working) population-weighted travel time in each NUTS-3 unit as the following:

$$TT_{NUTS}^{popw} = \sum_{i}^{N} TT_i \cdot \frac{POP_i}{POP_{NUTS}} \tag{1}$$

where N is the number of pixels falling within each NUTS unit; i identifies each pixel; TT is the travel time to the most accessible charging station; POP is the (working) population. ECD curves are calculated with a similar approach at NUTS-0 level.

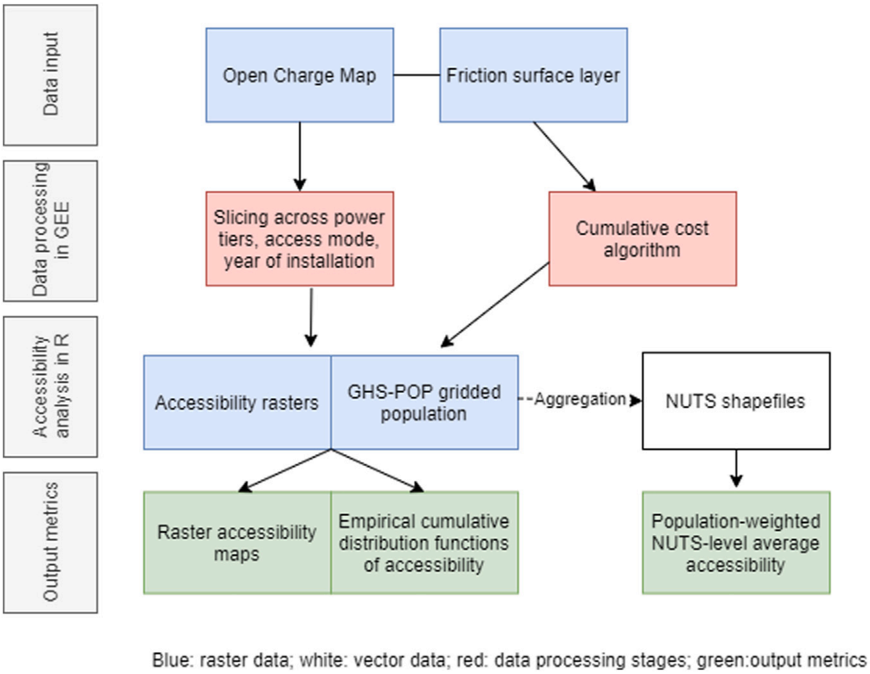

Fig. 1. Framework of the inputs, methodology and outputs of the spatial analysis carried out in this paper.

4. Results

The results of our analysis are reported in three sections, which address the evolution of the EV charging points deployment over time, their relation with the total EV sales in European countries, and the spatial analyses related to the network characteristics of EV charging points.

4.1. Evolution of EV charging stations

The historical trends over the last six years of the cumulative number of charging points and nominal charging capacity are reported in Figs. 2 and 3 respectively. The charts show a continuous evolution over the years, leading to a three-fold increase in the number of points and a four-fold increase of the total charging power. The fast and ultra-fast charging remain a minor share in the number of charging points (around 15% and 5% respectively in 2020), but when considering power their importance obviously grows (each of them representing about 30% of total installed power in 2020). Their increasing importance in the last years is partly triggered by the larger battery size of some new EV models.

As of November 30th, 2020, the countries with the highest installed capacity are Germany, Norway, the UK, Italy, Sweden, France and the Netherlands. Germany is by far the country with the highest installed capacity, representing almost the combined capacity of Norway and the UK. Moreover, considering the population of those countries, the position of Norway appears rather outstanding, thanks to a very advanced strategy on transport electrification, supported by dedicated incentives. The benefits of deploying EVs in Norway are particularly significant, thanks to the fact that virtually all electricity in the country is produced by renewable sources (mostly hydropower).

To put these data into perspective, it might be useful to compare the current figures with the future estimates provided by some studies. Transport & Environment (2020) presents an estimation of the future need of public charging points in European countries by 2025 and 2030. For the first five countries by number of charging points in the report (Germany, UK, France, Spain and Italy), the number of existing public charging points (according to the Open Charge Map database) is in the 3%–15% range compared to estimated numbers for 2025. Thus, significant increases are likely required in the future to meet those targets.

Another first-order comparison can be done for the ultra-high speed charging (higher than 150 kW), thanks to the data presented by Jochem et al. (2019) on the optimal size of charging stations on European highways for some countries in 2020 and 2030. The number of charging points with power greater than 150 kW that are currently installed in Germany are in line with optimized data for 2020 (they are 8% lower), but they need to increase 4-fold by 2030. Netherlands seems to be already above its 2020 target, while France remains well below the 2020 level (around 15% of the estimated optimum number of ultra-fast charging points), and a significant additional effort will be required to catch up.

Additional details on the distribution of EV charging points in European regions are reported in Figs. 4–6, which represent the ratio between charging points and vehicle ownership, population, and the working population, respectively. Comparing the three

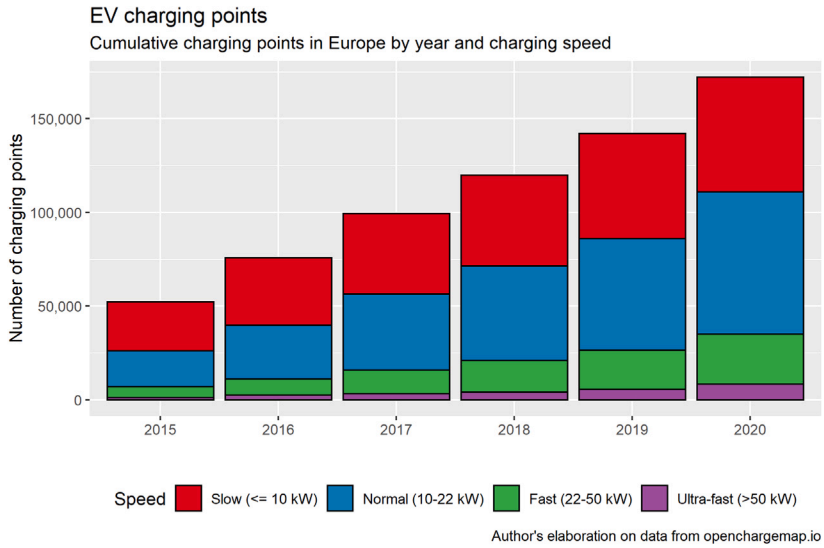

Fig. 2. Evolution of the number of installed EV charging points by year and charging speed (2020 data as of November 30th).

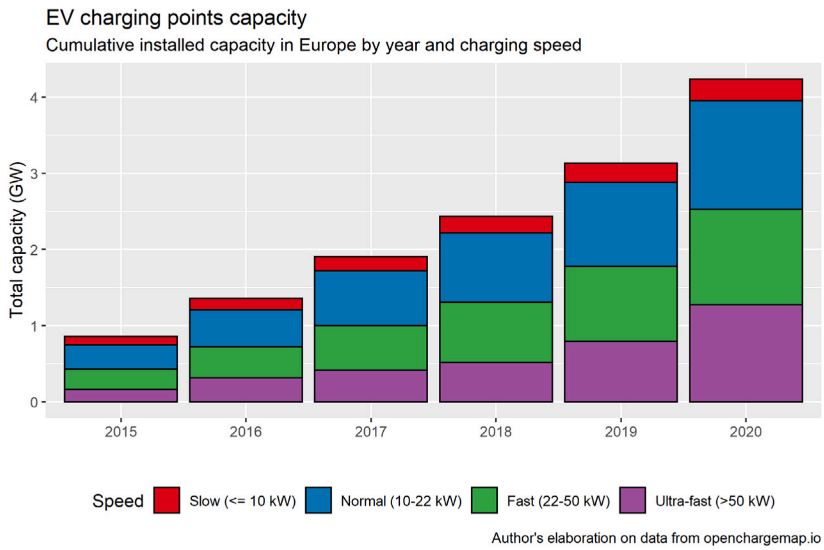

Fig. 3. Evolution of installed EV capacity by year and charging speed (2020 data as of November 30th).

maps is insightful because it helps appreciating differences across urban and rural areas, and chiefly the role of different motorization rates, which tend to be significantly higher in rural areas (Scheiner, 2012). In addition, the map in Fig. 6 is plotting the ratio of charging points per 10,000 working people. Employment is a significant driver of travel demand, Sessa and Enei (2009), and it is therefore interesting to compare the map with that in Fig. 5, based on the total population. In general, regions in Central and Northern Europe tend to show on average a larger number of charging points per capita, while in Eastern and Southern Europe (with the exception of Northern Italy and some areas of Portugal) people have a lower number of public accessible charging points for their EVs. The most prominent differences between the charging points-to-vehicle and charging points-to-population ratios can be observed in France, Portugal, England, Ireland, the Baltic countries and Hungary. Conversely, in EU countries with high motorization rates such as Italy, Poland and Spain, the discrepancy is significantly smaller. These differences among countries are to be considered by acknowledging the significant variability of dedicated policies from one country to another, given the fact that EV market is often in a preliminary stage, thus needing a public support to shift towards a growth stage.

4.2. Comparison with EV sales

Data on EV charging points could be analyzed in comparison with available annual data on EV sales at a country level. Fig. 7 shows the continuous increase in EV sales in Europe, both for BEVs and PHEVs. The data for 2020 show a dramatic increase over

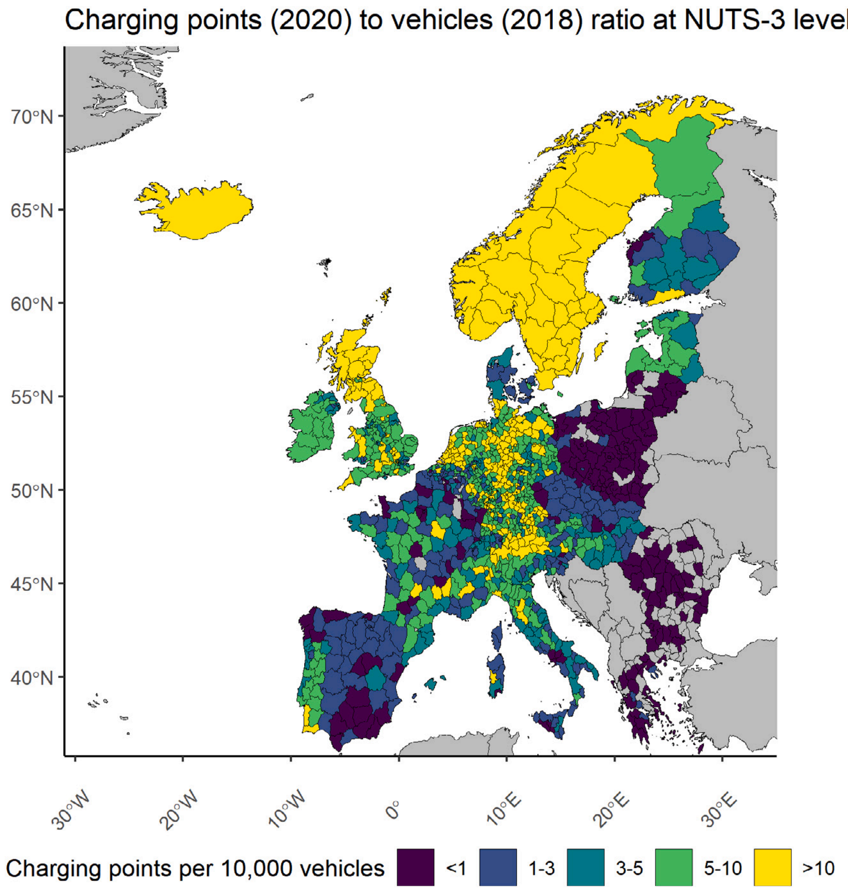

Fig. 4. Charging points per 10,000 passenger vehicles at the NUTS-3 level.

2019, with BEVs increasing by 106% year-on-year and PHEVs by 210%, notwithstanding the potential negative effect of COVID-19 on car sales.

Considering BEVs, Norway remained as the top-selling country until 2018, but in 2019 Germany and the Netherlands became the two countries with the highest EV sales (with 63,000 and 62,000 respectively). In 2020, Germany remained the top-selling country, reaching almost 200,000 cars, followed by France (111,000) and the UK (108,000). However, Norway remains the country with the highest market share of EVs, both for sales and stock, and with the highest sales per capita. This is partly due to very generous incentives for EVs part of a National strategy towards transport electrification, although subsidies are now gradually decreasing. Similar trends are noticeable for PHEVs, with 2020 sales of 200,000 cars in Germany, 75,000 in France, and more than 65,000 in the UK and in Sweden. Germany and France registered very strong PHEV sales increases over 2019, with +340% and +300% respectively.

Fig. 8 shows the evolution of the relation between the BEV stock and the charging points from 2015 to 2020. The BEV stock has been approximated by the cumulative sales from 2013 (with the sales in the previous years being negligible in most countries) due to the lack of data on previous years. Each line in the chart represents a country, and the axes are both in logarithmic scale to compare countries of very different size.

We have chosen to consider only BEVs in this representation, although in many countries also PHEVs often use EV charging infrastructure. Still, we believe that PHEVs are actually relying on electricity for a low share of their total travels (as recently confirmed by Plötz et al. (2020)), and thus the impact of EV charging points availability on consumer choices may be much lower.

It is interesting to see that most of the lines become gradually flatter, which means that in the first years the increase of EV charging points is larger than the increase of EV sales, while in the last years the opposite happens. This trend seems to suggest the importance of a well-distributed network of chargers to support an increase in EV sales, although there are other aspects that are of paramount importance (including household charging, economic incentives, etc.). This aspect is confirmed by the continuous increase over the last five years of the ratio between cumulative EV sales (which as discussed above approximates the EV stock) and total EV charging points. Considering the distribution of this ratio in each country, the median value has increased from 1.6 to 7.2 BEV per charging point from 2015 to 2020.

This number is generally increasing together with the maturity of the EV market. In the early stages EV charging points are often deployed to support an increase in EV sales, and then this ratio should ideally reach an optimal equilibrium value, which

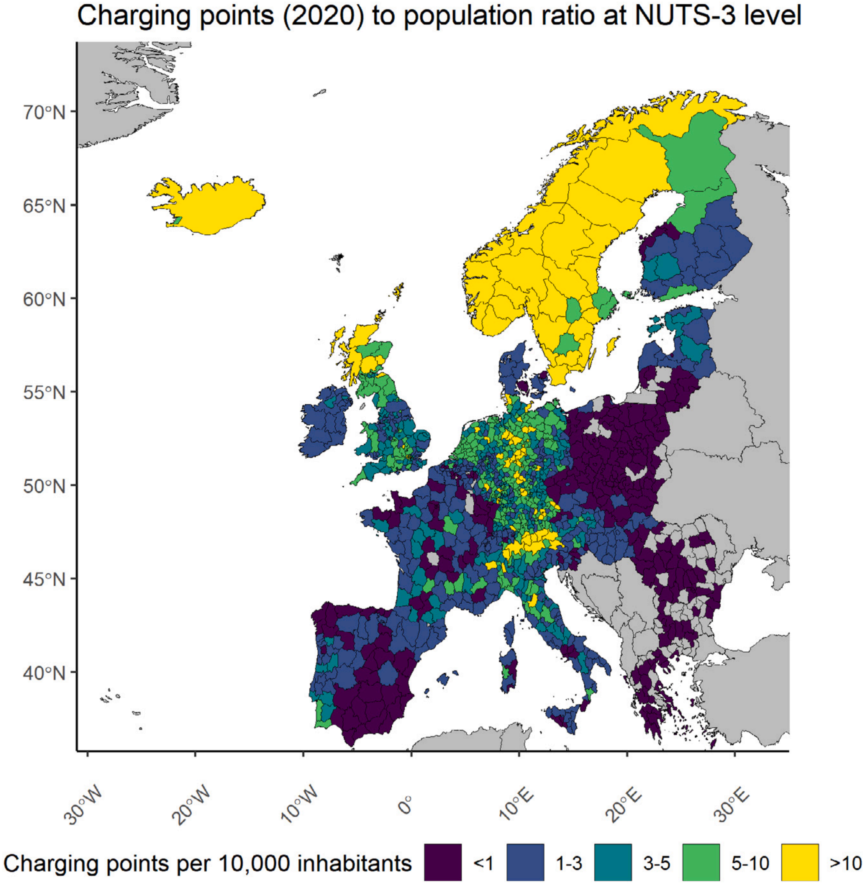

Fig. 5. Charging points per 10,000 inhabitants at the NUTS-3 level.

may vary depending on a number of factors (including the population density, the importance of public charging with respect to household/work charging, the charging power, etc.). An excessive number of BEVs per EV charging point may lead to problems of finding available charging infrastructure. These aspects may be particularly relevant when considering vehicle-to-grid (V2G) strategies, since vehicles should stay connected to the grid as long as possible. Thus, as we will be discussing in the following sections, V2G will likely require a larger number of charging points in comparison with standard charging strategies.

Additionally, the country-level correlation between the cumulative installed EV charging power and the cumulative count of BEV sales yields a $\rho = 0.77$ (p-value $<$2.2e−16), highlighting the strong link between private users BEV adoption and the availability of charging power within each European country considered in the analysis. Similarly, the correlation between the cumulative number of installed charging points and the cumulative count of BEV sales shows a $\rho = 0.67$ (p-value $<$2.2e−16). It must be remarked that the estimated correlation coefficients should not be interpret as a causal effect, but rather as an indication of potential link between these trends.

4.3. Accessibility to charging stations

The results of this section illustrate the accessibility situation to EV charging stations across the considered countries in Europe. While Fig. 9 illustrates the general accessibility situation, i.e. irrespective of the charging point power tier of access mode (public, public with membership, private), Figs. A.2–A.4 differentiate among this specific characteristics to shed light on the heterogeneous qualities of charging points across NUTS-3 regions of Europe. An additional map, considering the absolute travel time at each pixel irrespective of the NUTS region of belonging, is found at Fig. A.5.

Our estimates show that a stark inequality characterizes both across and within country accessibility to EV charging stations. The United Kingdom, the Netherlands, Belgium, large parts of Germany, France, and northern Italy appear as the areas in the considered countries in Europe with the quickest accessibility potential. Other scattered areas, in particular in the surroundings of large metropolitan areas in Spain, Portugal, southern Italy, Scandinavia and Poland are characterized by EV charging infrastructure availability in the proximity of population place of residence. Conversely, other areas such as a major portion of the Iberian

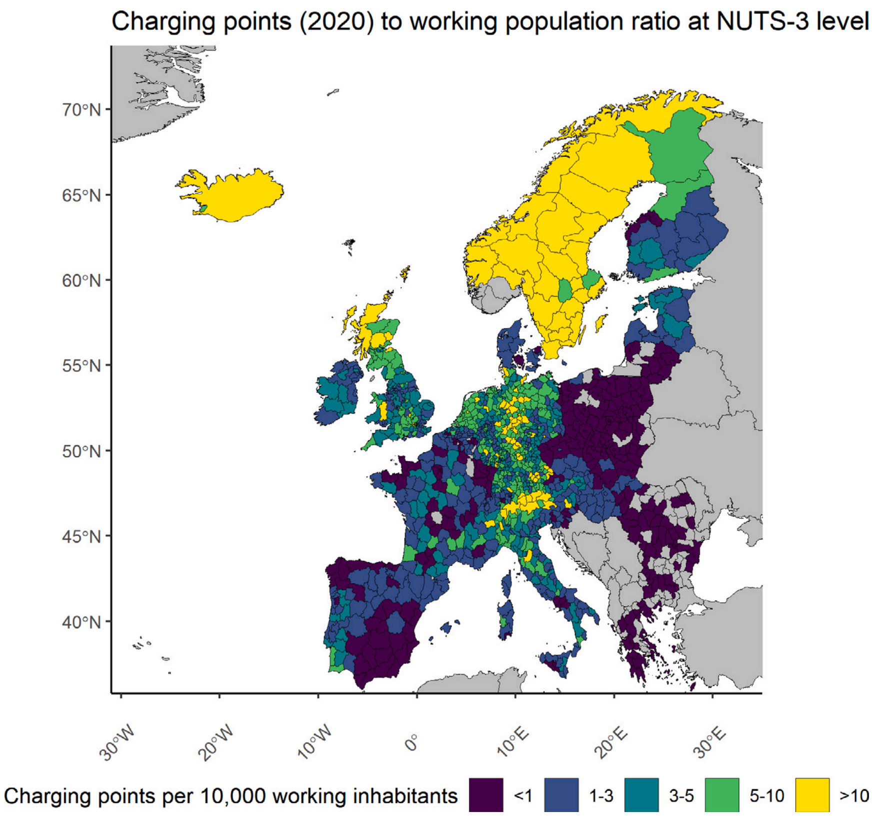

Fig. 6. Charging points per 10,000 working inhabitants at the NUTS-3 level.

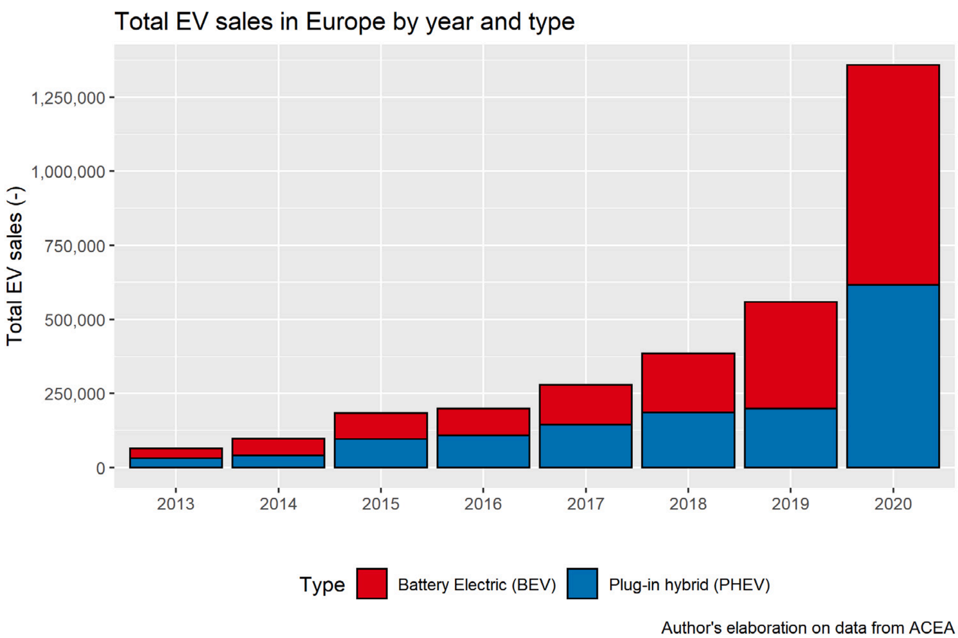

Fig. 7. Evolution of the number of EV sales in Europe by year and type.

Peninsula, Scandinavia, Greece, and Eastern Europe (at least in countries where data are available) show major accessibility deficit which would disincentive drivers purchasing EV vehicles or would discourage EV owners to travel towards these locations.

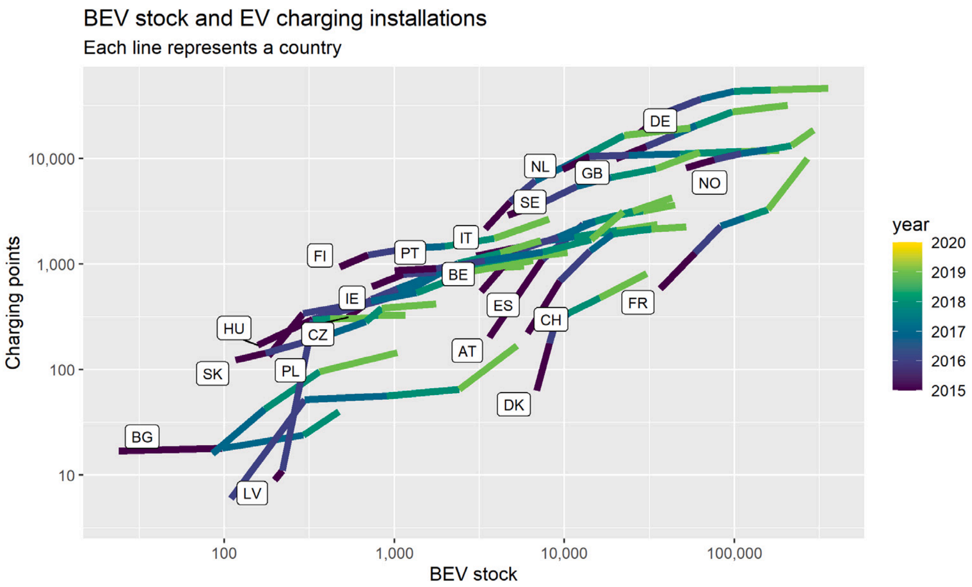

Fig. 8. Comparison of the evolution of EV stock and total EV charging points in European countries.

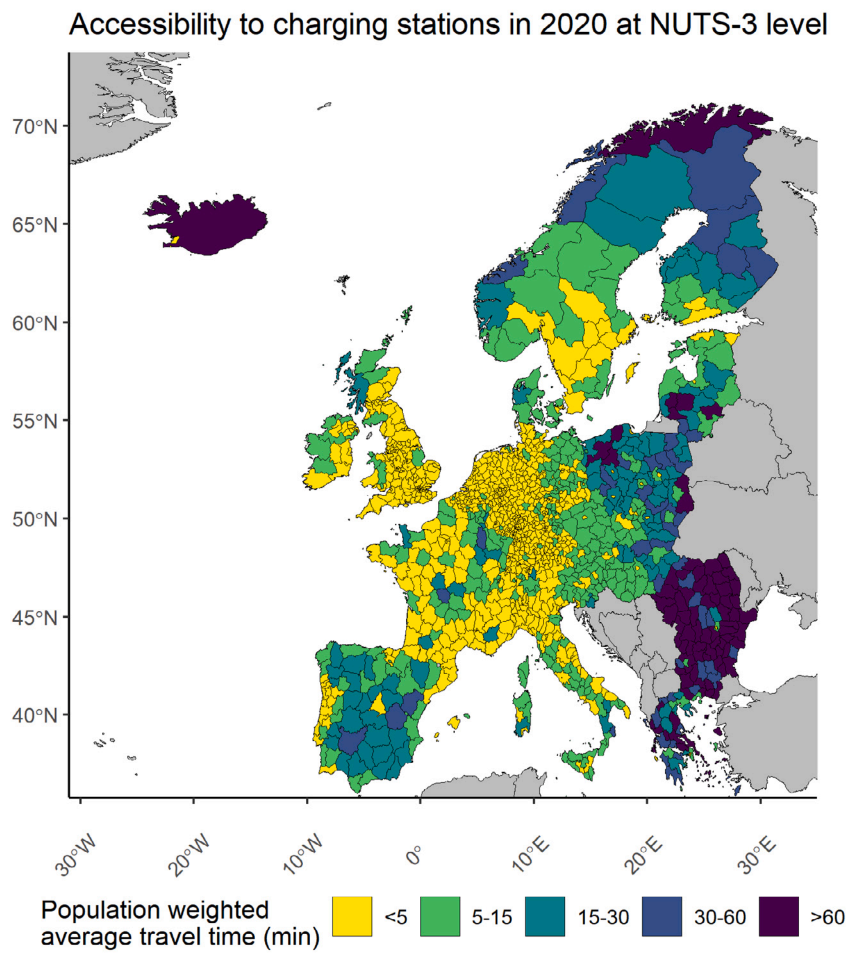

Fig. 9. Population-weighted NUTS-3 level maps of the travel time to the most accessible EV charging station.

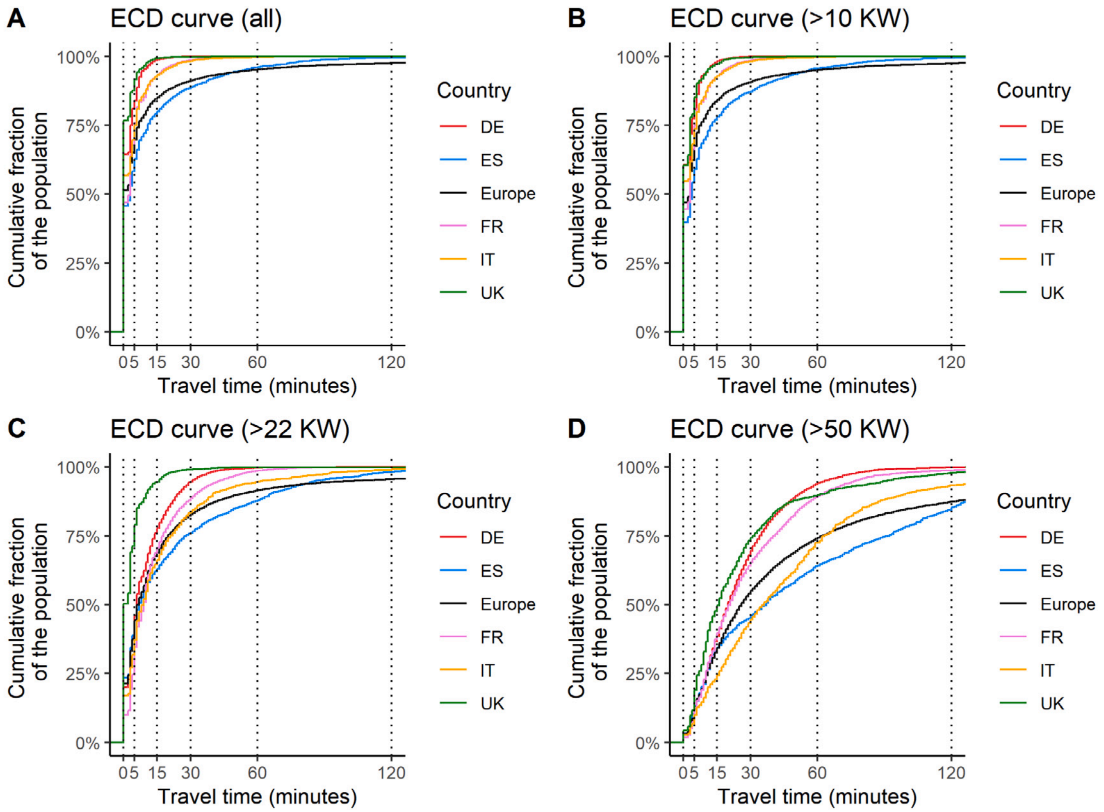

Fig. 10. Empirical cumulative distribution (ECD) curves for the share of the population as a function of the travel time to the most accessible EV charging station, by power tier.

Yet, while informative on the relative accessibility situation across regions, the map does not reveal information on the absolute number of people within certain EV charging travel time thresholds. To display this additional piece of information, the results are summarized at the country-level in the empirical cumulative distribution (ECD) curves in Fig. 10, which plot the (cumulative) distribution of the population as a function of the travel time to the most accessible charging station in selected European countries (the five most populous) and in the Europe as a whole (as considered in this study).

Vertical dashed lines are plotted at selected travel time thresholds. The graphs distinguish between charging stations power tiers. Panel A shows that – when considering all tiers of charging stations – the UK and Germany are the most virtuous countries in terms of accessibility relative to the residential population distribution. In both countries virtually the entire population lives within half an hour to the most accessible charging point. Italy and France show a very similar distribution, where full accessibility is approximated at about 60 min, as at 30 min there is still about 10% of each population not in reach of charging stations. These four countries however all outperform the European average (for the countries considered in this study), plotted in black, where about one fifth of the entire population lives > 30 min. away from the most accessible charging station. This fraction is even slightly higher in Spain, the additional country considered in this graph.

Further interesting insights can be drawn by comparing the evolution in the ECD curves when shifting across EV charging station tiers, which may also be representative of different kind of usage cases. For instance, when looking at fast and ultra-fast charging (panels C and D) it appears that the UK remains the leader country in Europe, as the proportion of people within accessibility thresholds changes only marginally compared to when considering all tiers of charging stations. Conversely, the curves for other countries seem to “bend” substantially. For instance, ultra-fast charging is > 30 min. away for nearly one quarter of the German population and for about one third of the population of the additional countries considered, including Europe as a whole. Finally, fast and ultra-fast charging are more than 120 min away from non-marginal fractions of the European population, including citizens of Spain and Italy. The changing accessibility dynamics conditional on the power tier considered, and thus at the charging speed available, can also be appreciated on map visualizations in Fig. A.2 at the NUTS-3 level. A similar ECD visualization is provided in the Appendix (Fig. A.3) as a function of the cumulative fraction of the vehicle stock. Note that the graph assumes that motorization rates are homogeneously distributed within each NUTS-2 unit, the smallest unit of data aggregation for which the metric is available.

An additional differentiation concerns the access mode of charging stations. A set of stations are publicly accessible ($n = 54{,}154$ among the active stations in the Open Charge Map as of 2020) to any user requiring power (although these stations might require the user to be registered to the operator, thus preventing ‘spontaneous’ use of the charging facilities). A smaller portion of the total

Table 1
EV charging stations situation in the 20 largest European cities (population calculated in a 25-km radius from city center).

	City	Population (million)	Charging points	Charging points per 10,000 inhabs.	Average travel time (min)
1	Paris	7.40	190.00	0.26	1.94
2	London	5.95	6508.00	10.94	0.01
3	Madrid	4.80	291.00	0.61	2.22
4	Barcelona	3.33	620.00	1.86	0.96
5	Berlin	3.06	1215.00	3.97	0.73
6	Milan	2.81	904.00	3.22	0.73
7	Rome	2.60	623.00	2.40	2.37
8	Naples	2.55	50.00	0.20	3.88
9	Budapest	2.06	596.00	2.90	1.55
10	Bucharest	2.04	57.00	0.28	7.73
11	Vienna	1.99	579.00	2.91	2.28
12	Warsaw	1.89	81.00	0.43	3.77
13	Munich	1.88	1063.00	5.67	0.80
14	Hamburg	1.70	2171.00	12.76	0.67
15	Turin	1.57	377.00	2.40	2.02
16	Cologne	1.54	529.00	3.43	1.09
17	Prague	1.44	232.00	1.61	1.77
18	Sofia	1.29	17.00	0.13	14.84
19	Stockholm	1.21	1607.00	13.32	2.08
20	Amsterdam	1.20	1020.00	8.50	0.76

number of stations in the database is private ($n = 7,301$), with exclusive access to certain categories of users (e.g. firm employees or local residents). Finally, $n = 14{,}102$ are missing an access mode label and are therefore classified as with "other" access mode in the analysis. The maps in Fig. A.4 illustrate the variation in the accessibility situation when considering all operational charging stations or only a given subset of these stations based on the access mode for (potential) users. It must be noted that in the Figure those stations classified as with "other" access mode are only included in the 'all stations' facet.

A further dedicated assessment is carried out for the case of the 20 largest cities in the European countries that have been considered. In particular, Table 1 describes and compares cities in terms of their population, charging points, and accessibility to charging stations. Since the listed cities differ substantially in terms of their urban sprawl, administrative boundaries, and morphology, we decided to calculate statistics within a 25 km radius buffer around each city core to improve the comparability of the reported metrics across cities. The city core is based on the coordinates reported in the World Cities Database. Population is calculated based on zonal statistic sum of GHS-POP gridded population within the buffer.

The results show that population within the 25 km radius buffer around each city core is not significantly correlated to the number of available EV charging points in the same area ($\rho = 0.35$, p-value = 0.1249). This result suggest that a significant role is likely played by the different degrees of market maturity as well as the public policy support to the installation of EV infrastructure in similarly sized cities. This is summarized by the charging points per 10,000 inhabitants metric, which reveals that Stockholm, Hamburg, and London are the European metropolitan cities with the largest penetration of EV charging infrastructure. They are followed – albeit at significant distance – by Amsterdam, the German cities of Munich, Berlin, and Cologne, and by Milan. The average travel time column of Table 1 summarizes the travel time to the most accessible charging station at each pixel falling within the 25 km buffers considered. It must be remarked that these times refer to the nominal travel times. Namely, in dense urban areas a single station might lead to the consideration of thousands of people as at <1 min from the most accessible charging point. The metric is therefore more useful in comparative terms across cities, rather than for its absolute value.

4.4. Competition in local EV charging markets

A further relevant element within the scope of our analysis concerns the degree of competition observed in the different local EV charging markets in the European regions that we considered. The map in Fig. 11 evidences the number of unique operators active with at least one charging station in each NUTS-3 unit. It differences between NUTS units with monopoly, duopoly, oligopoly, and competitive markets.

The map is particularly interesting when compared with the results of the charging station accessibility analysis, because it shows that while competition is positively correlated with accessibility, i.e. negatively correlated with travel time ($\rho = -0.39$, p-value = <2.2e−16), the correlation is not constant across regions. For instance, certain regions of northern and eastern Spain, central Italy, Poland and Scandinavia show fairly competitive markets (5–10 operators) and yet are still affected by charging station accessibility issues, likely because operations of several operators in these provinces is still at an early stage. Conversely, other areas show a oligopolistic tendency irrespective of generally good accessibility to charging stations. These areas include parts of Germany, France, the Netherlands and Belgium.

A necessary remark concerns the completeness of the raw data in terms of the operator variable indication. In Norway and Sweden about 80% of the stations in the Open Charge Map does not indicate the managing operator; the missing values stand at 30% in France, Denmark and Finland, and at 15% in Spain. In the remaining countries, missing values are all below 10%.

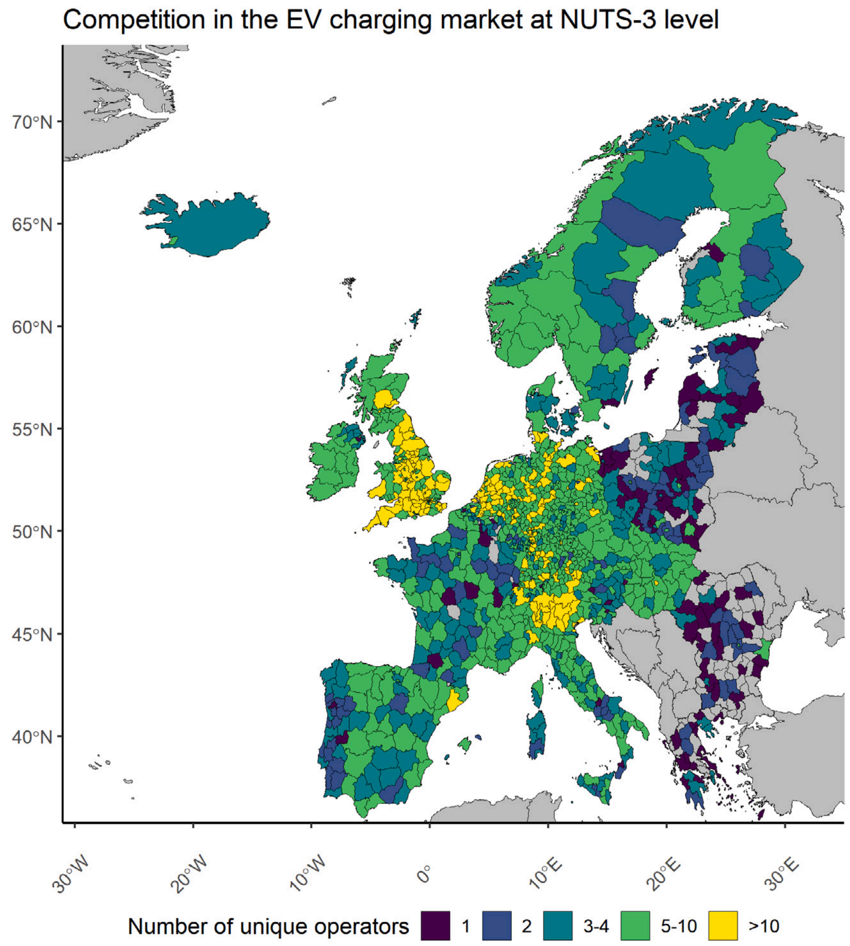

Fig. 11. Map of the absolute number of different EV charging service providers within each NUTS-3 unit.

An additional aspect to be considered for market competition is related to the pricing schemes of EV charging points. The data available from Open Charge Map include a field related to pricing information, but it is an optional information provided as text. As a result, more than half of the charging stations have no information on pricing, and the others result in a very large differentiation of pricing options (more than 2,000 different text strings). While meaningful quantitative information is hard to provide, from a qualitative perspective available schemes include:

- free charging, sometimes with additional constraints, including maximum duration, with fixed parking fees, required membership. In some cases the free option is limited to the first months/years of operation.
- annual or monthly pass, for a fixed cost.
- charging price based on energy, expressed in euro/kWh (or other currencies), with variable values related to the charging power that is available. The most popular schemes are in the range 0.25–0.50 euro/kWh (or equivalent).
- more complex pricing schemes, including combinations of energy consumption, duration and fixed price per charging. In some cases the cost is flat, with a maximum duration of the charging process.

An in-depth quantification of these figures would require a dedicated analysis, possibly validated by a check of additional sources for selected countries.

5. Discussion

5.1. Discussion and policy implications

The availability of detailed and updated data on the location of EV charging stations, together with additional geographical information, allows for an analysis of the evolution of the network in support to the EV market, a key technology for enabling the abatement of transport sector greenhouse gas emissions (Pasaoglu et al., 2012) and of some (mostly NO_x and CO) local pollutants (Soret et al., 2014). In particular, we highlight the importance of two indicators, which are (1) the ratio between the number of EV charging points and the population and vehicles in a given area, and (2) the average travel time to the most accessible charging station. These indicators have also been further investigated by differentiating the access type (public, public with membership and restricted to customers/workers), the charging power namely the charging speed, and the number of different operators in the market.

The results highlight the differences between European countries, which reflect the various levels of maturity of the EV markets. In this early stage, such levels are strongly related to the level of support from National policies, not only considering incentives for the deployment of electric cars, but especially for the support to a widespread network of public accessible charging points. The policy support for public charging may vary across countries, since strategies are based on the specific conditions of building types, population density, drivers' habits. These very same differences appear when focusing on the largest European cities, with a significant variability in both the average distance from a charging point and the number of installed charging points compared to the population. Additionally, differences emerge between urban and rural areas.

Our results suggest a correlation between the deployment of EV charging stations over a year and the annual sales of EVs on a country-basis. Moreover, when considering the historical evolution, the increase of charging points preceding the increase of EV sales is noticeable in most countries. Additionally, the more intense the competition between different operators in a specific region, the lower the average distance to a charging points for its citizens. While the estimated correlation cannot be directly translated into a causal relationship, these results can still be suggestive of the importance of a competitive market in improving the quality of the EV charging network. Further important aspects include the significance of the charging station access mode: operators should aim at partnering into a shared membership platform, possibly EU-wide, so that EV drivers can travel without 'range anxiety' in different regions as they would do with an ICE vehicle. This approach is gaining momentum in Europe, as several providers are currently offering to their customers the possibility of using the charging infrastructure of partner companies abroad (Ferwerda et al., 2018). For these reasons, we believe that to obtain the environmental benefits associated to an increasing penetration of EVs (in parallel to low-carbon electricity generation), dedicated strategies and policies to deploy the charging infrastructure considering the specific features of each region and area are required.

An important aspect to be discussed is the role of public charging in comparison with other solutions, including EV charging at home and workplace. Those solutions are currently representing the vast majority of EV charging in Europe (Transport & Environment, 2018), mostly due to lower electricity costs and the high number of hours during which cars remain parked. However, it is important to highlight that the current situation is one of an early market stage, in which EVs are adopted by users that have a higher comparative advantage in choosing them. In the next decades, an increased deployment of EVs in middle- and lower-income households without home-charging options, especially in urban environments, will likely require a significant public charging infrastructure. Estimations of the share of public EV charging in EU countries will increase from 5%–28% in 2020 to 47%–59% in 2030, depending on the scenario (Engel et al., 2018). These figures may vary from a country to another, depending on the share of urban and rural population, as well as on the prevalent building type: in countries with a very high share of detached and semi-detached housing, there may be less need for public charging infrastructure.

Moreover, different types of charging services are available to users based on the power level of the charging point. Fast and ultra-fast charging points are mostly installed along highways, since they are aiming at users that travel for long distances and need a quick source of energy supply. These stations thus show a low degree of flexibility in the demand and they are also charging higher prices to the customers per unit of energy supplied. Conversely, slow- and normal-speed charging points are generally used for occasional charging or a substitute for household or workplace charging for users that do not have access to those options. To account for this potential difference, we also presented our results with an additional level of detail on the power tier classification.

Additionally, in a perspective towards the decarbonization of the passenger transport, and the potential environmental benefits that are associated to this transition, it is important to note that the push towards EVs needs to be coupled to an increase of low-carbon electricity generation. The EV charging stations discussed in this paper, which exclude the household charging infrastructure, are mostly used during the day, which in some cases may cause additional power demand in peak hours (especially in the morning), with potential negative impacts on the grid that need to be addressed. Thus, proper measures need to be taken to ensure that the EV charging demand profiles can match the available power generation from renewables (Noussan and Neirotti, 2020), through the use of smart charging or other technologies providing grid flexibility. This will be particularly important for household or workplace charging. However, as discussed above, a part of the public charging infrastructure may show similar usage patterns, and thus it may require similar approaches. In general, proper planning and balance between EV charging at home or at workplace and the public charging infrastructure may further contribute to improve the sustainability of electric cars.

A final point to be addressed is the future development of V2G services, which aim at optimizing the benefits of EV batteries by providing auxiliary services to the power grid (including voltage and frequency control). Current charging infrastructure and EVs are often unsuitable for V2G operations, and to support a future V2G deployment is of paramount importance to define proper standards and targets. The deployment of a large charging infrastructure that would not be able to support V2G could represent a significant limitation for its future success. While V2G represents a promising flexibility solution, some barriers need to be addressed to ensure a widespread deployment. Those include the need of additional research on the potential impact of additional charging cycles on EV batteries lifetime, the need of additional charging infrastructure due to the increased connection times, and the little economic value that is currently associated to grid services. However, in a future scenario with high penetration of variable renewable sources, flexibility services will represent a crucial component of smart electricity systems. Moreover, the role of V2G in public charging infrastructure could remain limited, since generally long connection times of the vehicles are required and the additional investments required by this technology may not be justified in public charging business models.

5.2. Data limitations

While this large EV charging points database allows for multiple interesting insights, it is also important to acknowledge some important limitations. The database includes multiple features, but in some cases the unavailability of data in some regions or countries can limit the significance of the results. This is true for the information on the operator, the number of charging points per station, the type of station as well as the power level.

Additionally, while this is currently the most complete open source available worldwide, it remains mostly based on the work of voluntary contributors, thus potentially underestimating the actual infrastructure that is in place. This could also lead to biases across countries, due to the uneven use of this OCM in each country.

A further aspect to be mentioned is that the available information on the deployment date of the stations is related to the date in which they have been added to the database, which in some cases may include a delay from the actual date of installation. On a similar note, the absence of information on the pricing schemes for charging points, since this could have allowed to include additional analyses on competition in local EV markets. While the database included a field for pricing, the very large majority of records had no information, while the limited number of charging points with some information had non-standardized formats, that could not be used in the analysis. Additional data of pricing could prove very useful in supporting a range of indicators related to the economics of public EV charging across countries and regions.

With regards to the accessibility calculation, the friction surface layer from Weiss et al. (2020) adopted in the cumulative cost algorithm to calculate travel times *"enumerates land-based travel speed for all land pixels"*, where *"every pixel is allocated a nominal overall speed of travel based on the types occurring within that pixel, with the fastest travel mode intersecting the pixel being used to determine the speed of travel in that pixel"*. Therefore, in some instances the nominal speed reported in the layer might not accurately reflect the private vehicle travel time. However, we are not aware of similarly comprehensive friction layers that exclusively consider car journeys. Moreover, the accessibility metric is based on the GHS-POP gridded population product, which encapsulates own limitations (Schiavina et al., 2019). Granular working population data (a likely more precise indicator of travel demand than total population) would allow increasing the relevance of the estimated accessibility metric.

Overall, irrespective of these limitations, we believe that our results provide a first-order evaluation of the current state of the EV charging network in Europe which was hitherto missing in the literature. Our analysis – based on the most comprehensive available open data – is limited by the crowdsourcing nature of the database itself. We encourage European authorities to promote the development of a publicly maintained, open platform, as a basis for future research in support of EV charging strategies and policies.

6. Conclusions

The analysis carried out in this paper highlights the rapid and continuous increase of public accessible EV charging infrastructure in most European countries in the last five years, with a gradual increase of fast and ultra-fast charging points in 2019 and 2020. Such trend is in line with the increasing sales of EVs in European countries, which is even larger. In fact, our results show that the median value of the ratio between BEVs and public charging points in European countries has increased from 1.6 to 7.2 from 2015 to 2020.

As long as accessibility is concerned, about 15% of the population in the European counties considered lives >30 min away from an EV charging station, with the figure reaching one fourth of the population at >15 min. The deficit is concentrated in Spain, Greece and Eastern Europe. Although recent years have witnessed a notable expansion of the EV charging network, stark inequalities persist across and within countries, both in terms of accessibility and of the charging points available to users.

Moreover, average travel times alone are not enough to represent the effectiveness of EV charging points infrastructure, since another important indicator is the number of available points in relation to the population. Notwithstanding the continuous increase in the last years, as of 2020 most European regions have less than 0.5 EV charging points per 1,000 inhabitants, and this increasing pace of new installations needs to continue in the future to support an increase in EV fleets. The implications of our results suggest that decision makers concerned with the support to increasing EV fleets should not only focus on cities, but also guarantee an equitable access to infrastructure to citizens outside of the main urban areas, to avoid increasing the urban–rural divide. Still, it is important to remember that in rural areas household EV charging may play a more important role than in densely populated cities. Dedicated policies are required in the early stage of the EV charging market, while the support to competitive markets is generally improving the accessibility to EV charging stations.

Still, to reach effective environmental benefits in terms of climate emissions and local pollution, the deployment of a capillary charging network infrastructure needs to be coupled to additional measures to ensure an effective decarbonization of the transport system. The electricity supply to EVs need to be optimized by matching the charging profiles with the available generation from low-carbon sources, by means of smart charging strategies and other flexibility measures when needed. EV charging infrastructure should be part of a broader strategy that aims at optimizing the entire energy system.

CRediT authorship contribution statement

Giacomo Falchetta: Conceptualization, Methodology, Data curation, Formal analysis, Software, Visualization, Writing - original draft, Writing - review & editing. **Michel Noussan:** Conceptualization, Methodology, Resources, Data curation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Code and data availability

The R and Google Earth Engine Javascript code to replicate the analysis and the figures are publicly hosted at https://github.com/giacfalk/EV_charging_network_accessibility_analysis. The repository includes references to retrieve the input data.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.trd.2021.102813.

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