Do we need charging Infrastructure for electric vehicles?

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Abstract

The large-scale introduction of Electric vehicles can significantly reduce green house gas emissions from the transport sector. However, current battery technologies offer only limited ranges compared to conventional combustion engine vehicles. Thus, it has been argued that electric vehicles need many public charging points to compensate for the limited range. Here, we simulate a large data set of today's users driving profiles as battery or plug-in hybrid electric vehicles and study the effect of different charging options on the replaceability of today's vehicles and on electric driving shares of would-be plug-in hybrid electric vehicles. Our findings in answer to to major question of this paper "Do we need additional charging infrastructure for electric vehicles?" can be summarised as: "not much."

1 Motivation: Electric Vehicles and the Need for Infrastructure

Electric vehicles bear a high potential for making individual transport more sustainable, e.g. by reducing global CO_2-emissions and local traffic noise. Accordingly, this new propulsion technology has been identified by national governments as a promising option for future mobility and gained much attention and political as well as financial support. The same holds for Germany, where the federal government has set the goal of one million electric vehicles on the roads for 2020 [13].

Against this background, the question about public infrastructure for charging electric vehicles comes to the fore. On the one hand, battery electric vehicles have a very limited driving range compared to conventional vehicles which seems to point out, that charging infrastructure might be crucial. On the other hand, implementing a broad infrastructure is extremely costly and might not even be necessary for users. Thus, this issue warrants an in-depth analysis. Which kind of infrastructure is technically needed to ensure individual mobility? And which kind of infrastructure is needed from a consumer's point of view? In the present work we want to shed light on these questions by combining technical and psychological perspectives, drawing on data collected in several e-mobility projects. Section 2 introduces the methods and data used for our analysis. The following section 3 contains our results on technical (section 3.1) and psychological aspects (section 3.2) of user needs for charging infrastructure. Possible conclusions for political decision makers will be discussed in section 4.

2 Methods and Data

To analyse driving behaviour and to determine the technically necessary demand for infrastructure, we use a large data set of driving profiles which is called German Mobility Panel (MOP) [1] to study the share of vehicles that could be replaced by BEVs and to obtain the electric driving share as PHEVs. The mobility panel is a yearly data collection of circa 1,000 households which report their outdoor movements for one week. Using the data set from 1994 until 2008 we cover 12,812 households in total. Since these records are person-specific and also contain movements which were not made by car, we have to deduct the car-specific records, which reduces the sample to 6,629 car-specific driving profiles.[1] As the sample does not contain any car size information, we assume all vehicles to be medium-sized, as this is the largest car segment in Germany [3].

Using these driving profiles we can simulate the battery state of charge (SOC) for a specific point in time *t* with the following formula:

$$\mathrm{SOC}(t+\Delta t) = \begin{cases} \mathrm{SOC}(t) - d_{\Delta t} \cdot c & \text{for} \quad d_{\Delta t} > 0 \\ \min\{\mathrm{SOC}(t) + \Delta t \cdot P_{loc_t}, C\} & \phantom{\text{for}} \quad d_{\Delta t} = 0 \end{cases}$$

where the initial value is given by SOC(0) = *C*. SOC(t) denotes the state of charge of a simulated battery at time *t* in kWh. The consecutive state of charge $\mathrm{SOC}(t+\Delta t)$ after a time step Δt depends on the distance driven in this time period $d_{\Delta t}$. If there is a movement (first case), we subtract the energy needed by multiplying the distance driven $d_{\Delta t}$ in kilometres with the specific consumption c in kWh/km. If there is no movement (second case), we charge the battery with the power P_{loc_t} in kW available at the location where the car stopped at t multiplied by the time Δt to receive the energy which is added to the earlier state of charge $\mathrm{SOC}(t)$. If the battery is already fully charged or the energy that could be charged is larger than what is needed to recharge completely, the $\mathrm{SOC}(t+\Delta t)$ is set to its capacity C. In this simulation we use time sections of 15 minutes; the consumption is set to 0.194 kWh/km. The distance travelled as well as the location of the stopping point stem from the driving profiles. Since we want to compare

1 For further details on the allocation of household movements to vehicles see [2].

the minimal battery capacities needed under different infrastructure circumstances, we have to define charging infrastructure scenarios.

We distinguish between three common locations for charging infrastructure: private or domestic charging infrastructure is only accessible to the car owners and power ranges from 3.7 kW to 22.2 kW. Semi-public charging infrastructure can only be accessed by a specific group of people, e. g. the parking of a sports club or at work. Here power may range from 3.7 kW up to more than 100 kW. The same power can be charged at public charging facilities, which are open to everyone and account for the third group [2], [4–7]. As earlier works [2, 6] show that the power rate has only a small influence on users that may use an electric vehicle with a distinct battery capacity, we define three charging infrastructure scenarios (see also Table 1):

- In scenario A users are only able to charge at domestic locations with 3.7 kW.
- Scenario B adds semi-public charging infrastructure with a power of 11.1 kW.[2]
- In scenario C there is also charging infrastructure at public sites where vehicles could be charged with 11.1 kW.

Table 1 Charging infrastructure scenarios with power rates [kW]

Scenario	Private	Semi-public	Public
A Home-only	3.7	-	-
B Home-and-semi-public	3.7	11.1	-
C Everywhere	3.7	11.1	11.1

With these assumptions we analyse the above mentioned driving profiles to determine which share of vehicles could be replaced by a BEV or simulate electric driving shares of potential PHEVs in dependence of the battery size and infrastructure.

For the psychological part of our study, a set of survey data of participants in field trials from the eight pilot regions for electric mobility in Germany is analysed (N = 2306). This study was conducted within the programme “Electric Mobility in Pilot Regions” which was implemented by the German Federal Ministry of Transport, Building and Urban

2 In the MOP we define stops as semi-public charging facilities when the purpose of the trip is to go to work and to go shopping.

Development. In eight pilot regions several kinds of electric vehicles were tested by several types of users (private as well as business). All model regions installed some kind of charging infrastructure (for details see [12]). In sum, about 600 public or semi-public charging points were installed during the project phase. The vehicles are used in various business models: car-sharing or hired car, as company or fleet vehicles or in exclusive private use. The survey includes questions on the vehicle types, planned usage, demographics, expected advantages and disadvantages of the vehicles, and item batteries with general aspects of acceptance as well as more detailed questions about specific attributes of the electric vehicle and – most important for this paper – about the infrastructure. The survey was available online as well as in a paper version.

A longitudinal survey design was applied, i.e. users were invited to take part (T0) before starting to use the vehicle, (T1) after a short usage period to report first impressions (between one week and up to three months) and (T2) after a period of adaptation (after three months up to about a year). 835 individuals took part in T0, 781 participated in T1 and finally 690 individuals filled in questionnaire T2. However, very few participants took part in all three surveys, i.e. only few of them are identical. This is due to several reasons: in some cases the project duration was shorter than three months, in other cases questionnaires were not handed out in time. Thus, the three samples have to be treated as more or less independent samples of (future) users of EVs with a diverse degree of experience with the vehicle. Socio-demographic attributes were only measured in T0 and T1; they point out that the majority of the sample is male (77-85%), on average 40 to 42 years old and highly educated. Nevertheless, this sample is the most extensive survey of actual users of EVs in Germany which has been compiled so far. In this paper we focus on analyzing the T2 survey since these respondents have gained experience with their vehicle, its ranging and the handling of charging most extensively; thus, we assume that their evaluation regarding infrastructure is reliable. The size of this subsample is 293, because not all participants of T2 answered the questions on infrastructure. Table 2 provides an overview what type of vehicle was used by the respondents and how they used it.

Table 2 Sample characteristics

	Share
Electric vehicle used	
- Car/LDV	15.7 %
- Electric bike/motor-bike	84.3 %
Type of usage	
- For private transport	76.8 %
- For business	7.7 %
- Both	15.5 %

Nevertheless, this sample is the most extensive survey of actual users of EVs in Germany which has been compiled so far. Most important to this paper are the questionnaire sections referring to user perceptions on the infrastructure. Most items in the survey were quantitative, i.e. Likert-scaled from 1='not at all' to 6='fully agree'. Items were worded as positive statements, i.e. agreement with an item expresses a positive rating of the respective aspect and vice versa low agreement a negative evaluation. The following list outlines the items on infrastructural issues:

- EV range high enough
- trust into vehicle range
- short charging duration
- easy handling of charging
- charging facilities at workplace
- charging facilities at home
- public charging facilities

A further question asked participants to choose from a list of options where they think that additional infrastructure is most needed (see Figure 6 for list of options).

3 Results

3.1 Results on driving behaviour: the need for infrastructure from a technological perspective

The basis for assessing the usefulness and effect of installing charging infrastructure is an analysis of the current user behaviour, i.e. driving behaviour and data. Figure 1 shows the cumulative distribution function of daily driving distances for German and US drivers of mid-size vehicles (cf. [6] for Details).

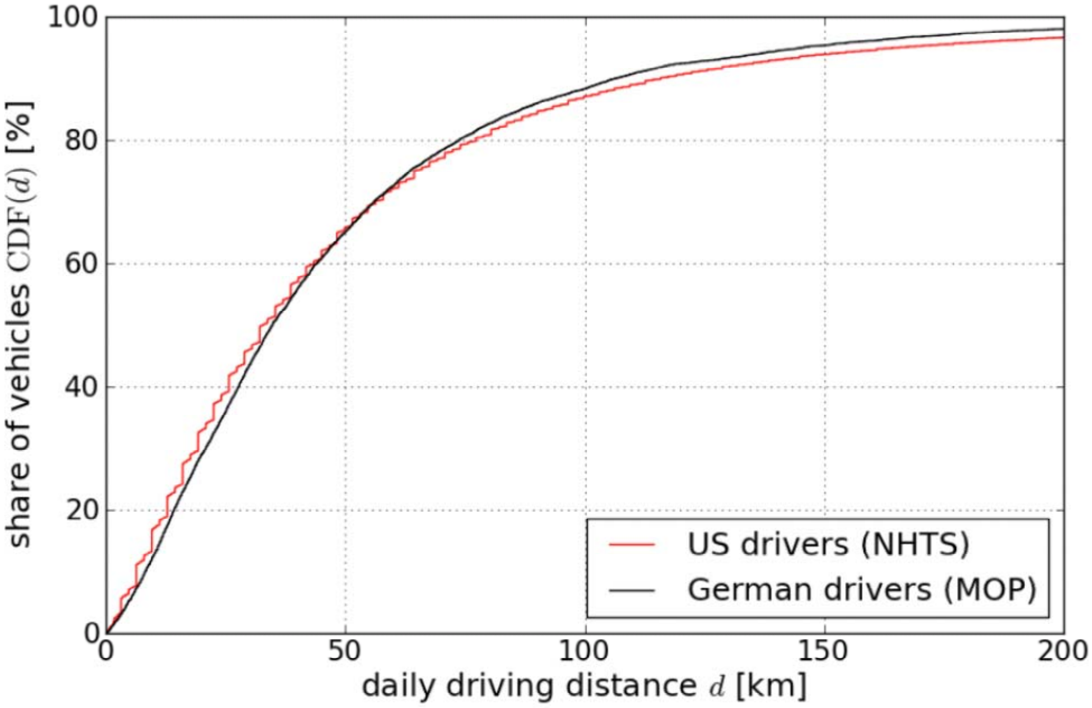

Figure 1: Distribution of driven daily distances for German and US drivers.

Figure 1 demonstrates that typical daily driving is mostly well below 100km and thus easily substituted by BEVs. About 70% of all users drive less than 50km per day and about 90% of the users less than 100km per day. We observe that the distribution functions for the US and Germany are very similar for the selected sub sample of users (mid-size vehicles, see [6]). However, the time span of observation for driving behaviour is rather important here, since longer trips might not take place on a single day of observation but the probability of occurrence of longer trips increasing with the observation time. Since comprehensive data sets over longer time periods are not available we restrict ourselves to one week of observation time.

The distribution of daily driving distances in Figure 1 is a first indicator that charging over night should be sufficient for a large number of users and no or little additional infrastructure would be required.

We now use the driving profiles to simulate existing cars as electric vehicles. Figure 2 shows the summary of such a simulation: All vehicles with all trips from one week are simulated as battery electric vehicles with the battery size as parameter. Displayed are the share of vehicles that could be operated as battery electric vehicles as a function of battery capacity. For comparison: 24 kWh result in a range of ca. 100 km. Even under the constraint that only drivers owning a garage (where charging options are available or could be easily installed) should be considered, we find that roughly 50 % of the German drivers could technically use a battery electric vehicle for all their trips in the week of measurement. Furthermore, Figure 2 shows that additional semi-public and public charging options can increase the share of vehicles that can be operated as battery electric vehicles, but only by roughly 15%. This is only a limited increase compared to the cost required for installation of ubiquitous public charging infrastructure [2].

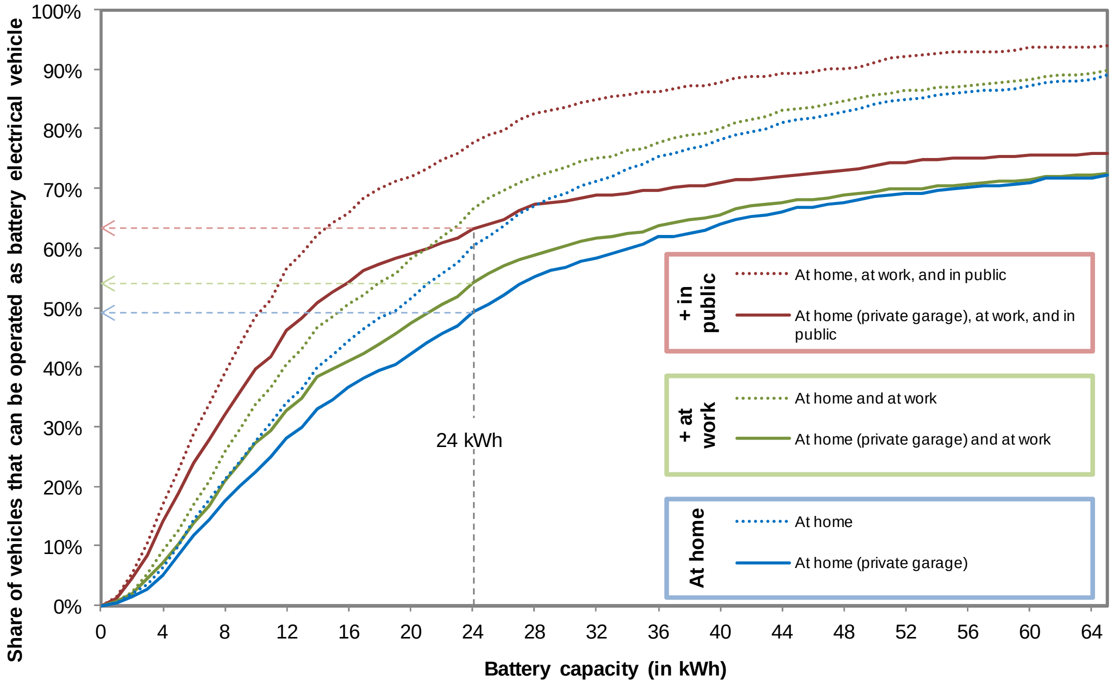

Figure 2: Simulated share of vehicles that could be operated as battery electric vehicles as a function of battery capacity.

In addition to battery electric vehicles, PHEV allow very long trips to be driven without any additional public or semi-public charging infrastructure. In fact, a detailed analysis shows that more than 90% of the drivers reach electric driving shares of 80% or higher when charging overnight [6]. Thus, charging at home is advisable in order to increase the electric driving share of PHEVs and to reduce the operational costs.

Figure 3 displays the distribution of electric driving shares when only home charging is possible as well as the effect of additional charging at public or semi-public stops the users encounter.

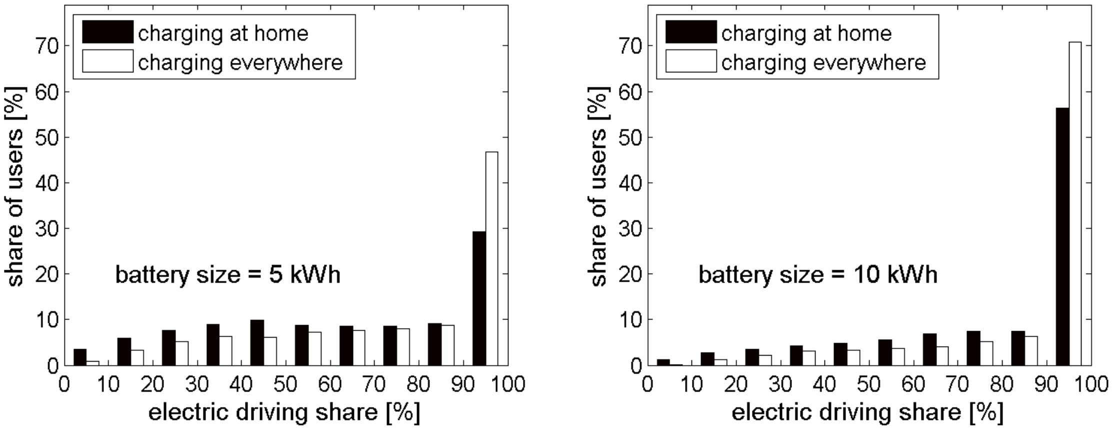

Figure 3: Distribution of electric driving share with and without additional charging infrastructure for 5 kWh (left) and 10 kWh (right) PHEV battery capacity.[3]

Additional semi-public and public charging infrastructure naturally leads to an increase of electric driving shares. In both cases PHEVs with assumed battery capacity of either 5 kWh or 10 kWh the share of users with about 100 % of electric driving share would increase by some 15 % from about 30 to 45 per cent. Thus, adding (semi-)public charging infrastructure clearly has an effect on electric driving, but it does not lead to a significant increase of electric driving.

Interesting to note that charging at home should be widely available for German car owners even in larger cities. Figure 4 shows the distribution of regular night parking spots for German car users [9]. In municipalities of up to 100,000 inhabitants – where the majority of cars are owned – more than 50% of all car owners usually park their car over night in garage. Whether or not these garages are equipped for electricity is not clear, but installing it there would certainly be the cheapest infrastructure option.

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[3] The battery capacities for PHEVs given in figure 3 are net capacities, i.e. the 5 or 10 kWh can be used completely. This ni contrast to the BEV capacities assumed for figure 2, where a depth-of-discharge of 75% is assumed instead of 100%.

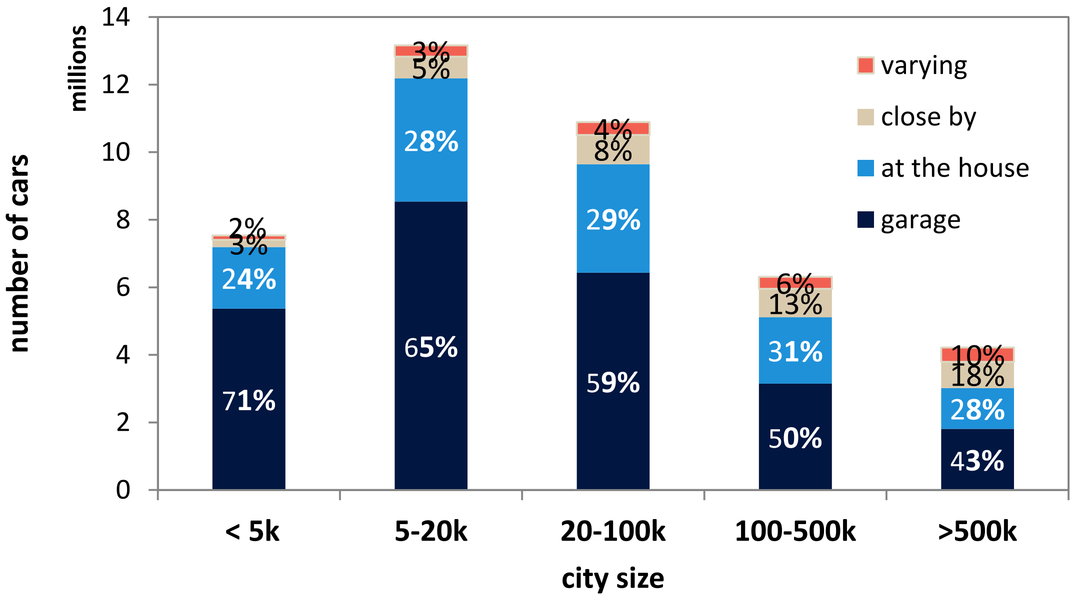

Figure 4: Distribution of usual parking options for German car users (source: own calculations with data from [14].

We conclude, from a technical point of view, for market introduction of electric vehicles there is only little need for public charging infrastructure and its installation promises only limited gain compared to significant costs.

3.2 Results on user needs and user behaviour from a psychological perspective

From a technical point of view public charging infrastructure may not be necessary; however, the restricted range and the long charging duration are the features that distinguish EVs most from traditional vehicles. At the same time, the infrastructure for traditional vehicles is very dense and highly developed. Thus, users are habituated to have the possibility to quickly refill their vehicles nearly everywhere. Charging an EV, however, has an important advantage: it can be done at home. And, as the technical analyses show, it may not be necessary to charge anywhere else. So what do users think about these issues?

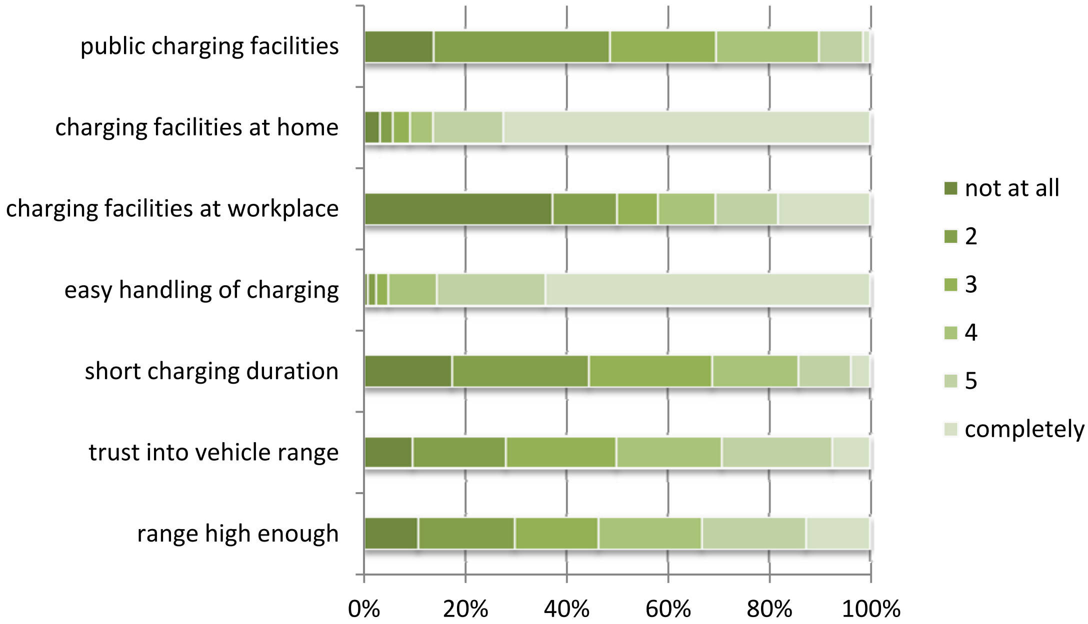

Figure 5: How do range, charging duration and charging facilities meet the user's requirements? (N=293-276)

Based on our user survey we find that the evaluation of the availability of public and semi-public infrastructure is critical: only 10 % rate them as sufficient (i.e. they rate them 5 or 6 – see Figure 5) while nearly half of the respondents evaluate them as insufficient (ratings of 1 or 2). Charging facilities at home are sufficiently available – 86 % fully agree with this statement (rating of 6). The evaluations of availability of charging facilities at the workplace are mixed: while 50 % rate them as insufficient, 31 % rate them as sufficient.

Hardly any users reports problems with the handling of charging the vehicle (86 % are positive, see Figure 5). Duration for charging the vehicle is perceived as too long (44 %) or moderately long (41 %, i.e. rating of 3 and 4). Findings on range are mixed, around 30 % report not to have sufficient trust in the range of the vehicle; the same proportion reports positive evaluations. A similar distribution is found for the range itself. Taken together, this indicates that EVs are not fully able to convince users with regard to the availability of charging facilities, charging time and driving range.

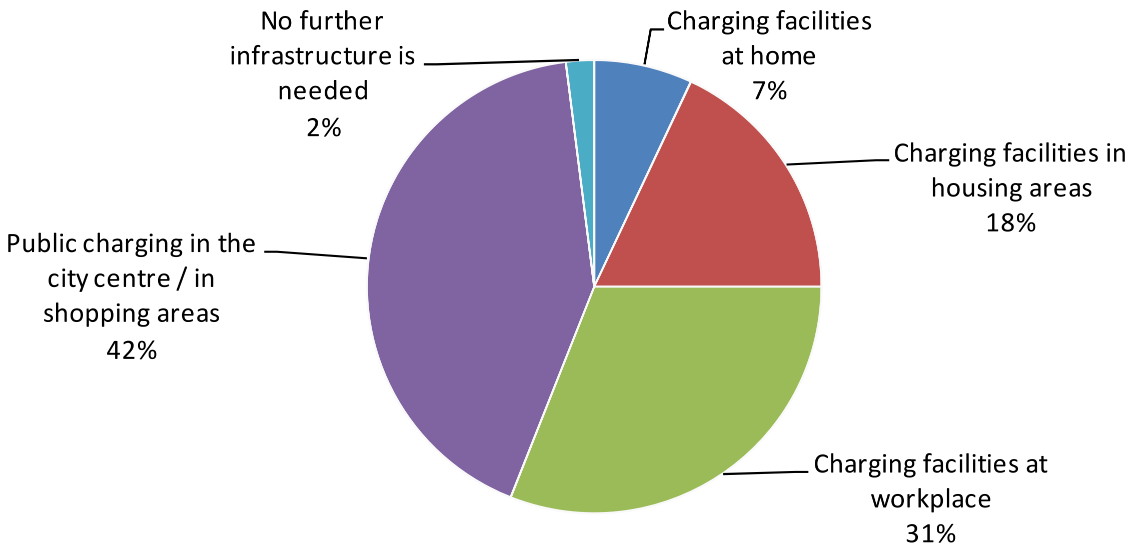

Figure 6: User preferences where further infrastructure is needed (N=293)

In line with this, users ask for developing the existing infrastructure especially with regard to providing charging options which can be used en route – 40 % want more charging possibilities in the inner city or at shopping points, 30 % think it is most important to invest in infrastructure at employer sites. Only 2 % regard the existing infrastructure as already good enough (see Figure 6).

The respondents of the T1 survey were also asked to name (policy) measures to promote electric mobility and the use of electric vehicles in Germany in an open question [10]. Most of the respondents believe that setting up (public) charging infrastructure is necessary in the short term range (until 2015). Only a few respondents state that this is needed right now.

Analyses from fleet trials indicate that the available public infrastructure is hardly used. A possible explanation for the gap between user's demand for public and semi-public charging infrastructure and the actual usage could be a badly chosen position of the public and semi-public charging facilities. Moreover, it is not clear how much infrastructure users expect to be satisfied. Some preliminary ideas will be developed in the remainder of this section by taking a closer look at the data.

Table 3 Bivariate correlation on charging facility evaluations (Pearson's correlation coefficient)

	Charging facility at home	Charging facility at workplace
Public charging facility	+0.016	0.315**
Charging facility at workplace	-0.151*	

Note. * - p< 0.05; ** - p<0.01

The ratings of the different charging facilities are interrelated (see Table 3): Those who rate the charging facility at home more positively tend to rate charging facilities at work a bit lower (r=-0.151, p<0.05). This might be due to project characteristics: Projects usually ensured that users had the possibility to charge their vehicle either at home or – in case of commercial usage – at their workplace.[4] The ratings of charging facilities at workplace are significantly correlated to ratings of public charging facilities. This correlation is also significant in the subgroup of private users (r=0.326, p<0.01, n=184), however not for those who used the vehicle primarily for business (r=0.048, p>0.10, n=19). The same tendency is observable the other way round: evaluations of charging facilities at home are not related to evaluations of public charging stations for private users (p=0.022, p>0.10, n=199), however tend to be related for commercial users (p=0.445, p<0.10, n=16). These patterns may always be due to specific project conditions. However, if we assume a similar public charging infrastructure for all projects these results could lead to a different interpretation: maybe charging facilities outside the "base" of the vehicle could compensate for each other. In a simplified way: if someone has the possibility to charge the vehicle on top of the vehicle's base (at home in case of private use, at the workplace in case of commercial use), he or she is more satisfied with the charging infrastructure in general.

[4] Data on existing infrastructure was not collected systematically. However, this assumption which was derived from informal contacts to project officials is supported by the finding that primarily private users rate charging facilities at home significantly more positive (T=11,5, df=37,3, p<.01) than commercial users and vice versa (T=3.9, df=16.4, p<.01). Ratings of public infrastructure do not differ significantly.

4 Discussion and Conclusion

For a market introduction of electric vehicles no public charging infrastructure is technically required since many potential users can charge at home easily. However, public charging infrastructure also has a psychological function: It reduces the well-known “range anxiety” of users of battery electric vehicles [8]. Moreover, some drivers might not be aware of their actual driving behaviour and might feel safer with public charging infrastructure widely available. Additionally, as it is not clear, if these charging stations will be profitable for their providers, at this point the market introduction of electric mobility may depend on financial support from the government or on the provision of some kind of incentive to the providers.

In summary, we find that some public charging infrastructure at well chosen locations seems advisable in order to facilitate the user’s decision for an electric vehicle and to reach the political targets for market shares of electric vehicles. However, before starting a roll-out of public infrastructure we recommend to analyze where and how much infrastructure is really needed.

Acknowledgements

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