Received: 29 June 2023 | Revised: 4 December 2023 | Accepted: 6 December 2023

DOI: 10.1111/geoj.12570

ARTICLE

Germany's public EV charging points: Analysing the 2023 state of expansion

Stefan Neumeier | **Torsten Osigus**

Thünen-Institute of Rural Studies, Braunschweig, Germany

Correspondence
Stefan Neumeier, Thünen-Institute of Rural Studies, Bundesallee 64, Braunschweig 38114, Germany.
Email: stefan.neumeier@thuenen.de

Abstract

The European Climate Law sets a legally binding target of net zero greenhouse gas emissions by 2050. In this regard, in 2023 the EU Environmental Council decided that from 2035 onwards only CO_2-neutral new cars will be licensed in the European Union. Simultaneously, since the energy crisis caused by the Russian invasion of Ukraine, fuel prices increased in Germany. This has made more and more households think about purchasing an e-car. However, not every household has the opportunity to install their own wallbox, and when travelling long distances, e-car users are dependent on the availability of ample public charging stations. Against this background, with a special focus on rural areas, this paper considers the questions whether and where spatial inequalities in the accessibility of public charging stations might currently exist. To approach these questions, based on an empirical analysis of the 2023 official location data of public charging points in Germany, we examine the nationwide distribution, accessibility and available capacity of public charging stations in Germany at small-scale from the point of view of the 'household' as well as those who travel by e-car within Germany. In order to evaluate the location data of public charging stations we mainly use raster-based accessibility analysis methods as well as isotropic kernel intensity estimates. We found that, in contrast to the common belief, the network of public charging stations is quite dense. However, taking a closer look reveals that the charging infrastructure in Germany has so far been tailored to the needs of intra-regional travelers (commuting, shopping, leisure) rather than to those of the residential population with no access to their own wallbox (daily recharging in close proximity to one‘s home) or the mid- to long-distance travelers.

KEYWORDS

Germany, mobility transition, public charging infrastructure, raster-based accessibility analysis, rural studies

1 | INTRODUCTION

Despite a broad public debate about e-mobility in Germany, there is little reliable data available on the current status of e-mobility and the required infrastructure. With the amendment of the Climate Protection Act, the German government set the goal of becoming greenhouse gas (GHG) neutral by 2045 (Kasten et al., 2022). For the German transportation sector, this means that in 2030, a maximum of 85 tons of GHG emissions may not be exceeded. Thus, Germany has to reduce its GHG emissions by 78 million tons (48%) by 2030 as compared to 2019 (Kasten et al., 2022). As vehicular traffic is the main emitter among all modes of transportation, a reduction in GHG emissions has to occur here (Kasten et al., 2022). Furthermore, in 2023 the EU Environmental Council decided that from 2035 onwards only CO_2-neutral new cars will be licensed in the European Union (Tagesschau, 2023a). Therefore, for people currently contemplating buying a new car, an e-car could already come under consideration. In this context, the further question arises as to whether the existing public charging infrastructure (CI) is currently set up in such a way that an e-car can really replace a combustion engine. Since, so far, a small-scale spatially differentiated analysis of the current German CI does not exist, we address the question how the CI is doing and whether and where spatial inequalities in the accessibility of public charging points (CP), especially in rural areas, might currently exist. For this purpose, after a short summary on what is known so far about the German CI and e-mobility usage, the overall distribution of public charging stations (CS), based on an empirical analysis of the 2023 official location data of CP for e-cars in Germany, is analysed. Then a small-scale accessibility analysis is presented which looks at how the accessibility situation is for the population and where accessibility deficits exist.

Finally, the number of CP accessible from a given location is analysed and intra-regional differences in the available charging capacity are highlighted. Thereby, in addition to an area-wide consideration, the situation in proximity to the important regional and national traffic arteries is examined, too, to also assess how the situation is experienced when travelling on these infrastructures.

Thus, the paper presents the results of the empirical analysis of the CS location data. The paper is not aimed at presenting a comprehensive overview of the state of accessibility research or the development of new analysis tools or methods. Six sections follow the introduction. Section 2 summarizes background information on the German CI and e-mobility usage. Section 3 introduces the concept 'accessibility'. Section 4 addresses data and methodological issues. In Section 5 the findings on CS accessibility are presented and discussed. Finally, in Section 6, the findings are summarized and suggestions for improving the CI are provided.

2 | INFORMATION ON INFRASTRUCTURE AND E-MOBILITY USAGE

While the Federal Network Agency (FNA) maintains a register of CS (listing a total of 42,293 CS with 80,541 CP as of 1 January 2023; FNA, 2023) no comparable dataset on private CS (wallboxes) exists. Therefore, the number of wallboxes can only be roughly estimated on the basis of the applications for funding. According to the statistics from the National Charging Infrastructure Coordination Center, a total of 688,562 wallboxes were put into operation by 2023, and a further 285,887 wallboxes are in the planning stage (Tagesschau, 2023b). Taking these figures as a basis, together with the number of wallboxes installed in private enterprises as well as non-subsidized wallboxes, the Tagesschau (2023b) estimates that more than one million private and commercial wallboxes are available for e-cars in Germany. The Tagesschau (2023b) continues that at present, presumably one CP exists for every e-car in Germany. In contrast, others come to the less optimistic conclusion that the gap between the number of e-cars and the number of public CS is problematic as currently only about 60% of private parking spaces for e-cars have a CP, which means that more than a third of the energy required has to be made available publicly or in company parking lots (Puttkamer, 2023). Together with the finding that currently 27 e-cars have to share a single charging station, this fits to the results of a FNA survey where 69% of respondents answered that they would not buy an e-car due to a shortage of available (public) CS (Puttkamer, 2023).

As to the installation of private wallboxes, Bamberg et al. (2020) point out that this is not easily possible everywhere. That is, either the electrical installations of older buildings are not adequate for operating wallboxes without cost-intensive renovations, or in residential areas with apartment buildings there are not ample private parking spaces available for installing wallboxes (Bamberg et al., 2020). One would assume that in rural regions the installation of private wallboxes is less problematic due to the better availability of space. However, a survey by the KfW-Bank, in which 34%–38% of the rural respondents stated that they can use a private charging facility and another 25% that they do not have this ability, suggests that this is not necessarily true (Siekmann, 2022). With regard to the available CP, it is interesting to note in conclusion that, although the number of e-cars in Germany is quite high, the number of CP is rather low, both in comparison to other EU countries and in relation to the number of e-cars (Puttkamer, 2023).

Just as there is no data available on the ratio of private to public CP, there are only estimates regarding the usage and demand of private and public CP. For example, the Nationale Plattform Zukunft der Mobilität (2019, quoted by Bamberg et al., 2020) assumes that 60%–85% of the charging takes place at private, and 15%–40% at public, CP. In contrast, the Verband der Automobilindustrie e. V. (2019, quoted by Bamberg et al., 2020) assumes that in the future the share of private to public CP will amount to 60%–70% (private) and 30%–40% (public).

We know from the study 'Mobilität in Deutschland' that on average people travel 29 km per day per car, on average 15 km in metropolitan areas, where the daily travel distance is shorter than in rural areas where it is on average 30 km (Bundesministerium für Verkehr, Bau- und Wohnungswesen, 2002). Furthermore, about 40% of the daily distances are less than 20 km and only about 5% are greater than 200 km (Bundesministerium für Verkehr, Bau- und Wohnungswesen, 2002). As at present there is not enough data on e-car usage available to be able to conclusively answer whether and how the daily driving distances and driving patterns of e-cars differ from those of conventional cars (Bamberg et al., 2020).

As to charging preferences, Philipsen et al. (2016) questioned the importance of the availability of fast-CS at different possible locations, and found that motorway service stations are the most important, followed by the workplace, petrol stations and shopping facilities. The least important is the availability of CS at leisure facilities or educational institutions (Philipsen et al., 2016). E-car users show a high willingness to make a detour of about 5 km or 10 min to reach a fast-CS, but find waiting times at CS or the need to vacate a CS once the charging process is finished unacceptable (Philipsen et al., 2016). But Philipsen et al. (2016) also reported that since long-distance travelling is a major use case for the fast-charging technology, there is evidence that long detours in terms of leaving the motorway to recharge are not accepted.

As these data show, besides attractive and affordable vehicles, in addition to the existing private CI, a well-developed CI in public spaces and in proximity to important traffic arteries comparable to that of the petrol station infrastructure will also be necessary to help electro-mobility achieve a breakthrough (Lücking & Adam, 2002).

3 | THE CONCEPT 'ACCESSIBILITY'

The term 'accessibility' originated in location theory and regional planning in the 1920s and has become more popular since the 1950s (Batty, 2009). Some see in accessibility the ability to physically access goods, services and destinations (Litman, 2021; Páez et al., 2012; Saif et al., 2018). Others define it in terms of expenses measured in travel distance, time or costs to reach services (e.g, Albacete et al., 2017; Bleisch et al., 2003; Dahlgren, 2008; Great Britain Department for Transport, 2012; Hansen, 1959; Hanson, 2009; Schürmann et al., 1997; Schwarze, 2005; Vulevic, 2016). Others again differentiate between access as possibility/ability to reach opportunities and accessibility as the potential to reach opportunities (Páez et al., 2012; Rauch & Rau, 2016; Saif et al., 2018). Sometimes accessibility is differentiated into 'normative accessibility', comprising people's expectations, and 'positive accessibility', meaning the actual experiences (Páez et al., 2012). Some highlight that when dealing with accessibility it is often overlooked that accessibility is a multi-dimensional concept in which non-spatial aspects like acceptance, affordability, ability, preferences as well as human action play as important a role as spatial aspects (Clary et al., 2017; Parvin et al., 2020; Penchansky & Thomas, 1981; Rauch et al., 2023). So, as this characterization demonstrates, accessibility is not a simple one-dimensional concept, but is multifaceted.

Within this paper, accessibility is addressed as the physical access to destinations in a geographical sense. The most significant approaches to measure this physical access are (cf. Neumeier, 2022):

- the generation of supply indicators, measuring the length of the traffic network, the number of infrastructure locations within a region, etc. (Neumeier, 2022; Spiekermann & Wegener, 2008);
- gravity models considering the decrease in accessibility by increasing travel costs (Handy & Niemeier, 1997);
- opportunity models, focusing on the cumulative amount of opportunities reachable from a given location within a defined travel time (Chen et al., 2011);
- utility models, measuring accessibility on an individual level (Handy & Niemeier, 1997);
- spatial interaction models, measuring flows between locations (Bleisch, 2005; Rodrigue, 2020; Schulz & Bröcker, 2007); and
- measurements of geographic accessibility, either focusing on the number of reachable opportunities within Euclidean

distances to a given location or on incurring costs within traffic networks (Geurs & Ritsema van Eck, 2001; Geurs & van Wee, 2004; Hemetsberger & Ortner, 2008).

Although supply indicators are easy to acquire, they are a simplistic measurement, as they are neither sensitive for intra-regional differences in infrastructure provision, nor do they take into consideration the traffic network to be used to reach the infrastructure location or existing connections between regions (Neumeier, 2022; Spiekermann & Wegener, 2008). Gravity, opportunity, utility and spatial interaction models deliver complex accessibility values that are somewhat distant from real life and difficult to interpret without knowledge of the specific models used and assumptions made. In contrast, measurements of geographic accessibility come close to real life and can generally be understood and interpreted without any prior knowledge. Therefore, to analyse the accessibility situation of CP as experienced by people living in Germany, it was decided to focus on geographic accessibility by measuring travel time, respectively the number of available opportunities within defined travel time windows, in the traffic network for the mode of transport car.

4 | DATA AND METHODOLOGY

The empirical analysis draws on following data:

- The Thünen-Typology of Rural Areas (Küpper, 2016).
- Location data of public CS 01/2023 (FNA, 2023).
- CS statistics (FNA, 2023).
- Statistics on registered motor vehicles and trailers 01/2022 (Kraftfahrt Bundesamt, 2023).
- Roads of national and intra-regional importance (RoI) (OpenStreetMap).
- A 250×250 m INSPIRE[1] compliant analysis grid (6,114,413 grid cells) covering the area of Germany, enriched with official population information of the latest (2011) 100×100 m census grid,[2] as well as the region types of the Thünen-Typology.
- The car traffic network and velocity profiles of the OpenStreetMap

4.1 | Thünen-Typology of Rural Areas

The Thünen-Typology of Rural Areas was developed by the Thünen-Institute of Rural Studies in 2016 at the administrative level of the 'Kreisregionen'.[3] Based on selected structural indicators (low population density, loosely structured residential buildings, dominance of agricultural and forestry areas, low number of inhabitants, peripheral location), it differentiates rural areas from non-rural areas (Küpper, 2016). Therefore, the lower the settlement density and population potential; the higher the share of agricultural and forest land and single- and two-family houses; and the worse the accessibility to large centres is, the more pronounced the rurality (Küpper, 2016). Subsequently, using selected socioeconomic indicators (average unemployment rate, average gross wages and salaries, median income, average municipal tax revenue, average net migration balance of 18–29 year olds, vacancy rate of housing, average life expectancy of women, average life expectancy of men, average high school dropout rate), the rural areas are further discriminated by whether they are in a good, respectively less good, socioeconomic situation (Küpper, 2016). By combining the resulting rural dimensions with the non-rural region type, one gets the following five types of rural areas (see Figure 1): 'very rural regions with less good socioeconomic situation' (16% population, 38% area), 'very rural areas with good socioeconomic situation' (11% population, 17% area), 'rather rural areas with good socioeconomic situation' (16% population, 15% area), 'rather rural areas with less good socioeconomic situation' (14% population, 21% area) and 'non rural areas' (43% population, 9% area; Küpper, 2016).

4.2 | Public charging station locations

The data on CS as of 1 January 2023 were obtained from the coordinating office of the FNA.[4] The dataset contains the geocoded CS locations together with the number of available charging points of all operators who have completed the notification procedure, and have agreed to publication on the Internet. CS for which the providers objected to publication

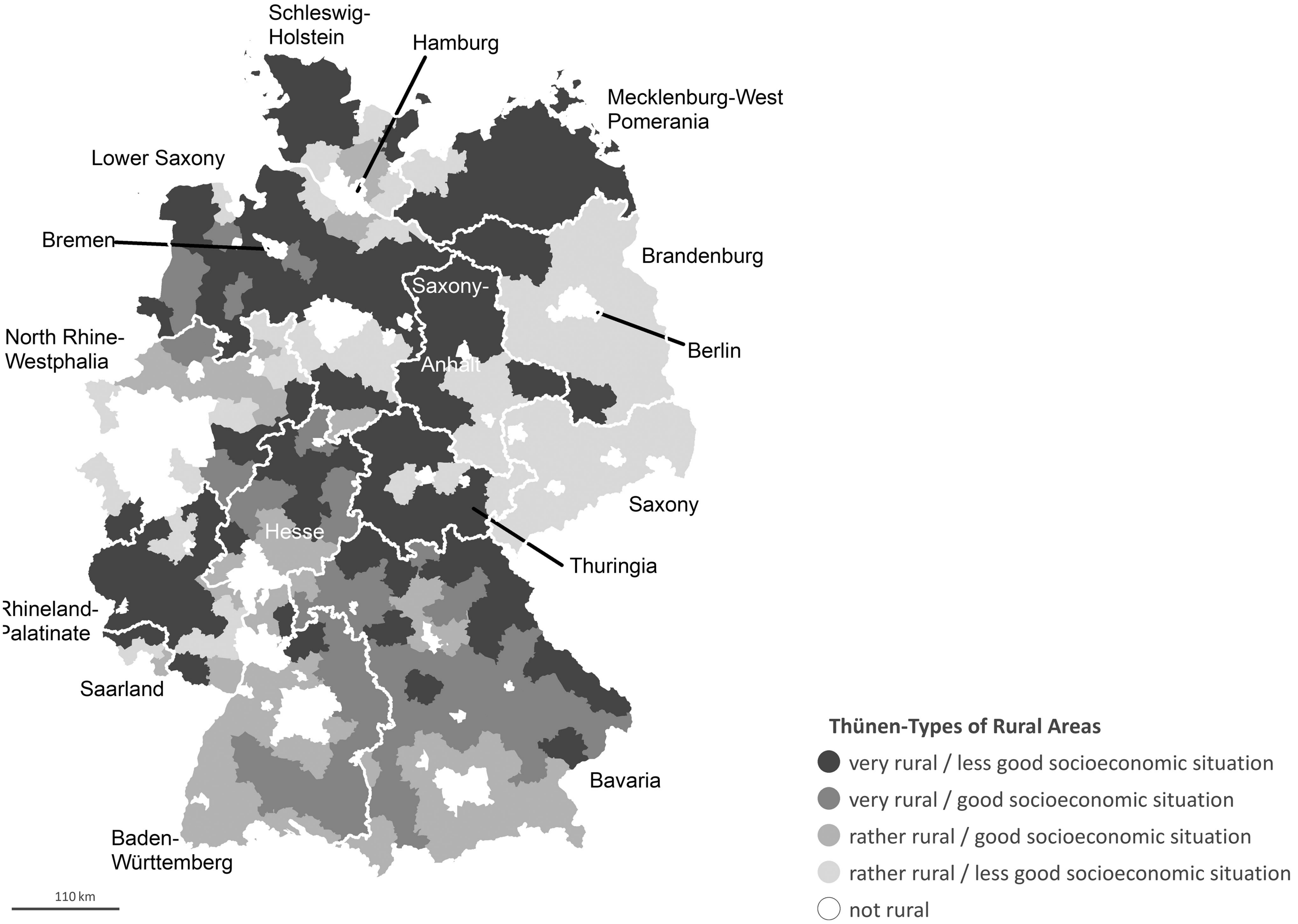


FIGURE 1 Thünen-Types of Rural Areas (*source*: Küpper, 2016; Administrative Boundaries, © GeoBasis-DE/BKG (2023); calculation by the authors).

are excluded. These are mainly operated by private persons who are registered as public solely for the purpose of siphoning off the GHG compensation, but who have actually no real interest in others utilizing their CS. The dataset contains 40,674 CS with a total of 77,285 CP. According to the FNA (2023), 42,293 CS with 80,541 CP existed as of 1 January 2023. So, 1619 CS (−3.8%) are missing from the dataset, whereby it can be assumed that the majority of these are CS where the providers objected to publication. A comparison of the number of CP per federal state as reported by the FNA (2023) with the number of data entries in our 2023 dataset reveals that the overall deviation of CP entries in the analysis dataset from the actually existing CP is, at −4% (3256), quite small and quite evenly distributed between the different federal states, with the strongest deviation in Thuringia (−9%) followed by North Rhine-Westphalia (−5.58%) and Saarland (−5.53%). The same is true when differentiating between normal charging equipment (charging power ≤ 22 kW) and fast-charging equipment (charging power > 22 kW; see Table S0).

4.3 | Accessibility model

The Thünen-Accessibility Model (Neumeier, 2022) was developed for policy advice concentrating on the determination of travel costs/time for the mode of transport 'foot', 'bicycle', 'car' and 'public transport' within the corresponding traffic networks for an individual to reach the closest infrastructure facility from the place of residence. The model is meant to answer the question of whether a specific service is available within a certain commonly accepted travel time or distance. Thus, it can deliver insight into the general accessibility situation as it presents itself for households. However, the model focuses on modelling accessibilities at the macro level of Germany. Hence, it represents a balanced compromise between feasibility and detail with regard to computation costs, available base data, etc. This means additional details that can be incorporated in analysing accessibilities at the micro level of a case study region are practically and/or technically out of scope for the nationwide modelling approach as either the necessary input data is not available nationwide (e.g., individual preferences, perceptions; service quality; options of choice; real-time traffic) or the necessary computation costs exceed what is feasible and reasonable (e.g., daily/weekly averages).

To be able to obtain small-scale scalable results, the model uses a 'raster-based modelling approach.' This means the accessibility is calculated for the single cells of a grid with a resolution of 250 × 250 m, enriched with population information with which the area of interest is overlain.

For the analysis the centroids of the grid cells are the sources, the CP locations are the sinks. Populated grid cells represent households. The model determines the shortest travel time to a sink for every source to obtain accessibility values for the mode of transport of interest.

Technically the calculation is performed by the Open Source Routing Machine with a traffic network based on the OpenStreetMap incorporated with the route and velocity profiles for the analysed mode of transport. To reduce the number of necessary calculations from all infrastructure locations to all 6.1 million grid cells, the actual accessibility analysis is conducted initially by a k-nearest-neighbour analysis identifying the 10 closest (by Euclidean distance) sinks per grid cell. Subsequently for every grid cell, the travel time to these 10 sinks is computed. Finally, the shortest computed travel time is assigned to the grid cell as the 'accessibility' value for the infrastructure under consideration. The decision to concentrate on the 10 closest sinks within the data reduction cycle is based on experiences and represents a compromise between incurring computation costs and the avoidance of potential inconsistencies in the analysis.

In this paper, 'accessibility' is designated as travel time by car. If interest is in travel distance instead, an average speed of 33 km/h to convert travel times to distances is a suitable reference as in Germany this corresponds to the door-to-door travel speed averaged over all road types (Bundesministerium für Verkehr, Bau- und Wohnungswesen, 2002).

5 | HOW IS THE PUBLIC CHARGING INFRASTRUCTURE DOING?

Between 2010 and 2023, the number of CP in Germany increased from 308 to 80,541 (+80,233; see Figure S0). In the same period the number of CP with standard-charging equipment shows an increase of +66,980 and the fast-charging equipment shows a weaker development with an increase of only +13,253 CP (FNA, 2023). On 1 January 2023, there existed 42,293 CS with 80,541 CP (FNA, 2023). Counting the unique locations in our dataset reveals that the CS are distributed across approximately 32,827 locations.

5.1 | Spatial distribution

The spatial distribution of CP is evident from the isarithmic maps of CP location clustering in Figure 2a3,a4. These maps are based on the calculation of an isotropic kernel intensity estimate of the point patterns of the CP. Jittering was applied to duplicate points, the Gaussian smoothing function was used and the bandwidth selection is based on Scott's rule. In the maps two facts can be identified: First, a west–east difference with a higher clustering of CP in the western part of Germany in all three maps; second, a high clustering of CP around the metropolitan areas Hamburg, Berlin, the Ruhr Area, the Frankfurt-Mannheim-Wiesbaden area, Stuttgart and Munich and to a lesser extent around Hannover-Braunschweig, Nuremberg and Dresden-Leipzig-Chemnitz in the total-CP and normal-CP maps. While the clustering pattern around the metropolitan areas Hamburg, Berlin, the Ruhr Area, Stuttgart and Munich can also be identified in the map of the fast-CS, the clustering around the Frankfurt-Mannheim-Wiesbaden, Hannover-Braunschweig, Nuremberg and Dresden-Leipzig-Chemnitz areas is only poorly pronounced here. The comparison of the maps of normal-CP and fast-CP shows that throughout Germany the cluster density per km^2 is lower for fast-CP.

Detailed information on the distribution of the number of CS locations, CS, CP (as of 1 January 2023) among the different rurality types of the Thünen-Typology is provided in Table 1. In addition, the table lists the registered motor vehicles and trailers in Germany as of 1 January 2022 differentiated by types of fuel and relates them to the CI.

In Germany, 98% of the motor vehicles are powered by conventional fuels. The share of e-powered vehicles of all motor vehicles is just 2.4%. Interestingly, the share of e-powered vehicles of all motor vehicles is similar in rural regions (1.3%) and non-rural regions (1.2%). Measured by the registered motor vehicles in the different region types only, it is interesting that the share of e-powered vehicles is slightly lower in the rural regions with 'less good socioeconomic situation.' The percentage of registered e-powered vehicles in rural areas as a share of all registered motor vehicles in rural

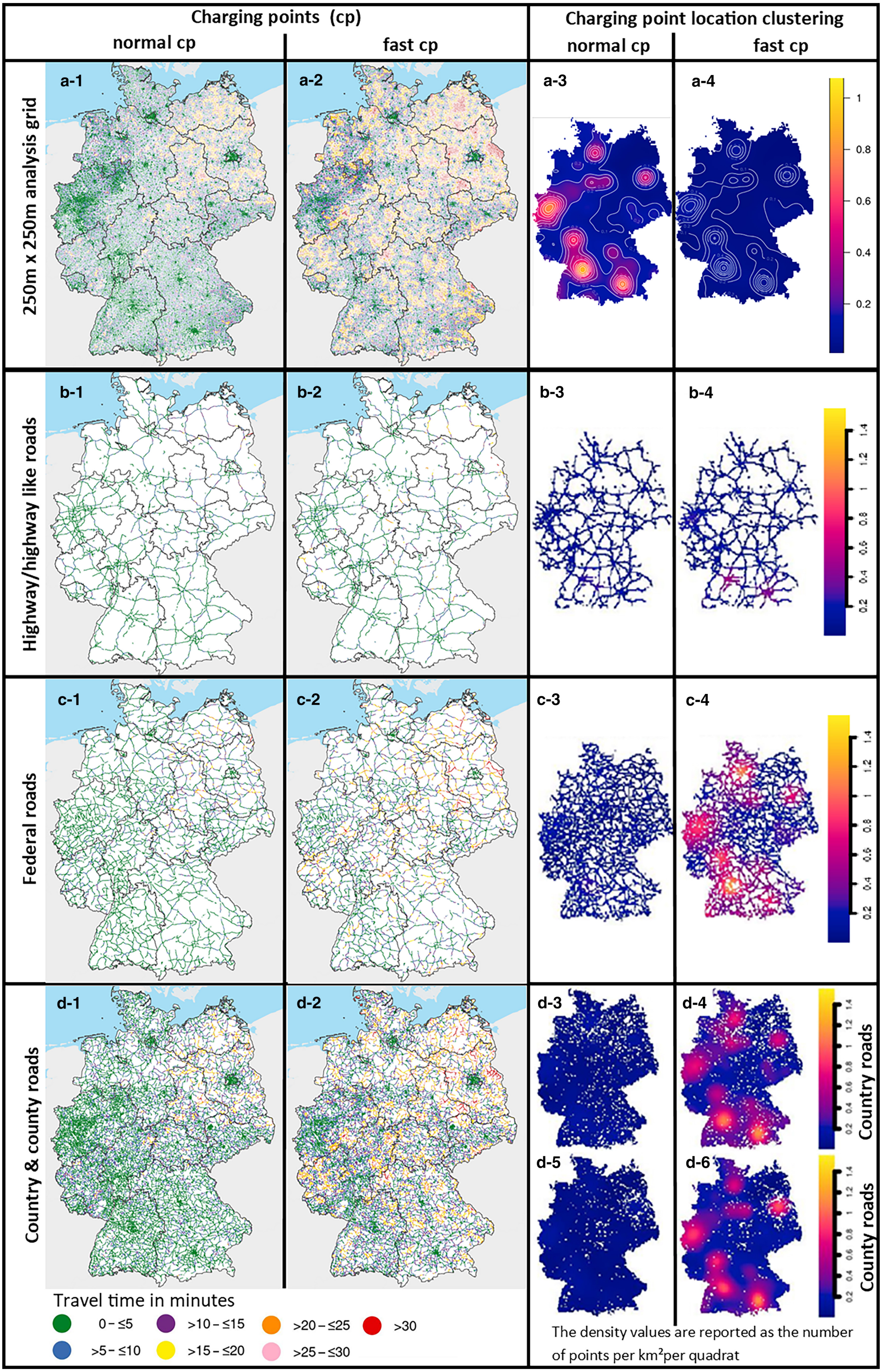


FIGURE 2 Accessibility of public CP in Germany and isarithmic maps of CP location clustering in Germany. (*sources*: CS locations, FNA, 2023; OpenStreetMap; Administrative Boundaries, © GeoBasis-DE/BKG (2023); calculation by the authors).

TABLE 1 Distribution of CS locations, CS, CP (01/2023) among the different rurality types of the Thünen-Typology in relation to the registered motor vehicles and trailers in Germany as of 1 January 2022 differentiated by types of fuel.

	Motor vehicles powered by gas, diesel, propane, hybrid			e-powered motor vehicles, plug-in-hybrid		
Thünen-types of rural areas	**Number in 1000**	**% of all motor vehicles**	**% of all motor vehicles in region type**	**Number in 1000**	**% of all motor vehicles**	**% of all motor vehicles in region type**
Very rural/less good socioeconomic situation	8072	16.6	98.2	146	0.3	1.8
Very rural/good socioeconomic situation	5892	12.1	97.8	131	0.3	2.2
Rather rural/good socioeconomic situation	8221	16.9	97.5	211	0.4	2.5
Rather rural/less good socioeconomic situation	7085	14.6	98.3	123	0.3	1.7
Rural total	29,270	60.3	97.9	612	1.3	2.0
Not rural	18,035	37.2	96.9	571	1.2	3.1
Germany total	47,346	97.5	97.5	1184	2.4	2.4
Motor vehicles not assigned to any region	41	0.1	97.1	1	0.0	2.9

Note: In the statistics of the registered motor vehicles and trailers in Germany as of 1 January 2022 differentiated by types of fuel, published by the Kraftfahrt Bundesamt, there is data missing for the district Trier.

Sources: CS information FNA, 2023; Registered motor vehicles and trailers in Germany as of 1 January 2022 differentiated by types of fuel, Kraftfahrt Bundesamt, 2023; calculation by the authors.

areas is, at 2.0%, only slightly lower than that of registered e-powered vehicles in non-rural areas as a share of all registered motor vehicles in non-rural areas, where it is 3.1%.

As for CS locations, it can be observed that approximately 55% are located in rural areas and 45% in non-rural areas. The ratio is similar when considering single charging stations (53% rural, 47% non-rural) or charging points (54% rural, 46% non-rural). When considering the different rurality types, it can be observed that the share of CS locations, CS and CP is highest in 'rather rural regions with good socioeconomic situation' and lowest in 'rather rural regions with less good socioeconomic situation'. Considering the higher consumer prices for e-cars one would assume that providers of CS would be more interested in developing the CI in more prosperous regions as higher demand can be assumed there. Therefore, it is counterintuitive that the share of CS locations and CP is the second highest in 'very rural regions with less good socioeconomic situation'.

Considering that the effective range of most e-cars is restricted to 250 km for e-cars in the lower price ranges and 350 km for e-cars in the higher price ranges, users of e-powered vehicles are dependent on the availability of CP in close proximity to RoI (EV Database, 2020). As such to get an impression of the charging situation for travellers on RoI, an overview of the availability of CP in close proximity to such roads in different types of rural regions is given in Table 2. As the available data do not allow us to determine CP that are directly accessible from RoI, it was decided to determine the share of CP in proximity to RoI by extracting highways and highway-like roads (highways) (Autobahnen, Schnellstraßen),[5] federal roads (Bundesstraßen),[6] country roads (Landstraßen)[7] and county roads (Kreisstraßen)[8] from the OpenStreetMap (OSM) and to determine the number of CP located within a buffer of 300 m around the roads of each type afterwards. We decided on a 300 m buffer to also include CP in proximity to the RoI, but where one has to leave these roads in order to reach them (e.g., CP at a service station) and not to include too many CP that are located next to the RoI, but which are not accessible from these roads.

Generally, in proximity to highways, the share of fast-CP (36%) is higher than that of normal-CP (9%). In rural areas with a 'good socioeconomic situation' the share of fast CP in proximity to highways is higher than in rural areas with a 'less good socioeconomic situation'. Altogether, in rural areas 39% of the fast-CP and 6% of the normal-CP are in proximity to highways. Considering federal roads, the difference in the share of normal-CP and fast-CP near these roads is lower than that near to highways. Interestingly, here, the share of fast-CP near federal roads is slightly higher in the rural region types with 'less good socioeconomic situation'. However, the differences are not too large.

Motor vehicles powered by other fuels			Charging station locations		Charging stations		Charging points	
Number in 1000	% of all motor vehicles	% of all motor vehicles in region type	Number	% of all charging stations	Number	% of all charging stations	Number	% of all charging stations
2	0.004	0.022	4584	14.0	5486	13.5	10,700	13.8
1	0.002	0.016	4092	12.5	5094	12.5	9585	12.4
1	0.003	0.017	5613	17.1	6819	16.8	13,265	17.2
2	0.004	0.027	3626	11.0	4123	10.1	8038	10.4
6	0.013	0.021	17,915	54.6	21,522	52.9	41,588	53.8
4	0.008	0.021	14,912	45.4	19,152	47.1	35,697	46.2
10	0.021	0.021	32,827	100.0	40,674	100.0	77,285	100.0
0.007	0.000	0.017						

The highest shares in CP can be found near country roads with 52% of the normal-CP and 53% of the fast-CP. The situation for county roads is similar to that of country roads albeit the shares of CP near this road type is lower. As to the rurality types, differences exist for all road types, but, in general, the deviation in the accessible share of CP is relatively small.

The spatial distribution of CP in close proximity to RoI can be taken from the isarithmic maps of CP clustering in Figure 2b3,b4,c3,c4,d3–d5. These maps are based on an isotropic kernel intensity estimate of CP along RoI. Jittering was applied prior to the analysis, the Gaussian smoothing function with a two-dimensional kernel was used and the bandwidth was determined by Scott's rule. As can be seen, fast-CP are mainly clustered around road segments of RoI within the greater metropolitan areas, that is Hamburg, Berlin, the Ruhr Area, the Frankfurt-Mannheim-Wiesbaden area, Stuttgart and Munich and to a lesser extent around Hannover-Braunschweig, Nuremberg and to an even lesser extent Dresden-Leipzig-Chemnitz. The cluster density of fast-CP is most pronounced around Stuttgart and Munich. However, the cluster density results of CP in proximity to RoI is thought-provoking considering the observation that along roads with special importance for long-distance travel, that is highways and federal roads, the share of CP in proximity is the least among all road types analysed. In contrast, roads of special intra-regional importance, that is country roads and county roads, have the highest level of CP in their vicinity.

5.2 | Accessibility

In this section, the focus shifts from the general view to a more detailed spatial analysis. The maps at the top of Figure 2a1,a2 show the travel time by car to the travel time to the next CP for populated cells of the analysis grid (grid cells with population values of zero are also shown, but with a reduced opacity). That allows us to roughly assess the accessibility situation at the small scale as it applies to the people.

The maps reveal that in great parts of the settlement areas, CP are accessible within 10 min travel time. But the maps also show that especially in the federal states of Mecklenburg-West Pomerania and Brandenburg, as well as greater parts of Saxony-Anhalt, CP are comparatively poorly accessible.

TABLE 2 CP within 300 m distance to RoI by different types of rural areas.

	Number of charging points		% accessible within 300 m around: Highways/highway-like roads (Autobahnen/ Schnellstraßen)		Federal roads (Bundesstraßen)		Country roads (Landstraßen)		County roads (Kreisstraßen)		Highways, highway-like streets, federal roads, country roads, county roads	
Thünen-types of rural areas	**Normal-charging point**	**Fast-charging point**	**Normal-charging point**	**Fast-charging point**	**Normal-charging point**	**Fast-charging point**	**Normal-charging point**	**Fast-charging point**	**Normal-charging point**	**Fast-charging point**	**Normal-charging point**	**Fast-charging point**
Very rural/less good socioeconomic situation	8482	2218	3.6	37.2	27.3	38.2	46.1	42.6	45.5	38.8	86.1	93.6
Very rural/good socioeconomic situation	7642	1943	6.8	45.2	19.0	31.7	54.1	50.7	53.2	42.6	89.0	95.5
Rather rural/good socioeconomic situation	10,946	2319	5.8	41.4	21.3	33.3	49.0	49.2	51.0	38.9	87.3	95.7
Rather rural/less good socioeconomic situation	6175	1863	6.8	30.1	24.8	35.4	44.9	45.3	48.1	38.3	84.3	94.2
Rural total	33,245	8343	5.6	38.7	16.0	24.5	48.7	46.9	49.6	39.6	86.8	94.8
Not rural	30,428	5269	12.8	31.4	27.5	37.3	54.5	62.0	55.3	52.6	91.3	96.8
Germany total	63,673	13,612	9.1	35.8	21.5	29.5	51.5	52.8	52.3	44.6	89.0	95.6

Sources: CS information FNA, 2023; Street Network Open Street Map – Geofabrik download germany-latest.osm.pbf 13.04.2023; calculation by the authors.

TABLE 3 Average accessibility of charging points and accessibility of charging points by population within defined travel time windows in different types of rural regions (populated grid cells of the 250 × 250 m analysis grid).

	Median travel time in minutes						Travel time by car in minutes																				
	Populated cells of the analysis grid			All cells of the analysis grid			0–≤5			>5–≤10			>10–≤15			>15–≤20			>20–≤25			>25–≤30			>30		
	Type of charging point (T: Total; F: Fast; N: Normal)																										
							T	F	N	T	F	N	T	F	N	T	F	N	T	F	N	T	F	N	T	F	N
Thünen-types of rural areas	T	F	N	T	F	N	Population in % (census 2011)																				
Germany total	5	10	5	7	12	7	80.0	43.6	77.6	16.1	33.2	17.7	3.1	13.9	3.6	0.6	5.5	0.8	0.1	2.2	0.2	0.0	0.9	0.1	0.0	0.6	0.0
Very rural/ less good socioeconomic situation	6	12	7	8	14	9	60.7	25.3	57.6	27.9	28.0	29.2	8.4	22.6	9.6	2.2	13.3	2.7	0.5	6.2	0.7	0.1	2.9	0.2	0.1	1.8	0.1
Very rural/good socioeconomic situation	5	10	5	6	12	6	71.0	30.5	67.9	24.3	32.8	26.6	4.2	22.4	4.9	0.4	9.3	0.5	0.1	3.2	0.0	0.0	1.0	0.0	0.0	0.8	0.0
Rather rural/good socioeconomic situation	4	9	4	5	11	6	83.1	35.3	80.8	15.3	39.4	17.3	1.5	18.1	1.7	0.1	5.5	0.2	0.0	1.3	0.0	0.0	0.4	0.0	0.0	0.1	0.0
Rather rural/less good socioeconomic situation	6	10	6	8	13	8	68.5	32.9	64.4	24.1	34.3	25.8	5.7	18.3	7.3	1.2	7.6	1.9	0.3	3.9	0.4	0.1	1.7	0.1	0.0	1.4	0.0
Not rural	3	6	3	4	7	4	92.7	60.9	91.2	6.9	32.7	8.3	0.3	5.3	0.4	0.0	0.9	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rural total	5	11	6	7	13	7	70.7	30.9	67.6	22.8	33.6	24.6	5.0	20.2	6.0	1.1	9.0	1.4	0.2	3.7	0.3	0.1	1.5	0.1	0.0	1.0	0.0

Source: Calculation by the authors.

Table 3 summarizes the spatial pattern depicted in the maps for different types of regions. For each region type the table shows the median travel time to the next CP as well as the share of population that is able to access the next CP within the travel time windows indicated. An extended version of this table for the federal states is included in the supporting information (see Table S1). Altogether, on average, one needs to travel 5 min when considering the populated cells of the analysis grid, respectively 7 min when considering all cells of the analysis grid to reach the next CP, respectively, normal-CP. To the next fast-CP one has to travel on average 10 min when considering the populated cells of the analysis grid only and 12 min when considering all cells of the analysis grid. Altogether the median travel times in non-rural areas (CP: 3 min; normal-CP 3 min; fast-CP 6 min in populated cells/CP: 4 min; normal-CP 4 min; fast-CP 7 min in all cells) are about the half of the median travel times in rural areas (CP: 6 min; normal-CP 6 min; fast-CP 11 min in populated cells/CP: 7 min; normal-CP 7 min; fast-CP 13 min in all cells). The differences in the median travel times between the rural region types are relatively small. Eighty per cent of the population can reach the next CP, 78% the next normal-CP and 44% the next fast-CP within a maximum travel time of 5 min by car. As to the share of the population that can reach the next CP within a specific travel time window, 93% of the people living in non-rural areas and 71% of those living in rural areas can reach the next CP within a maximum travel time of 5 min. Within a maximum travel time of 10 min, 96% of the population can access a CP, 77% a fast-CP and 95% a normal-CP. While in the non-rural as well as rural regions over 90% of the people can access a normal-CP, the share of people that can access a fast-CP within this time window differs considerably between rural (65%) and non-rural regions (94%). The share of people that can access the next fast-CP within a maximum travel time of 5 min is 31% in rural regions and 61% in non-rural regions, which is lower than that who are able to reach the next normal-CP (68% rural, 91% non-rural). The share of people that can reach the next CP within a maximum travel time of 5 min is least in rural regions with a 'less good socioeconomic situation' (61% 'very rural/less good socioeconomic situation'; 69% 'rather rural/less good socioeconomic situation'). At least 15% of the people living in rural areas have to travel more than 15 min to reach a fast-CP. Again, in the rural region types with 'less good socioeconomic situation' the share of people who have to travel more than 15 min to reach the next fast-CP is highest (24% 'very rural/less good socioeconomic situation'; 15% 'rather rural/less good socioeconomic situation') closely followed by that of the type 'very rural/good socioeconomic situation' where the share of people that needs to travel more than 15 min to access the next fast-CP is 14%.

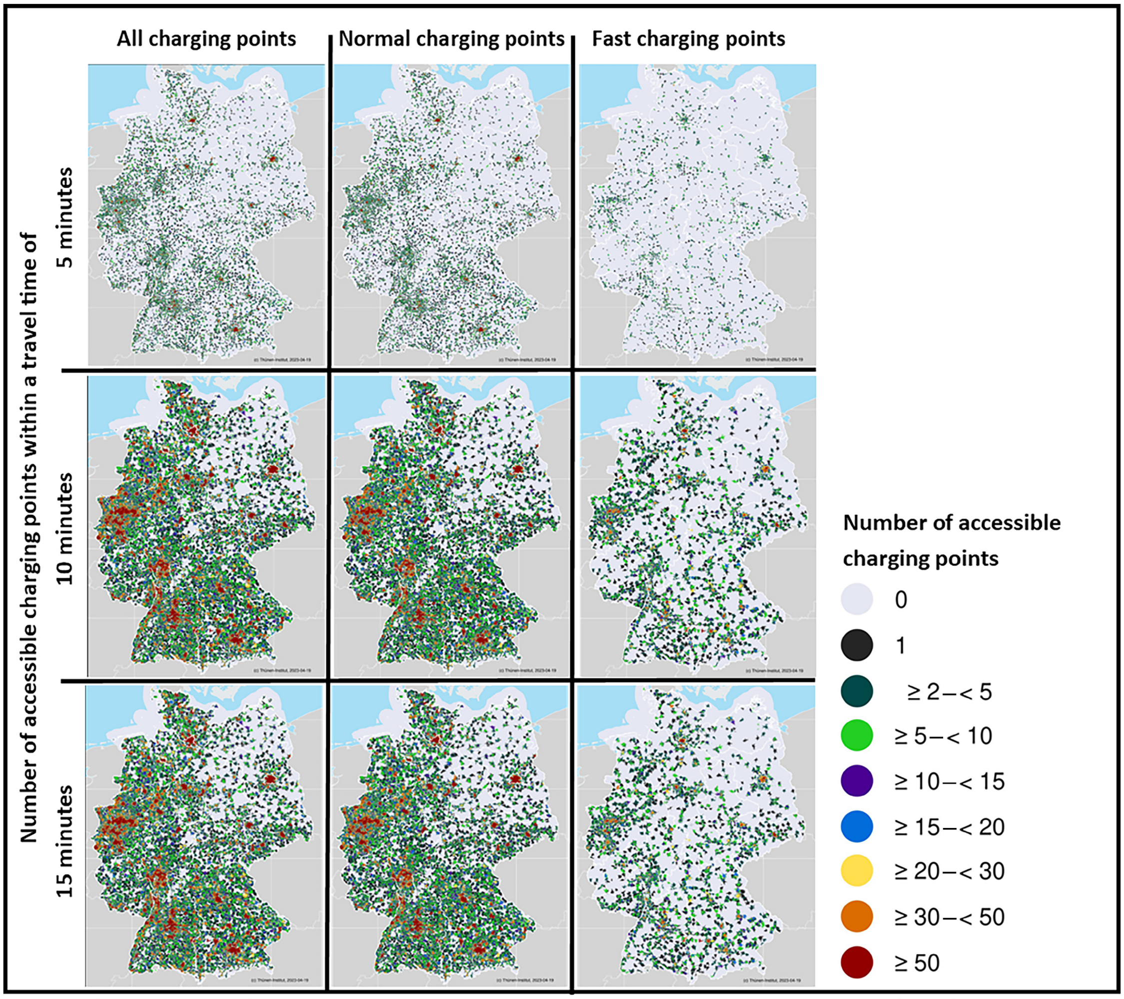
This allows the conclusion that the spatial distribution of CP locations is quite well developed with CP locations generally relatively well accessible, albeit with exceptions, especially in greater parts of Brandenburg, Mecklenburg-West Pomerania and Saxony-Anhalt. However, in rural areas and especially in 'rural areas with a less good socioeconomic situation', fast-CP locations seem to still be in short supply.

The maps in the middle and bottom row of Figure 2b1,b2,c1,c2,d1,d2 show the accessibility of the next CP by car travel time but, in contrast, it is not the populated cells of the analysis grid that are highlighted, but the cells that are crossed by RoI. This allows us to roughly assess the accessibility situation as it especially applies to people travelling mid- to long distances. Additional maps showing the accessibility of the next CP by car separately for the five road types being considered are presented in Figures S1–S4. Many grid cells of the analysis grid crossed by RoI have accessibility values in the 0–5 as well as the 5–10 min ranges. However, throughout all federal states and road types, one can also identify grid cells crossed by road sections with accessibility values with higher values. Travel times to CP from grid cells crossed by roads of intra-regional importance (Figure 2d1,d2) are in general shorter than travel times to CP from grid cells crossed by national traffic arteries (Figure 2b1,b2,c1,c2).

Apart from this, first, the maps also show a distinct difference in the accessibility of normal-CP and fast-CP. Throughout all federal states, regions can be identified with longer travel times to the next fast-CP. In a spatial sense, larger contiguous areas where this applies can be found in Mecklenburg-West Pomerania, Brandenburg and Saxony-Anhalt. Second, the accessibility patterns depicted in the maps indicate that fast-CP are better accessible from roads of national importance than from many road sections of roads of intra-regional importance. This suggests that the fast-CI is not as well developed as the normal-CI, but that it is especially tailored to meet the demand of mid- to long-distance travellers dependent on the availability of fast-charging opportunities in order to reach their destination in a reasonable overall travel time.

5.3 | Number of charging options available

Finally, using r5r's[9] accessibility function, we calculated the number of charging options available within the travel time windows up to 5, up to 10 and up to 15 min, for each cell of the analysis grid to determine the available charging



Average (arithmetic mean) number of accessible CP within defined travel time windows in minutes (x-axis) differentiated by rural and non-rural regions

level of analysis	type of area	all charging points					normal-charging points					fast-charging points				
		minutes travel time by car														
		5	10	15	20	25	5	10	15	20	25	5	10	15	20	25
		number of accessible charging points														
a) Average (arithmetic mean) number of accessible CP in populated cells of the analysis grid within defined travel time windows in minutes differentiated by rural and non-rural regions																
populated cells of the analysis grid	Germany total	4.8	26.3	73.9	155.4	277.0	4.0	21.8	60.7	127.2	226.7	0.8	4.6	13.3	28.3	50.4
	not rural	14.0	84.2	237.2	484.0	831.7	11.9	71.7	200.6	407.4	698.8	2.0	12.6	36.7	76.8	133.4
	rural total	2.9	14.6	40.7	88.7	164.4	2.4	11.6	32.3	70.3	130.9	0.5	2.9	8.5	18.4	33.5
b) Average Number of accessible charging-points, normal-CP and fast-CP within defined travel time windows in minutes differentiated by rural and non-rural regions as well as types of roads of national and intraregional importance																
traffic arteries total	Germany total	4.6	25.0	69.6	145.9	259.2	3.8	20.4	56.7	118.6	210.9	0.8	4.5	13.0	27.3	48.4
	not rural	16.0	93.3	257.1	518.2	879.5	13.6	79.3	217.4	436.4	739.6	2.4	14.0	39.9	82.1	140.4
	rural total	2.8	14.4	40.6	88.2	163.0	2.2	11.3	31.8	69.4	129.0	0.6	3.1	8.8	18.9	34.1
highway/ highway-like roads	Germany total	5.4	37.9	114.1	243.6	428.5	4.0	29.9	91.6	197.8	350.1	1.4	8.0	22.5	46.0	78.6
	not rural	11.7	89.9	275.5	583.1	995.4	9.6	75.6	232.3	492.5	840.1	2.2	14.3	43.4	90.9	155.9
	rural total	3.3	20.7	60.6	131.2	240.7	2.1	14.8	45.0	100.1	187.8	1.1	5.9	15.6	31.1	53.0
federal roads	Germany total	6.7	32.3	80.7	157.8	269.1	5.4	26.6	66.2	129.1	219.7	1.2	5.7	14.5	28.9	49.6
	not rural	22.7	120.1	301.0	569.9	934.4	19.3	102.4	255.2	480.1	784.9	3.4	17.8	45.9	90.1	150.1
	rural total	4.1	18.4	45.9	92.8	164.1	3.2	14.6	36.4	73.7	130.5	0.9	3.8	9.6	19.2	33.7
country roads	Germany total	5.4	27.7	75.7	157.1	276.6	4.5	22.9	62.0	128.2	225.7	0.9	4.8	13.7	28.9	51.0
	not rural	18.7	103.5	277.5	551.4	925.8	16.1	88.5	235.5	465.5	779.9	2.6	15.0	42.1	86.2	146.5
	rural total	3.2	14.8	41.2	89.7	165.7	2.6	11.7	32.4	70.7	131.1	0.6	3.1	8.9	19.1	34.7
county roads	Germany total	4.3	23.6	65.8	137.4	244.7	3.6	19.4	53.6	111.6	198.9	0.7	4.3	12.3	25.9	45.9
	not rural	17.0	96.1	257.8	509.2	857.2	14.5	81.5	217.4	427.6	719.1	2.5	14.6	40.5	81.8	138.5
	rural total	2.5	13.3	38.6	84.7	157.8	2.0	10.5	30.4	66.8	125.1	0.5	2.8	8.3	17.9	32.8

FIGURE 3 Number of accessible CP, normal-CP and fast-CP within defined travel time windows and arithmetic mean of accessible CP within defined travel time windows differentiated by rural and non-rural regions. (*Sources*: CS locations, FNA, 2023; Administrative Boundaries, © GeoBasis-DE/BKG (2023); calculation by the authors).

capacity. Considering the accessibility nationwide, the result shows a spatially differentiated distribution pattern (Figure 3: Table (a)). First, the average number of accessible fast-CP is lower throughout all travel time windows than that of the normal-CP. Second, for both normal-CP and fast-CP, the average number of accessible CP is greater in non-rural regions than in rural regions. In addition, the average number of accessible CP is lower for both normal-CP and fast-CP in the rural regions types with 'less good socioeconomic situation' (see Table S2). This difference is less pronounced between rural regions with a 'good' respectively a 'less good socioeconomic situation' in the lower travel time windows (up to 5 and up to 10 min) than in the higher ones and less pronounced for fast-CP than for normal-CP (see Table S2). However, this observation might be an effect caused by the more wide-meshed locational grid together with the lower number of fast-CP. These observations suggest that the CI is better developed in non-rural regions than in rural regions with a higher available number of CS with a comparable proportion of e-powered cars to be served (see also Table 1). The maps of charging options available confirm this urban–rural difference as to the accessibility and availability of CP as well as to the difference between normal-CP and fast-CP. But in addition, they also allow the regions with a comparatively less developed overall CI to be identified (see Figure 3). These can be found throughout all federal states, but larger contiguous regions can be identified most notably in Mecklenburg-West Pomerania, Brandenburg and Saxony-Anhalt. In comparison to the normal-CP, the significantly lower supply with regard to accessibility and number of charging options available of fast-CP is particularly noticeable, especially within the lower travel time windows of up to 10 min.

As the range of the majority of e-powered cars, and especially those of the compact and lower middle-sized class, is to date considerably lower (EV Database, 2020) than that of cars with a conventional engine, the availability of ample CP along and in proximity to the important traffic arteries is a key requirement for being able to also efficiently use e-cars for travelling mid- to long distances.

To get an idea of how the charging situation presents itself along these traffic arteries supplementary to the investigation of the number of charging options available in inhabited regions, the number of accessible CP in proximity to RoI were analysed (see Figure 3: Table (b) as well as Tables S3–S7). The pattern already registered when analysing average numbers of accessible CP in inhabited regions can also be observed when considering the average numbers of accessible CP along RoI only. That is, the average number of fast-CP accessible along RoI is lower throughout all travel time windows than that of the normal-CP. Second, both for normal- and fast-CP, the average number of accessible CP along RoI is greater in non-rural regions than in rural regions (see Figure 3: Table (b)). In addition, similar to the analysis of inhabited regions, throughout all road types analysed, the average number of accessible CP along RoI is lower, for both normal-CP and fast-CP in the rural regions types with 'less good socioeconomic situation'. This difference between rural regions with 'good,' respectively 'less good, socioeconomic situation' is less pronounced in the lower travel time windows (up to 5 and up to 10 min) than in the higher ones and less pronounced for fast-CP than for normal-CP (see Tables S3–S7).

Especially for highways but also for federal roads and country roads in the non-rural regions, especially in the travel time windows above 15 min, the average number of accessible normal-CP is above that of the county roads. This also applies to rural areas, although fewer normal-CP are accessible there on average, and in the travel time windows above 15 min, significantly more normal-CP can be reached from highways than from the other types of roads. Interestingly, the situation is similar for both normal- and fast-CP as well as non-rural and rural regions. However, as to fast-CP, there are generally significantly fewer CP available in both region types (see Figure 3: Table (b) and Tables S3–S7).

6 | SYNTHESIS AND CONCLUSION

First, the analysis results suggest that to-date, in inhabited regions, the CI is better developed in non-rural areas, and here especially in and around metropolitan areas than in rural areas. That is, although the share of CP on all CP as well as that of registered e-powered cars is nearly equal in rural and non-rural areas, the locational network of CP is more tightly meshed in non-rural regions, resulting in a higher overall CP density and consequently a better accessibility of both normal- and fast-CP in non-rural regions. This also means, that more possible alternative CP are available in close proximity to a location in non-rural regions.

Second, the observation that the majority of CP can be found in close proximity to RoI both in rural and non-rural regions suggests that, especially within settlement areas, the CI is geared more towards the needs of intra-regional short- to mid-distance traffic than towards the needs of the resident population. That is, especially in areas with a high proportion of rental apartments and/or older building stock which often do not have their own resident parking spaces, residents are dependent on the availability of ample CP in close proximity to their home as often the installation of their own wallboxes is not possible. However, the fact that the vast majority of publicly available CP are in close proximity to RoI means at the same time that CP along residential roads are still scarce.

Third, for people travelling long distances, the availability of ample fast-CP in proximity to the important national and intra-regional traffic arteries is crucial. However, although fast-CP seem indeed to cluster around the traffic arteries, the analysed data suggest that it is especially the road segments of these traffic arteries in non-rural areas where fast-CP are clustered most.

Together these observations suggest that to date the public CI is tailored rather to the needs of the intra-regional traveller (commuting, shopping, leisure) than to that of the resident population (daily recharging in close proximity to one's home) or the mid- to long distance traveller.

To upgrade the CI so that it can meet the current and future expected demand, there is a need for further network expansion (densification). That is, first the evident developmental deficit in the CI, especially in rural Mecklenburg-West Pomerania, Brandenburg and Saxony-Anhalt should be eliminated immediately. Second, ample charging solutions close to people's homes must be found for those who cannot make use of their own wallbox, e.g., by an expansion of the public charging network in residential areas, especially with block buildings or at parking lots at workplaces. Third, the still underdeveloped fast-CI should be further expanded both within settlement areas and especially along important traffic arteries.

ACKNOWLEDGEMENTS

The authors wish to thank the anonymous peer reviewers and the editors whose feedback helped improve the final version of the paper. For the purposes of open access, the author has applied a Creative Commons Attribution (CC BY-NC) licence to any Author Accepted Manuscript version arising from this submission. Open Access funding enabled and organized by Projekt DEAL.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are publicly available from the bundesnetzagentur at https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/E-Mobilitaet/Ladesaeulenkarte/start.html and are subject to the Creative Commons Namensnennung 4.0 International Lizenz.

ORCID

Stefan Neumeier https://orcid.org/0000-0002-1015-9264

ENDNOTES

[1] Infrastructure for Spatial Information in the European Community.

[2] https://www.zensus2011.de/DE/Home/Aktuelles/DemografischeGrunddaten.html.

[3] As in the federal states the size of the 'Kreise' varies, 'Kreisregionen' are an additional administrative level in which district towns with less than 100,000 inhabitants are combined with the associated districts to create better comparable spatial units (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2023).

[4] https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/E-Mobilitaet/Ladesaeulenkarte/start.html (Creative Commons Namensnennung 4.0 International Lizenz).

[5] OSM-tags 'motorway', 'motorway_link', 'trunk_link', 'trunk'.

[6] OSM-tags 'primary', 'primary_link'.

[7] OSM-tags 'secondary', 'secondary_link'.

[8] OSM-tags 'tertiary', 'tertiary_link'.

[9] r5r (https://github.com/ipeaGIT/r5r) is an R interface to the R5 routing engine (https://github.com/conveyal/r5).

REFERENCES

Albacete, X., Olaru, D., Paül, V. & Biermann, S. (2017) Measuring the accessibility of public transport: A critical comparison between methods in Helsinki. *Applied Spatial Analysis and Policy*, 10, 161–188. Available from: https://doi.org/10.1007/s12061-015-9177-8

Bamberg, C., Lackner, J., Siegemund, S. & Auf der Maur, A. (2020) *dena-STUDIE. Privates Ladeinfrastrukturpotenzial in Deutschland. Herausforderungen bei der Entwicklung der privaten Ladeinfrastruktur zur Beschleunigung des Markthochlaufs der Elektromobilität in Deutschland [dena STUDY. Private charging infrastructure potential in Germany. Challenges in the development of private charging infrastructure to accelerate the market ramp-up of electric mobility in Germany]*. Available from: www.dena.de/fileadmin/dena/Publikationen/PDFs/2020/denaSTUDIE_Privates_Ladeinfrastrukturpotenzial_in_Deutschland.pdf [Accessed 15th September 2023].

Batty, M. (2009) Accessibility: In search of a unified theory. *Environment and Planning. B, Planning & Design*, 36(2), 191–194. Available from: https://doi.org/10.1068/b3602ed

Bleisch, A. (2005) *Die Erreichbarkeit von Regionen. Ein Benchmarking-Modell*. Dissertation an der wirtschaftswissenschaftlichen Fakultät der Universität Basel.

Bleisch, A., Fröhlich, P. & Koellreuter, C. (2003) *Die Erreichbarkeit von Regionen [The accessibility of regions]*. Available from: http://e-collection.ethbib.ethz.ch/eserv/eth:27008/eth-27008-01.pdf [Accessed 27th September 2017].

Bundesinstitut für Bau-, Stadt- und Raumforschung. (2023) *Laufende Raumbeobachtung—Raumabgrenzungen Kreise und Kreisregionen [Ongoing spatial observation—spatial boundaries of districts and district regions]*. Available from: https://www.bbsr.bund.de/BBSR/DE/forschung/raumbeobachtung/Raumabgrenzungen/deutschland/kreise/Kreise_Kreisregionen/Kreise.html [Accessed 10th June 2021].

Bundesministerium für Verkehr, Bau- und Wohnungswesen. (2002) *Ergebnistelegram Mobilität in Deutschland 2002 [Results telegram Mobility in Germany 2002]*. Available from: https://www.mobilitaet-in-deutschland.de/archive/pdf/ergebnistelegramm_mobiltaet_in_deutschland_2002.pdf [Accessed 12th December 2023].

Chen, Y., Ravulaparthy, S., Deutsch, K., Dalal, D., Yoon, S., Lei, T. et al. (2011) Development of indicators of opportunity-based accessibility. *Transportation Research Record*, 2255(1), 58–68. Available from: https://doi.org/10.3141/2255-07

Clary, C., Matthews, S.A. & Kestens, Y. (2017) Between exposure, access and use: Reconsidering foodscape influences on dietary behaviours. *Health & Place*, 44, 1–7. Available from: https://doi.org/10.1016/j.healthplace.2016.12.005

Dahlgren, A. (2008) *Geographic accessibility analysis – Methods and application real estate science*. Department of Technology and Society, Lund University, Lund.

EV Database. (2020) *Range of full electric vehicles*. Available from: https://ev-database.org/cheatsheet/range-electric-car [Accessed 30th May 2020].

Federal Network Agency. (2023) *Ladeinfrastruktur in Zahlen [Charging infrastructure in figures]*. Available from: www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/E_Mobilitaet/Ladesaeuleninfrastruktur.xlsx [Accessed 30th March 2023].

Geurs, K.T. & Ritsema van Eck, J.R. (2001) *Accessibility measures: Review and applications*. RIVM Report 408505 006. National Institute of Public Health and the Environment, Bilthoven.

Geurs, K.T. & van Wee, B. (2004) Accessibility of land-use and transport strategies: Review and research directions. *Journal of Transport Geography*, 12, 127–140. Available from: https://doi.org/10.1016/j.jtrangeo.2003.10.005

Great Britain Department for Transport. (2012) *Accessibility statistics guidance*. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/66795/accessibility-statistics-guidance.pdf [Accessed 30th November 2020].

Handy, S.L. & Niemeier, D.A. (1997) Measuring accessibility: An exploration of issues and alternatives. *Environment and Planning A*, 29, 1175–1194. Available from: https://doi.org/10.1068/a291175

Hansen, W.G. (1959) How accessibility shapes land use. *Journal of the American Institute of Planners*, 25(2), 73–76. Available from: https://doi.org/10.1080/01944365908978307

Hanson, S. (2009) Accessibility. In: Gregory, D., Johnston, R., Pratt, G., Watts, M.J. & Whatmore, S. (Eds.) *The dictionary of human geography*. Chichester, UK: Wiley-Blackwell, pp. 2–3.

Hemetsberger, M. & Ortner, S. (2008) *Erreichbarkeitsbasierte Raster Raumanalyse – Anwendungen in der Landesplanung [Accessibility-based spatial raster analysis – Applications in regional planning]*. In: Schrenk M, Popovich V, Engelke D, Elisei P (Eds.): REAL CORP 008 Proceedings/Tagungsband, pp. 255–263.

Kasten, P., Minnich, L., Randrianariosa, J., Ritter, D., Vogel, M., Dünze, K. et al. (2022) *Szenarien und regulatorische Herausforderungen für den Aufbau der Ladeinfrastruktur für elektrische Pkw und Lkw [Scenarios and regulatory challenges for the development of charging infrastructure for electric cars and trucks]*. Available from: https://www.oeko.de/fileadmin/oekodoc/ENSURE-II_Ladeinfrastruktur.pdf [Accessed 31st March 2023].

Kraftfahrt Bundesamt. (2023) *Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Zulassungsbezirken. FZ1.2 Personenkraftwagen am 1. Januar 2022 nach Zulassungsbezirken, Kraftstoffarten und Emissionsgruppen [Number of motor vehicles and trailers by registration district. FZ1.2 Passenger cars on January 1, 2022 by registration districts, fuel types and emission groups]*. Available from: https://www.kba.de/SharedDocs/Downloads/DE/Statistik/Fahrzeuge/FZ1/fz1_2022.xlsx,jsessionid=6F8169B5F7DC4442D9D2998BC1EE7822.live11293?__blob=publicationFile&v=5. [Accessed 12th April 2023].

Küpper, P. (2016) *Abgrenzung und Typisierung ländlicher Räume [Delimitation and typification of rural areas]*. Thünen Working Paper 68. Available from: https://literatur.thuenen.de/digbib_extern/dn057783.pdf [Accessed 10th June 2021].

Litman, T. (2021) *Evaluating accessibility for transport planning*. Available from: www.vtpi.org/access.pdf. [Accessed 9th September 2021].

Lücking, G. & Adam, M. (2022) Ladesäulencheck 2019: aus Sicht der Kunden ein undurchsichtiger Dschungel und zu hohe Kosten. In: Liebl, J. (Ed.) *Electrified mobility 2019. Proceedings*. Wiesbaden: Springer Vieweg. Available from: https://doi.org/10.1007/978-3-658-32471-1_5

Nationale Plattform Zukunft der Mobilität, Arbeitsgruppe 5, Verknüpfung der Verkehrs- und Energienetze, Sektorkopplung. (2019) *Bericht März 2019, Sofortpaket Ladeinfrastruktur 2019 [March 2019 report, immediate charging infrastructure package 2019]*. Available from: https://www.plattform-zukunft-mobilitaet.de/wp-content/uploads/2019/03/Bericht-M%C3%A4rz-2019-AG-5-Sektorkopplung-der-NPM-Sofortpaket-Ladeinfrastruktur-2019.pdf [Accessed 22nd November 2023].

Neumeier, S. (2022) Accessibility of COVID-19 vaccination centers in Germany via different means of transport. *KN Journal of Cartography and Geographic Information*, 72, 41–58. Available from: https://doi.org/10.1007/s42489-021-00088-x

Páez, A., Scott, D.M. & Morency, C. (2012) Measuring accessibility: Positive and normative implementations of various accessibility indicators. *Journal of Transport Geography*, 25, 141–153. Available from: https://doi.org/10.1016/j.jtrangeo.2012.03.016

Parvin, F., Ali, S.A., Hashmi, S.N.I. & Khatoon, A. (2020) Accessibility and site suitability for healthcare services using GIS-based hybrid decision-making approach: A study in Murshidabad, India. *Spatial Information Research*, 29, 1–18. Available from: https://doi.org/10.1007/s41324-020-00330-0

Penchansky, R. & Thomas, J.W. (1981) The concept of access: Definition and relationship to consumer satisfaction. *Medical Care*, 19, 127–140. Available from: https://doi.org/10.1097/00005650-198102000-00001

Philipsen, P., Schmidt, T., van Heek, J. & Ziefle, M. (2016) Fast-CS here, please! User criteria for electric fast-charging. *Transportation Research Part F: Traffic Psychology and Behaviour*, 40, 119–129. Available from: https://doi.org/10.1016/j.trf.2016.04.013

Puttkamer, L. (2023) *Verbesserung der Ladeinfrastruktur in Deutschland [Improving the charging infrastructure in Germany]*. Available from: www.garten-landschaft.de/ladeinfrastruktur-deutschland/ [15th September 2023].

Rauch, S. & Rauh, J. (2016) Verfahren der GIS-Modellierung von Erreichbarkeiten für Schlaganfallversorgungszentren. *Raumforschung und Raumordnung*, 74(5), 437–450.

Rauch, S., Stangl, S., Haas, T., Rauh, J. & Heuschmann, P.U. (2023) Spatial inequalities in preventive breast cancer care: A comparison of different accessibility approaches for prevention facilities in Bavaria, Germany. *Journal of Transport & Health*, 29, 101567. Available from: https://doi.org/10.1016/j.jth.2023.101567

Rodrigue, J.-P. (2020) *The geography of transport systems*. New York, NY: Routledge.

Saif, M.A., Zefreh, M.M. & Torok, A. (2018) Public transport accessibility: A literature review. *Periodica Polytechnica Transportation Engineering*, 47, 36–43 Available from: https://rosap.ntl.bts.gov/view/dot/14882

Schulz, A.C. & Bröcker, J. (2007) *Die Erreichbarkeit der Arbeitsmärkte für Berufspendler aus den Gemeinden Schleswig-Holsteins*. In: IAB regional, Nr. 1.

Schürmann, C., Spiekermann, K. & Wegener, M. (1997) Accessibility indicators. Berichte aus dem Institut für Raumplanung 39, Institut für Raumplanung, Dortmund.

Schwarze, B. (2005) *Erreichbarkeitsindikatoren in der Nahverkehrsplanung [Accessibility indicators in local transport planning]*. Institut für Raumplanung Universität Dortmund, Fakultät Raumplanung. Arbeitspapier 184, Dortmund.

Siekmann, A. (2022) Elektrofahrzeuge E-Mobilität: Bleibt der ländliche Raum abgehängt [Electric vehicles E-mobility: Will rural areas be left behind]? Available from www.agrarheute.com/energie/e-mobilitaet-bleibt-laendliche-raum-abgehaengt-592806 [15th September 2023].

Spiekermann, K. & Wegener, M. (2008) *Modelle in der Raumplanung I. Erreichbarkeit I [Models in spatial planning I. Accessibility I.]*. Available from: www.spiekermann-wegener.de/mir/pdf/MIR1_5_181108.pdf [Accessed 27th September 2017].

Tagesschau. (2023a) *EU-Regeln ab 2035. Welche Zukunft der Verbrenner noch hat [EU rules from 2035: what future the combustion engine still has]*. Available from: www.tagesschau.de/wirtschaft/technologie/faq-verbrenner-kompromiss-e-fuels-101.html. [Accessed 28th March 2023].

Tagesschau. (2023b) *Umstieg auf Elektromobilität. Wie viele Ladesäulen braucht Deutschland [Switching to electromobility. How many charging stations does Germany need]?* Available from: www.tagesschau.de/wirtschaft/technologie/ladesaeulen-infrastruktur-elektromobilitaet-100.html [Accessed 14th September 2023].

Verband der Automobilindustrie e. V. (2019) *Position: Empfehlungen für einen erfolgreichen Hochlauf der Ladeinfrastruktur für Elektrofahrzeuge bis 2030 [Position: Recommendations for a successful ramp-up of the charging infrastructure for electric vehicles by 2030]*. Berlin. Available from: www.vda.de/dam/jcr:e425be3a-4bbd-444e-b438-2a8f90eb00a1/190520_Positionspapier%20Ladeinfrastruktur.pdf

Vulevic, A. (2016) Accessibility concepts and indicators in transportation strategic planning issues: Theoretical framework and literature review. *Logistics & Sustainable Transport*, 7(1), 58–67. Available from: https://doi.org/10.1515/jlst-2016-0006

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article. Data S1.

How to cite this article: Neumeier, S. & Osigus, T. (2024) Germany's public EV charging points: Analysing the 2023 state of expansion. *The Geographical Journal*, 00, 1–17. Available from: https://doi.org/10.1111/geoj.12570