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Consumer evaluation of public charging infrastructure for electric vehicles

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Abstract

The lack of public charging infrastructure is often referred to as an important barrier to the diffusion of electric vehicles. As the construction of charging stations is a costly endeavour, the question arises as to how maximum benefit for potential users can be achieved with limited resources. Therefore, our analysis deals with the factors that influence the attractiveness of public charging infrastructure from the perspective of potential users. Our analysis is based on the assessments of 1003 German car drivers on possible future charging infrastructure systems with different configurations regarding spatial coverage, charging duration and usage costs. We examined the preferences with regard to these features using a rating-based conjoint analysis. We also looked into the question of whether groups of car drivers can be identified that are characterised by specific preference constellations with regard to these features. Our key finding is that the majority of car drivers are unwilling to pay a basic fee for the possibility of using public charging infrastructure. Nevertheless, there are subgroups that value the public charging infrastructure more than other car drivers. In addition to implications for possible business models, this result indicates that public charging infrastructure could be important for attracting other target groups to electromobility besides classic early adopters of electric vehicles. Furthermore, our analysis shows that the charging duration at charging stations in cities and along the highway has a strong influence on the evaluation of the public charging infrastructure. The spatial coverage with charging stations in cities and along the highway, on the other hand, has a weaker influence. A central conclusion from this is that the existence of fast-charging stations should be prioritized over a close-meshed coverage with charging points when the charging infrastructure is expanded than.

Keywords – public charging infrastructure, EVSE, user perspective, electric vehicle, willingness to pay, target groups

1 Introduction

Battery electric vehicles (BEV) can reduce greenhouse gas emissions if powered with renewable energy. A barrier to their market diffusion is the current low driving range delivered by batteries. Although it is possible to find user groups who can meet their driving needs without public charging (see e.g. Jakobsson et al. (2016)), a broader market diffusion of BEVs requires either a noteworthy improvement in battery technology or a more extensive charging infrastructure or progress in both.

Sun et al. (2016) point out that there is comparatively little research done on user perceptions of and preferences for charging in the field of user perception and acceptance of electric vehicles (EVs). This is surprising as the need to charge the vehicle is one of the main differences to driving a vehicle with an internal combustion engine. Philipsen et al. (2016) come to the conclusion that electric vehicle drivers and people interested in electric vehicles want fast charging stations on motorways and in public places. Their results also indicate that respondents are more willing to make a detour than to accept waiting times for charging. This raises the question of how many fast charging stations are actually needed and to what extent electric vehicle drivers are willing to pay for their presence or use? These questions are especially important as fast charging infrastructure requires large investments (Schroeder and Traber, 2012). At the same time, the question arises how much charging infrastructure needs to be set up in order to effectively support the spread of electric vehicles (Hardmann et al., 2018). Thus, our study focuses on the following main research question: *Which factors influence private car drivers' evaluation of public EVSE?* Other questions linked to this are: *What attributes of public EVSE are most relevant to car drivers? Do different target groups have distinct preferences regarding EVSE?* Our results on the latter question are particularly useful for researching target groups for charging infrastructure, as there is a research gap in this field (Sovacool et al., 2017).

To address these questions, we conducted an empirical study with a sample of 1003 German car drivers. Our analysis employs a hierarchical linear model to analyse data collected by a rating based conjoint analysis to quantify the factors that influence the respondents' evaluation of (hypothetical) public EVSE options. The outline of this paper is as follows. The remainder of section 1 provides an overview of the literature that forms the basis for our study. Section 2 describes the methodology. Section 3 presents the results of our analysis. The main findings and conclusions are discussed in section 4.

In general, the topic of EVSE has been approached from different perspectives, in particular by studies analysing techno-economical aspects and those that focus on the preferences of (potential) users of public EVSE. Both approaches examine which kind of EVSE is needed where. Following these functional aspects, the question arises of the costs of EVSE and/or the users' willingness to pay as the deployment of EVSE has to be financed in some way.

In relation to the requirements and preferred locations for charging stations, gender, age and prior experience with battery electric vehicles were found to be important (Philipsen et al., 2016). The duration of the recharging process as well as the location and density of EVSE may affect the (perceived) usefulness and costs of EVSE (Philipsen et al., 2016; Schroeder and Traber, 2012). Furthermore, Philipsen et al. (2015) conclude that a detour of 5 km or 10 min to a fast charging station is seen as acceptable. Sun et al. (2016) from Beijing, China, study the willingness to take a detour for recharging, focusing on the opportunity to fast-charge an EV. They find an average willingness to detour of up to about 1750 meters for private car drivers on working days and 750 meters on non-working days based on the recorded mobility patterns of Japanese EV drivers. However, their sample was limited (24 drivers) and the results are certainly influenced by the current state of existing infrastructure, i.e. do not necessarily mirror the ideal situation desired by drivers. Sun et al. (2017) surveys actual EV users and highlights that nearly half the respondents want to be able to find a charging station within a 5-min drive if they need to charge their car. Only 16 % find it acceptable to drive for 10-20 min to a charging station. Density of charging stations is also found to be significantly correlated with EV satisfaction. Furthermore, Szierchula et al. (2014) identify EVSE density as positively correlated with PEV sales.

These user-centric analyses of preferred locations and density of EVSE are mirrored by techno-economic studies. A common approach in such studies is to maximize the number of electric miles travelled or reduce the number of unfulfilled trips if all vehicles were BEV (Alhamzi et al., 2017; Dong et al., 2014; Shahraki et al., 2015). For example, Alhazmi et al. (2017) optimize the allocation of EVSE with respect to electrifying as much car travel as possible. Dong et al. (2014) also optimize EVSE locations and analyse the number of range-constrained days and trips for the greater Seattle region. Shahraki et al. (2015) perform a similar analysis applied to taxis in Beijing.

While the aforementioned studies focus on how the usefulness or utility of public EVSE can be maximized, it is important not to neglect the question to what extent public EVSE is needed at all. For example, the sample of Sun et al. (2017) consists mostly of EV drivers who usually charge at public charging stations (around 80%), but many (around 40%) would prefer to charge at their own parking lot. From a techno-economic point of view, the impact of EVSE on the market diffusion of EVs has been analysed by various studies. Gnann (2015) as well as Gnann and Plötz (2015) find that a large share of vehicle-owning households in Germany are equipped with garages and require EVSE only for long-distance travel. In addition, Jakobsson et al. (2016) conclude that multi-car households can better handle the restricted range of BEVs and depend less on public charging infrastructure.

The actual need for public EVSE is important as the scale of EVSE deployment is crucial for the direct and indirect costs of the system. The economic dimension is addressed e.g. by Guo et al. (2016) who look at the business perspective and investment planning for charging station providers. Similarly, Sadeghi-Barzani et al. (2014) look at how to minimize the total cost of charging station investment including grid costs. The indirect costs of EVSE are analysed by Wang et al. (2013) who look at the distribution system with the objective of minimizing power losses and voltage deviations.

The cost of public EVSE leads to the question of who is willing to pay (how much) for its construction and use. It seems reasonable to assume that the willingness to pay is influenced by the usefulness attributed to EVSE by individuals. Thus, the question arises whether there are target groups with higher or lower evaluations of EVSE or distinct requirements regarding EVSE.

The results of the reviewed studies provide useful insights that will guide our own analysis and can be summarized as follows: The density of an EVSE grid is considered to be an important factor when evaluating its usefulness. Density is not only defined by geographical distance – the time needed for a detour to a charging point is also important. Thus, the location of EVSE can also be important for its utility as it defines the ease of its accessibility. The relevance of detour time and the few studies that focus on fast charging also indicate that the duration of the charging process might be relevant for EVSE utility.

2 Methods

The main aims of our study were to obtain insights about the trade-offs between different attributes of EVSE and identify target groups. We conducted an explorative and inductive analysis. Likewise, the content of our data collection is guided by the results of the literature review. The resulting research design and data collection are described in section 2.1. Section 2.2 outlines how the collected data was prepared and analysed.

2.1 Research design

Sampling procedure. Potential EVSE users are the most relevant population for our study. We defined potential EVSE users as persons who regularly use a passenger car (at least once a week) that is owned by themselves, a member of their household or a family member. Therefore, car ownership and regular car use were the two basic requirements to participate in the survey. The requirement of car ownership aimed to ensure that the respondents represent potential EV adopters. The precondition of regular car use was used as a proxy for potential relevance of EVSE in the case of a (future) EV adoption.

To obtain a sample of the above described population, we tasked the fieldwork to a market research institute and defined screening criteria and quotas for the sample. The screening criteria reflected the two requirements that constitute the definition of the relevant population. The quotas aimed to ensure that the sample sufficiently covers the relevant population. To derive these quotas we used data of a previous study by [To be inserted after the blind review process] who collected a sample that was representative for the adult population of Germany. After limiting this sample to cases who satisfied the two screening criteria, we used the demographic properties of the remaining subsample to define the quotas that our own sample had to meet. These quotas referred to gender, education and age (cf. Table 1). The resulting sample was collected via an online survey and eventually comprised 1003 respondents from Germany.

Gender	Male	49.9%	**Age** (mean = 48 year)	18 to 30 years	16.7%
	Female	50.1%		31 to 40 years	17.0%
Education	No graduation/ GCSE EQF-Level 2*	26.0%		41 to 50 years	19.8%
	GCSE EQF-Level 3**	31.0%		51 to 60 years	16.8%
	A-level/university degree	43.0%		Older than 60 years	29.7%

European **Q**ualification **F**ramework equivalent for *“Hauptschulabschluss” and **“Mittlere Reife”

Table 1: Sampling quotas

Questionnaire design. The online survey consisted of four parts. The first part contained questions about demographic information to check the screening criteria and quotas at the beginning of the survey. The second part of the survey contained questions about the mobility behaviour and mobility features of the respondent or his/her household. These questions were placed deliberately before the evaluation of EVSE offers (which was the third part of the survey) in order to make respondents aware of their mobility needs and behaviour. I.e. we aimed to foster a framing effect so that the respondents evaluate the EVSE offers in the light of their personal mobility requirements. The fourth part of the questionnaire contained items to measure attitudinal characteristics. These items were placed at the end of the questionnaire to avoid the evaluations of the EVSE offers being influenced by perceived social desirability or pressure to give answers in accordance with reported attitudes.

Variable	**Categories and descriptive statistics**	
Occupation	Full time employee	43%
	Part time employee	11%
	Something else (student, retired, etc.)	46%
Household net income per month (Mean = €2,780)	First quartile	€1,700
	Median	€2,500
	Third quartile	€3,200

Table 2: Demographic variables

Besides the information needed to assign respondents to the sampling quotas (cf. Table 1), additional demographic information was collected in the first part of the questionnaire in order to identify and describe target groups. This additional information is presented in Table 2.

Mobility needs and mobility behavior were surveyed in the second part of the questionnaire. The respective descriptive statistics are reported in Table 3. Car size and car acquisition are relevant information as these properties can influence the willingness or ability to adopt an EV and thus facilitate some needs and preferences with regard to EVSE. The number of cars in the household, the availability of a parking place with a wall socket, the frequency of long distance trips and the annual mileage are considered to be decisive for the dependency on public EVSE and may further increase the need for EVSE in certain places, e.g. near to home or along the highway (Jakobssen et al., 2016; Gnann, 2015; Gnann and Plötz, 2015).

Variable	**Categories and descriptive statistics**	
Car size (measured by cylinder volume)	Small (<1.4 liters)	25%
	Middle (≥1.4 to ≤2 liters)	63%
	Large (>2 litres)	10%
	Not specified	2%
Car acquisition	New car	50%
	Pre-owned car	50%
Number of cars	One car	68%
	Two or more cars	32%
Parking place with socket	Regularly available	47%
	Not regularly available	53%
Frequency of trips with more than 100km	> 3 times per month	18%
	3 times per month	11%
	2 times per month	13%
	Once per month	16%
	Less than once per month	42%
Annual mileage	First quartile	7.000 km
	Median	10.000 km
	Third quartile	16.000 km

Table 3: Mobility-related variables

Figure 1 shows how these EVSE offers were depicted in the third part of the online survey. Each participant had to rate the attractiveness of ten EVSE offers presented pairwise within five tasks. Each task consisted of an introductory text, a table with information about the properties of two EVSE offers and two six-point Likert-scales to evaluate the attractiveness of each EVSE offer (from 1 = "very unattractive" to 6 = "very attractive"). We decided to conduct a rating-based conjoint analysis instead of a choice-based conjoint analysis, because a six-point Likert-scale as the dependent variable allows more nuanced evaluations of the EVSE offers by the respondents.

Please imagine you have just bought an electric vehicle. The range of the electric vehicle is **[XXX] km** (even when the heating or AC is on). If you have a parking space at home with access to a wall socket, you can charge your electric vehicle there (costs: approximately €5 per 100 km range; duration: approximately 5 hours per 100 km range).

In addition, there are two providers of public charging infrastructure for electric vehicles. You have to sign a contract with the provider to use their charging infrastructure. The power for 100 km range costs 7 euros **at both providers**. Some providers charge you **an additional monthly basic fee**.

Apart from purely financial aspects, the question arises how well a provider's offer matches your mobility needs and personal circumstances. This might depend, for example, on how many charging spots exist **(density)**, where they are located **(in cities or along highways)** and how long it takes to charge here **(charging duration)**. You can find information about these aspects in the table below.

	Provider A	Provider B
Monthly basic fee	[xxx] Euro	[xxx] Euro
Density of charging spots **in cities**	Every [xxx] meters	Every [xxx] meters
Charging duration for 100 km range **in cities**	[xxx] minutes	[xxx] minutes
Density of charging spots **along highways**	Every [xxx] km	Every [xxx] km
Charging duration for 100 km range **along highways**	[xxx] minutes	[xxx] minutes

How do you think about the attractiveness of these two offers?

	I totally disagree	I largely disagree	I rather disagree	I rather agree	I largely agree	I totally agree
The offer of **provider A** is very attractive.	O	O	O	O	O	O
The offer of **provider B** is very attractive.	O	O	O	O	O	O

Figure 1: Evaluation of EVSE offers

We considered it important to enable these more nuanced evaluations for two reasons: (1) The subject of the analysis (attractiveness of EVSE) can be assumed to be psychologically distant (cf. Liberman et al. 2008), because EVs are a new and unknown technology - only 1.5% of our respondents actually owned an EV. Therefore, we expected respondents would find it easier to answer using a graduated evaluation of attractiveness than by making a decision where the only options are A vs. B vs. neither A nor B. (2) Prior studies provide not enough information regarding the properties of EVSE offers that are acceptable for customers. Therefore, a choice with three options (A vs. B vs. neither A nor B) would have entailed the risk that many respondents select "neither A nor B", thus limiting the practical relevance of our results. Allowing more graduated evaluations mitigates this risk since these provide information about which factors affect attractiveness of EVSE offers even for respondents who would not choose either of the two alternatives offered.

The EVSE offers were characterised by different attributes, which are symbolized by the placeholders depicted as "[xxx]" in Figure 1. One placeholder (range of the hypothetical EV) was part of the introductory text and one of three options was displayed based on a random selection: 150 km, 250 km or 350 km. The values between 150 km and 350 km represent the range of EVs that were available on the market at the time of the survey (December 2016).

The range of the hypothetical EV differed between the respondents but was the same over all five exercises. In contrast, the displayed attribute levels of the hypothetical EVSE offers (depicted in the table in Figure 1) changed each exercise. Which attribute levels were displayed was randomly selected. Each attribute had five possible levels:

- Monthly basic fee: €0, €5, €10, €15 and €20
- Density of charging spots in cities: none, every 250 meters, every 500 meters, every 750 meters and every 1,000 meters
- Density of charging spots along the highway: none, every 25 km, every 50 km, every 75 km and every 100 km
- The attribute levels of "charging duration in cities" and "charging duration along the highway" were identical: N/A (if density was "none"), 10 minutes, 30 minutes, 60 minutes or 120 minutes for 100km range

We included the attribute 'monthly basic fee' as our literature review had identified the willingness to pay for the existence of public EVSE is an understudied issue. In addition, we included density of EVSE (in cities and along the highway) to address the need for detours for recharging and perceived mobility restrictions due to a lack of charging spots. The attribute levels for EVSE density in cities is based on the findings of Sun et al. (2016). The attribute levels for EVSE density along the highway was chosen proportional to the distances in cities. As the duration of the charging process was identified as an important aspect (Philipsen et al., 2016; Schroeder and Traber, 2012), we included it as an attribute. The attribute levels for the duration of the charging process approximately reflect the technological performance of currently available charging systems (December 2016). In order to direct respondents' attention to the changed attribute levels, additional advice was displayed after the respondent went on from the first to the second task.

Part four of the survey measured attitudinal constructs. Our analysis comprised the variables 'environmental consciousness' and 'technophilia' as well as 'general attitude towards EVs'. The constructs environmental consciousness and technophilia were measured by existent and validated scales that consist of multiple items as indicators of these psychological constructs (Wingerter, 2014; Neyer et al., 2016). The general attitude towards EVs was measured by a single item that has been used by the authors in prior surveys. The variables and the respective items that were used as indicators are shown in Table 4. The descriptive statistics (mean, standard deviation and the range of values) are displayed in brackets.

Like the evaluations of the EVSE offers, these items are Likert scales, i.e. the respondents could choose different options to agree or disagree with these statements. The item used as an indicator for the general attitude towards EVs had six options as possible answers – three affirmative and three depreciating options (I totally / predominantly / rather (dis)agree). Unlike the evaluation of EVSE offers, there is an additional "not specified" option. This design has the advantage that respondents either have to reveal a general tendency or deliberately refuse to answer (Weiber and Mühlhaus, 2014).

Variable	Item text (mean; standard deviation; min/max)
Environmental consciousness	It worries me when I think about the environmental conditions our children and grand-children will have to live with. (3.5; 1.1; 1 to 5)
	If we just carry on as before, we are heading for an environmental catastrophe. (3.7; 1.0; 1 to 5)
	I am often angry and appalled when I read reports about environmental problems in newspapers or watch these kinds of TV programmes. (3.4; 1.0; 1 to 5)
Technophilia	I am very interested in the latest technology developments. (3.4; 1.1; 1 to 5)
	It doesn't take me long to learn to like new technology developments. (3.3; 1.1; 1 to 5)
	I am always keen to use the latest technological devices. (2.8; 1.2; 1 to 5)
	If I had the chance to do so, I would use the latest technical products even more often than I do at present. (3.0; 1.2; 1 to 5)*
General attitude towards EVs	In general I think electric vehicles are a good thing. (4.4; 1.5; 1 to 6)

* Due to a lack of construct validity we exclude this from the analysis (cf. section 2.2)

Table 4: Attitudinal constructs

The items used as indicators for environmental consciousness and technophilia contained 5 answer options including two affirmative options (I totally/rather agree), two depreciating options (I totally/rather disagree) and one neutral option (I partly agree and partly disagree). This design is considered less advantageous by some methodological studies as the neutral option may indicate medium consent with the statement as well as the general absence of a clear sentiment towards the statement (Trommsdorff, 1975; Green and Rao, 1970). However, we decided to use five answer options to adhere as closely as possible to the original and validated form of the items of Wingerter (2014) and Neyer et al. (2016). In general, high values indicate affirmation of the statements while low values indicate disagreement. In our analysis we considered the level of measurement of Likert scales to be quasi-metric (cf. Norman, 2010).

2.2 Data preparation and Analysis

The preparation of the data for analysis consisted of five steps: (1) a confirmatory factor analysis (CFA) to test whether the items depicted in Table 4 are valid and reliable indicators of the proposed theoretical constructs listed in the left column. (2) Imputation of missing values to reduce bias resulting from estimations impacted by missing values. (3) Rearranging the structure of the dataset so that the evaluated offers constitute cases, i.e. rows in the dataset. (4) Excluding unsuited cases (i.e. evaluations of EVSE offers) from the dataset. (5) Dichotomising all variables with non-(quasi)-metric level of measurement and mean centring all non-binary variables. We explain the steps in more detail below.

The first step of data preparation addressed the variables that refer to psychological constructs and use multiple items as indicators, i.e. 'environmental consciousness' and 'technophilia'. The values of the different indicators had to be combined to a common value for each variable for the analysis. The presence of factor reliability and construct validity is a prerequirement for this. Whether factor reliability and construct validity are given can be assessed by a confirmatory factor analysis (CFA). An acceptable global fit in a CFA is a necessary but not sufficient condition for construct validity in a factor model. Furthermore, the factors should feature convergent and discrimanent validity, which refers to the local fit of the factors comprising the model consists of (Weiber and Mühlhaus, 2014; Kline, 2011).

Table 5 shows the parameters for the global fit resulting from the CFA. The initial factor model contained the three indicators for environmental consciousness and the four indicators for techophilia from Table 4. In reference to the thresholds for a good or acceptable global fit (second and third line in Table 5), the outcomes of the CFA illustrate that the co-variance structure postulated by the initial model did not adequately reflect the empirically observed co-variance structure (fourth line in Table 5). Modification indices suggested a problem with the indicators displayed in the third and fourth lines of the subsection “technophilia” in Table 4. As the item “I am always keen to use the latest technological devices” showed a slightly higher indicator reliability (.74 compared to .69; not displayed in Tables 5 and 6) than the item “If I had the chance to do so, I would use the latest technical products even more often than I do at present”, we excluded the latter from the analysis. This is reasonable as the latter refers to intention while the other three items refer to actual behaviour.

	p	**CFI**	**RMSEA**	**PClose**	**Hi90**
Model	n.a.	>.95*	<.08*	>.05*	≤.10*
	>.05**	>.97**	<.05**	n.a.	n.a.
Initial model	.000	.967	.102	.000	.117
Revised model	.010	.996	.039	.785	.060

Thresholds for acceptable* and good** model fit

Table 5: Results of CFA for global model fit

A factor model with only three indicators for technophilia shows an improved global fit (fifth line in Table 5): While the χ^2-test indicates that there are still significant deviations between the postulated and observed co-variance structure (p = .010), the other parameters indicate a good fit of the model. CFI and RMSEA are above or below their threshold values. The value for PClose indicates a close fit of the model as the hypothesis that RMSEA is higher than .050 can be rejected. In addition, a poor fit of the model can be ruled out as the upper bound of the confidence interval of RMSEA is below .100 (Hi90 = .060). The χ^2-test is disputed in the methodological literature because it tests for differences between postulated and observed co-variance structure. As the sensitivity of the χ^2-test increases with sample size, and as no model fits the data perfectly, χ^2 will always indicate insufficient global fit given a large enough sample. Thus, we consider our model fits the data sufficiently (Weiber and Mühlhaus, 2014; Kline, 2011).

	Factor reliability	AVE	Squared max. intercorrelation
Factor	>.6*	>.5*	< AVE*
Environmental consciousness	.844	.643	.074
Technophilia	.887	.724	.074

* Thresholds for acceptable local fit

Table 6: Results of CFA for local model fit

In the revised model, the two factors (environmental consciousness and technophilia) also show factor reliability and construct validity as illustrated by the parameters for the local fit reported in Table 6. We therefore combined the values of the respective indicators by calculating their average scores for each respondent.

In the second step of data preparation, we used Expectation-Maximization-imputation to estimate the values for missing data. This was necessary as listwise deletion (as the default option to deal with missing data) presumes that missing data is missing completely at random. Especially for some of the demographic information in our analysis (e.g. household income), this claim is untenable as previous studies found that the occurrence of missing data correlates with the value of the respective variable (e.g. higher incomes are more likely to be not reported than lower incomes (Acock, 2005)).

The third step of data preparation was to change the structure of the data set. This was due to the necessity to analyse our data using a hierarchical linear random effects model (cf. section 3) with the respondents as macro-level units (level 2) and the EVSE offers as micro-level units (level 1). Accordingly, we changed the format of our dataset so that the EVSE offers are the cases (lines) of the data matrix and the respondent is indicated by an ID variable.

In a fourth step we deleted all cases (now EVSE offers), which had the attribute level “none” for either of the two attributes “Density of charging spots in cities” and “Density of charging spots along the highway”. This was necessary as “none” corresponds to “N/A” for the charging duration in cities or along the highway respectively. Therefore, the exclusion of these cases was inevitable due to the occurrence of perfect multi-collinearity between the two variables. The reason we included “none” in our questionnaire in the first place was that analysing the value placed on the very existence of public EVSE in cities and along the highway was a secondary objective of our study. However, this objective is beyond the scope of this paper. As a result of this data adjustment, our dataset contains evaluations of 8887 EVSE offers from 1003 respondents, i.e. 1143 evaluations of EVSE offers were excluded (between 4 and 10 evaluations of EVSE offers per respondent remained; on average each respondent evaluated 8.86 EVSE offers).

In step five, we dichotomised all the non-metric variables included in our analysis (e.g. gender) and defined a baseline value for each variable (e.g. female). Therefore, the effects for the dichotomised variables reported in section 3 indicate how EVSE offers differ in attractiveness depending on respondent characteristics compared to the baseline value (e.g. "men" compared to "women"). In addition, we improved the interpretability of the results by mean centring ($X - \overline{X}_{sample}$) all the non-dichotomous variables (all the attributes of the EVSE offers and respondent characteristics like age, net household income or the theoretical constructs depicted in Table 4). Therefore, the effects of the EVSE offers` attributes in section 3 can be interpreted as the conditional effects for average EVSE offers (average monthly basic fee, EVSE density and charging duration) evaluated by a baseline respondent (e.g. female) with an average age, household income, technophilia etc. (cf. Algina and Swarninathan, 2011).

3 Results

The presentation and discussion of the results of the hierarchical linear model is guided by the advice of Peugh (2010) and Hox (2010). The results of our analysis are summarized in Tables 7 to 10 (variables without significant effects are excluded from the analysis; non-significant results are omitted for the sake of clarity).

As recommended by Hox (2010) we pursued a bottom-up strategy for our analysis. This means (1) we first set up an unconditional model before (2) we built a level 1 model with fixed effects, (3) included level 2 variables, (4) added random effects for level 1 variables and (5) incorporated cross-level interactions. These steps resulted in the different models presented in the columns 2 to 5 of Table 7. The unconditional model (step 1) did not comprise any independent variables except for the ID of the respondents. This step assessed the share of variance of the dependent variable explained by the clustered structure of the data (cf. column 2). Step 2 estimated fixed effects for level 1 variables (attributes of EVSE offers), i.e. no variations of the level 1 effects between the level 2 units (respondents) were allowed (cf. column 3). Results for steps 3 and 4 are reported together in column 4. Step 3 comprised the inclusion of level 2 variables (respondent characteristics) to explain the variance between respondents. Step 4 estimated the effects of level 1 variables (EVSE offers) separately for the level 2 units (respondents). Comparing the results of step 2 and step 4 provides information on the extent to which the explanation of the dependent variable by level 1 variables is improved by taking the nested structure of the data into account. Interactions between level 2 and level 1 variables were included in step 5 (column 5). This provides information about where the improvement in step 4 originates from.

Model evaluation. Table 7 provides a summary of the models. The model which contains cross-level interactions (“interaction”) entails fewer parameters that need to be estimated than the “random” coefficient model without cross-level interactions (38 vs. 41 parameters). The reason is that the “interaction” model does not contain random effects for the level 1 variable “monthly basic fee” in contrast to the “random” coefficient model. After the inclusion of the cross-level interactions depicted in Table 7, there remains neither a significant variance of the slopes for "monthly basic fee" nor a significant variance of the co-variances between "monthly basic fee" and the other level 1 variables. In other words, if the cross-level interactions are taken into account, the strength of influence (i.e. the slope) of "monthly basic fee" on the evaluation of an EVSE offer does not differ significantly between respondents.

As Peugh (2010) points out, there is no measure for effect strength comparable to Cohen's d for hierarchical linear models. With regard to explanatory power, we find a correlation of .802 between the real evaluations of EVSE offers and the values predicted by the 'interaction' model. The pseudo-R^2 of this model is .643, i.e. the model explains 64.3% of the variance in the evaluations of EVSE offers (Peugh, 2010). In contrast, the 'random' coefficient model yields a correlation of .843 between predicted and observed values, which equates to a pseudo-R^2 of .710. However, despite the lower explanatory power of the 'interaction' model, it is more useful in the context of our research question: We aim to describe potential target groups – thus the explanatory power and parsimony of the model is not an end in itself. The cross-level interactions are useful to describe potential target groups.

Parameters	**Unconditional**	**Level 1:fixed**	**Level 2 & level 1: random**	**Interaction**
Pseudo-R^2	.481	.529	.701	.643
Deviance statistic	28,734.842	28,073.576	27,586.353	27,627.860
Number of estimated parameters	3	13	41	38

Table 7: Summary of the hierarchical linear model

The fixed effects reported in Table 8 are unstandardized regression parameters for direct effects of level 1 variables (γX/0), level 2 variables (γ0/X) and cross-level interactions between level 1 and level 2 variables (γX/X). Table 9 comprises the variance of the residuals of the dependent variable (σ^2), the variance of the intercepts of level 2 units (τ00), the variance of slopes of level 1 variables between level 2 units and the covariance between level 1 variables among the level 2 units. The last two variance components are only present if the model comprises random effects, i.e. the slopes of level 1 variables can differ between level 2 units. The standard errors of the parameter estimates are listed in parentheses.

Level 1 effects (effects of attributes of EVSE offers). The model contained those variables described in section 2.1, which significantly affected the evaluations of EVSE offers. As described in section 2.2, we (grand-) mean centred our non-dichotomous independent variables as this improves the interpretability of the regression parameters and interaction effects. Consequently, level 1 effects are conditional effects for an average EVSE offer by and baseline and average respondent. An average EVSE offer has the following properties: €10 monthly basic fee, charging spots every 624 meters in cities and every 62 km along the highway, 55 minutes to charge for 100 km range at charging points in cities and along the highway. The mean evaluation of such an average EVSE offer is 2.5 (γ0/0 of the interaction model), i.e. between the answer options “I predominantly disagree” and “I rather disagree” regarding the approval of the statement that such an offer is attractive.

To further improve the clarity of the information provided by the regression coefficients, we divided the values of ‘density EVSE in cities’ by 100 (resulting unit = 100m) and the values of ‘charging duration in cities/along the highway’ as well as ‘density EVSE along the highway’ by 10 (resulting unit = 10 minutes / 10km). As a consequence of centring and harmonization the effects in Table 7 can be interpreted and summarized in the following way: An in all other respects average EVSE offer is evaluated .033 points less positive for every euro increase in the basic monthly fee. Similarly, increasing the distance between charging points in cities/along the highway by 100m/10km results in a .014/.016 point less favourable evaluation, respectively.

Conditional level 1 effects (effects of attributes of EVSE offers conditional on respondent characteristics). If charging for 100km range takes 10 minutes longer in cities, the evaluation of an otherwise average EVSE offer by a respondent of average age (the mean age is 48 years) and technophilia (3.2 points of 5) worsens by .037 point. The effect is .001 point more/less negative (γ3/7) for every year the person is older/younger than the average. Furthermore, this effect is .011 point more/less negative (γ3/9) for every point the person is above/below average on the technophilia scale. The effect for charging points along the highway is in a similar range. Increasing charging time for 100km by 10 minutes results in a .042 point less favourable evaluation for persons with an average attitude towards EVs (4.4 points of 6). This effect is .006 point more/less negative (γ5/10) for every point the person is above/below average on the scale that measures the general attitude towards EVs.

Level 2 effects (effects of respondent characteristics). In general, men evaluate an average EVSE offer .169 point less favourably than women (γ0/4). The level of formal education has an ambiguous effect: Compared to people with an educational qualification not higher than GCSE (equivalent to EQF-Level 2), academics rate an average EVSE offer worse by .612 point (γ0/6), while respondents with A-levels rate it more favorably by .092 point (γ0/5). Furthermore, the average EVSE offer is rated more negatively the older the respondent is – for every year a person is older, the rating decreases by .008 point (γ0/7).

Attitudinal factors also influence the evaluations of EVSE offers. For each point increase on the environmental consciousness scale an average EVSE offer is rated .099 point better (γ0/8). Furthermore, the evaluation of an average EVSE offer is .129 point more favourable for a one-point increase on the technophilia scale (γ0/9). Also an increase of one point on the scale which measures the general attitude towards EVs results in a more positive evaluation by .266 point (γ0/10).

Parameters	Unconditional	Level 1:fixed	Level 2 & level 1: random	Interaction
Intercept (γ0/0)	3.648*** (.032)	3.038*** (.376)	2.455*** (.370)	2.489*** (.367)
Monthly basic fee (γ1/0)	-	-.033*** (.002)	-.032*** (.002)	-.033*** (.002)
Density EVSE in cities (γ2/0)	-	-.014** (.004)	-.016*** (.004)	-.014** (.004)
Charging duration in cities (γ3/0)	-	-.037*** (.003)	-.038*** (.004)	-.037*** (.003)
Density EVSE along the highway (γ4/0)	-	-.016*** (.004)	-.015** (.004)	-.016*** (.004)
Charging duration along the highway (γ5/0)	-	-.041*** (.003)	-.042*** (.004)	-.042*** (.003)
$Mean_{res}$: Monthly basic fee (γ0/1)	-	n.s.	.024* (.011)	.024* (.011)
$Mean_{res}$: Charging duration in cities (γ0/2)	-	.063** (.023)	.056** (.020)	.057** (.020)
$Mean_{res}$: Density EVSE along the highway (γ0/3)	-	n.s.	n.s.	.059* (.029)
Gender (γ0/4)	-	-	-.168** (.057)	-.169** (.056)
A-level (γ0/5)	-	-	.097* (.041)	.092* (.041)
University degree (γ0/6)	-	-	-.640** (.230)	-.612** (.229)
Age (γ0/7)	-	-	-.008*** (.002)	-.008*** (.002)
Environmental consciousness (γ0/8)	-	-	.103** (.033)	.099** (.033)
Technophilia (γ0/9)	-	-	.129*** (.031)	.129*** (.031)
General attitude towards EVs (γ0/10)	-	-	.271*** (.021)	.266*** (.021)
Charging duration in cities*age (γ3/7)	-	-	-	-.001* (.000)
Charging duration in cities*technophilia (γ3/9)	-	-	-	-.011** (.003)
Charging duration highway* Gen. attitude EVs (γ5/10)	-	-	-	-.006** (.002)

Significance of parameters indicated by *p<.050; **p<.010; ***p<.001

Table 8: Effects and interactions of level 1 and level 2 variables

Parameters	Unconditional	Level 1:fixed	Level 2 & level 1: random	Interaction
Residual (σ^2)	1.186*** (.019)	1.075*** (.017)	.870*** (.019)	.921*** (.018)
Intercept (τ00)	.851*** (.044)	.864*** (.044)	.617*** (.033)	.608*** (.032)
Slope monthly basic fee (τ11)			.003*** (.000)	n.s.
Slope density EVSE in cities (τ22)			n.s.	.002* (.001)
Slope charging duration in cities (τ33)			.005*** (.001)	.004*** (.001)
Slope density EVSE along the highway (τ44)			.002* (.001)	.002* (.001)
Slope charging duration along the highway (τ55)			.004*** (.001)	.004*** (.001)
Covariance density EVSE in cities / density EVSE along the highway (τ24)			.002** (.001)	.002*** (.001)
Covariance charging duration in cities / density EVSE along the highway (τ34)			.001* (.001)	.002*** (.000)
Covariance charging duration in cities/ charging duration along the highway (τ35)			.002*** (.000)	.001*** (.000)

Significance of parameters indicated by *p<.050; **p<.010; ***p<.001

Table 9: Variance components (random effects) of the hierarchical linear model

Beside the variables described in section 2.1, we further included the respondent mean ($\bar{x}_{respondent}$) of each level 1 variable to control for effects of level 1 variables on level 2 as recommended by Algina and Swarninathan (2011). In Table 8, these variables are labeled by the prefix "$Mean_{res}$". The effects of these variables imply that respondents evaluate EVSE offers more positively that have on average a higher monthly basic fee, longer charging duration in cities and fewer charging spots along the highway. Although the significance levels of these effects are comparatively low, this counter-intuitive finding might indicate a psychological effect known from prospect theory (cf. Thaler et al., 1997): gains usually have a weaker effect than losses of the same absolute magnitude. This means for respondents confronted with on average relatively unfavourable EVSE offers, there is less latitude for (more) influential losses compared to respondents who evaluated EVSE offers that are more favourable on average.

Variance components (random effects). Furthermore, the results reported in Table 9 indicate that the effects of density of EVSE in cities (τ22) and along the highway (τ44) as well as the effects of charging duration in cities (τ33) and along the highway (τ55) vary significantly among respondents even after controlling for cross-level interaction effects. The significant co-variance between the density of EVSE in cities and along the highway (τ24) indicates that respondents who assign more value to EVSE density in cities also assign more value to EVSE density along the highway. Similarly, respondents who stronger appreciate the charging duration in cities also stronger appreciate the density of EVSE (τ34) and the charging duration (τ35) along the highway.

Proportional reduction of variance (PRV). Due to the lack of a measure for effect strength comparable to Cohen's d for hierarchical linear models we subsequently report the proportional reduction of variance for the variance components of the different variables (PRV = $(Var_{NoPredictor}-Var_{Predictor})/Var_{NoPredictor}$; for σ^2, τ00 and τXX (Peugh, 2010)). In Table 10, we report PRV on a percentage basis (PRV*100) for the inclusion of level 1 variables (PRV of residuals of the dependent variable at level 1), level 2 variables (PRV of intercept between level 2 units) and cross-level interactions between level 2 variables and level 1 variables (PRV of slopes between level 2 units).

Variable / interaction	PRV
Level 1 variables: PRV of residuals (σ^2)	
Monthly basic fee (γ1/0)	5.5%
Density EVSE in cities (γ2/0)	4.7%
Charging duration in cities (γ3/0)	7.7%
Density EVSE along the highway (γ4/0)	5.0%
Charging duration at the highway (γ5/0)	9.9%
Level 2 variables: PRV of intercepts (τ00)	
Gender (γ0/4)	1.0%
A-level (γ0/5)	0.4%
University degree (γ0/6)	0.6%
Age (γ0/7)	2.3%
Environmental consciousness (γ0/8)	1.0%
Technophilia (γ0/9)	1.7%
General attitude towards EVs (γ0/10)	15.3%
Cross-level-interaction: PRV of slopes (τXX)	
Slope charging duration in cities (τ33) by age (γ3/7)	3.2%
Slope charging duration in cities (τ33) by technophilia (γ3/9)	3.4%
Slope charging duration along the highway (τ44) by general attitude towards EVs (γ5/10)	2.3%

Table 10: Proportional reduction of variance (PRV)

For level 1 variables, i.e. the attributes of EVSE offers, charging duration in cities (7.7%) and along the highway (9.9%) have the highest PRV. The other three attributes provide a PRV of about five percent, in particular 5.5% for the monthly basic fee, 4.7% for the density of EVSE in cities and 5.0% for the density of EVSE on highways. These numbers do not simply add up – in total, the inclusion of all level 1 variables results in a PRV of 22.3%.

The variance of the intercept between the respondents can be explained by level 2 variables. Here, the general attitude towards EVs has by far the highest PRV (15.3%). The remaining level 2 variables have comparatively low PRVs between 2.3% (age) and 0.4% (A-level compared to no graduation/GCSE equivalent to EQF-Level 2). Again, these numbers do not simply add up – the PRV that results from including all the level 2 variables is 28.1%.

In addition, level 2 variables can help to reduce the variance of slopes of level 1 variables. The variance of the slope of charging duration in cities between respondents can be reduced by 3.2% by taking into account the interaction with age. A similar reduction in the variance between respondents results from including the interaction with technophilia in the model (3.4%). The reduction of slope variance of density of EVSE along the highway by including the interaction with the general attitude towards EVs is slightly below these numbers (2.3%).

4 Discussion

Overall, it can be said that the variance in the evaluations of the attractiveness of the EVSE offers by the 1003 car drivers in our sample is well explained by our statistical model. In addition, our data provide insightful results with regard to our three research questions. With regard to the research question of which factors influence the overall assessment of public charging infrastructure, our results show that a basic charge as well as the charging duration and density of charging stations have a significant influence. With regard to the second research question, how strong the influence of these factors is on the evaluation of public charging infrastructure, our results underline the importance of charging duration. The basic fee and the density of the charging points have a weaker influence on the ratings.

With regard to the third research question concerning target groups with different preference structures for public charging infrastructures, it should first be noted that the overall evaluations show that EVSE offers are not very attractive. An average EVSE offer, i.e. with €10 monthly basic fee, charging spots every 624 meters in cities and every 62 km along the highway, 55 minutes to charge for 100 km range at charging points in cities and along the highway, receives a mean evaluation of 2.5 (between 2 = "largely unattractive" and 3 = "rather unattractive"). Even if the charging duration in cities and along the highway would be only 20 minutes for 100 km range and the density of charging point would be increase to every 300 meters in cities and every 30 km along the highway the estimated evaluation would still be negative (2.9). This value is still well below 3.5, the middle of the evaluation scale, from which one could assume that such an offer would be taken up and that there would be a willingness to pay.

Further analysis into attitudinal variables suggests that there are certain groups who assign more value to public EVSE than others. In particular, environmental consciousness, technophilia and the general attitude towards EVs correspond to evaluations that are more favourable. In the context of the effects of gender, education and age this implies that younger non-academic women who are especially environmental conscious, technophile and open minded towards EVs are a group who value public EVSE more than others. Some of these variables also affect the valuation of different aspects of public EVSE. For technophilia and the general attitude towards EVs we found significant cross-level interactions with charging duration in cities and along the highway. These interaction effects indicate that more technophile and EV-friendly persons are more sensitive to longer charging durations. Thus, not only does charging duration have the strongest overall influence on the ratings of EVSE offers - the effect is also particularly strong among car drivers, who generally value public charging infrastructure more highly.

The results discussed above illustrate that our model provides useful insights into the preferences regarding public EVSE. However, there are also some limitations of our study. The result that the level 2 variables explain only 28.1% of the respondent-related variance suggests that relevant additional characteristics exist, which are not covered by the model. In this regard, it seems noteworthy that several level 2 variables turned out to be non-significant. In particular, this applies to the variables that relate to mobility needs and mobility behaviour (cf. Table 3) as well as demographic variables that usually correlate with general mobility (net income of household and professional occupation) and the electric range of the hypothetical EV (cf. Figure 1). In combination with the very strong influence of the general attitude towards EVs, this might indicate that the hypothetical evaluation of EVSE offers is psychologically distant (cf. Rezvani et al. (2015) for the consequences of hypothetical evaluations of EVs). The evaluations of EVSE offers might be based more on basic beliefs towards (the usefulness of) EVSE rather than on a deliberate assessment of the respondent's own mobility needs. Similar to the suggestions of Rezvani et al. (2015) with regard to studies of EV evaluation, future studies might benefit from analysing samples, which deliberately overrepresent respondents with actual experience of using EVs. Preferences might change after gaining hands-on experience (cf. Bunce et al. (2014) who finds that actual users of EVs even perceive public recharging as more convenient than refuelling). Furthermore, the relevance of additional attitudinal characteristics like risk-tolerance or the general willingness to adjust behavioural routines should be explored by future research.

5 Conclusions

On the basis of the results discussed above, several conclusions can be drawn with implications for possible business models and transport policy measures. Against the background that there is only very limited, if any, willingness to pay for public charging infrastructure, the cost-efficiency of the overall system is of central importance. In this respect, the strong influence of the charging duration is advantageous for two reasons (cf. Gnann et al., 2018): (1) a high utilisation of public EVSE, which can be fostered by a smaller number of charging spots, is important to find a viable business case. (2) Installation costs due to necessary groundwork etc. account for a large share of the total costs of public EVSE. If car drivers can be satisfied with a smaller number of charging points, this is would lead to lower investments. In addition, if detours do not bother car drivers too much, the charging spots can be placed at locations where installation cost are low (e.g. due to convenient access to medium-voltage network).

Even if the construction of public charging infrastructure is very cost-efficient, it will be difficult to develop viable business models due to the low willingness to pay. Accordingly, there is likely to be a need for political support measures. Our results provide some indications that this could also contribute to the further spread of electric vehicles. First of all, the strong positive influence of the general attitude towards EVS on the evaluation of EVSE offers can be seen as an indication that public charging infrastructure is particularly important for people who are more likely to adopt EVs. The influencing factors relating to attitudes can also be regarded as a corresponding indicator. In particular, environmental awareness and technophilia were previously identified as characteristics of early adopters of EVs (Plötz et al., 2014). In contrast, the demographic characteristics (gender, education, age) that influence the basic evaluation of EVSE offers do not fit the classic early adopter clientele who are described by Plötz et al. (2014) as middle aged males with a high socio-economic status. Taken together, this can be seen as an indication that public charging infrastructure is particularly important for potential buyers of electric vehicles that do not correspond to the classic early adopted clientele. Public charging infrastructure could therefore help to win these target groups over to electric mobility.

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