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Diary-Based Evaluation of Bidirectional Electric Vehicle Charging in a Long-Term Study: Method and Insights

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Abstract

The aim of this paper is to explore the applicability of a BDC system in a real-world context and to test the use of semi-structured online diaries in a long-term study. During a 15-month trial phase of a BDC pilot project, twenty pilot users recorded their experiences with a BDC system in online diaries. Throughout the study period, participants reported 72 experiences that were significantly more frequently rated negative than positive or challenging. The wallbox was the most often mentioned concerned system element and was always associated with negative or challenging experiences. Positive experiences referred to the correct functioning of the BDC system. Recoding of the concerned system elements by independent raters revealed that pilot users attributed their experiences to different elements than the raters. Thus, some of the described problems may be due to the pilot users having an incorrect or incomplete understanding of the BDC system. The results indicate that the applicability of a BDC technology does not only depend on the smooth functioning of the system. Moreover, users should be enabled to understand the system and receive sufficient feedback about the system states and processes. Regarding the use of diaries in a long-term study, the total number of diary entries was rather low and varied greatly between individuals and over time. Therefore, the method should be adapted.

Keywords: bidirectional charging; user experience; diary studies; V2X; electric vehicle (EV)

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1. Introduction

By 2030, the annual energy demand for charging electric vehicles (EVs) could increase by more than 8% in Germany compared to the current energy demand (Bermejo et al., 2021). At the same time, the share of renewable energy sources is increasing but fluctuating. Bidirectional charging (BDC) is a concept to counteract the higher demand and grid bottlenecks by using the EV as a “rolling battery” and storing the excessive energy in the car battery (Freymann, 2020). Various modelling studies show positive impacts of smart or bidirectionally chargeable EVs on local energy systems (Child et al., 2018; Hanemann and Bruckner, 2018; Wei et al., 2022). Kern and Kigle (2022) analyzed different modelling approaches of bidirectionally chargeable EVs in a complex multi-energy system model and evaluated their impact on the European energy system. The study finds that bidirectionally chargeable EVs have numerous positive effects, including supporting the integration of photovoltaic generation, lowering the required installed capacities of conventional power plants and other storage technologies, decreasing overall energy system costs and electricity prices, and contributing to the security of supply of the energy system. Thus, as an energy-balancing tool, bidirectionally charged EVs could offer benefits to individual consumers, energy providers and society in general. However, EVs primarily have to fulfil users’ mobility needs. Therefore, one of the biggest challenges in BDC management is to optimally balance users' mobility needs with the energy requirements of the home or the public power grid.

As the concept is not yet freely available in Europe, most studies on BDC either focus on technical (Hinterstocker et al., 2022; Müller et al., 2022), economic (Ostermann et al., 2022) or legal aspects to model user behavior (Eickelmann and Engel, 2022*)*. Existing user studies mainly explore user acceptance or needs in hypothetical scenarios, such as questionnaire or choice task studies (Daziano, 2022; Kubli, 2022; Lagomarsino et al., 2022). However, it has been shown that direct experience has a significant influence on acceptance of EVs and smart charging (Bühler et al., 2014; Schmalfuß et al., 2015). In addition, personal experience influences users’ understanding of energy systems (Kim and Shcherbakova, 2011). Henriksen et al. (2021) conducted interviews with participants in a Norwegian charging project and identified different motivations for smart charging. Nevertheless, user research reflecting real experiences with BDC is sparse so far. The continuous recording of negative and positive experiences when interacting with a BDC system could therefore help to understand external and internal usage barriers and incentives.

Diary studies or so-called experience sampling methodologies (ESM) offer insights into everyday experiences and at the same time allow the recording of the emotions evoked. They can be classified in interval-, signal-, and event-contingent diaries (Wheeler and Reis, 1991; Bolger et al., 2003). In the interval-contingent design, participants report their experiences in regular, predetermined intervals, while in signal-based designs participants rely on a signal prompting them to provide reports. In event-based studies, participants self-report every time an event in question occurs. Bolger et al. (2003) summarized the advantages of diary studies. Key advantages are that they capture events and experiences in their natural, spontaneous context and apply different methods. Participants are able to log in entries on a daily basis, therefore providing longitudinal data in either open forms in terms of recording events, thoughts, feelings, and behaviors using their own words (Poppleton et al., 2008) or in a more structured form using standardized questions (Ohly et al., 2010). Furthermore, memory and recall biases can be avoided (Scollon et al., 2003) if the time span between the experience and the recording is kept to a minimum. In addition, no presence of the researcher is required, so there is minimal influence of the researcher on the users. However, diary studies have several limitations. One of these relates to self-selection bias, as only certain individuals might be willing to participate in this type of study or report experiences. This could result in an unrepresentative sample of participants or reported experiences if reports are voluntary (Scollon et al., 2003). Second, diaries rely on self-report and therefore depend on the motivation and conscientiousness of the participants. Especially event-based diary studies require participants’ motivation to report on their experienced events, what Csikszentmihalyi and Larson (1987) called a “viable research alliance” (p.529). In this context, the “negativity bias” could play an important role, i.e. the tendency to “pay far more attention to, learn from and use negative information than positive information” (Vaish, 2008). Consequently, diaries are designed to be short and concise so that participants are able to complete them in a few minutes (Bolger et al., 2003). Further disadvantages relate to the statistical analyses of the collected data. As the data depend on time, individuals, and triggering events, the analyses often require complex mathematical models (Bolger et al., 2003; Lischetzke and Könen, 2021; Scollon et al. 2003).

2. Present study

Due to the lack of knowledge about real-world user experiences with BDC, the study pursued two main goals (1) the continuous recording of subjectively meaningful experiences around BDC in order to identify barriers to BDC and (2) to test the use of semi-structured online-diaries in a long-term study. Thus, the related research questions are:

(1) Which experiences and problems do users face, when interacting with BDC and how do they rate these experiences?

(2) Are diaries suitable as a data collection tool for a longer period in terms of the frequency of entries over time?

An exploratory approach was applied to answer the research questions, accompanying twenty pilot users who tested a BDC system in a 15-month long-term pilot study.

3. Methodology

This diary study was part of the German pilot project "Bidirectional Charging Management". The aim of the pilot project was to develop and test a holistic, user-oriented concept for integrating bidirectionally chargeable EVs into the energy system.

3.1. Participants

The participants were twenty pilot users of the German pilot project "Bidirectional Charging Management". They were recruited by ads in online forums or by contacts of the involved project partners. Interested persons applied for the participation of the pilot project by a screener questionnaire. In addition to the screening data, a technician inspected the participants' home to ensure the feasibility of the execution of the project. The selection of the final pilot users relied on whether and with what effort the technical implementation of the BDC system was feasible. The resulting sample ($N = 20$) consisted of $n = 1$ female and $n = 19$ male participants with an average age of 46 years ($SD = 11.55$, $Min = 30$, $Max = 74$). 15 of the 20 participants owned a higher education degree (university or university of applied sciences). 11 participants worked for companies involved in the project or associated companies. Since the BDC system was also available to all household members, it was not possible to control whether the persons registered as pilot users or a family member entered data into the diary.

3.2. BDC system

Selected participants were equipped with a BDC system at home including an EV, a wallbox and a charging app. They also received several meters in order to record all incoming and outgoing energy. The tested car was a standard BMW I3 enabled to discharge energy in addition to charging. Participants also received a wallbox that was able to charge the car as well as feed the energy from the car battery either into the house or into the electric grid. The app was the user interface of the system and essential for smart charging. It provided participants with the functionality to set departure times, a target state of charge (SoC) and a minimum SoC, to switch from instant charging mode (charging now) to BDC mode, to provide feedback and report problems to BDC customer service, as well as to start and stop the charging process and to receive information about the current and historical charging processes. The app was further developed and continuously updated during the pilot project. In addition, the photovoltaic modules (PV) of sixteen participants were integrated into their BDC system.

From July 2021 to October 2022, participants gradually tested the use of the system and different use cases, namely Vehicle-to-Grid (V2G), Business-to-Consumer (B2C) and Vehicle-to-Home (V2H), if a PV was installed. The V2G use case (including B2C) addressed time arbitrage and intraday trading. In this use case, EV flexibilities were aggregated for charging or discharging and marketed on the intraday market. Thus, the EVs were charged when demand and prices were low and discharged when demand and prices were high. The difference in prices then generates revenue for the participants in the B2C use case. The aim of V2H was to increase self-consumption of the energy generated by the participants' own PV systems. Therefore, only participants with a PV system could take part in this use case. Surplus energy generated by their own PV system and not currently needed by the household was fed into the car battery, stored and fed back into the household when needed. This reduced the need to purchase additional and more expensive energy from the grid. Thus, the participants were able to increase their degree of self-sufficiency and the consumption of self-generated energy and therefore save money. For more details on the use cases refer to Ostermann et al. (2020).

3.3. Participants' tasks

When participating in the pilot project, the participants had several tasks. They had to use the electric car, maximize the time the car was plugged in (even if the car's SoC was high), and use the app to set the departure times and the target SoC. They were regularly contacted by the project team to give feedback in surveys or interviews and to fill in the diaries consisting of an experience diary and a charging diary. If problems occurred, they were supposed to contact the customer service to solve the problem quickly so that the pilot study could continue.

3.4. Diaries

During the pilot project, participants were asked to fill out two different forms of diaries. An interval-based charging diary, where participants should record all of their charging processes during three fixed time frames of two weeks each, as well as an event-based experience diary. Here, the participants should record all subjectively significant (positive, challenging or negative) experiences and events. For this purpose, they received a personal account on Calidat's "ID-X platform" using a QR code or a personal internet login. After logging in, they could choose between which type of diary entry they would like to make, followed by the decision to enter a new entry or change one. Each entry requested the following data: (a) date and time of the experience, (b) concerned system element (participants could select one or multiple elements such as *EV*, *Wallbox*, *Charging process*, C*harging cable*, *App*, *PV*, *Billing*, *Social event*, C*ustomer service* and *Miscellaneous*), (c) rating of the experience (*positive*, *negative*, *challenging*), (d) experienced emotion (*enthusiastic*, *positive*, *neutral*, *negative* and *shocked*), (e) text or image description of the experience, and (f) free description of further ideas, wishes or suggestions. If the entry concerned a problem, participants were asked for additional information about the problem and its consequences, as well as about the problem-solving process, its success and their satisfaction with the solution and support. The participants were able to change an entry within a week. Date of entry and changing dates were automatically logged by the IDX platform.

According to the event-based approach, participants were not given fixed periods or times to report their experiences. However, participants were regularly reminded to enter their experiences. Unlike most uses of event-based diaries, no specifications regarding which particular events the participants should report were made. Here, the explorative character of the study was in the focus.

3.5. Procedure

The schedule was specific to each participant. The meters were installed at participants' homes between February 2021 and September 2021, with most installations taking place in July 2021. The wallboxes were installed between June 2021 and September 2021 and the app was launched between July and September 2021. The cars were handed over on 9 July 2021, along with access to the diary software, at an official kick-off event organized by the project team. From then on, participants could enter data into the diaries until 30 September 2022.

Pilot users were able to use the EVs after the official handover and kick-off event in July, but only with the option of direct charging. The use cases were implemented gradually for the participants, starting with V2H. This initially enabled BDC for pilot customers with PV systems only. Since October 2021, participants also began testing V2G, with few remaining in the V2H use case. The use cases were tested in total until October 2022. Even though the first participant left the pilot study in August 2022. Participants could submit diary entries until 30 September 2022. In November and December 2022, the decommissioning and dismantling of the various technical components and meters took place. Fig. 1 (a) shows the distribution of participants per use case.

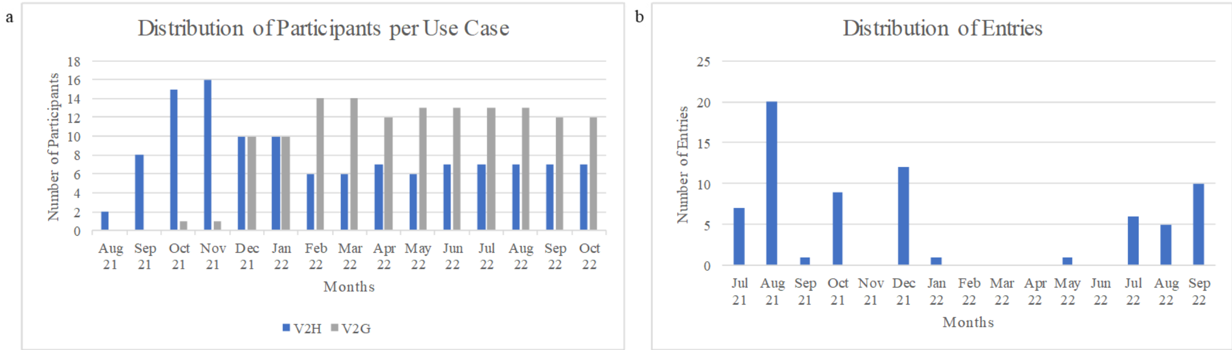

Fig. 1. (a) Number of Participants per Use Case; (b) Distribution of Entries per Month.

4. Results

During the study period, the pilot users reported a total of $N_E = 72$ experiences in the diaries. Thereby, the number of reported entries widely differed between the pilot users and varied between 0 and 15 experiences per pilot user. The reported experiences were various and of different kinds of nature (Table 1). The majority of entries (27.8%) mentioned technical problems, such as a failure to connect to the system (e.g. "*The vehicle was plugged in on Thursday with a remaining range of 30 km. Charging did not work. ...*"), incorrect messages and information ("*Wallbox displays an incorrect message*"), and others. In further 15.3%, the participants described how the BDC system performed in their use case - especially in V2H - such as "*Today I used the time window with the nice weather again and charged 2 hours of electricity from the PV system with 11 kW at home*". 12.5% of the entries referred to perceived inconsistencies or difficulties related to the BDC settings 'Departure Time' and 'SoC', e.g., "*I forgot to set the departure time and SoC. It will be difficult today*". However, other entries indicate that pilot users misunderstood the role of the settings, e.g., "*In the app I set the target SoC to 59%. Nevertheless, the vehicle was charged to the maximum SoC*". Besides, pilot users also reported external events, not directly related to the BDC project, e.g. regarding the environment bonus of the German Federal Environment Agency, mobility costs and more.

Regarding the concerned element of the entry, participants most frequently named the *Wallbox* (34.7%), the *Charging process* (25.0%), the *EV* (26.4%) or the *App* (16.7%), considering multiple choices. The rest of the entries falls into the other categories such as *Charging cable*, *PV*, *Billing*, *Social event*, *Customer service* and *Miscellaneous*. If only the entries that were assigned to one specific element are counted, the order of the mentions remains almost constant: 23.6% refer to the *Wallbox*, 18.1% to the *Charging process*, 16.7% to the *EV* and 11.1% to the *App*. The remaining experiences (13.9%) relate to *Billing*, *Customer service*, the *PV* and *Miscellaneous*. Additionally, 16.7% of the entries mentioned more than one element.

Analysis of the data showed that the element concerned, named by the pilot users, was sometimes not the element that caused the event for the entry. Therefore, all entries were recoded by two independent raters who had a deeper understanding of the technical processes underlying the experiences. As many entries referred to a communication problem within the backend of the BDC system, a new category *Communication* was created. In addition, raters were instructed to avoid coding multiple elements and only indicate when multiple experiences with different system elements were described in one diary entry. With a nearly perfect interrater reliability ($\kappa = .88$), the raters coded the *Charging process* (27.8%) as the most frequently concerned element, followed by *Communication* (18.1%), the *EV* (12.5%), the *Wallbox* (11.1%) and the *App* (9.7%). Compared to the pilot users, the main differences concern the frequencies of the coding of *Wallbox* (-12.5%), *Communication* (+18.1%) and *Charging process* (+9.7%). For testing the statistical significance, we had to consider that the category *Communication* was not available to the pilot users and referred to several system elements at the same time. This means that in the case of a communication problem, users were forced to indicate multiple concerned elements. Thus, all user entries referring to a communication problem and stating multiple concerned elements were recoded into the category *Communication*. To meet test requirements, all remaining entries referring to multiple elements were consolidated in a new category

Multiple, and entries referring to *Billing*, *Customer service*, *PV*, *Social events* and *Miscellaneous* were grouped under *Other* in both the pilot users' and raters' coding. Results of a chi-square test show a significant association between coder and concerned element ($\chi^2(6) = 13.98$, $p = .028$, $V = .31$). Thus, the pilot users assigned their experiences to different elements than the raters. Table 1 shows the most frequently mentioned experiences for each element coded by pilot users and raters and their ratings into *positive*, *negative* or *challenging* experiences.

Table 1. Most frequently mentioned experiences, concerned element and ratings.

concerned element coded by raters	Description of experience	Number & ratings of experiences per concerned element							total*
		Charging process*	Commu-nication*	EV*	Wallbox*	App*	Multiple*	Others*	
Charging process	User feedback of the functioning of BDC use case	**4(3/-/1)**	-/-	-/-	1(-/-/1)	2(-/1/1)	3(2/-/1)	1(-/-/1)	11(5/1/5)
	Perceived problems related to Departure Time and SoC	**4(-/3/1)**	-/-	1(-/1/-)	2(-/2/-)	-/-	2(-/1/1)	-/-	9(-/7/2)
Commu-nication	No connection to the system	2(-/2/-)	**2(-/2/-)**	-/-	5(-/4/1)	-/-	-/-	-/-	9(-/8/1)
	Plug cannot be unlocked	-/-	**1(-/1/-)**	1(-/-/1)	-/-	-/-	-/-	1(-/1/-)	3(-/2/1)
EV	General statements	-/-	-/-	**2(2/-/-)**	-/-	-/-	-/-	-/-	2(2/-/-)
	Limited range	-/-	-/-	**2(-/1/1)**	-/-	-/-	-/-	-/-	2(-/1/1)
Wallbox	Ventilator (noise level and power consumption)	-/-	-/-	-/-	**2(-/2/-)**	-/-	1(-/1/-)	-/-	3(-/3/-)
	Incorrect message on the display	-/-	-/-	1(-/-/1)	**3(-/3/-)**	-/-	-/-	-/-	4(-/3/1)
App	Usability	-/-	-/-	-/-	3(-/2/1)	**2(-/-/2)**	2(2/-/-)	-/-	7(2/2/3)
	Unsatisfactory or incorrect functions/ information	-/-	-/-	-/-	-/-	**4(-/4/-)**	-/-	-/-	4(-/4/-)
Others		3(2/-/1)	1(-/1/-)	5(2/3/-)	1(-/1/-)	-/-	-/-	**8(4/3/1)**	18(8/8/2)
total		13(5/5/3)	4(-/4/-)	12(4/5/3)	17(-/14/3)	8(-/5/3)	8(4/2/2)	10(4/4/2)	72(17/39/16)

Note: * = overall(positive/negative/challenging); Entries assigned to the same element by the raters and by the pilot users are in bold.

About 75% of all entries described a challenge or a negative event, with some pilot users reporting exclusively negative experiences. The results of a chi-square test show, that the differences in the distribution of the experience ratings in *positive*, *negative* and *challenging* are statistically significant ($\chi^2(2) = 14.08$, $p < .001$). According to the pilot users' assignment, most of the negative experiences arose from the *Wallbox* (35%), while the raters assigned more than half of them to other elements. Reported positive experiences related to the *Charging process* (29.4%) with participants describing how their BDC system or use case works, to the *EV* (23.5%), to *Multiple* (23.5%) or other elements (23.5%). As expected, experiences rated as *negative* or *positive* were associated with negative or positive emotions respectively. In contrast, *challenges* were not experienced negatively and the emotions were described as *neutral*. The number of reported challenges closely corresponds to the number of positive experiences. While the users related *challenges* equally to the system elements *Wallbox*, *App*, *EV* and *Charging process*, the raters assigned most challenges to the *Charging process*.

To investigate whether the quantity of entries changed over time, the distribution of entries was analyzed. Fig. 1 (b) shows the distribution of entries with the most entries in August 2021 (13.9%). No entries were recorded in November 2021, from February 2022 to April 2022 and in June 2022. Chi-square test shows significant different distributions of entries per month ($\chi^2(9) = 43.35$, $p < .001$).

5. Discussion

5.1. Summary and Implications

With regard to the experiences' that users face, when interacting with BDC in a real-world context, negative experiences and challenges are more frequently reported by the participants than positive ones. On the one hand, this outcome can be attributed to the "negativity bias"; on the other hand, it indicates that the smooth functioning of the system is an essential prerequisite for the applicability of BDC. However, some of the problems described, may be due to the pilot users' mental representation of the BDC system being incorrect or incomplete. This conclusion is supported by the fact that the pilot users attributed their experiences to other BDC elements than the raters. Since they attribute most negative experiences - such as system failures - to the wallbox, the pilots can be assumed to have understood the wallbox as the intelligent or coordinating element of the BDC system. The results indicate that not only does experience impact understanding, but also understanding influences the perception of experience. To avoid misinterpretation and thus problems and negative emotions, it is important to give future users a correct understanding of the system. The users also mentioned experiences associated with positive emotions. Here, the correct functioning of the BDC system was a central issue. Therefore, it is essential to provide users with transparent feedback on the BDC system with the corresponding states and processes. In summary, functional problems of the system, inappropriate user understanding, and insufficient system feedback can create barriers to the applicability of BDC.

Regarding the usage of diaries in long-term studies, diaries are only conditionally suitable as a data collection tool for a longer period, as participants seemed to be less motivated to make entries. The number of entries was rather low and varied greatly between the individual users; some did not record any entries at all. Furthermore, the number of entries varied over time. This may be due to the fluctuating occurrence of triggering events, as no experiences were reported, especially in months when all participants encountered a use case but no major changes were introduced. Therefore, a combination of event-based and signal- or interval-based approaches is recommended. Participants could be asked to report about their experiences at defined points in time by recording a voice message or making a phone call in addition to a voluntary open event-based diary. On the other hand, open diaries should not be completely discarded, as they offer the possibility to spontaneously report on special events when they occur, as shown by some pilot users.

5.2. Limitations

As the study followed a qualitative approach, the focus was on describing the different experiences on an event-based level. Limitations arose mainly due to the small sample and the small number of diary entries. Since not all participants reported an equal number of experiences, subjective biases can have a significant impact. This refers to the experiences themselves, their interpretation and their resulting evaluation. More data is therefore needed to generalize the results. Future research should also analyze people's understanding of complex systems such as BDC in addition to their experiences.

6. Conclusion

Through the implementation of experience diaries, barriers in the use of BDC could be identified. These mainly concern technical problems or arise from users' inappropriate mental model about the charging system. To increase the suitability of BDC, the reduction of barriers seems to be more promising than the implementation of incentives to use the technology. However, the diary method has limitations and should be adapted. In order to achieve a high usage and acceptance of the diaries, the effort should be reduced and the users should be explicitly asked to make an entry for specific times.

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