Enhancing sustainability of electric vehicles: A field study approach to understanding user acceptance and behavior

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Introduction

Increasing concern about the environmental impact of current road transport systems as well as the analyses of risks associated with peak oil (Hirsch et al., 2005) have led to greater interest in sustainable transportation. Mobility systems based on electric vehicles (EVs) are considered promising for coping with these challenges. Many countries have set up action plans to increase the proportion of EVs within the road transport sector (Die Bundesregierung, 2009). However, the positive effects of EVs on the sustainability of the transport sector are still debated (Horst et al., 2009; Huo et al., 2010). It has been shown that these effects are largely dependent on how an electric mobility system (EMS) is set up as well as how it is used (Eggers and Eggers, 2011). Hence the user is a critical parameter in the equation of the net environmental benefit of EMSs. Adopting the perspective of human centered systems engineering (Nemeth, 2003) three essential components should to be taken into account when optimizing user-system interaction: technical system, user and task. The task of EMSs is to increase sustainability. Much is known about the theoretical sustainable potential of certain technical system variants for sustainability, but little is known about user factors in this equation.

The objective of the large-scale field study outlined in this chapter was to gain a comprehensive understanding of the user-driven dynamics of sustainability in EMSs. Acceptance of favorable system layouts and efficient interactions with system resources are key dimensions. Adaptation processes occurring on these dimensions as well as personal characteristics (for example dispositions, traits, needs) may yield promising variables to increase our understanding of the dynamics in these dimensions related to sustainability.

First, important success factors and associated research topics which have evolved from these factors will be structured. Then, the field study approach is outlined with a detailed account of study methodology. Thereafter, focused analyses on selected research topics follow. A final discussion and outlook concludes the chapter.

Factoring users into the equation of EMS sustainability

Sustainability is a multidimensional concept. Three pillars should be addressed: environmental protection, social development and economic development (UN General Assembly, 2005). The sustainability of EVs has been intensely discussed, particularly with respect to the environmental dimension. Lower local noise and exhaust emissions are the two least contested factors. However, significant reductions in greenhouse gas emissions depend on the energy source used for propulsion and production (Holdway et al., 2010). Although there are contradictory findings in the literature (Brady and O'Mahony, 2011; Thiel et al., 2010) there is a tendency to believe that the environmental benefits of EMSs will be negligible for a fossil-fuel-based scenario (Huo et al., 2010). However, even under such a worst-case scenario EVs may still have some utility on social and economic dimensions because of their potential to mitigate risks

associated with peak oil prices (Hirsch et al., 2005). In addition, EMSs can help to integrate renewable energy into the grid by acting as flexible energy storage buffers and thereby promoting sustainability of the general energy supply.

Hence, there are considerable degrees of freedom concerning the sustainability that EVs offer. We argue that the (potential) user is a critical factor in this equation. As a best-case scenario, we assume that the maximum benefit for sustainability would be achieved if all car buyers with high daily EV-capable mileage would switch to an EMS with a sustainable layout. Such a setup would mean low resources and emissions needed for production (for instance battery size determined according to actual user need) and operation (such as exclusive use of excess energy from renewable sources). The mobility resources that such an EMS could offer would then have to be utilized in an energy efficient manner. This could be accomplished if all individual mobility needs were transferred to this EMS, with optimal utilization of range and recharging options. Moreover, this successful adaptation would require ecological behavior while using the system (that are eco-driving, treating battery for longevity, assisting excess energy use by exhibiting appropriate mobility and charging patterns). Interacting in this way with the EMS should not compromise the quality of the user experience and should ensure acceptance so that users still act as disseminators. Ideally such setups should be amenable to multi-modal and multi-person usage scenarios (for example intuitive design of user interfaces in whole EMSs).

We propose that two factors should be distinguished in interrogating and optimizing the user as a factor in the sustainability of EMSs: (1) Users should prefer sustainable system layouts, and (2) users should efficiently interact with system resources to assure that the sustainable potential of a given setup is maximized.

Assumptions of the best-case scenario described earlier together with these two proposed factors resulted in the following research questions:

First, concerning the acceptance (positive attitudes and purchase intention) of sustainable EMS layouts, research questions are: Is there a general high acceptance concerning an essentially sustainable EMS? Do users accept and actively prefer the use of excess energy from renewable sources? Do they accept lower buffers in terms of mobility resources (range and recharging options)? Do users prefer low noise setups or do they experience a conflict between low noise emissions and traffic safety?

Second, research questions that address the utilization of the sustainable potential of a given setup, by optimal user–system interactions include: Do users transfer significant shares of mobility to EMSs? Do drivers optimally utilize available mobility resources (e.g. range, recharging options)? Do users consider longevity in their treatment of the EMS?

Variance within and between these variables may be explained by several moderator variables, which in turn can inform strategies to optimize sustainability of EMSs. Research questions concerning these moderating effects are: Does experience (as practice, knowledge) moderate score values? Do personal variables (as traits, dispositions, needs) yield interaction effects? Is suboptimal behavior more a function of conflicting behavioral intentions or of behavioral abilities? Insights provided by these questions can help to quantify the real-world impact of the user factor on EMS sustainability and to identify promising variables for its enhancement.

A field study approach to understanding user-driven dynamics in sustainability of EMS

Research on factors of EMS sustainability previously focused on modeling the user factors with statistical data like data from travel surveys (Brady and O'Mahony, 2011). In addition, studies of potential car-buyers with little knowledge of EMSs have dealt with acceptance-related topics (Chéron and Zins, 1997), with some studies simulating experience with reflexive methodologies (Kurani et al., 1996). However, these studies are limited in predicting what car-buyers in markets with already experienced customers (after societal adaptation to EMS has occurred) will accept and in quantifying the dynamics introduced by user behavior. As a result field studies have been requested which yield adapted interaction patterns with experienced users in realistic settings (Kurani et al., 1994). These studies also have methodological limitations (Golob and Gould, 1998), but are nevertheless accepted for investigating the user perspectives on EMSs also providing validity for acceptance related issues in markets that do not exclusively comprise inexperienced first-time buyers.

The methods outlined in the following refer to a large-scale EMS field study incorporating two subsequent user studies which took place in the Berlin metropolitan area in 2009 and 2010 (see also Cocron et al., forthcoming). Addressing a major criticism of EMS field studies, several measures were taken to ensure high ecological validity for an EMS likely for the coming years. An electric vehicle was paired with private and public charging infrastructure supporting the use of excess energy from renewable sources in a metropolitan area. Users were recruited via an online screener application that was publicized via advertisements in newsprint and online media. Subjects were selected according to several must-have criteria and further distribution criteria that aimed to prevent restriction of variance on several basic sociodemographic

and mobility-related variables. Users had to agree to pay a monthly leasing fee over the six-month study period. Study length was designed to allow for full adaption to the EMS. Hence the resulting sample is expected to reflect the viewpoint of early customers of EMSs.

In addition a multi-method approach that incorporated structured qualitative interviews, questionnaires, diary methods, experimentally oriented methods, and continuous data logging of vehicles and charging infrastructure values offered the possibility of data triangulation and fusion, filling gaps in scientific knowledge on user experience and behavior in EMSs. For these analyses a main-user approach was adopted such that in a household only main EV user data was collected whereby a special car key was assigned for subsequent allocation of data logger data.

Sequence of data collection and method corpus

Table 1 depicts the sequence of data collection events for each user over the period of a user study. Data was collected before receiving the EV (T0), after three months of experience (T1), and after six months at vehicle hand back (T2). The sequence of events was the same in the two user studies except that a second test drive was applied only in the second user study (S2) and a few of the questions from the pre-experience interview were shifted to a preceding telephone interview in the first user study (S1). Most essential methodological elements were the same for both user studies with the method corpus increasing from 873 items in S1 questionnaires to 1,380 items in S2 (plus nearly 200 h of verbatim-transcribed interview data). The following description focuses on S2 methodology as it is most representative, while noting essential differences to S1. A structured matrix of central topics and sub-topics of questionnaires and interviews is depicted in Figure 1.

Table 1. Sequence of data collection events within user studies.

Timeline (months)	Data collection event	Acronym
-3	*Screening*	
-0.5	Baseline diary week	T0
0	Pre-experience questionnaire and interview	T0
0	Test drive	T0
0	Post-test drive questionnaire and interview	T0
0	*Vehicle handover*	
2.5	diary week after experience	T1
3	questionnaire and interview after experience	T1
3	Test drive*	T1
5.5	Final diary week	T2
6	Final questionnaire and interview	T2
6	*Vehicle handback*	

* Second user study only.

In the online-screener all applicants were asked to submit basic sociodemographic and mobility-related information. After selection of users from the applicant list (for details on the sample see Neumann et al., 2010) and prior to vehicle handover (T0), each of the 40 resulting main users filled out a seven-day baseline travel diary, which was structured according to established travel survey designs (Kunert and Follmer, 2005). The diary aimed at assessing mobility patterns and determining indicators for mobility needs. This diary was applied again at T1 and T2 in an extended form designed for tracking changes in mobility patterns associated with the introduction of the EV to the main-user's mobility resources. In addition, the seven-day charging diary at T1 and T2 was designed to assess time, location, energy status and motivation related to each charging process. Much of the questionnaire content was also included in the semi-structured face-to-face interviews to assure high data quality. A standard six-point

Likert scale (ranging from 1 = *completely disagree* to 6 = *completely agree*) was applied in scales constructed for the study. The first test drive was conducted to gain a qualitative picture of first impressions while driving the EV and to assess certain interaction skills, which were again assessed in the T1 test drive. Additional methods employed during interviews included, for example, a range game (Franke et al., forthcoming) and a choice-based conjoint analysis (Krems et al., 2010).

1. Impression

Safety appraisal | critical situations

System competence/ knowledge previous knowledge | technical background knowledge

Regenerative braking adaptation | acceptance[1] | usage and influence on driving task | trust

Eco-driving acceptance of eco driving[1] | knowledge | user behaviour | driving style

Range adaptation | utilization | satisfaction & preferences | psychological range levels and buffer values | knowledge | concerns

Charging controlled charging (acceptance, behaviour) | handling | user-battery interaction | future concepts | battery lifetime | motives of charging | public charging

Acceptance purchase intention | attitude towards EVs | usefulness & satisfaction[1] | influencing factors (attitude and prejudice of social network, joy of use, barriers)

Mobility (mal)adaptation | mobility resources needs | satisfaction | future mobility concepts | mobility patterns

Personality car-affinity | personal driving style[2] | control beliefs in dealing with technology[3] | sensation seeking[4] | affinity for technology[5] | uncertainty avoidance[6]

Acoustics adaptation | safety evaluation | estimation of speed | critical situations | sound design

Human–machine interface/ handling adaptation | usage | perceived usability | preferences | users' conceptions

Environmental value/ renewable energies environmental concerns | renewable energies (acceptance & preferences

Demographics

[1] Van Der Laan et al., 1997 | [2] French et al. 1993 | [3] Beier, 1999 | [4] Beauducel et al., 2003 | [5] Karrer et al., 2009 | [6] Dalbert, 1999

Figure 1. Matrix of research topics examined in the field study. Only exemplary sub-topics are depicted.

Focus-analyses of user factors affecting sustainability of EMSs

A subset of the presented research questions are addressed in the following. For selected topics, moderator effects will also be discussed. Because of limitations of space, results of the first user study are presented exclusively. The second user study, however, revealed a comparable pattern of results.

Do users accept and prefer sustainable EMS layouts?

Several scales were constructed and adapted from the literature (Bühler et al., 2011) to assess facets of EMS acceptance. Here we focus on a seven-item attitude scale (Bühler et al., 2011) and a single-item indicator for determining purchase intention, which stated "I would spend a third more for an electric vehicle like the MINI-E than for a comparable vehicle with a conventional engine". Attitudes, which were already very positive at T0, increased with experience (T0: $M = 4.62$, $SD = .71$; T1: $M = 4.91$, $SD = .74$) yielding a significant ($p<.05$) effect (Bühler et al., 2011). In terms of purchase intentions 64 per cent agreed on the item at T0 (dichotomization of six-point Likert scale). This value decreased to 51 per cent at T1. The relatively high score values are probably supported by selection bias. However, increasing acceptance with experience might indicate that attitudes can be positively influenced by hands-on experience. Further qualitative results from the study suggest that even a short test drive can enhance attitudes toward EVs. However, decreases in purchase intentions may indicate increased price sensitivity when users are past the honeymoon phase. This problem could be ameliorated if users were willing to accept less range resources decreasing the additional costs of EVs in comparison to combustion vehicles.

Users' preferences in terms of energy sources for charging the EV were not in conflict with principles of sustainability. From the scales that were assessed (Rögele et

al., 2010) the three-item scale on attitudes towards usage of renewable energies in EVs indicated high acceptance (T0: $M = 4.79$, $SD = 1.09$; T1: $M = 4.79$, $SD = 0.88$) and users indicated strong preferences for renewable energy sources (Rögele et al., 2010).

To increase market potential and environmental benefit it would be favorable if users accepted lower buffers in terms of mobility resources. Past research has shown that inexperienced users have very high preferences concerning range and recharging options (Eggers and Eggers, 2011). We also found range preferences to be relatively high in the present experienced user sample (available range under daily conditions evaluated as just acceptable at T1: $M = 156$ km, $SD = 81$ km, $Q_3 = 180$; range evaluated as sufficient at T1: $M = 227$ km, $SD = 124$ km, $Q_3 = 300$). Only 37 per cent of users judged range setups, which were equal to or smaller than those offered by their current EV, as sufficient. Even in users who stated they could use the EV for >95 per cent of daily trips, this number could only be increased to 53 per cent if passenger and luggage space were not restricted. A similar number (60 per cent) was yielded for users who completely agreed that the current range was sufficient for daily use.

Do users prefer low-noise EMSs or do they experience a conflict between low noise emissions and traffic safety? Within the present study, few critical incidents were reported by users: 68 per cent had no incidents and 84 per cent had <10 incidents within the six-month study period (Cocron et al., 2011). Moreover, only a small proportion of users (13 per cent) preferred active sound design. In addition, low noise was perceived as one of the main advantages and attractions of EVs and thus might be essential for general acceptance of EMSs (Cocron et al., 2011). However, it remains to be verified if the general public and public authorities share the same positive appraisal of low noise emissions in EMSs.

Do users exploit the sustainable potential of EMSs to the fullest extent?

A central factor in sustainability is that users transfer the maximum possible share of their mobility needs to more sustainable transport options. Modal split is used as an indicator in this area of research (Schafer, 1998). For the present analyses data from travel diaries of 30 users were analyzed that fitted the necessary conditions for comparing their data to available statistical data from nation-wide surveys (Ahrens, 2009). Taking the baseline-data from T0, the user sample had relatively high shares of individual motor car traffic (trips by foot: 9.0 per cent, bike: 8.3 per cent, public transport: 12.2 per cent, individual motor traffic: 70.5 per cent) compared to panel data for the population of Berlin (by foot: 28.6 per cent, bike: 12.6 per cent, public transport 26.5 per cent, individual motor traffic: 32.3 per cent [Ahrens 2009]). After the introduction of the EV as a sustainable transport option this distribution changed substantially (trips by foot: 5.4 per cent, bike: 1.7 per cent, individual combustion-powered motor traffic: 21.3 per cent, public transport: 1.8 per cent, EV: 70 per cent). Although temporal shifts should be interpreted with caution, the general pattern indicates that the EV could substantially reduce the share of individual combustion-powered motor traffic in the user sample, however reduction in shares of the other sustainable transport options might indicate that these are less used as a result of the availability of the more convenient option the EV offers.

Closely related to this topic, users should be willing and able to optimally utilize the valuable range resources that the EMS has to offer. Results show that users reserve a substantial buffer in the range they are willing to utilize (Franke et al., forthcoming). Within the sample users were only comfortable with utilizing a mean average of 82 per cent ($SD = 11$ per cent, $Q_1 = 76$ per cent, $Q_3 = 90$ per cent) of the range that they achieved under daily conditions. Interestingly, there was a moderate relation between

the tendency to actively test the range ("I deliberately tried to exhaust the range in order to see how far I could go with the MINI E" at T2) and the acceptance of higher utilization of range resources. Thus, helping the user explore the range might also promote the use of available range resources.

Finally, the low and variable lifetime of batteries may present a barrier to purchase intentions and compromise the efficiency of resources needed for the production of EMSs. Although it is very difficult to quantify the influences of optimal user behavior it can be assumed that charging and discharging patterns have a significant impact on battery life. In the present sample, 61 per cent of users agreed to an item stating "Throughout the EV trial I tried to handle the battery in a way that would prolong its life". 76 per cent of users agreed when the context was revised to "If I had paid for the EV outright". Subjective knowledge (assessed as the mean confidence in nine ratings on the effectiveness of certain behaviors to prolong battery life, such as "avoid frequent charging at high charge levels") was related to actual treatment for longevity (median split, 47 per cent tried to prolong battery life in the low knowledge group, and 74 per cent in the high knowledge group) indicating that an increase in user knowledge, or rather problem awareness, could lead to better interaction with the lifetime resources of the battery.

General Discussion and Outlook

This chapter has emphasized the importance of including the user as a factor in determining sustainability of EMSs. A field study approach outlined together with study results aimed to provide an overview of exemplary user factors in a state-of-the-art EMS. From these results it can be concluded that there are substantial variations in the user factor: between the different facets important for EMS sustainability and within

users. In general it was found that users prefer and accept sustainable system setups and exploit the sustainable potential of the EMS in an acceptable way. However, there still seems to be substantial potential for increasing the sustainability of EMSs given the variance in the measured variables and the indicated moderating effects. Helping users make full use of given mobility resources is an important topic here. Guided exploration of mobility needs and mobility resources could be a fruitful approach as the experience-related moderator effects suggest.

The analyses presented herein gave an exemplary overview of user-driven factors in EMS sustainability. However further analyses are necessary to more closely examine and replicate findings with data triangulation. Selection bias is also an important consideration in the present study. We are currently testing the transferability of core results in follow-up studies, in users without private charging options and in study settings that allow more freedom in recruiting users. Furthermore we are working on replicating important results in additional experimental settings such that causal conclusions may be made.

The present field study revealed that state-of-the-art EMSs are already well suited to a substantial sample of users. During the history of the EV, positive findings in user acceptance and positive evaluations of suitability for daily use have often led to the conclusion that stakeholders should just wait for the very next improvement in vehicle technology because this final step would then finally lead to high market potential and hence high sustainability of investing resources in the development and marketing of EMSs. However, we are still far from the situation where EMSs perfectly mimic combustion-powered mobility systems. Still, especially from the indications of high acceptance and price-sensitivity we conclude that further technical improvements should be implemented with the aim of reducing prices rather than increasing

performance, hence reducing the entrance threshold for attracting new users. That is, users need to be sensitized to the special characteristics offered by EMSs, discouraged from internal combustion engine vehicle comparisons, and encouraged to consider the resources offered by EMSs in meeting their personal needs. This might be a societal adaptation process that could be supported by giving more people the chance to experience EMSs in real-life.

The present study also has implications for future research. For example, the paradoxical disparity of range satisfaction and range preferences, which has been attributed to different methodological approaches in the past (Kurani et al., 1994), has also been found, albeit less intensely, in the sample of users in the present study. This finding needs further investigation, for example, focusing on possible tradeoff effects. Also, this study might help inspire the development of indicators for the sustainability of EMSs that integrate the user as an important factor. It is also our aim to design more reliable, valid and economic indicators in future studies (for example extending modal split to EMSs in fleet settings).

As a final remark, we would like to clarify the perspective on EMSs adopted in this chapter. We do not wish to imply that it is the user's fault if an EMS does not reach its intended sustainable potential. Nor do we argue that it is the *user* who should adapt to the *system*. We believe that a positive, satisfying and joyful user experience is key to ensuring EMS sustainability. And it is much more favorable to adapt the system to the user than to adapt the user to the system (Good et al., 1984). However to reach this aim, a comprehensive understanding of the user factors in EMSs is indispensable.

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