Addressing the Different Needs for Charging Infrastructure: An Analysis of Some Criteria for Charging Infrastructure Set-up

Simon Árpád Funke, Till Gnann and Patrick Plötz

Abstract Electric mobility is an important means to decarbonise the transport sector. Especially in cities, the use of zero-emission vehicles like electric vehicles is favourable, as emissions of conventional cars cause severe air pollution. Besides CO_2, the most important emissions are nitric oxides, particular matter and noise. Given the trend of urbanisation, the problem of air pollution in large cities will rather grow than diminish. Although electric vehicles are an infrastructure-dependent technology, one important advantage of plug-in electric vehicles (EV) compared to hydrogen-powered vehicles is the possibility to use the existing electricity infrastructure in households for charging. While additional public charging infrastructure is also needed for interim charging or overnight charging for the so-called 'on-street parkers' without own garage, the majority of vehicles could be operated as EVs without additional public charging infrastructure. However, public charging infrastructure is an important component for the large-scale diffusion of electric vehicles and political action seems necessary since no business models are presently available. In the present paper the authors combine different data sets concerning German charging points and mobility patterns to describe the different needs for charging infrastructure, and provide an overview of the underlying different technical options. Based on the current charging infrastructure stock, the set-up methodology and the impact of user needs on charging infrastructure, the authors compare a coverage-oriented and a demand-oriented approach. The authors also estimate the number of public charging points for those two approaches. Finally, criteria for charging infrastructure are categorised and related to the different approaches. It results that the number of charging stations needed for the two

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different scenarios and the actual distribution of this predefined number of charging stations are answers to fundamentally different questions. As one consequence, an explicit statement on the number of charging stations needed on large scale (such as Germany) is difficult to make on the basis of (local) user demand.

Keywords Electrification of transport · Electric vehicles · Charging infrastructure set-up · Coverage-oriented and demand-oriented approaches

1 Introduction

Electric mobility is widely recognised as an instrument to fulfil the greenhouse gas emission targets in the transport sector (c.f. German Federal Government 2011). Electric vehicles (EVs) help to reduce both global, European, national and local emissions. Locally, in contrast to conventional vehicles, EVs have no pollutant emissions. Therefore, EVs are particularly suited to improve air quality in cities (especially with high smog, like, e.g. Beijing, c.f. AQI 2014; OECD 2014 and UN 2012). Additionally, their noise emissions are vanishingly low at lower speeds. Finally, EVs could help to reduce the dependence on fossil fuels. Although some EVs are on the roads already, there are still obstacles to overcome for wide market diffusion. Consumer surveys often find purchase price reductions and the installation of charging infrastructure to be means of supporting a large-scale diffusion of electric vehicles (see, e.g. Dütschke et al. 2012). It is often postulated (NPE 2012), and a common (but perhaps not psychological) sense approach, to install charging infrastructure in line with demand for it driven by electric vehicles. But the determination of actual demand for the different types of charging infrastructure is difficult and knowledge about it is rare. This might be one reason for the European parliament to engage national governments to build up an 'appropriate number of electric recharging points accessible to the public' until 2020 (European Voice 2014) instead of setting specific targets as suggested by the European Commission (European Commission 2013). For Germany, the European Commission suggested a target of 1.5 million charging points in total until 2020, 150,000 of them in public (cf. ibid.). The proposal is based on a supranational top-down approach to address geographical coverage as well as user demand. User demand is derived from the forecasted number of electric vehicles (NPE 2012). However, the general aim of public charging infrastructure is to provide a social infrastructure, i.e. to guarantee a minimum standard of service at low cost to the widest possible public (cf. Wirges and Fulda 2010). A demand-oriented installation of charging infrastructure might not be in line with this task of building up the aforementioned social infrastructure. A comparable conflict of interests can be found in public transport. Scarcely used railway lines are operated to guarantee mobility for the widest possible public, although these lines are operated at a loss. In conclusion, for a holistic view, the construction of public charging infrastructure has to be regarded from different levels of perspectives. Consequently, literature on charging infrastructure set-up is very heterogeneous. Approaches range from the discussion of location criteria to the estimation of charging infrastructure demand based on complex mathematical models (see, e.g. BMVI 2014a, b; Lam et al. 2013; NPE 2013; Sandin 2010; Siefen 2012; Stroband et al. 2013; TU Berlin 2011). Therefore, an overview of the different options could serve stakeholders to better decide which approach to apply for the installation of public charging infrastructure in the special case. However, to the authors' best knowledge, a holistic overview including the main different approaches does not exist. To address this gap, this paper categorises public charging infrastructure into different options and show the different stakeholders involved in the set-up of the different options. The paper combines the qualitative discussion of different types of public charging infrastructure with quantitative models used to estimate demand as well as with the authors' calculations. The work is intended to answer the question whether generally applicable criteria exist for the set-up of charging infrastructure or whether their application depends on different types of charging infrastructure.

Thus, the authors provide a brief overview of the different types of charging infrastructures and relate them to user needs as well as to the underlying technical options. The paper is structured as follows. In Sect. 2, it provides background information about public charging infrastructure as well as the methodology used in the following approach. To be more precise: An overview of the most relevant characteristics and design possibilities of charging infrastructure is supported by a discussion about the current state of infrastructure construction (Sect. 2.1). The authors describe their methodology and identify the main user needs for public charging infrastructure (Sect. 2.2). In Sect. 4.1 the authors use available data on user needs to roughly estimate the number of public charging points based on a geographical coverage and on a demand-oriented coverage for EV drivers without a garage and fast-charging options for rare long-distance trips. In Sect. 4.2 the authors derive general criteria from current approaches for building up charging infrastructure to be able to compare them to the results given in Sect. 4.1 (Sect. 5). Finally, the authors conclude with an outlook for future set-up of public charging infrastructure (Sect. 6).

2 Background and Methodology

2.1 Background and Current Status of Public Charging Infrastructure

Charging infrastructure can be distinguished in many ways, including according to its accessibility, its power, connection type and many more (see, e.g. Kley et al. 2011 or Michaelis et al. 2013 for a detailed description). In the following, the most relevant characteristics of charging infrastructure are presented. Table 1 provides an overview of the criteria for differentiation. Accessibility to EV charging infrastructure is

Table 1 Characteristics and design possibilities of charging infrastructure (adapted from Kley et al. 2011, p. 3396)

<table>
<tr><th>Characteristic</th><th colspan="6">Design possibility</th></tr>
<tr><td>Accessibility</td><td colspan="2">Private</td><td colspan="2">Semi-public</td><td colspan="2">Public</td></tr>
<tr><td>Power connection</td><td>1-phase
(level1; 3.7 kW)</td><td colspan="2">3-phase
(level 2; 11-22 kW)</td><td colspan="2">High voltage AC
(level 3; >22 kW)</td><td>High voltage DC
(level 3; >50 kW)</td></tr>
<tr><td>Connection type</td><td colspan="3">Unidirectional</td><td colspan="3">Bidirectional</td></tr>
<tr><td>Information flow</td><td colspan="2">None</td><td colspan="2">Unidirectional</td><td colspan="2">Bidirectional</td></tr>
<tr><td>Type of billing</td><td colspan="2">No fee</td><td colspan="2">Fixed rate</td><td colspan="2">Pay-per-use</td></tr>
<tr><td>Metering</td><td colspan="2">No metering</td><td colspan="2">At charging station</td><td colspan="2">In vehicle</td></tr>
</table>

distinguished as private, semi-public or public charging infrastructure. While private charging infrastructure is only accessible to one person, vehicle or household and thus it is the most restricted option (e.g. a garage), public charging stations are open to everybody (e.g. at a public parking spot). Semi-public charging points are restricted to a certain group of people, e.g. the member's of a sports club or the paying users of a car park. From here on, the paper focuses on public charging stations.

The power connection of charging points ranges from 1-phase AC charging, up to 50 kW high-voltage DC charging, while most public charging options are expected to offer at least 11 kW (level 2). The connection as well as the information flow may be uni- or bidirectional, while for billing feeless systems, fixed rates and pay-per-use options can be distinguished. Finally, the metering differs: there are systems without any metering and others that use metres either in the charging station or in the vehicle (see Dallinger et al. 2013).

The current status of public charging infrastructure in Germany is quite diverse. Currently, there are about 2,900 locations for public charging with approximately 4,900 charging stations and 8,400 sockets in Germany (Lemnet 2014). Almost half (45 %) of the stations are equipped with simple type 1 sockets, another 38 % with type 2 (three phase). The majority of the charging stations (51 %) have a power of up to 3.7 kW. Another 30 % of the charging stations have a power higher than 16.7 kW, predominantly operated by 3-phase alternating current. In total, only 68 of the charging stations reported are operated with direct current (DC). Until today, it is not clear whether DC charging or 3-phase AC charging will become standard for fast charging (NPE 2013). These numbers support the assumption that public charging infrastructure is needed primarily for charging at low power. Fast charging points are also needed, but only in a limited number. Concerning the geographical location, we find about 60 % of all charging stations in Bavaria, Baden-Württemberg and Northrhein-Westfalia, the federal states with the highest populations and also the highest number of EVs in Germany. Among them, Baden-Württemberg has the highest charging infrastructure density per capita (0.1 charging stations per 1,000 inhabitants). It is not surprising that the city states Berlin and Hamburg have a charging infrastructure density per square kilometre that is about 15 times higher than the German average (0.22 charging stations per square kilometre for both city states compared to 0.015 on average) (see also Schneider et al. i.p.). They have a high population density and, furthermore, these states were part of the publicly funded project family German Pilot Regions (BMVBS 2011). Compared to this, the third city state in Germany, Bremen, has a relatively low number of charging stations resulting in an infrastructure density of 0.09 charging stations per kilometre. The market of charging station operators is very concentrated. About 25 % of the charging stations are operated by one of the four large energy providers, with RWE (ca. 11 % of all charging stations) being the most prominent. The highest proportion of charging stations, 12 %, is operated by local energy providers. Altogether, public utilities and local energy providers operate around 35 % of all charging stations in Germany (Lemnet 2014). Another very important part of charging infrastructure is formed by privately operated infrastructure. The access to private charging points is restricted to private persons and members, respectively (see, e.g. Park&Charge 2014 and Table 1). This limitation allows for a simple and therefore cheap infrastructure. Private infrastructure is also installed for marketing reasons, e.g. by restaurants. Ca. 50 % of non-public charging infrastructure can be used free of charge (Lemnet 2014).

The installation of further charging points in different projects has already been announced. In context of the project family E-mobility Show Case Regions (see, e.g. E-mobil BW 2014) charging infrastructure is one focus. In Baden-Württemberg, the construction of 1,000 additional charging points until 2015 is planned (E-mobil BW et al. 2013). Within the publicly funded project "SLAM—Schnellladenetz für Achsen und Metropolen" another 400 DC fast charging points are about to be installed by 2017 (see, e.g. Fraunhofer IAO 2014).

2.2 *Impacts of User Needs on Charging Infrastructure*

The usage of passenger cars is highly heterogeneous and the daily driving of passenger cars is not very regular (Wietschel et al. 2013). However, vehicles return home overnight for the vast majority of days per year, i.e. a long-distance travel with overnight stay is exceptional (Pasaoglu et al. 2013; Axhausen et al. 2002). Thus, for EV users with own garage, 'at home' is the location that could be used to charge most of the time. In small villages (less than 20,000 inhabitants) a high percentage of 82 % does have a garage or a carport at its disposal, in big cities (more than 1 million inhabitants) this proportion is at 44 % (Nagl and Bozem 2014). However, there is a certain number of potential users without a permanent parking space, the so-called 'on-street parkers'. For these potential users public infrastructure is needed to compensate the lack of a possibility to charge at home. After charging at home, the highest increase in electrification of driven kilometres is achieved by charging at work (Santini 2013). For company cars, the same conclusions as for private cars can be applied. If company cars cannot be charged at the company ground, public infrastructure is needed. This could be the case for small companies without own parking areas. Due to the long parking periods overnight for both cases, low power charging is sufficient.

Nonetheless, on some days per year users drive long distances and spend the night away from home. In this case, when the daily driving distance exceeds the technical range of a BEV, fast charging infrastructure is needed for interim charging during rare long-distance trips, though arguable hotels should also be encouraged to supply them. Plug-in hybrids (PHEV) do not necessarily need infrastructure for interim charging, since they can go long distances with an internal combustion engine that serves as range extender. Additionally, interim charging can generally be applied at low power during longer parking periods. This might be the case for longer trips to, e.g. shopping outlets where the total daily trip is interrupted by the parking time at the shopping centre.

To conclude, different user needs and their impact on public charging infrastructure are summarised in Fig. 1. Generally, public charging infrastructure can be distinguished into (1) infrastructure for ‘on-street parkers’ and (2) for ‘interim charging’. The need for ‘on-street parking’ infrastructure arises from (a) private drivers without own garage and (b) workplace charging for employees at companies without own parking spots. The latter one is not absolutely necessary but offers large benefits for many private users. ‘Interim-charging’ is needed for long-distance trips with BEVs for both private and company cars. Depending on the trip purpose, interim charging can further be distinguished into (c) charging with low power in the proximity of shops, restaurants, etc. and (d) fast charging. This categorisation follows the Swiss Forum for Electromobility (Schweizer Forum Elektromobilität 2012) (see also Schatzinger and Rose 2013) as, in the authors’ view, it represents an appropriate categorisation of the different types of charging infrastructure in an easily comprehensible way by using the activities probably carried out during charging. The categories of activities used are the most likely during parking time (Follmer et al. 2010b). For other classifications see, e. g. Botsford (2012) and Sandin (2010). However, the above-mentioned classification is not without overlap. On-

Fig. 1 Types of public charging infrastructure by user needs (own illustration, categorisation based on the Swiss Forum for Electromobility—Schweizer Forum Elektromobilität (2012))

street parkers (case a, Fig. 1) could use the same infrastructure that is used for interim low-power charging (case c). While the infrastructure is used by the first group overnight, the latter application would be during the day. This overlap for the different types of infrastructure has to be considered when analysing the involved stakeholders (see Sect. 4.2) for the different types of public charging infrastructure.

The described use cases are determined by user needs and are analysed below to estimate the demand for public charging infrastructure from the user perspective (Sect. 4.1).

3 Methodology

Diverse factors make the decision about the construction of charging infrastructure complex. On the one hand, charging infrastructure should guarantee a minimum standard of service implying the need for a dense charging infrastructure. On the other hand, a demand-oriented construction of charging infrastructure is desirable. In this work, the authors analyse and compare both different approaches. Together with the different types of public charging infrastructure and the different approaches for their set-up, a holistic view is given. For the analysis of the different approaches, the authors use different methods of technology assessment. An overview of these methods is given in Tran and Daim (2008). First, in a kind of a top-down approach, the authors estimate the number of charging stations needed on the basis of a predefined geographical coverage. Different data sets on vehicle registrations and demography are combined. Secondly, the authors estimate the number of charging stations on the basis of user behaviour and user need. As the authors consider the single user as point of reference for this approach, the analysis is characterised by a bottom-up view. A mathematical model comprises the use of different scenarios on mobility patterns, the prediction of potential buying decisions based on a total cost of ownership (TCO) analysis (Wietschel et al. 2013). The aforementioned approaches are supplemented by user-specific requirements on public charging infrastructure in the form of general criteria. Literature and general information about ongoing projects is reviewed thoroughly to provide a holistic view. The data obtained is clustered and categorised systematically to make a differentiated understanding of the needed information possible.

4 Results

4.1 Estimation of Real Needs for Charging Infrastructure

As we mentioned before, charging infrastructure can be set up according to a broad coverage of all regions (geographical coverage) or according to users' needs (user-oriented coverage) (see Ball and Wietschel 2009, pp. 415–417). In this section, the authors estimate the number of charging infrastructure stations that would result from both approaches and discuss their usefulness.

4.1.1 Geographical Coverage with Charging Infrastructure

For a geographical coverage, the population density can be analysed. The present number of refuelling stations in Germany (currently about 14,700) leads to one charging station every 3.4 km.[1] As it is known that there is a higher refuelling stations density in cities than in rural areas, one can be a little bit more precise for this estimation. There is a common differentiation between area types into:

- core cities: cities with more than 100,000 inhabitants
- condensed areas: areas with a population density >150 inhabitants/km^2
- rural areas: areas with a population density <150 inhabitants/km^2

The number of charging stations for a geographical coverage depends on the area and the maximum distance between two charging stations as shown in Fig. 2.

It seems clear that a small distance between two charging stations leads to a higher number of charging points, but also the total numbers are important as they are connected to the areas. At a first glimpse, one would argue that the charging network should be denser in core cities than in rural areas. Thus, assuming that a charging station every 500 m is sufficient in core cities, one obtains a result of about 25,000 charging stations as the surface area is only about 13,000 km^2. The authors used a separating distance of 2 km between charging stations in condensed areas and 5 km for rural areas (Table 2) which return a total of about 51,500 charging stations.

Thus, although the largest share of surface area is in rural areas, the number of charging stations is small if one assumes that the charging stations density can be low. The assumed distances also point out that even if the surface area is low in core cities, a dense network of charging infrastructure results in more than 50 % of charging stations in core cities with this geographical approach.

An estimate based on vehicle registrations in the area types yields a different distribution of charging points as more vehicles are registered in the rural areas. If one studies only those vehicle owners that do not own a garage or parking spot close by and 2.5 % thereof (equivalent to 1 million EVs of 40 million vehicles in total), one finds about 41,300 charging stations that would be necessary for overnight charging in Table 3.

Although the total number of charging stations is fairly equal to the first estimation, it neglects the fact that some users are more likely to buy EVs than others, which is subject to the following subsection.

[1]One has to divide the area of Germany (357,097 km^2) by the number of refuelling stations multiplied by $\sqrt{3}$ (intersection point of three equal circles).

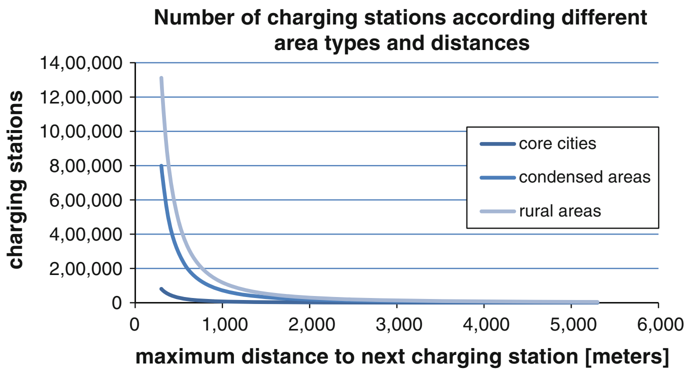

Fig. 2 Number of charging stations according to different area types and distances between charging stations

Table 2 Charging stations in different area types (1) (Destatis et al. 2013)

Area types	Core cities	Condensed areas	Rural areas
Surface area (km^2)	13,086 (3.9 %)	130,181 (36.5 %)	213,831 (59.9 %)
Maximum distance between two charging stations (m)	500	2,000	5,000
Charging stations hence to area	28,900	17,900	4,700

Table 3 Charging stations in different area types (2) (Follmer et al. 2010a, b; Destatis et al. 2013)

Area types	Core cities	Condensed areas	Rural areas
Vehicles	11,364,366	21,457,184	12,949,325
Vehicles not parking on own ground or close by	863,692	536,430	297,834
Charging stations weighted with vehicle stock (share of 2.5 % EVs 2020)	19,800	13,600	8,000

4.1.2 User Need for Charging Infrastructure

The paper now turns to the estimate of required public charging infrastructure based on user behaviour as discussed above. The authors estimate the order of magnitude for the years 2020 and 2030 based on the market evolution results contained in Wietschel et al. (2013).

Since on-street parking infrastructure serves as an alternative to home charging, the need for it results both for BEVs and REEVs or PHEVs respectively. Of these EVs in Germany about 1.5 % is expected to be on-street parkers (Wietschel et al. 2013). For the potential one million BEVs in 2020 and six million BEVs in 2030 the authors thus arrive at 15,000 charging points in 2020 and 90,000 in 2030 for on-street parkers. The demand for fast public charging infrastructure can be estimated by the number and distances of rare long-distance driving that BEV would take in 2020 or 2030. The average number of days per year with more than 100 km of driving (requiring interim recharge for BEVs) has been estimated by Plötz (2014) based on the assumption of log-normal distributed daily vehicle kilometres travelled and is given by about 30 days. The typical distance on these days is given by the mean excess function of the log-normal distribution and is (for typical parameter values as displayed in Plötz (2014)) in the range 160–220 km, so that one recharging per long-distance driving day seems typical. The number of required fast charging points is determined by the number of EV users multiplied by the number of long-distance driving days per year divided by the number of days per year. The result for assumed one million EV users in 2020 would be 20,500 recharging events per day in 2020 and 125,000 in 2030 if charging events are distributed equally over the year. If each charging point can on average serve 10 users per day once finally arrive at a user demand of 2,000 fast charging points in 2020 and 12,500 fast charging points in 2030. These numbers are linear in the assumptions for the EVs in the respective years and the number of users that can be served by a charging station. However, this does not take into account that drivers might use other alternatives for these long-distance trips (e. g. rental cars, car sharing or public transport) which would decrease the number of required public fast charging stations. Please note that these rough estimates provide an order of magnitude for the public charging infrastructure demand that are intended to help analyse the different criteria for charging infrastructure set-up discussed in the next section.

4.2 Current Heuristics for Charging Infrastructure Set-up

After the estimation for the numbers of charging stations needed for the two different approaches, geographical coverage and demand-oriented coverage, the paper now takes a look at strategies or heuristics that are used in projects today and compare them to the above-described approaches. The need for the development of specific strategies for the construction of public charging infrastructure results from the fact that existing refuelling infrastructure cannot be used to charge electric vehicles. Besides, the integration of charging stations into the existing gas station infrastructure is not viable due to the long charging periods (Lam et al. 2013). Car sharing stations are not suitable either for charging stations since they are designed for round trips (Wirges and Fulda 2010). In Germany, apart from private initiatives, infrastructure is installed in politically funded projects (e.g. the German Pilot Regions and the Show Case Regions, see e.g. BMVI (2014a) and E-mobil BW (2014)).

4.2.1 Characterisation of Stakeholders Involved in the Construction of Charging Infrastructure

Building up infrastructure means to take the fundamentally different primary objectives of the different stakeholder groups into account. We identify four different stakeholder groups: (1) EV drivers, (2) the operator of the charging infrastructure and the electric grid respectively, (3) the municipality in which charging infrastructure is installed (local authority) as well as (4) the national or supranational (e.g. EU) authority. While the driver of an electric vehicle will accept limitations neither in mobility patterns nor in high costs, the operator of the charging station pursues the development of a business model. However, the aim of the local and the national authority is to ensure a minimum standard of service. Concerning charging infrastructure in particular, the public supply mandate may imply the integration of its set-up into a general urban plan (Rothfuss et al. 2012), especially as the target group of charging infrastructure, the electric car drivers, is still very small (KBA 2014) and public space is a scarce resource. As a summary of this section, Table 4 displays criteria for the involved stakeholder groups. The list comprises criteria concerning the visibility, the handling and cost of the charging stations. They are divided into categories described in the following:

Table 4 Categorisation of criteria for charging infrastructure (on basis of BMVBS 2011; Wirges and Fulda 2010; Hoffmann 2013)

		Electric Vehicle Driver	**Local/ national Authority**	**Infrastructure Operator**
Primary Objective		No limitation in mobility at limited additional cost	Charging Infrastructure as consequence of the public supply mandate	Charging Infrastructure as Business Model
Basic/Excluding Criteria		Charging infrastructure must be: • Fully accessible • Unrestricted • Safe	Obeying of different regulations: • Fire prevention • Protection of historical monuments	Profitability and Grid Stability
Target Criteria on micro level Detailed Characterization of Location	Visibility	• Visibility as a pioneer • Station easy to find & recognize	• Inconspicuous Integration into Cityscape vs. Image as Green City	• Visibility to reach high utilization rate
	Site/Handling	• Simple access & declaration • Safety & weather protection	• Non-discriminatory access of public charging infrastructure • Safety & ease of traffic (safety obligation)	• Extendibility • Low cost for installation & maintenance
Target Criteria on macro level General Overview		Comfort & Practicability: • Demand-oriented • High availability	Integration into Urban Development: • No shortage of parking space • BUT: Limitation of land use for parking • Support of intermodality	Utilization: • High utilization vs. Grid stability
	Cost	Limited additional cost for charging	Parking fees as income	Low cost e.g. for parking space and grid connection

4.2.2 Categorisation of Criteria by Decision Level

As shown, diverse criteria at different decision levels make the set-up of charging infrastructure complex. Decisions have to be taken by different stakeholders and the criteria for evaluation are heterogeneous as they have, e.g. technical or legal character (Wirges and Fulda 2010). Therefore, a categorisation of the criteria used for the location of charging infrastructure by its decision level into (1) micro level and (2) macro level is practical. The specific distinction into those two categories depends on the actual level of decision. Thus, criteria on the macro level can affect either a nation[2] or a city as a whole. However, criteria on macro level affect the charging infrastructure in general, whereas criteria on micro level affect the specific location and the detailed realisation of the charging points. Thus, recommendations concerning the realisation of charging infrastructure given in the actual publicly funded projects often affect the micro level. They emphasise the need for further standardisation of technical equipment of billing and communication infrastructure. In Europe, the combined charging system is announced to become the standard plug for electric vehicles (ENS 2014). However, different infrastructure operators use different unharmonised billing systems that still make the use of public charging infrastructure uncomfortable (WIWO 2014). Additionally, possibilities to integrate charging infrastructure into existing neighbourhoods as in parking metres and bollards are presented (BMVBS 2011). On this level, a harmonised approach is difficult to implement. On the micro level, a further distinction of criteria into excluding and non-excluding criteria or into (1) basic and (2) target criteria (BMVBS 2011) is practicable. Basic conditions comprise, e. g. the protection of historical monuments or fire prevention regulations. In general, charging stations should not be built in historical view centres, nor on public places or in the proximity of public listed buildings (Wirges and Fulda 2010).

4.2.3 Fundamental Distinction of Approaches into Maximum Coverage and Demand-Oriented Coverage

On the macro level, different approaches for the set-up of charging infrastructure are possible. The distinction used in Sect. 4.1 into (1) an approach to reach the maximum possible coverage and (2) a demand-oriented approach has fundamental character. While the latter takes an economic or a user-specific view, respectively, the aim of this approach is to reach a high utilisation rate of the charging infrastructure. The first approach, however, takes a more social view: a broad reachability of charging infrastructure (Sect. 1). The remarkable difference in the numbers of charging stations for the two different approaches underlines their contradictory character (Sect. 4.1). Social infrastructure could also help reducing range anxiety of EV drivers. In Tokyo,

[2]Or supranationally if agreed at that level, or if devolved to federal state level at that level.

e.g. the technical range of electric vehicles was fully used only after the installation of public charging infrastructure (E-mobil BW 2013).

An optimal geographical coverage of charging infrastructure can be determined with methods of operations research. Depending on focus, evaluation criteria of infrastructure set-up are (besides others): (1) the number of demand sides covered, (2) the average number of reachable charging points or (3) the mean minimal distance between the supply sides as an indicator for infrastructure density (Siefen 2012). In general, centre problems and covering problems can be distinguished (Hoffmann 2013). While centre problems intend to minimise the distance between the supply and the different demand points, covering problems suppose a given maximal reachability to ensure a given minimum standard of service. Mainly, location problems are formulated as covering problems. If the number of charging stations p to be installed is predefined, the problem is called a maximum-p-covering problem (Siefen 2012). Overall, these methods provide optimal results, but are solvable with reasonable effort only for a limited number of demand points. A viable way is to use heuristics[3] (Lam et al. 2013). The described methods of defining a maximum possible coverage can be combined with methods to determine user demand for infrastructure (Stroband et al. 2013). One possible way to determine demand is to divide the city into cells and analyse detailed data on travel behaviour (see, e.g. Wirges and Fulda 2010; Vélib 2014). A huge amount of data makes this approach time-intensive and probably costly. Alternatively, demand requirements can be estimated. For charging infrastructure, e.g. population size and the penetration rate of electric vehicles could be used (Lam et al. 2013) (see Sect. 4.1). In studies for practical application, a combination of both perspectives, the maximum coverage and demand-oriented approach, can be found (Hoffmann 2013, Wirges and Fulda 2010; TU Berlin 2011). Taking a macro view first, a rough estimate on needed charging stations (see Sect. 4.1) is a useful starting point to predefine a number of charging stations p to be installed. In a second step, this number can be used for solving a maximum-p-covering problem. Depending on the defined criteria, suitable locations for the predefined number of charging stations can be identified. Finally, the selected areas can be analysed in more detail.

5 Summary and Discussion

Comparing the different types of approaches for infrastructure set-up, the authors distil two different main questions: (1) The number of charging stations needed in total and (2) the actual distribution of this predefined number within a certain area. The decision concerning these questions has to be taken by different authorities on

[3]The word heuristics in this context is used as the description of a mathematical method to approximate the optimal solution. In contrast, the word heuristics in the title is used to describe generally an experience-based approach for infrastructure set-up strategies.

different decision levels. Therefore, the different approaches and methodologies for the analysis of charging infrastructure reach from rough estimates to complex models suitable for the different decision levels. On the macro-level rough estimates using different data sets are a viable way to estimate the number of charging stations needed on national scale. In contrast, a demand-oriented approach on a national view is difficult to implement. Due to a detailed analysis of local traffic volumes, this approach is data-intensive and therefore particularly suitable for a local analysis with a predefined limited number of charging stations. Concerning the distribution of the predefined number of charging stations, different stakeholder interests have to be taken into account. As an example of different interests, the authors compare an approach to reach a maximum coverage and a demand-oriented approach. In the early phase of the electric vehicle market, a demand-oriented approach will lead to a lower number of charging stations than a maximum coverage approach (see Sect. 4.1). For 2020, the authors estimate the number of charging stations for a maximum coverage-oriented approach in the range of 50,000 and for the demand-oriented approach in the magnitude of 17,000 charging stations. Although it is complex to estimate a demand-oriented need for charging stations taking a macro view, these numbers underline the contradictory character of the two approaches. The postulated number of 75,000 public charging stations[4] in European Commission (2013) is even higher. The high number of charging stations could be an indicator for the installation of a dense social infrastructure with the aim to push market penetration, although this might not trigger the diffusion by itself (Gnann and Plötz 2015).

6 Conclusions and Outlook

In the set-up of public charging infrastructure different stakeholder groups with different interests are involved. Furthermore, decisions about the installation of public charging infrastructure are taken on different decision levels. The authors find that, depending on the level of the decision, e.g. nationwide or locally, the analysis of needs for public charging infrastructure has different implications. The analysis presented here shows that the estimation of the total number of charging stations for a specific area and the decision about the distribution of a predefined number of charging stations are two different questions. While the use of detailed mobility data to estimate the number of charging stations needed on national scale is not viable due to high data intensity, rough estimates based on data sets are imprecise on local scale. Therefore, the involved stakeholders first have to become clear about the form and main target of the respective infrastructure to be installed.

[4]In the document 150,000 charging points are postulated. For the estimation of the resulting number of charging stations, the authors assume two charging points per charging station (Lemnet Europe e.V. 2014).

On basis of this information a suitable approach can be applied by comparing the different approaches. To do so, the authors conducted a holistic analysis by integrating all the different approaches at the different levels into one approach. The analysis in this paper focuses on public charging infrastructure. However, charging infrastructure is expected and recommended to emerge first in private and semi-public areas (Rothfuss et al. 2012; BMVI 2014b; Kley 2011) and is sufficient for a large number of car owners (Wietschel et al. 2013). For local authorities a possible way is to partnership with private utilities to build up publicly planned infrastructure on private ground, e.g. in car parks (i.e. semi-public charging infrastructure, see Sect. 2.1).

The overview provided in this paper allows for a better understanding of the underlying assumptions and targets of the different approaches for public charging infrastructure set-up as well as of their implications. Nevertheless, further research is needed to determine the impact of public charging infrastructure on EV purchase decision. This is key for the understanding and prediction of real user demand for charging infrastructure. Besides the psychological effect, the impact of technical development on the need for public charging infrastructure is important. An extended driving range, e.g. due to a higher energy density of a new battery technology, probably will affect substantially the need for public charging infrastructure. Finally, for infrastructure operators the rentability of the stations is essential. Part of further research thus should contain the development of a detailed model to determine the utilisation rate and potential business models for charging points at different locations.

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