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Consumers' evaluation of public charging infrastructure for electric vehicles

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Abstract

This paper explores factors that determine the usefulness of public charging infrastructure for electric vehicles from the point of view of its potential users. Our analysis is based on evaluations of different (hypothetical) public charging infrastructure networks by 1003 drivers of passenger cars from Germany. We employ a hierarchical linear model to explore the relevance of the attributes of public charging infrastructure as well as the influence of personal characteristics on the respondents' evaluations. Our main conclusions of the results are that public charging infrastructure is generally important to attract additional consumer segments to EVs. In addition charging duration at the autobahn as well as in cities seems to be more important to the mainstream passenger car drivers than the density of public charging spots. Our results also provide some indications regarding distinct target groups and the willingness to pay for public charging infrastructure.

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

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1 Introduction

Battery electric vehicles (BEV) can reduce greenhouse gas emissions if powered with renewable energy. A barrier to the market diffusion is the low range given by current batteries. Though it is possible to find user groups who fulfill their driving needs while remaining economical without public charging (see e.g. [1]), a broader market diffusion of BEVs requires either a noteworthy improvement in battery technology or a more extensive charging infrastructure or advancement in both.

Sun et al. [2] point out that research into user perceptions and preferences for charging is comparatively less frequent 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 an ICE. Philipsen et al. [3] find that EV drivers and individuals interested in EVs prefer charging points (hereafter called **E**lectric **V**ehicle **S**upport **E**quipment) at motorways and places for daily needs. Their results also indicate that respondents are more willing to make a detour than to accept waiting times. This warrants the questions how many fast charging stations are actually needed and how much users are willing to pay for it or its availability as large investments are required for the case of fast charging infrastructure? [4] Thus, our study focuses on the following research question: *Which factors influence the evaluation of public EVSE for electric vehicles (EVs) by private car users?* Connected to this major question are: *Are there trade-offs between relevant attributes of public EVSE? What are target groups with distinct preferences regarding EVSE?*

To address these questions we conduct an empirical study with a sample of 1003 German car users. Our analysis employs a hierarchical linear model to analyze the factors that influence the respondents' evaluation of (hypothetical) offers for public EVSE.

The outline of this paper is as follows. The remainder of section I provides an overview of the literature that guides the content of our analysis. Section II is devoted to the description of the methodology. Section III presents the results of our analysis. The main findings are discussed in section IV and conclusions are drawn in section V.

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

With regard to local distribution of EVSE some lessons can be learned from earlier research into users' preferences for refueling. These studies find that drivers prefer to make as little detours as possible and that they prefer to refuel at the beginning or the end of a trip and at places which are easy to reach e.g. from home or work; these preferences are also transferred to the case of alternatively fuelled vehicles [5, 6].

With respect to recharging EVs the before mentioned study of [3] was preceded by a qualitative study which concludes that a detour of 5 km or 10 min is seen as acceptable [7]. Furthermore a recent study by Sun et al. [8] from Bejing, China, surveyed actual EV users and points out that nearly half of 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 to EV satisfaction. Furthermore Szierchula et al. [9] identify EVSE density as positively correlated with PEV sales.

These user centric analyses of preferred locations and density of EVSE are mirrored by techno- economical studies. A common approach of such studies is to maximize the amount of electric miles travel or similarly reduce the number of unfulfilled trips if all vehicles would be BEV [10, 11, 12]. For example, Alhazmi et al. [10] optimize the allocation of EVSE with respect to electrify as much car travel as possible. Dong et al [11] also optimize EVSE locations and analyze the number of range-constrained days and trips for the greater Seattle region. Sharaki et al. [12] perform a similar analysis with application to taxi driving in Beijing.

The duration of the recharging process as well as the location and density of EVSE may affect the (perceived) usefulness and costs of EVSE [3, 4]. Sun et al. [2] 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 users on working days and 750 meters on non-working days based on recorded mobility patterns from Japanese EV drivers.

However, their sample was limited (24 drivers) and results are certainly influenced by the current state of existing infrastructure, i.e. do not necessarily mirror the ideal situation desired by users.

While the afore mentioned studies focus on the question 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. E.g. the sample of Sun et al. [8] mostly consists of EV drivers who usually charge at public charging stations (around 80%), however, many (around 40%) would prefer to charge at their own parking lot. From a techno-economic point of view the impact of EVSE on market diffusion of EVs has been analyzed by various studies. E.g. Gann [13] as well Gnann and Plötz [14] 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. [1] conclude that multi-car households can better handle the restricted range of BEVs. Thus, multi-car households depend less on public charging infrastructure.

The actual need for public EVSE is important as the scale of EVSE buildup is decisive for the direct and indirect costs of the system. This economic dimension is addressed e.g. by Guo et al. [15] who look at the business perspective and the investment planning for charging station providers. Similarly, Sadeghi-Barzani et al. [16] look on how to minimize the total cost of charging station investment including the grid costs. Indirect costs of EVSE are analyzed by Wang et al. [17] who look at the distribution system with the objective to minimize power losses and voltage deviations.

The costs of public EVSE leads to the question of who is willing to pay (how much) for its buildup and use. It seems reasonable to assume that the willingness to pay is influenced by the usefulness an individual attributes of EVSE although we are not aware of studies that explicitly address this issue. Thus, the question arises whether there are target groups with a higher or lower valuation of EVSE or distinct requirements regarding EVSE.

A study by Will and Schuller [18] looking into the acceptance for smart charging, surveys 237 early electric vehicle adopters. They find that among a range of other factors also interest in EVs, technological innovativeness and eco-values are not related to acceptance. This is somewhat surprising as Li et al. [19] identify several studies in a comprehensive review that point to psychological variables like environmental concern, technology awareness etc. are related to BEV acceptance.

Socio-economic criteria are likely to be related to charging preferences. First of all, studies on early adopters for EVs find that e.g. in Germany middle-aged men with technical professions living in rural or suburban multi-person households are most likely to become EV users [20]. This is also strongly supported by the review of Li et al. (2017). Second, in relation to requirements and preferred locations for charging stations, both prior experience with battery electric vehicles, gender as well as occasional variations for age were found to be important (Philipsen et al. 2016).

Please imagine you have just bought an electric vehicle. The range of the electric vehicle is **[XXX] km** (even if the heater or AC is in operation). If you have a parking place with a wall socket at home you can charge your electric vehicle there (costs: approximately 5 Euro per 100 km range; duration: approximately 5 hours per 100 km range).

In addition there are two providers who run public charging infrastructure for electric vehicles. To use the charging infrastructure of a provider you have to conclude a contract. Electricity for 100 km range costs 7 Euros at both providers. In addition some providers charge you with **a monthly basic fee**.

Beside financial aspects the question arises whether the offers of the providers consort with your mobility needs and your personal circumstances. This could e.g. depend on how many charging spots exist **(density)**, where these charging spots are located **(in cities or at the autobahn)** and how long it takes to charge at this charging spots **(charging duration)**. You can find information about these attributes 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 at charging spots **in cities**	[xxx] minutes	[xxx] minutes
Density of charging spots **at the autobahn**	Every [xxx] km	Every [xxx] km
Charging duration for 100 km range at charging spots **at the autobahn**	[xxx] minutes	[xxx] minutes

How do you rate the attractiveness of these two offers?

	I totally agree	I predominantly agree	I rather agree	I rather disagree	I predominantly disagree	I totally disagree
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: Visualization of hypothetical EVSE-offers in the online-survey.

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 important for its usefulness. Density is not necessarily defined by the geographical distance – the time the detour to a charging point is also important. Thus the location of EVSE can also be important for its utility for users 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. The users' trade-offs between these attributes of EVSE and the costs for the use of EVSE seems to be an understudied topic and prompts the question if there are certain target groups with distinct requirements with regard to EVSE. The empirical identification and description of such target groups by demographic characteristics, mobility needs and behavior as well as attitudinal aspects would be of practical relevance in particular as techno-economic models usually rely on assumptions about the relevance of such properties. The aim of the present paper is to contribute to this empirical identification and description.

2 Methods

The main research interest of our study is to bring forth insights about the trade-offs between different attributes of EVSE and the identification of target groups. Thus we pursue an explorative and inductive analysis. Likewise, the content of our data collection is guided by the results of the literature review. The research design and data are described in section 2.1. Subsequently we outline how the collected data is prepared and analyzed (section 2.2).

2.1 Data Description

We use an online-questionnaire which contained the evaluation of (hypothetical) EVSE-offers. On the one hand the decision for this design is motivated by the fact that the number of current EV users and thus potential users of EVSE is very limited. On the other hand, it is even more important to include respondents without usage experience of EVs and EVSE as these persons represent an untapped market for EVs. This consumer group needs to be opened up as otherwise EVs will remain a niche product and any large scale public EVSE will be useless. Figure 1 shows how these EVSE-offers were depicted in the online survey. The participants of our study had to rate the attractiveness of multiple of such EVSE-offers which differed with regard to some attributes. These attributes are symbolized by the placeholders depicted as "[xxx]" in figure 1. One placeholder (range of the hypothetical EV) is part of the introductory text. Based on a random selection one of three options was displayed: 150 km, 250 km or 350 km. The inclusion of this element is motivated by the fact that the need of EV users for EVSE depends on the actual range of the EV. The manifestations represent the range of EVs that are currently available in the market.

Each respondent had to evaluate ten EVSE-offers, i.e. the exercise depicted in figure 1 was repeated in total five times (each time with two EVSE-offers). The displayed range of the hypothetical EV differed between the respondents but was the same over all five exercises. In contrast the attributes of the hypothetical EVSE-offers (displayed in the table in figure 1) changed between each exercise. Which manifestation of the attributes was displayed was subject to a random selection. In order to call the attention to the changed attributes an additional advice was displayed above the introductory text after the respondent went on to the second exercise. In addition, all non-bold parts of the introductory text were displayed in grey color after the first exercise to make clear that no new information is provided. Each attribute had five possible manifestations:

- 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 autobahn: none, every 25 km, every 50 km, every 75 km and every 100 km
- The possible manifestations of the attributes "charging duration in cities" and "charging duration at the autobahn" 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 the willingness to pay for the existence of public EVSE was identified as an understudied issue by our literature review. In addition we decided to include the attributes regarding the density of EVSE (in cities and at the autobahn) based on geographical distance as time related issues of public charging are covered by the attributes regarding the duration of the charging process. The range of values for EVSE density in cities is based on the findings of Sun et al. [2]. The range of values for EVSE density at the autobahn was chosen proportional to the distances in cities. The values for the duration of the charging process approximately reflect the technological performance of currently available charging systems.

The actual evaluation of the EVSE-offers was based on a Likert-scale with six answer options. The answer options are coded from one (I totally disagree) to six (I totally agree). For our analysis the measurement level of these values is considered to be quasi-metric [21]. The mean evaluation of the EVSE-offers is 3.7, i.e. located between "I rather agree" and "I rather disagree".

Our analysis is based on a sample of 1003 respondents from Germany. All participants of our survey stated that they regularly use a passenger car (at least once a week) that is owned by themselves, a member of their household or a family member. I.e. regular car use was a basic requirement to participate in the survey. We considered this restriction to be necessary as the potential future adopters of EVs who might rely on EVSE will be persons who regularly use passenger cars. The sample of our study was collected via an online-access panel. To gather a representative sample certain quotas were ensured. These quotas are reported in table 1.

Table 1: Sampling quotas.

Gender	Male	49.9%
	Female	50.1%
Education	No graduation/ GCSE EQF-Level 2*	26%
	GCSE EQF-Level 3**	31%
	A-level/university degree	43%
Age	18 to 30 years	16.7%
	31 to 40 years	17.0%
	41 to 50 years	19.8%
	51 to 60 years	16.8%
	Older than 60 years	29.7%
	Mean	48 y

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

These quotas are representative for the adult population of Germany and acquired in an earlier survey [22]. To account for our focus on regular car users we derived the quotas from a subsample of this prior survey which only contained respondents who stated that they use a passenger car at least once a week. Thus, our sample is approximately representative for German adults who regularly use a passenger car.

The online survey consisted of four parts. The first part contained questions on demographic information. This unusual arrangement became necessary as the quotas had to be checked at the beginning of the survey. The second part of the survey contained questions about the mobility behavior and mobility features of the respondent or his household. These questions were placed deliberately before the evaluation of EVSE-offers (which are the third part of the survey) in order to make the mobility needs and behavior of the respondents present to themselves. This was intended to make the respondents to evaluate the EVSE-offers in the light of their personal conditions. The fourth part of the questionnaire contains items to measures attitudinal characteristics of the respondents. To avoid that the evaluations of the EVSE-offers are influenced by perceived social desirability or an allegedly pressure to give answers in accordance with reported attitudes these items were placed at the end of the questionnaire.

Beside the information needed to assign the respondents to the sampling quotas (cf. table 1) additional demographic information was polled in the first part of the questionnaire in order to identify and describe target groups. This additional information is presented in table 2. The demographic information presented in table 1 and 2 is potentially relevant for the identification of target groups as gender, education, age and occupation are characteristics that enable the description of early adopters of EVs in prior studies [20]. In addition, it seems plausible that the net income of a household might influence the willingness to pay for EVSE.

Table 2: Demographic variables.

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

Please note that the analysis in section III treats some of the demographic variables (education and age) differently compared to the quota assignment. For the quota assignment education was divided in three categories – in the analysis "A-level" and "university degree" are separated categories. Furthermore, age consists of five categories for the quota assignment but is included as continuous variable in the analysis.

Mobility needs and mobility behavior were collected in the second part of the questionnaire and 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 facilitate the need for EVSE in certain places, e.g. near to the own residence or at the autobahn [1, 13, 14].

Table 3: Mobility-related variables.

Variable	Categories/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

* Frequency of long distance trips is included as a continuous variable in our analysis.

Part four of the survey measures attitudinal constructs. Our analysis comprises the variables 'environmental consciousness' and 'technophily' as well as 'general attitude towards EVs'. The constructs environmental consciousness and technophily are measured by existent and validated scales that consist of multiple items as indicators of these psychological constructs [23, 24]. The general attitude towards EVs is 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 evaluation scale of the EVSE-offer these items are so called Likert scales, i.e. the respondents can choose between different options in order to agree or disagree with these statements. Like the evaluation of EVSE-offers the item used as indicator for the general attitude towards EVs has six options as possible answers – three affirmative and three depreciating options (I totally / predominantly / rather (dis)agree). In contrast to the evaluation of EVSE-offers there is an additional option "not specified". This design offers the advantage that respondents either have to reveal a general tendency or have to deliberately refuse an answer [25].

In contrast the items that are used as indicators for environmental consciousness and technophily contain 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 as less advantageous by some methodological studies as the neutral option may indicate a medium consent with the statement as well as the general absent of a clear sentiment towards the statement [26, 27]. However, we decided to use five answer options to adhere the original and validated form of the items of Wingerter [23] and Neyer et al. [24].

Table 4: Demographic variables.

Variable	**Item text (mean; standard deviation; min/max)**
Environmental consciousness	It worries me when I think about the environmental conditions our children and grandchildren will have to live with. (3.5; 1.1; 1/5)
	If we just carry on as before, we are heading for an environmental catastrophe. (3.7; 1.0; 1/5)
	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; 1/5)
Technophily	I am very interested in the latest technology developments. (3.4; 1.1; 1/5)
	It doesn’t take me long to learn to like new technology developments. (3.3; 1.1; 1/5)
	I am always keen to use the latest technological devices. (2.8; 1.2; 1/5)
	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; 1/5)*
General attitude towards EVs	In general I think electric vehicles are a good thing. (4.4; 1.5; 1/6)

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

In general, high values indicate an affirmation of the statements while low values indicate refusal. For our analysis we consider the level of measurement of Likert scales to be quasi-metric (cf. [21]).

2.2 Data preparation and Analysis

The first step of data preparation adresses the variables that refere to psychological constructs and use multiple items as indicators, i.e. 'environmental consciousness' and 'technophily'. For the analysis the values of the different indicators have to be combined in a common value for each variable. The presence of factor reliability and construct validity is a prerequirement for this. Whether factor reliability and construct validity are at hand can be assessed by a confirmatory factor analysis (CFA) which we conduct using SPSS AMOS 21. 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 the model consists of [25, 28].

The parameters for the global fit resulting from the CFA are displayed in table 5. The initial factor model contains the three indicators for environmental consciousness and the four indicators for techophily displayed in table 4. In reference to the thresholds for a good or acceptable globle fit (second and third line in table 5) the outcomes of the CFA illustrate that the co-variance structure postulated by the initial model does not reflect the empiracally observed co-variance structure in a sufficient way (fourth line in table 5). Modification indices point towards a problem with the indicators which are displayed in the third and fourth line of the subsection "technophily" in table 4. As the item "I am always keen to use the latest technological devices." shows 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 exclude the latter one from the analysis. This is furthermore reasonable as the latter item refers to intention while the other three items refer to actual behavior.

Table 5: Results of cfa for global model fit.

	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

A factor model with only three indicators for technophily shows an improved global fit (fifth line in table 5): While 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 p-value is considered as problematic in the methodological literature as it tends to indicate even the slightest deviations between postulated and observed co-variance structure as an increasing sample size also improves the sensitivity of this test. Thus we assume the fit of our revised model to be (at least sufficiently) good [25, 28].

For the revised model the two factors (environmental consciousness and technophily) also feature factor reliability and construct validity as illustrated by the parameters for the local fit reported in table 6. Thus we combine the values of the respective indicators by calculating their average scores for each respondent.

Table 6: Results of cfa for local model fit.

	Factor reliability	AVE	(max. intercorrelation)^2
Factor	>.6*	>.5*	< AVE*
Environmental consciousness	.844	.643	.074
Technophily	.887	.724	.074

* Thresholds for acceptable local fit

As a second step of data preparation we use SPSS 21 for Expectation-Maximization-imputation to estimate the values for missing data. This is necessary as list wise 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 showed 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) [29].

The third and fourth steps of data preparation accrue from the necessity to analyze our data using a hierarchical linear model (cf. section III) with the respondents as macro level units (level 2) and the EVSE-offers as micro level units (level 1). Accordingly, we change the format of our dataset. In the new format 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 delete all cases (now EVSE-offers) which contain the manifestation "none" for either of the two attributes "Density of charging spots in cities" and "Density of charging spots along the autobahn". This is necessary as the manifestation "none" corresponds to the manifestation "N/A" for the charging duration in cities or at the autobahn respectively. Thus the exclusion of these cases is inevitable due to the occurrence of perfect multi-collinearity between the two variables. The reason why we included the manifestation "none" in our questionnaire in the first place is that analyzing the value of the very existence of public EVSE is 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 are excluded (between 4 and 10 evaluations of EVSE-offers per respondent remained, on average each respondent evaluated 8.86 EVSE-offers).

Researchers are advised to center the independent variables of multilevel models. There are two options how variables can be centered: Grand-mean centering ($X - \bar{X}_{sample}$) and group- mean centering although this term is misleading in our context as a 'group' of cases in our dataset are the different evaluations of EVSE-offers by a respondent ($X - \bar{X}_{respondent}$). As a fifth and last step of data preparation we grand-mean center the independent variables of our model, except for dummy variables at level 2. Grand-mean centering is appropriate as we are also interested in the effects of level 2 variables, i.e. respondent specific characteristics like gender or technophily (cf. [30]).

3 Results

The presentation and discussion of the results of the hierarchical linear model is guided by the advice of Peugh [31]. The results of our analysis are summarized in table 7 and table 8 (variables without significant effects are excluded from the analysis; non-significant results are omitted for the sake of clarity). The presented parameters are calculated using a restricted maximum likelihood estimator (REML) as the focus of our study is not the comparison of models that differ in regression coefficients as well as variance component estimates [31].

As recommended by Hox [32] we pursue a bottom-up strategy for our analysis. I.e. (1) we first set up an unconditional model before (2) we build the level 1 model with fixed effects, (3) include level 2 variables, (4) add random effects for level 1 variables and (5) incorporate cross-level interactions. These steps result in different models presented in the columns 2 to 5 of table 7. The unconditional model (step 1) does not comprise any independent variables except for the ID of the respondents. This step allows assessing the share of variance of the dependent variable that is explained by the clustered structure of the data (cf. column 2). In step 2 fixed effects for level 1 variables (attributes of EVSE-offers) are estimated. I.e. no variations of the level 1 effects between the level 2 units (respondents) are allowed (cf. column 3). Results for step 3 and 4 are reported together in column 4. Step 3 comprises the inclusion of level 2 variables (respondent characteristics) to explain the variance between respondents. In step 4 the effects of level 1 variable (EVSE-offers) are estimated separately for the level 2 units (respondents). The comparison between the results of step 2 and step 4 gives information to what extent 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 are included in step 5 (column 5). Thereby information is provided where the improvement in step 4 originates from.

The fixed effects reported in the upper section of table 7 are unstandardized regression parameters for direct effects of level 1 variables ($\gamma X/0$), level 2 variables ($\gamma 0/X$) and cross-level-interactions between level 1 and level 2 variables ($\gamma X/X$). The second section ("variance components") comprises the variance of the residuals of the dependent variable (σ^2), the variance of the intercepts of level 2 units ($\tau 00$), 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 at hand 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. The last section provides a summary of the models (cf. [31]).

3.1 Model evaluation

The first finding that can be derived from table 7 is that our research design indeed facilitates the need to apply a hierarchical linear model. This becomes apparent in the light of a design effect of 4.286. The design effect can be calculated by Eq. (1):

$$\text{Design effect} = 1 + (n_c - 1) * ICC \qquad (1)$$

The interclass correlation (ICC) can be in turn calculated based on the parameters of the unconditional model by Eq. (2):

$$ICC = \tau_{00} / (\tau_{00} + \sigma^2) = .418 \qquad (2)$$

The average number of micro-units per macro-unit (n_c) is 8.860. A design effect value above 2 is considered as indicative for the need to use a hierarchical linear model instead of an ordinary least square regression [31].

Further information provided in table 7 is that the model which contains cross-level-interactions (“interaction”) entails less 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. I.e. 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 between the respondents significantly.

With regard to the explanatory power we find a correlation of .802 between the real evaluations of EVSE-offers and the values predicted by the ‘interaction’-model. Thus 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 [31]. 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 helpful to describe potential target groups. To this end the information that the evaluation of EVSE-offers is influenced by differences in the willingness to pay between the respondents (cf. $\tau 11$ in the ‘random’ coefficient model) is less informative as no further insights are provided how respondents with a higher or lower willingness to pay can be characterized. Thus we base our further analysis on the ‘interaction’-model.

Table 7: Results for the different models resulting from the bottom-up approach of the analysis.

Parameters	**Uncon-ditional**	**Level 1: fixed**	**Level 2 & level 1: random**	**Interaction**
Regression coefficients (fixed effects) of the hierarchical linear model				
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 at the auto-bahn (γ4/0)	-	-.016*** (.004)	-.015** (.004)	-.016*** (.004)
Charging duration at the au-tobahn (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 at the autobahn (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 conscious-ness (γ0/8)	-	-	.103** (.033)	.099** (.033)
Technophily (γ0/9)	-	-	.129*** (.031)	.129*** (.031)
General attitude towards EVs (γ0/10)	-	-	.271*** (.021)	.266*** (.021)
Charging duration in cit-ies*age (γ3/7)	-	-	-	-.001* (.000)
Charging duration in cit-ies*technophily (γ3/9)	-	-	-	-.011** (.003)
Charging duration at the au-tobahn* General attitude to-wards EVs (γ5/10)	-	-	-	-.006** (.002)

Parameters	Uncon-ditional	Level 1: fixed	Level 2 & level 1: random	Interaction
Variance components (random effects) of the hierarchical linear model				
Residual (σ^2)	1.186*** (.019)	1.075*** (.017)	.870*** (.019)	.921*** (.018)
Intercept ($\tau 00$)	.851*** (.044)	.864*** (.044)	.617*** (.033)	.608*** (.032)
Slope monthly basic fee ($\tau 11$)			.003*** (.000)	n.s.
Slope density EVSE in cities ($\tau 22$)			n.s.	.002* (.001)
Slope charging duration in cities ($\tau 33$)			.005*** (.001)	.004*** (.001)
Slope density EVSE at the autobahn ($\tau 44$)			.002* (.001)	.002* (.001)
Slope charging duration at the autobahn ($\tau 55$)			.004*** (.001)	.004*** (.001)
Covariance density EVSE in cities / Density EVSE at the autobahn ($\tau 24$)			.002** (.001)	.002*** (.001)
Covariance charging duration in cities / Density EVSE at the autobahn ($\tau 34$)			.001* (.001)	.002*** (.000)
Covariance charging duration in cities/ Charging duration at the autobahn ($\tau 35$)			.002*** (.000)	.001*** (.000)
Summary of the hierarchical linear model				
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

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

3.2 Effects of attributes of evse-offers (Level 1)

The model contains those variables described in section 2.1 which significantly affect the evaluations of EVSE-offers. As described in section 2.2 we (grand-) mean center our independent variables as this improves the interpretability of the regression parameters and interaction effects. To further improve clarity of the information provided by the regression coefficients we harmonize the range of values of level 1 variables. To do so we divide the values of 'density EVSE in cities' by 100 (resulting unit = 100m) and the values of 'charging duration in cities/at the autobahn' as well as 'density EVSE at the autobahn' by 10 (resulting unit = 10 minutes / 10km).

As a consequence of centering and harmonization the effects of in table 7 can be interpreted and summarized in the following way: An in all other respects average EVSE-offer is evaluated .033 point less favorable for every Euro increase of the basic monthly fee. Similarly, an increase by 100m/10km distance between the charging points in cities/at the autobahn results in a .014/.016 point less favorable evaluation.

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 (48 years) and technophily (3.2 points of 5) worsens by .037 point. The effect is .001 point stronger/weaker (γ3/7) for every year the person is younger/older than the average (the mean age is 48 years). Furthermore, this effect is .011 point stronger/weaker (γ3/9) for every point the person is below/above the average on the technophily scale. As these interaction effects are not standardized they depend on the range of values of the variables. The proportional reduction of variance reported in table 8 indicates that the explanatory power of both interaction effects is about the same magnitude.

The effect for charging points at the autobahn is in a similar range – increasing charging time for 100km by 10 minutes, results in a .042 point less positive evaluation for persons with an average attitude towards EVs (4.4 points of 6). This effect is .006 point stronger/weaker (γ5/10) for every point the person is below/above the average on the scale that measures the general attitude towards EVs.

3.3 Effects of respondent characteristics (Level 2)

Attitudinal factors also directly influence the evaluations of EVSE-offers. Respondents with a one-point higher score at the environmental consciousness scale rate an average EVSE-offer .099 point better. Furthermore, the evaluation of an average EVSE-offer is .129 point more favorable for a one-point increase on the technophily scale. Also an increase of one point on the scale which measures the general attitude towards EVs results in a .266 point more positive evaluation.

In general men evaluate an average EVSE-offer .169 point less favorable than women. The level of formal education has an ambiguous effect: Compared to people with a graduation not higher than GCSE (equivalent to EQF-Level 2) academics rate an average EVSE-offer .612 point worse while the rating of respondents with an A-level graduation is .092 point more favorable. Furthermore, the rating of an average EVSE-offer becomes the more negative the older the respondent is – for every year a person is older the rating decreases by .008 point.

Beside the variables described in section 2.1 we further include 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 7 these variables are labeled by the prefix "$Mean_{res}$". The effects of these variables imply that respondents who are confronted with EVSE-offers which have on average a higher monthly basic fee, longer charging duration in cities and less charging spots at the autobahn evaluate EVSE-offers more positive. Although the significance levels of these effects are comparatively low this counter intuitive finding might point towards a psychological effect known from prospect theory (cf. [33]): due to loss aversion of humans gains usually have a weaker effect compared to losses of the same absolute magnitude. I.e. for respondents who are confronted with on average relatively unfavorable EVSE-offers there is less latitude for (more) influential losses compared to respondents who evaluate EVSE-offers which are on average more favorable. This would again underscore the need to take the nested structure of the data into account by applying a hierarchical linear model.

3.4 Variance components

Furthermore, the results with regard to the variance components of random effects indicate that the effects of density of EVSE in cities and at the autobahn as well as the effects of charging duration in cities and at the autobahn vary significantly among the respondents even after controlling for cross-level interaction effects. Significant differences between the respondents further exist with regard to the co-variances between density of EVSE in cities and at the autobahn ($\tau 34$). Also there are significant deviations between the respondents for the covariance of charging duration in cities and density of EVSE at the autobahn ($\tau 34$). The same finding can be reported for the covariance between charging duration in cities and charging duration at the autobahn ($\tau 35$).

3.5 Explanatory power of effects

The range of values of the independent variables in our model differ and as there is no measure for effect strength comparable to Cohen's d for hierarchical linear models. Therefore, we subsequently report the proportional reduction of variance (PRV) to assess the relative importance of the variables for explaining the variance in evaluations of EVSE-offers (Peugh, 2010). In table 8 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 intercepts of level 2 units) and cross-level-interactions between level 2 variables and a level 1 variables (PRV of slopes of level 1 variables).

Table 8: Proportional reduction of variance (PRV).

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 at the autobahn (γ4/0)	5.0%
Charging duration at the autobahn (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%
Technophily (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 technophily (γ3/9)	3.4%
Slope charging duration at the autobahn (τ44) by general attitude towards EVs (γ5/10)	2.3%

For level 1 variables, i.e. the attributes of EVSE-offers, charging duration in cities (7.7%) and at the autobahn (9.9%) contribute the most to the explanation of the variance of evaluations of EVSE-offers. 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 at the autobahn.

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 most explanatory power (15.3%). The remaining level 2 variables have comparatively low PRVs between 2.3% (age) and 0.4% (A-level graduation compared to people with a graduation not higher than GCSE equivalent to EQF-Level 2). Again these numbers do not simply add up – the PRV that results from the inclusion of all level 2 variables is 28.1%.

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

3.6 Discussion

The results presented in section III on the evaluation of EVSE option require a discussion. In general, the pseudo-R^2 of .643 indicates that the share of variance explained by the ‘interaction’ model is quite substantial. The PRV implies that this number is reduced by 22.3% (i.e. 14.3 percentage points) if level 1 predictors (attributes of EVSE-offers) are excluded from the model.

The results with regard to the level 1 variables (attributes of EVSE-offers) provide useful insights regarding potential designs of a public EVSE system. The charging duration in cities and even more at the autobahn contributes the most to the explanation of the variance of evaluations of EVSE-offers. The PRV of charging duration at the autobahn alone is higher than the PRV of density of EVSE in cities and at the autobahn combined. Therefore, a conclusion might be that an installation of public EVSE should rather focus on charging duration than on a dense distribution of charging points although building fast charging infrastructure is a costly venture. However, this finding could partially derive from expectation on recharging that have been acquired using conventional vehicles. Furthermore, the comparatively low impact of EVSE density could allow to place public fast charging points at locations were installation costs are minimal for example because sufficient power is directly available from the electricity grid.

Furthermore, the conversion of the effects of the level 1 variables into each other may provide additional indications for techno-economic models how a public EVSE system could be optimized. E.g. the increase of the distance between charging points in cities (density EVSE) by 100 meters affects the evaluation of an average EVSE-offer is equal to an increase of the monthly basic fee by 42 euro cent. An increase of the distance of charging points at the autobahn by 10km equals a 49 euro cent increase of monthly basic fee. The respective values for charging duration are 1 euro and 12 euro cent for a 10 minutes increase in cities and 1 euro and 27euro cent for a 10 minutes increase at the autobahn.

The ICC of .418 indicates that differences between the respondents account for 41.8% of the variance in the evaluations of EVSE-offers. 28.1% of these differences (i.e. 9.3 percentage points) are explained by the level 2 variables (characteristics of the respondent) that the model contains.

Although the PRVs for the level 2 variables (characteristics of respondents) are rather low, except for the general attitude towards EVs, some conclusions can be drawn with regard to the identification and description of target groups for public EVSE. An average EVSE-offer is evaluated more favorable by women and younger respondents while the influence of education is ambiguous – an A-level degree fosters more favorable evaluations; an academic degree correlates with less positive ratings. Furthermore, respondents with a more distinct environmental consciousness, technophily and positive attitude towards EVs encounter an average EVSE-offer in a more favorable way.

The latter three findings are in line with results of prior studies [19, 20] that focus on the identification of early adopters of EVs (the term "early adopter" refers to Rogers` [34] classification of adopter groups during the process of innovation diffusion). In contrast to our results these studies also identified early adopters of EVs primarily to be male and academics. I.e. respondents with a similar mindset but different demographic properties like early adopters of EVs evaluate an average EVSE-offer better than other respondents. A possible interpretation of these commonalities and differences can be that public EVSE is important to open up additional target groups for EVs beside the classical clientele of innovators and early adopters. An ad-hoc conjecture about the background of this conclusion is that classical early adopters are considered as more risk-tolerant [34] – accordingly public EVSE could help to attract more risk-averse groups who are nevertheless keen on EVs.

The results with regard to cross-level-interactions are consistent with the conclusions drawn from the findings for level 1 and level 2 variables. Properties of public EVSE that are in general important to the average respondent (charging duration in cities and at the autobahn) have a smaller effect on the evaluations by respondents with typical characteristics of innovators/early adopters of EVs (older, technophile respondents with a positive attitude towards EVs). I.e. powerful EVSE in cities and at the autobahn seems to be more important for customers who likely belong to later adopter groups of EVs.

The result that the level 2 variables explain 28.1% of the respondent related variance suggests that additional relevant respondent 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 the mobility needs and mobility behavior (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 high PRV of the general attitude towards EVs (15.3%) this might indicate some limitations of our study as it could indicate that the hypothetical evaluation of EVSE-offers is psychological distant (cf. Rezvani et al. [25] for the consequences of hypothetical evaluations of EVs). Therefore, the evaluations of EVSE-offers might rely more on gut feelings towards (the usefulness of) EVs than on a deliberate assessment of the own mobility needs.

This might also be an explanation for the different results of Will and Schuller [18] who study a sample of actual EV users and our findings. Similar to the suggestions of Rezvani et al. (2015) with regard to studies about EV evaluation it might be beneficial if future studies analyze samples in which respondents with actual using experience of EVs are deliberately overrepresented and the psychological distance of the evaluation task is surveyed by respective control variables. Furthermore, the relevance of additional attitudinal characteristics like risk-tolerance or the general willingness to adjust behavioral routines (cf. [26]) who find that EV drivers even perceive recharging as more convenient than refueling) should be explored by future research.

4 Conclusions

Conclusions based on the discussion of our results can be summarized in the following way: EVSE-offers are evaluated more positive by respondents with an EV-affine mindset but different demographic properties than innovators or early adopters of EVs. This may indicate that the mere existence of public EVSE is important to open up customer groups who are next to innovators/early adopters in the market diffusion of EVs (e.g. labeled as the early majority, cf. [34]). In order to reach customer segments that are even more distant to innovators/early adopters in the process of EV diffusion (e.g. the late majority) it is important to provide powerful public EVSE in cities and at the autobahn that allows for quick charging of EVs.

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