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Understanding user acceptance factors of electric vehicle smart charging

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ABSTRACT

Smart charging has been the focus of considerable research efforts but so far there is little notion of users' acceptance of the concept. This work considers potentially influential factors for the acceptance of smart charging from the literature and tests their viability employing a structural equation model, following the partial least squares approach. For a sample of 237 early electric vehicle adopters from Germany our results show that contributing to grid stability and the integration of renewable energy sources are key motivational factors for acceptance of smart charging. In addition, the individual need for flexibility should not be impaired through charging control. Further well known influential factors like economic incentives do not seem to have a significant impact in the sample group under scrutiny. These and further findings should be taken into account by aggregators when designing attractive business models that incentivize the participation of early adopters and ease market rollout.

1. Introduction and background

Electric Vehicles (EVs) have the potential to transform individual mobility habits and substantially reduce transport related emissions. In order to harness this potential EVs must be recharged with electricity from sustainable sources. Since these sources are predominantly volatile in their generation patterns, EVs as a flexible load must adapt their charging demand in such a way as to use the available energy for charging in a smart manner, while still fulfilling the mobility requirements of the EV user. Since EVs are quite a new technology in their current form, much attention is still devoted to the assessment of the technology as a whole and in particular to the technical components like the battery, that play a crucial role for range capabilities and economic prospects. Our work goes one step further and analyzes the consumer attitudes towards smart charging concepts.

1.1. Research approach

Smart charging approaches have been under thorough investigation with respect to the employed mechanisms, the different objectives such as grid support or economic optimization and the overall effects in EV adoption scenarios in the context of smart grid research (Sortomme and El-Sharkawi, 2011). Most studies find beneficial effects that can be harnessed from shifting of charging times of EVs, ranging from the reduction of individual charging costs or emissions to enabling peak demand clipping and loss minimization in distribution grid settings.

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However, most studies assume that users either participate fully on a voluntary basis or are part of a mandatory program in the corresponding charging coordination approach. This in turn neglects the fact that successful technology adoption is also determined by the acceptance of the users. In this context we want to address the following main research question: *How do users perceive control interventions in their charging behavior and what are the main factors driving the acceptance of smart charging programs?*

In order to answer these questions we perform a survey-based analysis directed at early adopters of EV technology. Our analysis encompasses the formulation of a PLS-based structural equation model (SEM) which enables us to identify significant relationships between relevant factors of smart charging acceptance. Our results are based on a sample of 237 valid answers of EV early adopters from Germany.

1.2. Background and related work

One of the first to consider EVs as a flexible resource on the demand side in the power system for a contribution to peak load reduction was Heydt (1983). Since then a multitude of further work assessing the different possibilities for EV charging management and coordination has been performed. Most work is dedicated to assess the effect of shifting of charging times to fulfill a given technical or economic objective. This encompasses for instance distribution loss minimization options (Acha et al., 2010), cost minimizing purchase strategies given variable prices (Rotering and Ilic, 2010), power system cost impact assessments (Sioshansi and Miller, 2011; Waraich et al., 2013), charging infrastructure deployment planing based on user preferences (Yang et al., 2016), or renewable energy system integration abilities (e.g. balancing of wind generation (Galus and Andersson, 2011)). Charging coordination, or “smart charging” can be performed in different control architectures. These can either be direct load control options of the grid operators or control by the owners of the EVs given a price incentive (Schuller et al., 2015; Flath et al., 2012). Recently a hybrid form of both paradigms has been introduced and evaluated which consists of a hierarchical or mediated control architecture through the role of an aggregator (Schuller et al., 2015; Gonzalez Vaya and Andersson, 2012; Bessa et al., 2012). EVs have also been evaluated as short term storage devices for the power grid and for the provision of ancillary services, which is known as vehicle-to-grid (V2G) (Kempton and Tomić, 2005). These options were found to be slightly profitable even under consideration of battery degradation (Peterson et al., 2010), but mostly do not account for uncertainty of grid availability and power price developments. All of these options, and in particular V2G, rely on the ability to control the charging process of the EV. This is one of the reasons why this study is further focusing on the acceptance of smart charging as a facet of demand response in the smart grid.

Table 1 gives an overview of related studies and the identified acceptance factors that were the focus of investigation in these papers. It can be observed, that most sources consider the impact of monetary incentives and their design on the acceptance and effectiveness of smart charging (Paetz et al., 2012b; Ensslen et al., 2014). The ability of smart charging to support the integration of RES is assessed in most studies, e.g. in (IZT, 2012). Grid stability is regularly addressed in the theoretical work mentioned above, but is not (yet) often investigated as a motivational aspect for smart charging in empirical studies. Further aspects, such as the trust in the involved institutions, are still under scrutiny and involve different national regulatory environments. The effects of reduced potential flexibility with respect to the mobility requirements is often considered since range anxiety is attributed to EV users (Franke and Krems, 2013b) even though most mobility requirements can be fulfilled on average (Pearre et al., 2011).

Other studies focus more on the characteristics of EV users and their attitudes toward the abilities of the battery rather than on the capability of the vehicle to shift its load according to a selected objective, cf. (Axsen et al., 2015; Bailey and Axsen, 2015; Franke and Krems, 2013a). Recently one of the most comprehensive studies with respect to the current group of active EV users in Germany, their demographics, their driving behavior as well as an evaluation of the overall experience was conducted by Frenzel et al. (2015). This rather descriptive study has similarities to the presented work, in particular with respect to the characteristics of the participant sample, but it does not further investigate potential determinants for the successful implementation of smart charging. This is where our work contributes to guide further design decisions for smart charging regimes that take into account the experience and the attitude of early adopters of EV technology. Thus we consider in particular the design requirements of aggregators, grid operators and energy service companies that plan to offer a product which includes utility-influenced or smart charging.

2. Model, methodology and data

In this section we first formulate the main hypotheses with respect to influential factors for smart charging acceptance and secondly, derive the structural model for further analysis. Additionally, the survey characteristics and response data are described.

2.1. Structural model

Most EV-owners have so far been unable to experience smart charging first hand and have thus no opportunity to adequately assess its potentials and risks. Due to this lack of conceptual experience in the target group, our work cannot be solely based on popular and well-tested behavioral models, such as the *Theory of Planned Behavior (TPB)* (Ajzen, 1991), the *Technology Acceptance Model (TAM)* (Davis, 1989) or the *Unified Theory of Acceptance and Use of Technology* (Venkatesh

Table 1
Literature review and discussed influence factors for the acceptance of smart charging.

Author(s)	Method	Monetary incentives	RES - integration	Grid stability	Features	Customization	Flex. mobility need	Trust in institutions	Data privacy	Technological innovativeness	Eco values	EV - interest	Experience	Sample Size	V2G
IZT (2012)	Review	+	o	o	(x)									–	x
Grahn and Söder (2011)	Review	+		(x)	(x)		(x)	(x)						–	x
Paetz et al. (2012b)	Focus groups	+	+		+	+	(x)							6	
Ensslen et al. (2014)	van Westendorp	o												70	
Dütschke et al. (2013)	Discrete choice	+	+											1027	x
Paetz et al. (2012a)	Interviews	o	+			+	(x)			o				14	x
Geske (2014)	Discrete choice	+	+	(x)			–				+			611	x
Frenzel et al. (2015)	Descriptive survey	(x)	+				o	(x)	(x)		+	+	+	3111	
Axsen et al. (2015)	Discrete choice	(x)	(x)								(x)	(x)	(x)	1754	
Deffner et al. (2012)	Focus group/ interview	(x)	+				–				(x)			48/12	x
Franke et al. (2012a)	Choice based conjoint		+											40	
enercity (2014)	Descriptive survey	(x)	(x)	(x)				(x)		(x)	(x)			40	
This study	SEM	o	+	+	o	+	–		o	o	o	o	o	237	

Meaning of symbols: + = positive impact on acceptance; o = no effect; – = negative impact on acceptance; (x) = factor studied insufficiently.

et al., 2003), which all hinge on users' hands-on experience with or at least clear understanding of a product and the consequential purchase or usage intention. We develop our own approach based on relevant parts of the theories mentioned before, thus following the suggestion of Mathieson (1991) to combine models like TAM and TPB in order to generate additional insights. We continue with the analysis in this way since our focus is not to explore the personal beliefs of the early adopter sample but their opinion on a theorized and currently abstract product. As our subject of inquiry is not sufficiently covered by the mentioned approaches, we have to develop our own constructs to gain understanding for the smart charging concept in general, rather than one specific implementation and its interface. In consequence, our study has some exploratory character and should serve as a basis for further analyses.

Since we want to assess a concept that is not in place yet we select early adopters of EV technology (cf. Hidrue et al., 2011) as primary target group for our survey. Early adopters have at least some general understanding of the implications of electrified individual transport in daily routines. Without this understanding, an assessment of the particular acceptance for smart charging would necessitate extensive additional explanations of the consequences, potentially leading to biased survey results (Raab-Steiner and Benesch, 2012). By putting the research focus on users with at least basic experience with EVs, it can be assumed that there are less general concerns about the technology of EVs as a whole. This allows a more detailed assessment of the then relevant and influential factors for smart charging.

For the formulation of the model, we considered fundamental advantages and disadvantages of the smart charging concept from the point of view of an EV-owner. Theoretically, such advantages are a prospect of financial compensation for the provision of flexibility and a contribution to grid stability (IZT, 2012; Hahn et al., 2013; Wörner et al., 2014). Possible perceived disadvantages are a loss of flexibility in individual mobility which unfolds in additional planning and scheduling costs of trips. The application of potentially distrusted technology and insecurity towards data privacy with respect to mobility behavior are further possible disadvantages (Frenzel et al., 2015). General attitudes towards topics related to smart charging are a third field of interest with potential links to the acceptance of the overall concept (cf. Plötz et al., 2014).

The influential components of smart charging acceptance investigated here were based on the literature, a focus group discussion and our own considerations. In the following, the components are explained and modeled.

2.1.1. Monetary incentives

Monetary compensation is often referred to as a key influential factor for the acceptance of smart charging mechanisms (e.g. Grahn and Söder, 2011). In the survey, we distinguish between a compensation via a discount on the rate per kWh (*discount* kWh-*price*) and a *discount* to the monthly *base price* and ask for the respondents minimum discount required for participation, expressed in percent of their monthly electricity bill. We hypothesize that a higher requested discount implies less approval of the concept of smart charging and therefore a lower level of acceptance. In consequence, the relationship between acceptance and the requested discount percentage is assumed to be negative (H1, H2).

2.1.2. System effects

Additional advantages of smart charging comprise the integration of renewable energy sources (*RES-integration*), such as wind power or photovoltaics, via shifting of charging times (H3). This can lead to improved *grid stability* in times of high RES-generation, especially in low-voltage distribution grids (Wörner et al., 2014). A positive perception of these advantages is hypothesized to result in a high acceptance for the concept of smart charging and thus a positive relationship is assumed (H4). Grid stability is a technical concept that manifests itself on the consumer-side through an increased security of supply for all consumers, which, from an economic point of view, is a common good. In particular high power loads like EVs have to be integrated efficiently in the distribution grids to keep the established level of security of supply. This aspect is therefore included in the analysis since it is one of the most important reasons for a smart charging program from the perspective of an aggregator or utility company.

2.1.3. Usability

Moving to potential disadvantages of smart charging, we first address the usability of the system from a conceptual perspective. It is hypothesized that the *perceived risk* of smart charging, i.e. the risk that the participation in such a program leads to potential losses (like reduced operational range), reduces acceptance (H5). The influence of an increased need for flexible mobility (*flex. mobility-need*) is also assumed to have a negative impact on acceptance of smart charging (H6). Furthermore, we offer a number of control parameters to be transmitted to a possible smart charging operator, such as planned departure time or minimum range. The survey participants were asked to state which parameters or features they require in order to trust a charging scheme. A high number of these *features* represents little confidence in the scheme and therefore leads to less acceptance of smart charging (H7). This relation does not infer a linear relationship between the sole number of the features and the confidence in the scheme, but also captures how much transparency and individual control on the charging management scheme is desired by the user. Another hypothesis assumes a positive influence of a high demand for *customization* functionalities on the acceptance level. We refer to customization in this context as automation technology enabled charging decision support and the application of machine learning techniques to simplify the coordination of reoccurring charging patterns at known locations. This customization of the smart charging process should support a regular usage and thus acceptance (H8).

2.1.4. Data privacy

Another influential factor for the acceptance of smart charging could be *data privacy*. It is often stated that smart charging operators are able to deduct mobility patterns from the supplied information (Frenzel et al., 2015). We thus hypothesize a negative influence of a respondent's general data privacy concerns on acceptance (H9).

2.1.5. General attitudes

A final group of hypotheses concerns general attitudes with potential relevance to smart charging, which the literature often associates with affinity towards electric vehicles. First, the survey directly tests the early adopters' general interest in electric mobility (*EV-interest*, H10). According to Egbue and Long (2012), people with a tendency to buy new products and to be among the first to try out innovative technologies are more likely to favor EVs. With measuring respondents' *technological innovativeness* (H11) we test if such interests can promote acceptance of smart charging. Similar arguments can be made for testing the influence of respondents' attitude towards a sustainable lifestyle (*eco values*, H12) (Schuitema et al., 2013). Practical *EV-experience* (H13) has a positive effect on EV-acceptance (Franke et al., 2012b) and could therefore also influence users' opinion of intelligent charging schemes. Positive influences on the acceptance of smart charging are assumed for all four hypotheses H10-13. They can also be used to assess sample fit with the early adopter target group. Fig. 1 summarizes the hypotheses.

2.2. Methodology: partial least squares

The goal of this investigation is to discover and quantify causal dependencies between the discussed constructs in order to discern their influence on the acceptance of smart charging. For such an analysis of latent variables, structural equation models (SEM) are often used to explore theorized relationships (Backhaus et al., 2013). The hypotheses as depicted in Fig. 1 represent the structural model of the SEM-analysis. The measurement model is described in Table 2. Due to the relatively high number of formative constructs, we do not apply the *covariance analysis* but perform an *analysis of variance* according to the *Partial-Least-Squares approach* (Wold, 1966, 1975, 1982). This approach is superior for formative constructs and for newly proposed models and allows us to correctly map the relations for these individual constructs (Jarvis et al., 2003). This way we do not bias the indicator/construct-relationship but cannot apply the same set of quality criteria to assess the global model fit as compared to models consisting only of reflective constructs (Weiber and Mühlhaus, 2014). A further in-depth discussion of the validity and robustness of the employed PLS approach will be performed in Section 3.

2.3. Survey design and operationalization

The survey design is based on items and scales from literature and from questions directly related to the measured construct. Participants were first shortly briefed about the survey procedure and also received a clear definition of the terms "electric vehicle" (EV) and "plug-in hybrid electric vehicle" (PHEV) in the context of this work. In the next step participants were asked about their overall experience with driving a vehicle (electric or conventional). Respondents stating that they had no or little driving experience or no driving license were excluded from further analysis. All other participants were guided

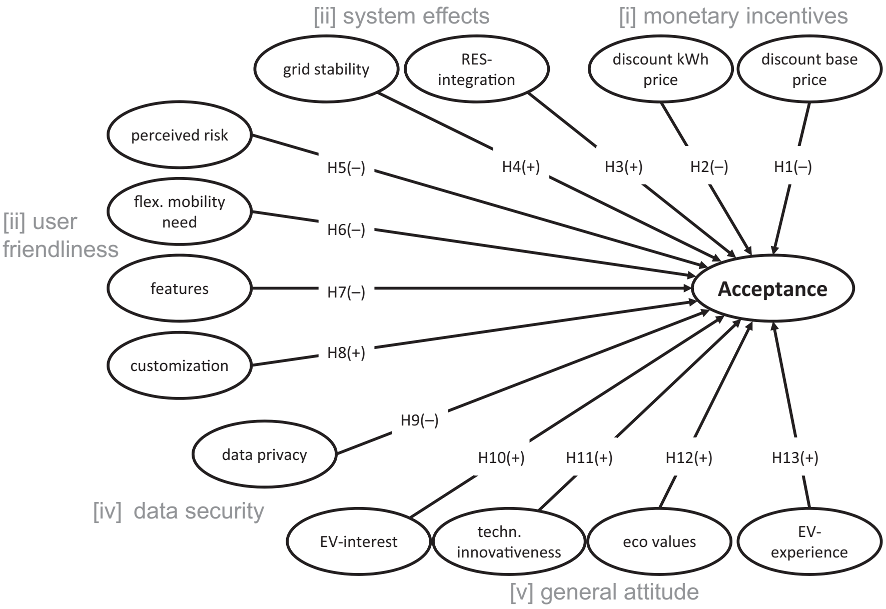

Fig. 1. Structural model and hypotheses.

Table 2
Overview of measurement models.

Hypothesis	Construct	Composition	# of indicators	Source
H1	Discount base price	Direct	1	–
H2	Discount kWh-price	Direct	1	–
H3	RES-integration	Formative	4	–
H4	Grid stability	Formative	6	–
H5	Perceived risk	Reflective	3	Laurent and Kapferer (1985)
H6	Flex. mobility-need	Reflective	3	–
H7	Features	Direct	1	–
H8	Customization	Formative	3	–
H9	Data privacy	Reflective	5	–
H10	EV-interest	Reflective	3	Laurent and Kapferer (1985)
H11	Techn. innovativeness	Reflective	5	Bruner and Kumar (2007) and Bruner et al. (2007)
H12	Eco values	Reflective	4	Haws et al. (2010)
H13	EV-experience	Direct	1	–
–	Acceptance	Reflective	2	van der Laan et al. (1997)

through the survey in dependence of their experience level with EVs. In particular EV owners and people with regular, occasional and isolated EV experience were first directed to the item group measuring their EV-interest, followed by questions regarding technological innovativeness and eco values. Following this, a short introduction of the smart charging concept and the role of the aggregator was given (cf. Fig. 2). The description further included a short list of potential advantages and disadvantages with a balanced number of arguments on each side. The next group of questions referred to monetary incentives, system effects, user friendliness, data privacy and finally acceptance. The survey closed with further demographic questions and a free comment box. Finally, information were given for a lottery in which participants could obtain one of eight Amazon vouchers with a value of 20 EURO. Overall the survey encompassed between 26 and 30 questions requiring 60–66 assessments from the participants.

For the operationalization of the hypotheses, this work largely refers to existing and well tested scales from marketing research. Bearden et al. (2011) and Bruner (2012) were especially helpful for the constructs of general attitudes, despite necessary translations into German language or adaptations to a theoretical concept. For most other constructs, however, new indicators had to be created but were often based on existing literature. The questions were phrased in an easily understandable fashion and from the point of view of the participant in order to ensure a simpler approach and understanding towards this rather abstract topic (cf. Table 2).

Since we aimed at a concise survey and due to the refinements in the pretest, the constructs for EV-experience, the monetary discounts and the number of features were measured directly. All other constructs were measured by five-point likert scales. Multiple items were inverted for validity testing. For some constructs, such as *grid stability*, it was necessary to assess different aspects of the respective factor (e.g. opinions on limiting power line construction or contribution to fewer power outages) which as a whole contribute to a factor's measurement. A respondent's positive valuation of *RES-integration* could e.g. originate from general concerns for the climate or a wish to reduce their personal carbon footprint. Respondents will also have differing appreciations of *customization*-possibilities based on their personal experience with a range of abilities from stored input-profiles to machine learning. By assessing these constructs with formative measurement models their various aspects can be efficiently covered without complicating the structural model with theorized hidden reflective constructs.

At this point it should be noted that formative measurement models provide fewer means for statistical assessments of reliability and validity. Formative measurement models use indicators that are as uncorrelated as possible. Despite this potential shortcoming, we propose a formative measurement for the three factors mentioned above in order to correctly

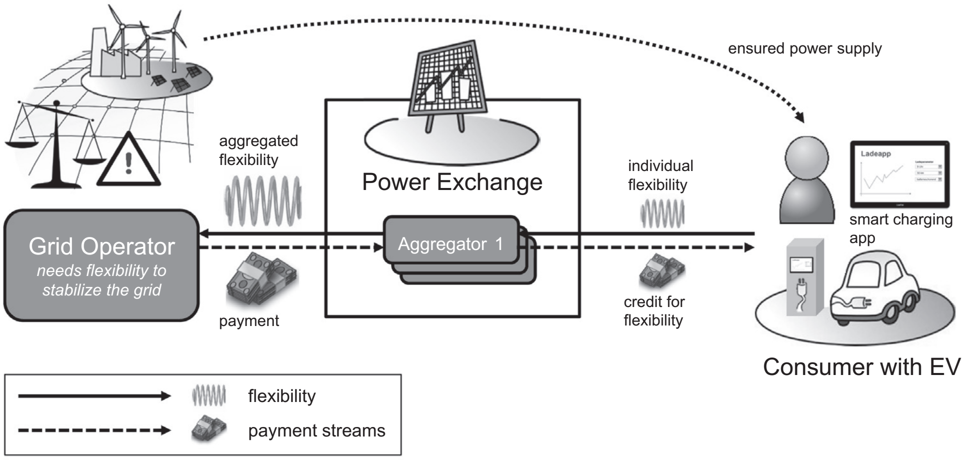

Fig. 2. Translated scenario description displayed in the survey.

capture the relations regarding the respective factor. In fact, Jarvis et al. (2003) and Eberl (2004) find that up to 28% of the articles in peer reviewed marketing literature erroneously define reflective instead of formative measurement models.

For the reflective constructs *flex. mobility need* and *data privacy* we could not rely on established literature. In consequence we developed a range of items and used the pretest to their improvement. Reliability testing led to further refinement of the measurement models.

The central construct *acceptance* was modeled in accordance with van der Laan et al. (1997). They propose a simple measurement scale of acceptance based on nine mirrored semantic differentials. Leaning on the Technology Acceptance Model, this scale assesses the usefulness of and satisfaction with the concept in question, which represent the two indicators of the acceptance-construct.

Additionally, the participants were asked about their EV-behavior and demographics.[1] Table 2 summarizes the characteristics of the measurement models.

2.4. Survey implementation and sample data

After a small pretest with 26 valid responses for improvements on composition and appearance, the survey went live for a period of 22 days in January and February 2015. It took roughly twelve minutes to complete. The link to the survey was distributed mainly through German EV-associations and EV-newsletters, who agreed to share it with their members and subscribers. Around 19,100 addressees received the survey-link via these channels. It is, however, probable that the number of actual individuals is lower, since respondents may have been contacted through multiple channels. Addressees who had subscribed to multiple newsletters or are part of more than one organization were contacted multiple times and may therefore be over-represented in the sample. This potential self-selection bias is ameliorated by our scope to address early adopters.

A total of 346 responses were collected, 270 (78%) of which were complete and therefore valid input for the model.[2] After filtering for respondents with insufficient EV-experience (seven respondents with very little driving experience or without driver's licence), plausibility (four answers with inconsistent answers to manipulation checks), too fast (19 answers completed in less than eight minutes or less than 45 s spent on reading the smart charging introduction) or obviously incorrect answers (three respondents explicitly stated to have answered incorrectly), 237 valid responses form the basis for the following analysis.

With only 24 of these 237 respondents registering as female (10%), the sample is not representative of the German population but nevertheless typical for early adopters of electric mobility. Almost one third of the sample are between 26 and 35 years old, 76% between 26 and 55. 76% of the respondents are working full-time, 8% still in education and 7% retired. This and the high education level (79% with university degree) lead to relatively high average monthly incomes per household between 2601 and 4000€ for 25% of the sample and 4001 and 6000€ for another 22%. With 45% the largest share of respondents lives in suburbs of larger cities, 30% in rural areas and 25% in urban areas. Fig. 3 summarizes the demographic information of the sample. A further comparison of our sample with the largest descriptive study on EV owners in Germany from Frenzel et al. (2015) shows that early adopters are characterized in a very similar way. Frenzel et al. (2015) also observe a sample that encompasses 89% male participants, 70% working full time, with a median age of 51 years and 15% being retirees. The sample in our study is slightly different in this case since we only observe 7% to be already retired. The place of residence is also resembling since 66% of the sample in Frenzel et al. (2015) live in small or medium sized cities while 45% of our sample live in suburbs. Residents from rural areas are potentially over-represented in our study, but since the categories are not comparable in detail we can still see a convincing resemblance in nearly all relevant indicators of our sample with this largest yet presented study in this field.

In conclusion, the sample displays satisfactory compatibility with definitions of early adopters by Hidrue et al. (2011) and Plötz et al. (2014). According to Chin (1998) the sample size is sufficient for a PLS-analysis with the proposed model.

3. Evaluation

In this section we provide an empirical evaluation of relevant sample data. In the following SEM analysis, the modeling results are discussed under consideration of the respective quality criteria.

3.1. Empirical evaluation

3.1.1. Electric mobility behavior

41% of the sample ($n = 237$) own an EV (31% private, 10% company car), making this the largest experience group. Another 26% have driven an EV at least once. Only 10% of the sample have no personal experience with EVs. These results indicate adequate experience with EVs for this early adopter sample. Respondents with at least some experience were asked about their EV-usage ($n = 214$). Most respondents use EVs for commuting (69%) while leisure (52%) and shopping (43%) are additional important use-cases. Fig. 4 displays the absolute empirical results for theses two aspects of EV-behavior.

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[1] The complete questionnaire is available in German and English upon request to the corresponding author.

[2] Complete data was needed for a consistent evaluation of each individual construct. Therefore every question that directly included measurement models was mandatory.

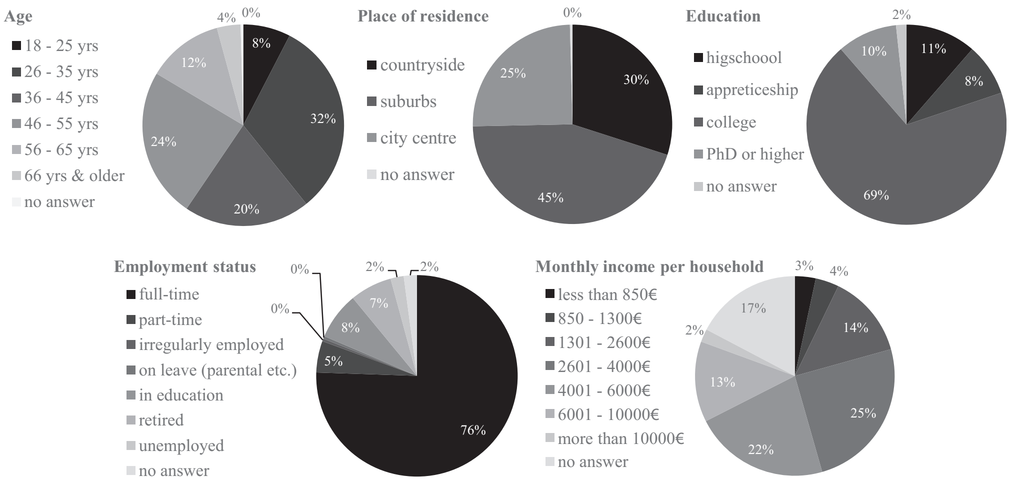

Fig. 3. Demographics of the sample.

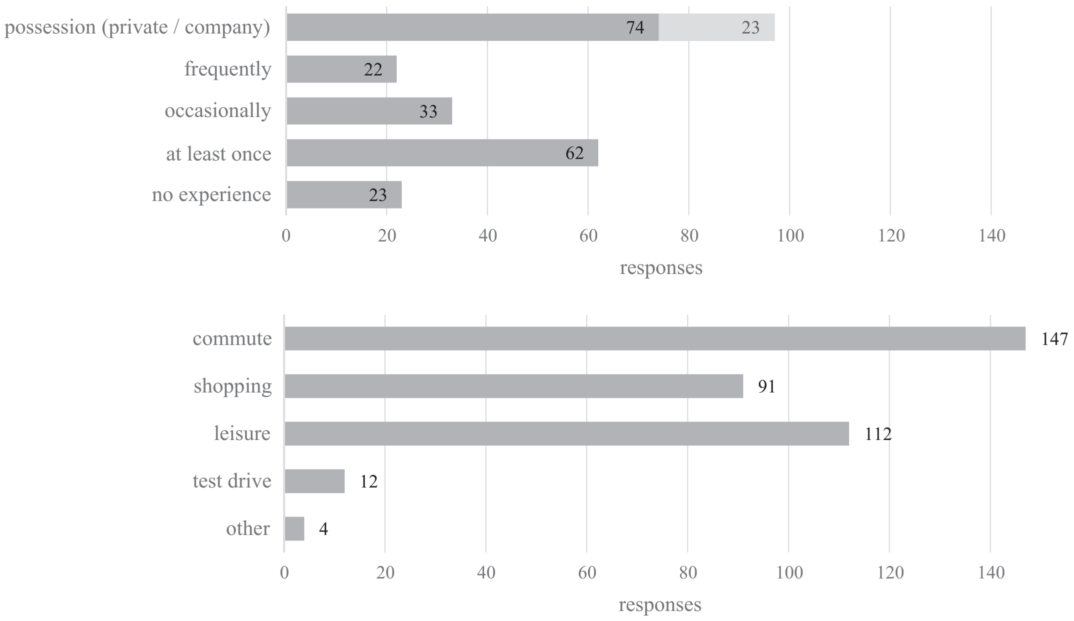

Fig. 4. EV-experience in the sample (top), primary EV use (bottom, $n = 214$).

3.1.2. Features

When asked to point out the features which they expect in a smart charging system, most respondents request an option to submit a minimum range (77%). The average minimum range requested in the sample is 70 km (median 50 km). The ability to override the smart charging process and charge directly is another highly demanded feature (76%) as well as the submission of a planned time of departure (71%). Other than the minimum range, 60% of respondents opt to submit a planned range which serves as an upper threshold beyond which no additional battery charge is necessary. Gentle charging for a prolonged battery life is specifically requested by 56%. Another 37% consider a variation range around their arrival time as useful. Only 3% of the sample do not request any features at all. Respondents also request options for the use of self-produced electricity from e.g. PV and V2G-functionalities. Fig. 5 displays the empirical observations for this question.

3.1.3. Demanded compensation

In the literature monetary incentives are one of the primary drivers for participation in a smart charging scheme (cf. Table 1). By providing a short calculation example on the ensuing savings to allow for easier evaluation and to provide a frame of reference, we asked respondents about their discount expectations for the two price components of a classic electricity tariff used for charging. Fig. 6 gives a detailed account of the answers. In general, high discounts are requested and

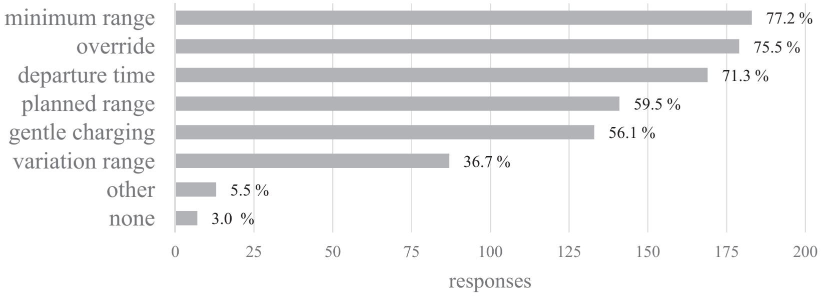

Fig. 5. Requested features for the smart charging application sorted by frequency of request ($n = 237$).

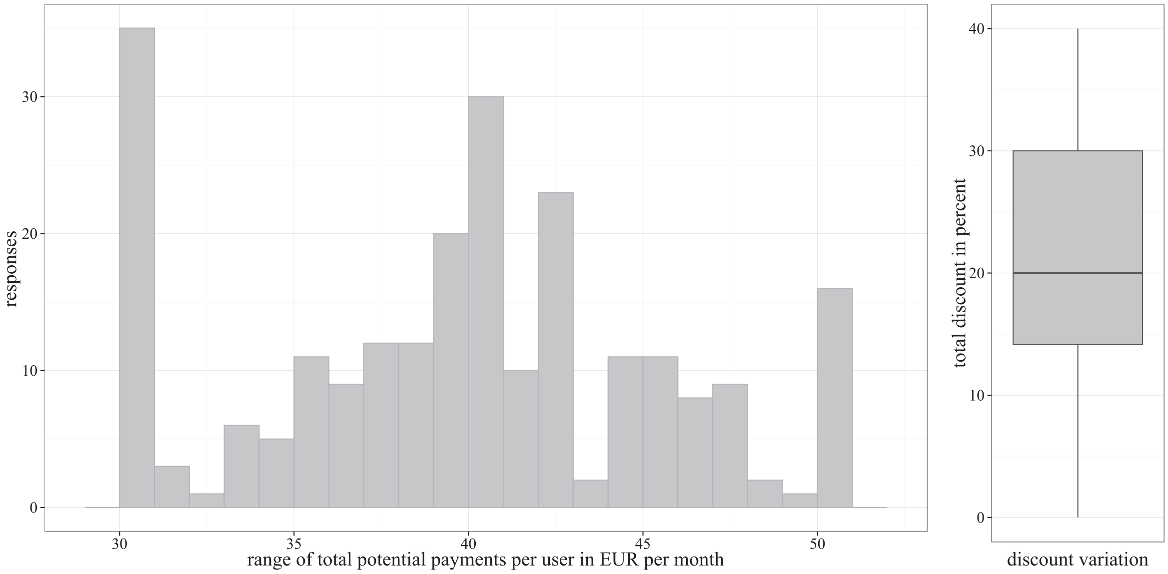

Fig. 6. Distribution of responses of potential total monthly payments based on the given example (15,000 km/year at 12.7 kWh/km) in the survey (left) and the variation of the demanded overall discount (right).

average around 20% rebate[3] for both price components. If one considers the potential payments per month given the calculation example, the majority of users would request a discount. On the other hand there is a substantial number of respondents that do not prefer a discount at all. Further dedicated analyses with a focus on the estimation of the economic valuation of charging time flexibility should therefore be conducted.

3.1.4. Acceptance

Being the focal point of this analysis, Fig. 7 displays the variation of the empirical results for the two indicators "usefulness" and "satisfaction" of the construct *acceptance*. The median is considerably higher for "usefulness" than it is for "satisfaction". About 60% of the sample appraise "usefulness" at an average score of 4 or higher whereas only 37% rate "satisfaction" at a similar level. Together, average evaluations are towards the positive end of the scale which indicates substantial approval of the concept of smart charging. However, "usefulness" is appraised more positively than "satisfaction", indicating that smart charging is indeed seen as a valid concept but so far lacks optimal implementation.

3.2. SEM results

The core of this work is an extensive SEM analysis on the factors driving smart charging acceptance. The modeling results are discussed in the following with regard to their statistical robustness.

3.2.1. Modeling results

The PLS algorithm reached a solution after seven iterations with a threshold of 10^{-7}. Results are displayed in Fig. 8 and Table 3.

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[3] The answer "more than 30%" was included in the calculation with a discrete value of "40%".

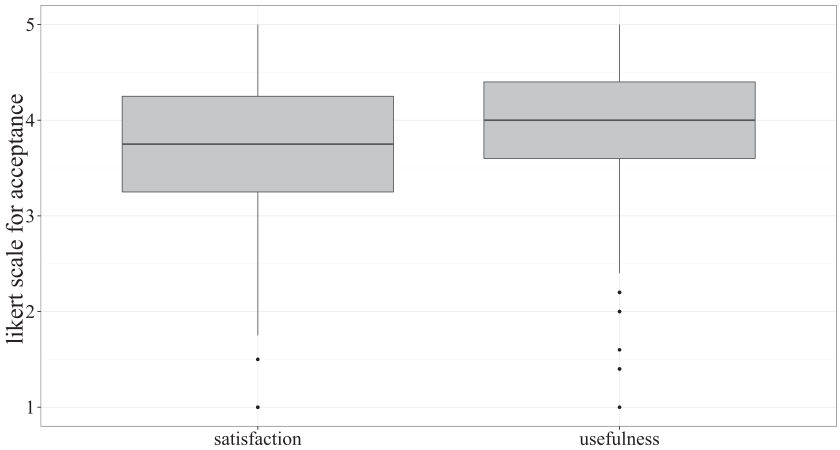

Fig. 7. Empirical results for the variation of acceptance of smart charging based on statements on satisfaction and usefulness on a five point likert scale.

The analysis yields the constructs *grid stability* ($\beta = 0.380; t = 4.743; p < 0.01$), *RES-integration* ($\beta = 0.214; t = 3.250; p < 0.01$) and *flex. mobility-need* ($\beta = -0.147; t = 2.331; p < 0.05$) as the only (strongly) significant influencing factors on the acceptance of smart charging. The relationship between the construct *customization* and *acceptance* is only weakly significant ($\beta = 0.117; t = 1.846; p = 0.065$), while none of the remaining constructs show a statistically noteworthy contribution.[4] The R^2-value for *acceptance* of 0.560 indicates a good model fit. Global model quality is satisfactory with $SRMR = 0.060$. According to the f^2 values in Table 3 the four significant constructs do have noticeable individual effects on *acceptance* and significantly contribute to the predictive value[5] of $Q^2 = 0.483$, another sign towards a promising overall model fit. These numbers indicate that *grid stability*, *RES-integration* and *flex. mobility need* (as well as *customization* in part) do contribute strongly to acceptance of smart charging, even though limited significance of a number of potentially influential factors shows that the model can benefit from further refinement in future work.

3.2.2. Quality criteria: identifiability, reliability and validity

In accordance with Backhaus et al. (2013) the overall identifiability of the model is guaranteed (749 degrees of freedom). The reflective measurement models are identifiable due to the Rule of three (Bollen and Lennox, 1991), the directly measured constructs are identifiable by definition. Due to the sequential approach in regression analyses in PLS, identifiability of formative constructs is given naturally (Weiber and Mühlhaus, 2014).

An analysis of multi-normal distribution of the sample data would be necessary for the application of a Maximum-Likelihood approximation in a covariance analysis. However, such an analysis shows, that the sample data is non-normally distributed (possibly due to high coherency of the target group), further supporting the use of the variance analysis instead.

To put the model results into perspective, we performed an extensive quality analysis. Reflective measurement models were analyzed for their unidimensionality, reliability and validity. An exploratory factor analysis of the reflective items yielded $KMO = 0.784$ and a Bartlett-test with $p = 0.000$. The Kaiser-criterion was met by all reflective factors, indicating unidimensionality. Individual KMO-values and communalities of *perceived risk*, *flex. mobility-need* and *data privacy* indicate a slight need for indicator improvement in future work (cf. Tables 4–6 in the Appendix A).

Reliability testing yielded Cronbach's Alphas greater 0.5 for all constructs indicating construct reliability. Internal consistency measured by corrected item-to-total-correlation was again not entirely satisfactory for the constructs *perceived risk*, *flex. mobility-need* and *data privacy*. Analysis of second generation criteria, i.e. described variance, factor reliability and AVE, led to satisfactory reliability results for all reflective constructs.

Discriminance validity was assured through an analysis of the average variance extracted (AVE). The Fornell/Larcker-criterion holds for all constructs. Convergence validity was assured, as the factor loadings in a confirmatory factor analysis are non-zero and significant for all reflective constructs.

Different to reflective measurement models, quality analysis of formative measurement models cannot be based on correlation analysis since formative items should cover the whole thematic reach of a construct.

Therefore, a comprehensive statistical quality analysis as performed for reflective measurement models is not defined. For the benefit of the reader, we conducted an exemplary quality analysis for the three formative constructs in order to theoretically assess a reflective interpretation.

All three originally formative measurement models fulfill the theoretical requirements for unidimensionality, also if measured against the original reflective constructs. On the other hand, both *grid stability* and *RES-integration* contain one item that produces poor communalities and reliability (res1_env and gs5_flex). These items are clearly not as closely correlated to the

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[4] *T*-test results from Bootstrap-algorithm implemented in *SmartPLS 3.0*.

[5] Values from Blindfolding-procedure implemented in *SmartPLS 3.0*.

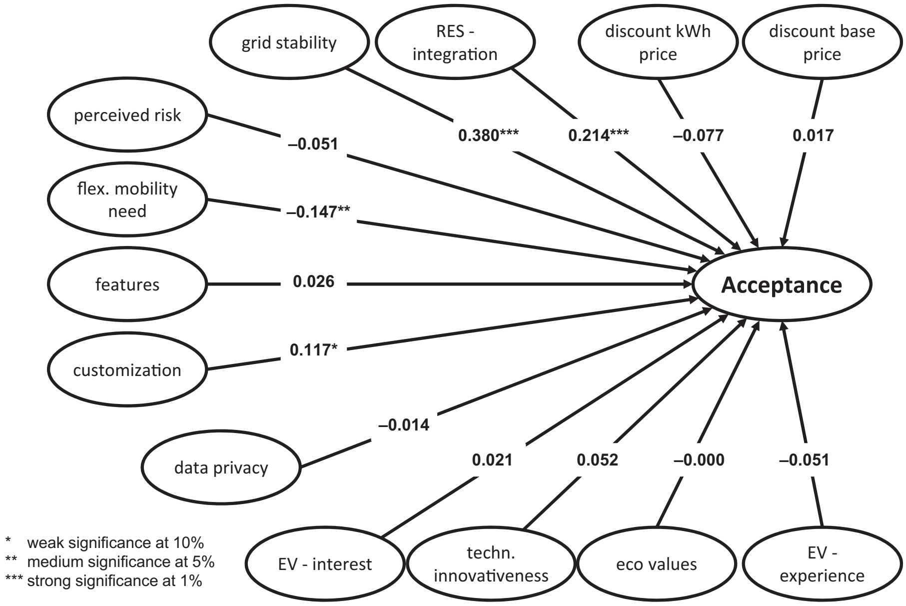

Fig. 8. Results of the SEM analysis.

Table 3
Detailed results of the SEM analysis.

Construct	Hypothesis	Total effect	*t*-value	*p*-value	*f*-value	*q*-value
Discount base price	H1(−)	0.017	0.344	0.731	0.000	−0.002
Discount kWh-price	H2(−)	−0.077	1.421	0.155	0.009	0.001
RES-integration	H3(+)	0.214	3.250	0.001	0.057	0.042
Grid stability	H4(+)	0.380	4.743	0.000	0.144	0.107
Perceived risk	H5(−)	−0.051	0.983	0.326	0.005	0.000
Flex. mobility need	H6(−)	−0.147	2.331	0.020	0.029	0.027
Features	H7(−)	0.026	0.541	0.589	0.001	−0.004
Customization	H8(+)	0.117	1.846	0.065	0.022	0.020
Data privacy	H9(−)	−0.014	0.302	0.762	0.000	−0.004
EV-interest	H10(+)	0.021	0.462	0.644	0.001	−0.002
Techn. innovativeness	H11(+)	0.052	1.122	0.262	0.005	0.002
Eco values	H12(+)	0.000	0.013	0.990	0.000	−0.002
EV-experience	H13(+)	−0.051	1.088	0.277	0.005	0.003

other items in the measurement models, which points to their coverage of an entirely different aspect of the respective factor. This indicates that a reflective measurement of these constructs would have been unjustified. *Customization* on the other hand yields satisfactory reliability results throughout and could theoretically have been implemented as a reflective construct. However, we are of the opinion that a formative implementation is more appropriate given the relationship of the items to the factor.

The values for the theoretical reflective implementation are not further reported since they cannot truly be interpreted for de facto formative measurement models.

Meanwhile, an assessment of test-retest reliability for the formative constructs was impossible due to the survey design. All formative indicators are non-collinear in their original implementation with $VIF < 5$, allowing for the application of variance analysis (cf. Table 7 in Appendix A).

With strongly significant correlations between indicators and their constructs (cf. Appendix A), indicator validity is assured. An assessment of construct validity is only possible through the approximation of the entire model. All three formative constructs *grid stability*, *RES-integration* and *customization* show sufficient significance and support their respective hypotheses.

To conclude, our model achieves good global model fit and validity. Merely the reliability of some reflective measurement models could require refinement in further analyses.

4. Discussion

In this section the individual hypotheses of the SEM analysis will be discussed and critically reflected upon. We then further discuss the implications of the acceptance or the rejection of the formulated hypotheses for the given sample.

Hypothesis H1 assumed that a higher requested base price would decrease the acceptance for participating in a smart charging scheme. According to the SEM results, the total effect is not significant and H1 must therefore be rejected. Since the survey participants could explore the effect of different base price discount steps in the survey, they could also explore the total effect of this price element. Despite the empirical mean of nearly 20% demanded discount (cf. Fig. 6), the overall impact of the base price discount has to be considered statistically irrelevant for the acceptance of smart charging.

In the next step, H2 assumed that a high variable electricity price would reduce the acceptance. The SEM path coefficient seems to confirm the direction of influence of the hypothesis, but the relationship is again not significant. Thus this hypothesis also has to be rejected. Following the empirical observation, the variable component has a higher impact on the overall costs for charging with a mean of 21.4% demanded discount in the sample. Further effects that could be mediated through EV-experience or the demographic group were not found.

In the context of this sizable discount request, monetary incentives must play a role in the design of smart charging schemes. However, our study does not yield reliable evidence for their contribution to the acceptance of the *concept* of smart charging. This result is somewhat contrary to most related literature (cf. Table 1). The discrepancy could be explained by the fact that respondents were able to experiment with the discount size and experience its rather small effect on total mobility costs: a maximum delta of 20 EUR/month in the (in reality unlikely) case of a discount of 40% might have been too little for some to compensate for the loss of flexibility (extremely high discount request) or to matter at all (very low request). The results show that such potential considerations are decoupled from the acceptance of the smart charging scheme itself. Future work should further challenge this finding in a more specific setting that also considers early adopters. The main implication from this finding for a product designer would be not to focus only on the potential economic advantages of a smart charging program but also to address other factors.

H3 considered the fact that the more the integration of RES can be fostered through smart charging, the higher the acceptance for this concept would be. The total explanatory effect of this construct is 0.214 at the 0.1%-significance level. This relation is the second strongest in the whole analysis, supports H3, and therefore confirms the majority of the literature in relation to this factor. Any smart charging management program put forward by an aggregator should therefore consider objectives related to better RES-integration or communicate the effects of a charging management program on the ability to better utilize these sources of electricity, e.g. omitted greenhouse gas emissions.

H4 hypothesized that if smart charging could contribute to an increased *grid stability*, the acceptance for the program would also be higher. This construct has the highest individual overall effect in the SEM analysis (0.380) at the 0.1%-significance level. Thus the hypothesis is being supported. Empirical answers show that EV users do not want to take too much responsibility for grid stability from the grid operators. But the overall relation in the construct shows that all users are aware of their potential contribution and thus make this argument the strongest in terms of explanatory value. This straight forward option to increase the acceptance of smart charging should therefore always be considered to foster smart charging approaches. One potential implementation to communicate participants' contribution to grid stability could be for the aggregator to share information on his successful participation on balancing power markets.

H5 assumed that an assessment of a higher *perceived risk* of the participation in a smart charging program leads to reduced acceptance. The perceived risk represents the subjective evaluation of the impact of a mispurchase. This construct was not found to have a significant impact on acceptance in our sample and H5 is thus rejected. The next hypothesis H6 assumed that the higher the need for flexibility in individual mobility, the lower the acceptance for smart charging. Two of three studies explicitly discussing this factor reached a similar conclusion and we can confirm this relation with an explanatory value of -0.147 at the 5%-significance level. Even though individual flexibility need is an important factor that has to be considered in the design of smart charging programs, the statistical reliability of the construct needs to be improved in further studies. Overall there is a clear perception in the sample that individual flexibility is important, but due to the lack of experience with a particular instance of a smart charging scheme more specific investigations have to be performed.

H7 investigated the impact of the availability of a number of technical *features* on acceptance. This construct did not have a significant explanatory value and the hypothesis is rejected. From a descriptive point of view the early adopters demand between three to four main features (range buffer, manual override, expected departure time, planned range) and do not want an overly complex interaction with the system. Further work could therefore evaluate explicit features on different levels of complexity. It is also important to notice that we do not imply a linear relationship between the number of features and the confidence in the charging management program. The type of feature and the personal disposition of the EV user towards the charging management technology must also be considered in the future as an influence for the acceptance in this case. H8 made a first step to address this by assuming that a higher degree of *customization* of automated data provision to the charging management system will in turn increase the acceptance. This construct was found to be weakly significant at the 10%-level. Further analyses, including a MANCOVA, did not yield any hidden group effects to explain the lack of significance. It can thus be concluded that customization can improve acceptance but is not the most important driver. Related work also points in this direction (cf. Table 1).

H9 hypothesized that a higher need for data privacy would have a negative effect on acceptance. This relation could not be confirmed. H10 in turn assumed that a higher *EV-interest* would lead to higher acceptance. Due to the sample structure the overall interest in this technology was already quite high and thus, in contrast to findings in related work, cannot be said to have an explanatory effect for acceptance in this context. H11 assumed that a higher *technological innovativeness* would lead to a higher acceptance. This hypothesis could not be supported. Further investigations did not yield any effect of the demographic group on this result (e.g. younger participants to be more inclined to smart charging).

The hypothesis, that more distinctive *eco values* would have a positive effect on acceptance, H12, could also not be confirmed in the early adopter sample. As with *EV-interest*, this could again be due to the homogeneity of the sample with respect to this attitude. Finally, H13 assumed that a higher *EV-experience* would have a positive effect on the acceptance of smart charging. This relation was also not found to be significant. Especially the last discussed constructs should be reevaluated in the future in a more heterogeneous, representative panel for additional insight.

5. Conclusion

Smart charging has been the focus of considerable research efforts but so far there is little notion of users' acceptance of the concept. This work considers potentially influential factors for the acceptance of smart charging from the literature and tests their viability employing a structural equation model variance analysis, following the PLS approach, for a sample of 237 early adopters from Germany.

The analysis reveals a high acceptance of the concept and underlines the importance of communicating the benefits of smart charging to the users. These are namely the positive effects on grid stability and integration of renewable energy sources, which are found to be the strongest influential factors for acceptance. The users' identified desire for an individual and flexible mobility in turn hampers acceptance of smart charging. The provision of customization possibilities for data input is another noticeable but only weakly significant influential factor. Contrary to the literature, the level of monetary compensation for the participation in a smart charging scheme cannot be considered an influential factor. Moreover, users largely expect varying amounts of compensation, on average around 20% discount to their monthly individual charging costs, independent from their actual acceptance level.

Beyond these four relevant factors, we tested nine others without obtaining significant results. The size of the model may have lead to a crowding out of the effect sizes, possibly diminishing individual contributions of constructs. Low reliability scores of some constructs could also originate from little space for construct improvement through a consequently limited number of items. Additionally, a generalization of the findings to the German public is inappropriate, since only early adopters were considered. Statistically, the presented model explains 56% of the acceptance of smart charging. This leaves room for further improvement, but also shows that the majority of influential factors has been considered.

However, the findings of this study show which factors, beyond monetary incentives, should be taken into account upon roll out of smart charging tariffs and innovative business models in this domain. Tariff designers need to find ways to communicate the public benefits that EV early adopters are willing to create by restricting their personal flexibility in private transportation. Such tariffs could include information on balancing power contribution or omitted carbon emissions. Aggregators might even consider offering charging tariffs that bill according to a customers' contribution to grid stability or RES integration. Meanwhile, the fear of giving up the aforementioned flexibility has to be addressed through transparency and the provision of customization possibilities in addition to a strong integrity of the aggregating agent.

Taken together and given the respective legislative framework, our findings could serve to ease and accelerate the implementation of smart charging and in consequence materialize the positive system effects that were found to be so motivational to the early adopters.

The expansion of the target group to the general public, also beyond German borders, is a logical next step for future research. Such an analysis should contain more room for manipulation checks and redundant items to improve reliability. The proposed model is the first in this field and future modeling efforts could benefit from a greater focus on promising constructs and their respective mediators. This paper thus lays the exploratory foundation for a more refined understanding of customer wishes and potential marketing perspectives for the realization of smart charging.

Acknowledgements

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Appendix A

Table 4
KMO and Bartlett-test of exploratory factor analysis for determination of dimensionality of reflective factors.

Construct	KMO	Bartlett-test		
		χ^2 (approx.)	df	p
Perceived risk	0.593	73.198	3	0.000
Flex. mobility need	0.576	64.126	3	0.000
Data privacy	0.737	183.313	6	0.000
EV-interest	0.680	187.642	3	0.000
Techn. innovativeness	0.887	617.244	10	0.000
Eco values	0.816	484.338	6	0.000
Combined	0.784	1,901.053	231	0.000

KMO = Kaiser-Meyer-Olkin criterion.
df = degrees of freedom.

Table 5
Coefficients of measurement models in confirmatory factor analysis.

Indicator	Estimate	S.E.	C.R.	*p*	Factor loading	Loading squares
EV-interest 1	0.728	0.090	8.081	***	0.617	0.380
EV-interest 2	1				0.836	0.699
EV-interest 3	0.572	0.065	8.777	***	0.721	0.520
Technical innovativeness 1	1.216	0.092	13.198	***	0.789	0.623
Technical innovativeness 2	1.157	0.085	13.593	***	0.808	0.653
Technical innovativeness 3	1.075	0.093	11.532	***	0.709	0.502
Technical innovativeness 4	1				0.811	0.658
Technical innovativeness 5	1.063	0.078	13.662	***	0.811	0.658
Eco values 1	0.830	0.057	14.623	***	0.794	0.631
Eco values 2	1				0.894	0.799
Eco values 3	0.946	0.063	14.959	***	0.807	0.651
Eco values 4	0.782	0.065	11.973	***	0.691	0.477
Data privacy 1	0.797	0.118	6.741	***	0.550	0.302
Data privacy 2	1				0.707	0.500
Data privacy 3	1.060	0.135	7.857	***	0.716	0.512
Data privacy 4	0.898	0.134	6.711	***	0.547	0.299
Flex. mobility need 1	1				0.622	0.387
Flex. mobility need 2	0.593	0.134	4.414	***	0.394	0.155
Flex. mobility need 3	0.970	0.169	5.749	***	0.640	0.410
Perceived risk 1	0.397	0.087	4.580	***	0.414	0.172
Perceived risk 2	0.516	0.102	5.069	***	0.498	0.248
Perceived risk 3	1				0.822	0.675

S.E. = standard error, C.R. = critical ratio, Estimate = unstandardized factor loadings.
*** Significant on the 1%-level.

Table 6
Reliability values of reflective constructs.

Indicator\threshold	CITC ⩾ 0.5	Item reliability ⩾ 0.4	Cronbach's α ⩾ 0.6	Explained variance ⩾ 0.5	Factor reliability ⩾ 0.6	AVE ⩾ 0.5
Perceived risk 1	0.330	0.172	0.584	0.548	0.778	0.542
Perceived risk 2	0.391	0.248				
Perceived risk 3	0.484	0.675				
Flex. mobility need 1	0.442	0.387	0.548	0.530	0.745	0.499
Flex. mobility need 2	0.260	0.155				
Flex. mobility need 3	0.390	0.410				
Data privacy 1	0.567	0.500	0.723	0.548	0.810	0.523
Data privacy 2	0.452	0.302				
Data privacy 3	0.567	0.512				
Data privacy 4	0.459	0.299				
EV-interest 1	0.538	0.380	0.767	0.683	0.862	0.676
EV-interest 2	0.632	0.699				
EV-interest 3	0.617	0.520				
Technical innovativeness 1	0.735	0.623	0.890	0.694	0.916	0.686
Technical innovativeness 2	0.747	0.653				
Technical innovativeness 3	0.666	0.502				
Technical innovativeness 4	0.751	0.658				
Technical innovativeness 5	0.750	0.658				
Eco values 1	0.741	0.631	0.873	0.725	0.911	0.719
Eco values 2	0.807	0.799				
Eco values 3	0.726	0.651				
Eco values 4	0.639	0.477				

CITC = corrected item-to-total correlation.
AVE = average variance extracted.

Table 7
Factor loadings, *p* and VIF values of the formative indicators of the SEM.

Construct	Indicator	Factor loading	*p*-value	VIF
Customization	c1-save	0.882	0.000	1.818
	c2-profil	0.880	0.000	1.745
	c3-learn	0.738	0.000	1.525
RES-integration	res1-env	0.821	0.000	1.272
	res2-co2	0.813	0.000	2.564
	res3-res	0.733	0.000	2.209
	res4-clim	0.818	0.000	3.104
Grid stability	gs1-stabl	0.821	0.000	2.127
	gs2-trans	0.513	0.000	1.320
	gs3-ben	0.846	0.000	2.423
	gs4-nec	0.865	0.000	2.398
	gs5-flex	0.718	0.000	1.514
	gs6-gen	0.327	0.001	1.213

VIF = variance inflation factor.

Table 8
Factor loadings and *t*-statistics of the measurement models of the SEM.

Construct		Indicator	Factor loading	*t*-value	*p*-value
Customization	←	c1_save	0.882	12.346	0.000
Customization	←	c2_profil	0.880	11.606	0.000
Customization	←	c3_learn	0.738	6.854	0.000
Data privacy	→	dp1	0.730	6.631	0.000
Data privacy	→	dp2	0.586	3.841	0.000
Data privacy	→	dp3	0.913	17.334	0.000
Data privacy	→	dp4	0.616	5.081	0.000
RES-integration	←	res1_env	0.821	11.585	0.000
RES-integration	←	res2_co2	0.813	12.347	0.000
RES-integration	←	res3_res	0.733	8.480	0.000
RES-integration	←	res4_clim	0.818	12.561	0.000
EV-interest	→	evi1	0.808	4.524	0.000
EV-interest	→	evi2	0.798	4.107	0.000
EV-interest	→	evi3	0.860	5.170	0.000
EV-experience	→	exp	1.000		
Flex. mob. need	→	fmn1	0.676	7.952	0.000
Flex. mob. need	→	fmn2	0.835	16.225	0.000
flex. mob. need	→	fmn3	0.585	7.084	0.000
Features	→	funct_sum	1.000		
Grid stability	←	gs1_stabl	0.821	15.520	0.000
Grid stability	←	gs2_trans	0.513	6.626	0.000
Grid stability	←	gs3_ben	0.846	15.002	0.000
Grid stability	←	gs4_nec	0.865	18.094	0.000
Grid stability	←	gs5_flex	0.718	12.077	0.000
Grid stability	←	gs6_gen	0.327	3.283	0.001
Techn. innovativeness	→	ti1	0.807	7.372	0.000
Techn. innovativeness	→	ti2	0.801	6.292	0.000
Techn. innovativeness	→	ti3	0.798	8.570	0.000
Techn. innovativeness	→	ti4	0.844	8.744	0.000
Techn. innovativeness	→	ti5	0.886	1.717	0.000
Eco values	→	eco1	0.894	29.377	0.000
Eco values	→	eco2	0.907	28.496	0.000
Eco values	→	eco3	0.812	11.818	0.000
Eco- values	→	eco4	0.773	12.502	0.000
Disc. base	→	discBase	1.000		
Disc. kWh-price	→	discCons	1.000		
Perceived risk	→	pr1	0.703	5.188	0.000
Perceived risk	→	pr2	0.634	6.026	0.000
Perceived risk	→	pr3	0.855	12.719	0.000
Acceptance	→	usefulness	0.970	235.765	0.000
Acceptance	→	satisfaction	0.962	146.966	0.000

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