ANALYSIS OF THE INTRADAY USE CASE IN THE FIELD TRIAL OF THE BIDIRECTIONAL CHARGING MANAGEMENT PROJECT

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Abstract

This paper presents an overview of the findings of the intraday use case in the Bidirectional Charging Management project's pilot study. The intraday use case aims to trade energy for the financial profit of the customers. Each day the flexibility of the EV fleet is forecasted for the next day accordingly a load forecast is predetermined, and the forecasted flexibility is used to make trades on the continuous intraday market. The customer behaviour is a key aspect for the success of the intraday use case, as it determines the provided flexibility. Another factor is the performance of the system itself. The optimizations of scheduling improved the execution of trades from 58% for charging and 36% for discharging in April to 79% for charging and 61% for discharging in July. The round-trip efficiency of the intraday use case was determined at 80% which is competitive with storage methods such as pumped storage power plants. To increase the revenues of the use case further optimizations are still possible since for example the trades are limited to the night and thus only hourly spreads in the night time were taken advantage of.

1 Introduction

The European Union (EU) set itself the ambitious target to become climate neutral by 2050 as part of its commitment to the Paris Agreement, keeping global warming below 2 °C. [1]. In 2019, the emissions of the European electricity sector were 39 % lower compared to 1990 levels [2]. However, the EU will only achieve climate neutrality by subjecting all energy consumption sectors of industry, buildings (heating and cooling), and transport to extensive electrification based on renewable energy. As opposed to the other sectors, the greenhouse gas (GHG) emissions in the transport sector increased between 2013 and 2019 [3]. Therefore, GHG reduction measurements in the transport sector are urgently needed. Electric vehicles (EVs) are one of the most promising means to reduce emissions in this sector, provided that the used electricity is exclusively generated climate neutral [4]. Recent reports from the international agencies on energy (IEA) and renewable (IRENA) underline the relevance of smart charging strategies to achieve an efficient and cost-effective integration of EVs into the energy system and the electricity grids [5] [6]. Smart charging describes the case where EVs charge when e.g., surplus energy or a low electricity price is available, instead of charging with maximum power once they are plugged in. Unidirectional smart charging is also referred to V1G. Next to V1G, vehicle-to-grid (V2G) technology allows bidirectional charging of EVs, meaning to charge and discharge the battery, thus providing more flexibility and enabling new use cases, such as EVs participating in the spot market [7]. The project Bidirectional Charging Management (BCM), which launched in May 2019, aims to develop and test a holistic, user-oriented offer for the integration of bidirectional EVs into the energy system. In BCM, different use cases are demonstrated in a field trial with 20 bidirectional BMW i3s at private and over 30 bidirectional i3s at fleet customer sites. A description of the use cases can be found in [8] and [9]. This work focuses on the so-called intraday use case tested at private customer sites.

2. System Description

The following sections describe the intraday market in Germany and the intraday use case implemented in BCM.

2.1. German Intraday Electricity Market

In most countries in the EU, electricity can not only be traded on future and day-ahead markets but also until shortly before the period of delivery on intraday electricity markets. At the German intraday market at the European Power Exchange (EPEX SPOT) 15-min, 30-min, as well as 1-hour contracts can be traded [4]. In Germany, contracts can be traded up to 5 min before delivery, while the smallest amount of one contract is 0.1 MWh as on the day-ahead market [10]. The intraday auction is possible until 15:00h of the previous day. The continuous intraday trading of 1-hour contracts starts directly afterwards, while 15-min contracts can be traded at 16:00h for the subsequent day. In contrary to the day-ahead and intraday auction where price formation is set by merit-order, the continuous intraday prices are set by pay-as-bid auction. Consequently, the continuous intraday price formation is no uniform pricing, meaning that depend on the trading moment different prices for the same product occur. Buy or sell orders are placed for a specific amount of electricity, specific delivery interval, and specific maximum and minimum prices. As soon as two entered orders (partially) match each other, the corresponding transaction is immediately processed, therefore continuous. [4] Intraday trading serves primarily to keep discrepancies between feed-in and offtake regarding the balancing group at a minimum and, therefore, avoid expensive balancing power costs. Further, the intraday market plays a pivotal role in integrating renewable energy [11]. Forecasting renewable production improved considerable over the last years. However, since intermittent renewable production is still subject to forecast errors, the possibility to trade close to delivery makes the intraday market most relevant for renewables [11]. The possibility to trade close to delivery is also beneficial when it comes to procuring energy for EVs. While in 2010 the traded volumes on the intraday market of EPEX SPOT amounted to 24 TWh, five years later, in 2015, the volume more than doubled to 59 TWh, and in 2021 it doubled again to 123 TWh with more than 60 TWh alone in Germany [12]. [13] provides the maximum hourly and daily price spreads and hourly and daily standard deviations of electricity prices of the day-ahead and intraday auction as well as of the continuous intraday market from 2018 to 2021. In particular, the 2-2.5 times higher standard deviation of daily day-ahead and intraday prices in 2021 compared to 2020 shows the significantly increased revenue potential of intraday flexibilities [13]. In 2021, daily and hourly maximum price spreads, averaged over the year, of 143,5 and 33,8 respectively in €/MWh were observed for the continuous intraday market for the 15-min contract [13]. With the current market situation, it seems likely that electricity price volatility continues to increase in 2022, thus further increasing the revenue potential of use cases driven by temporal arbitrage.

2.2. Intraday Arbitrage Use Case in BCM

Bidirectional charging makes it possible to feed electricity back into the grid to generate revenues on the electricity markets through temporal arbitrage. Therefore, the charging and discharging flexibility is aggregated by an aggregator and the charging and discharging processes are optimized based on projected intraday prices. The goal of the use case is to charge the EV or the EV pool at times with low electricity prices and discharged at times with high electricity prices. Due to the different prices, energy can be procured cheaply and sold more expensively. The difference in prices generates revenue. There are several prerequisites for the implementation of the intraday case. In BCM, 20 private customers received a bidirectional BMW i3 and a combined charging system (CCS) based bidirectional DC electric vehicle supply equipment from Kostal with a charging power of 11 kW, discharging power of 10 kW and a battery capacity of 42 kWh. Every private customer participating in the intraday use case needs a recording power measurement, which enables a power measurement per 15 min. Therefore, in BCM smart meters are used. The system architecture and measurement concept are described by in [9]. Further private customers need a new electricity contract, which allows direct marketing of electricity. In BCM, NEXT Kraftwerke fulfills the role of the electricity supplier and aggregator.

The private customers have an app where they can enable the bidirectional charging functionality or set the EV into instant charging mode (IC). If the EV is in IC it charges with maximum power to 100% State of Charge (SoC), otherwise the EV follows an optimized charging or discharging profile. Depending on the use case, the EV either follows a signal from the electric vehicle supply equipment to achieve local load balancing (e.g., to increase self-consumption of self-generated electricity) or a set charging profile (e.g., for intraday use case). Additionally, the customer can set departure time and target SoC via app and monitor charging processes, current SoC, and charged and discharged energy over time. The target SoC is crucial for the use case since it limits the provided flexibility. If the target SoC e.g. is set to 60%, the system, when in bidirectional charging mode, won't discharge below this threshold to guarantee customer satisfaction. Further, if the SoC is below 40% (SoC_{Min}) when the EV is plugged in, the EV will charge to this threshold with maximum power. Based on historic charging data and user input data, a forecast for each customer is made and a preliminary day-ahead baseline and flexibility schedule for the whole pool with 96x15 min slots is send to the aggregator. Subsequently, based on this schedule, the aggregator performs trades within the flexibility ranges and sends an adapted schedule back. The adapted schedule is then disaggregated by BMW in form of charging and discharging profiles for each individual EV.

After a development phase, the field trial started in July 2021 and will last until October 2022. The intraday use case was launched in November 2021, with several customers switching from the increase of self-consumption (PV) to the intraday use case. As of 6th of December 2021, 10 private customers took part in the intraday use case and 14 from 1st of February 2022 onwards.

3 Results

The potential revenues for the intraday use case are not only limited by price spreads, but also several technical factors [14]. In addition to the pool size, i.e. the number of EVs as well as their total capacity, the availability and the target SoC are decisive for the actual flexibility available. The following section describes customer behaviour that influences the intraday use case.

3.1 Customer Behaviour

During the first weeks of the field trial, the availability was low compared to the time when the users had an active use case available. One possible explanation for this trend could be either that the customers are more motivated to plug-in their EV when a use case is active or that they needed some familiarization time with their new EV. Further, customers were reminded via newsletter and during informative events of the importance to plug-in their EV and set a target SoC as low as possible without restricting their level of comfort. As mentioned before, the total number of EVs in the pool varies over time with a maximum of 14 EVs in the beginning of February 2022. Fig. 1 displays the number of connected EVs over time in blue. In grey the total number of EVs participating in the intraday use case is depicted and in red the monthly moving average.

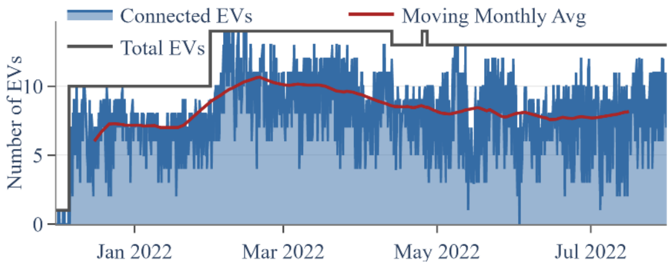

Fig. 1 Connection and availability of intraday use case customer over time

At first, an average amount of six to seven connected EVs can be observed. With increasing amount of total EVs the moving average also increases first with around ten connected EVs, then slowly decreases again. The plot shows that almost at no time all EVs are connected. On 1st of April 2022, a new gamification feature was launched for the app to further incentivize the customers to connect their cars and set a low target SoC. Looking at Fig. 1, no improvement of the availability after this date can be observed. The same is true for the average daily connected time of an EV, which was 16.5h before the feature launched and 14.7h afterwards. Factors such as the termination of the homeworking measures on 20th of March 2022 were likely predominating and lead to an increasing volume of mobility in Germany in the months from April onwards [15] [16]. To further investigate the distribution during the day, Fig. 2 shows the share of average connected EVs over 24 hours. In red the mean share for weekends and in blue the one for working days is displayed. For each customer, the considered period starts when the intraday use case was enabled until 31.07.2022.

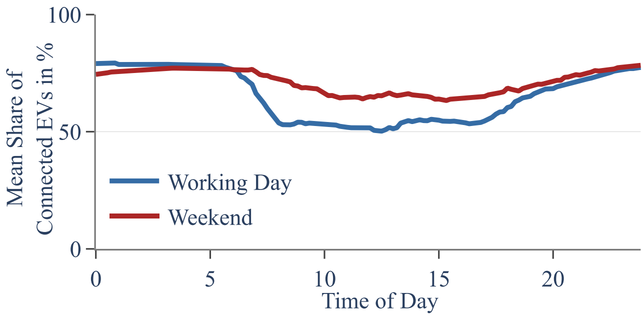

Fig. 2 Mean share of connected EVs in % over the day for working day and weekend

For working days, the mean share of EVs is around 50% during the daytime. During the night, the mean share of working and weekend days is similar with around 75%. Before the 1st of April 2022, the mean share of connected EVs was 69.6% on weekdays and 78.2% on weekends. After this date, the share decreased to 60.8% on weekdays and 64.8% on weekends. The decline at weekends may be explained by the fact that with the start of spring the weather in Germany improves from April onwards and therefore, people likely take more trips on the weekend. Fig. 3 shows the relative frequency of the plug-in time for the intraday customers. Again, for each customer, the considered period starts when the intraday use case was enabled till 31st of July 2022. In red the weekend days are displayed and in blue the working days.

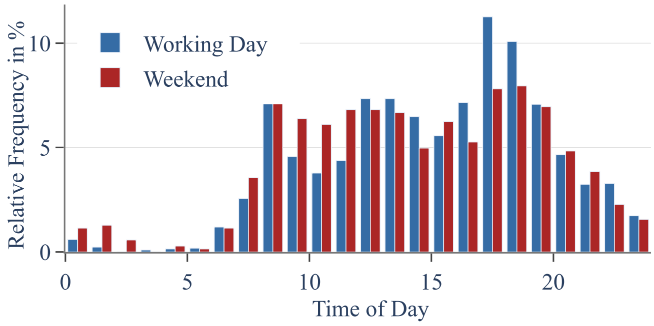

Fig. 3 Relative frequency in % of plug-in time for working day and weekend

On working days, a peak around 16:00h and 18:00h can be observed. During this time, more than one quarter of plug-in events are registered. On the weekend, the plug-in events are more evenly distributed. When the user plugs in the EV, the SoC averages 58.9%.
Even if the availability of vehicles is greater at night, this does not necessarily mean that more flexibility is available. Besides the availability, the other crucial factor limiting the flexibility is the target SoC, which is set by the customer per app. The target SoC must then be reached for the given departure time. Fig. 4 pictures the relative frequency of the target SoC in % for different time periods of the field trial for all intraday customers. In red, the first phase of the field trial is shown. The period displayed in blue starts with the beginning of the intraday use case. The introduction of the incentive gamification feature marks the beginning of the yellow period.

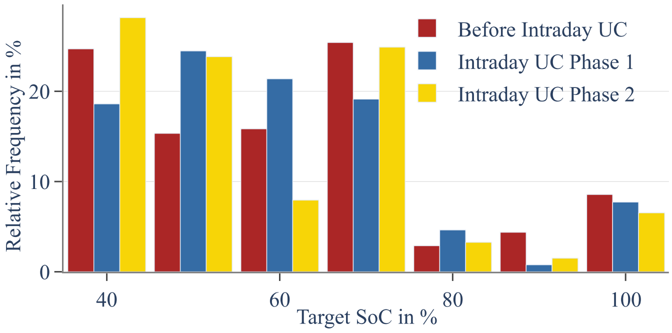

Fig. 4 Relative frequency in % of target SoCs in % for different field trial periods

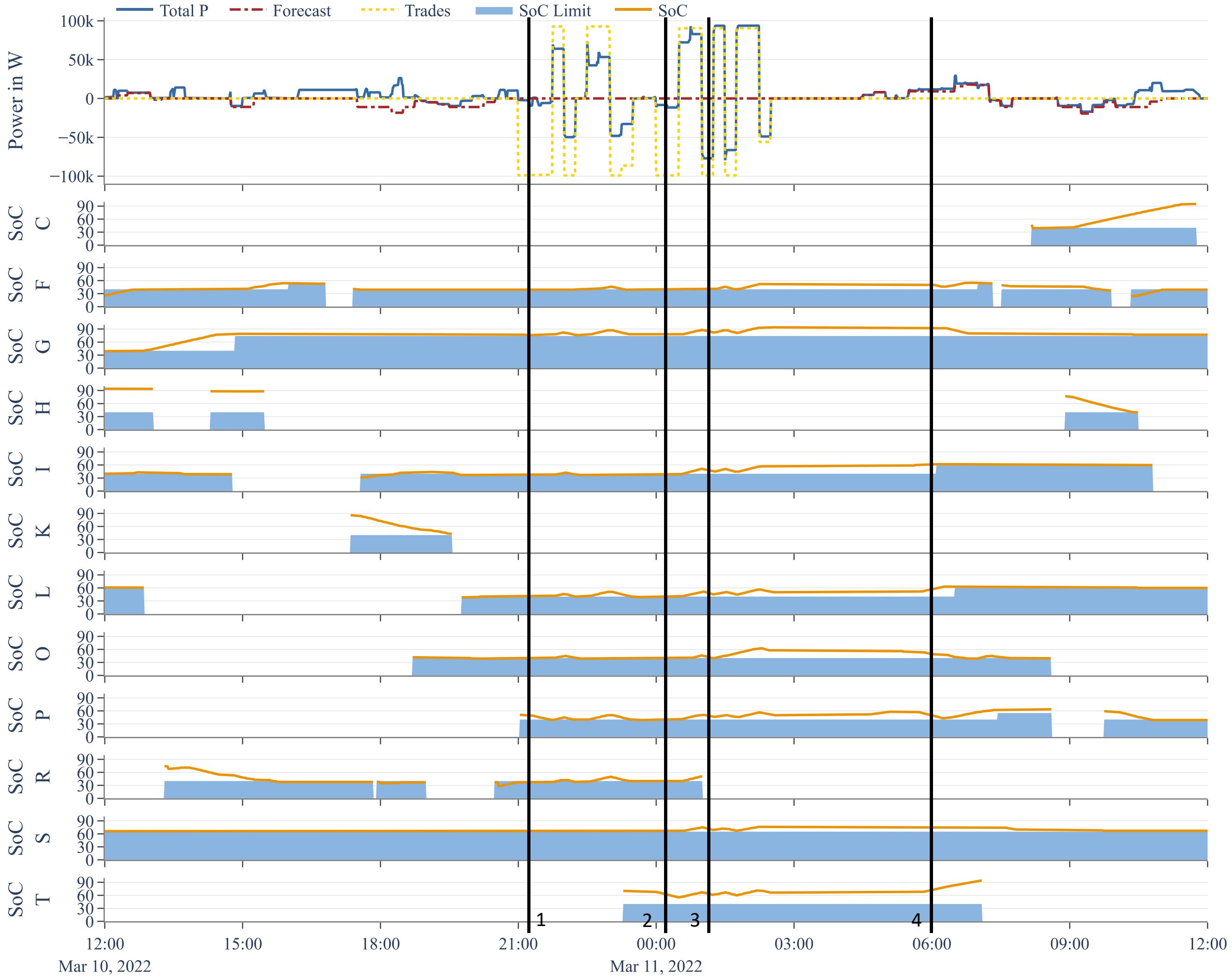

Fig. 5 Overview of the intraday fleet; On top, the power of the entire fleet is shown (Total P, dark blue) and how well this power matches the scheduled forecast (red) and trades (yellow). In each of the following rows the SoC of an EV belonging to the intraday pool is shown while the EV is plugged in (orange). Additionally, the limit SoC (light blue) is shown below which the EVs SoC is not allowed to fall below. This is the minimum SoC (40%) if a target SoC was set by a customer the SoC limit jumps to the target SoC at the set departure time. Customer B and J are not shown as their EV is not plugged-in during this period.

The default target SoC value is 70% when opening the app. During the first period of the field trial the default value is the most frequent option. The 90 and 100 % target SoCs are selected in more than 10 % of the beginning period. During the second phase, the default value of 70 % decreases by more than 5 %, which may be explained by potentially increased use of the app by the users. During the third phase, a shift towards the lower target SoCs can be observed. The lowest possible target SoC of 40 % is the most frequent option. Further, the 90 and 100 % target SoC decreased. Even though it cannot be said with certainty that only the incentivization further reduced the target SoC, a significantly lower target SoC can be observed in the second and third periods compared to the beginning phase. However, confidence in correctly estimating the range of the vehicle probably prevails. Further, the new feature should incentivize customer to plug-in their EV.

3.2 System Behaviour

The following sections discuss the behaviour of the system regarding the scheduled forecast and trades and the reaction of the intraday pool.

The schedule is separated into two parts, the forecasted schedule and the adapted schedule including the trades that should be executed as can be seen in Fig. 5. Here the power is positive for consumption and negative for feed-in. In orange, the SoC of the EVs is displayed. Further, Fig. 5 shows the SoC limit or target SoC in light blue, which on the one hand sets the discharging threshold. On the other hand, it shows the departure time to which the target SoC needs so be reached. Further four moments are highlighted with black lines. During the exemplary period between the 10th and 11th of March, no additional trades were scheduled during the day, thus the intraday pool tries to follow the forecast schedule. This behavior is due to NEXT marketing the pool only from

20:00h to 06:00h in BCM. Looking at moment number four no additional trades were made by NEXT and the pool needs to follow the forecast. To reach this goal, customers F, P and O discharge on the 11th at 06:00h even though the pool has a positive power forecast to balance the customers who are charging. After 21:00h at moment number 1, trades are scheduled, and the first trade is negative. However, the fleet cannot follow this trade and only customer P is able to discharge. All other plugged in EVs are just above their target SoC, therefore they are not allowed to discharge. Similarly, after 00:00h, the negative trade can only be executed by customer T as the other EVs are not able to discharge due to their high SoC limit.

At the third moment, the pool just executed a positive trade, therefore the negative trades can be followed by more EVs since their SoC is now above the SoC limit. The SoC limits the flexibility due to previous choices of the target SoC and the set departure time by the customer. E.g., the customer G did not drive off at scheduled departure time. Thus, the limiting target SoC remains over the whole period resulting in a diminished flexibility of the pool. Hence, the flexibility of the fleet was diminished by

a) high values for the target SoC remaining there despite the departure time having long passed
b) a too small share of plugged-in EVs.

The flexibility prediction is dependent on historical data and reliable user input. By collecting additional data as the field trial progresses, the forecast will get better. Further, the user input reliability issues were also addressed during the field trial by the introduction of incentives to choose a low target SoC and to plug in the EV more frequently. Additionally, a holiday mode to signal that the EV will not be moved in a selected period was introduced. Finally, multiple departure times and target SoCs will be launched as a feature during the final phase of the field trial. Hence, the battery storage of the EV can be used even more freely. The execution of the trades still leaves room for improvement as the scheduled trades rely on the flexibility predictions. Therefore, the actual flexibility of the intraday pool, especially to discharge, was often overshot by the scheduled trades.

Fig 6 shows the mean charging and discharging power of a single EV and the deviation from the mean intraday price in percent from the 1st of December to the 31st of July.

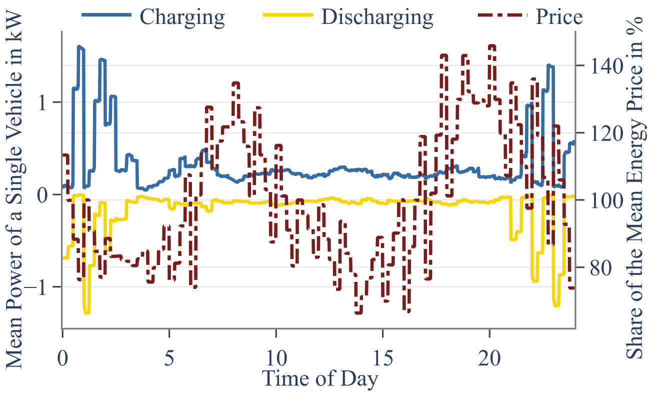

Fig. 6 Mean of the discharging power and charging power of the pool and on the secondary y-axis the mean deviation at this time from the mean intraday price

As it was shown before, the share of vehicles is the highest at night (see Fig 2). Therefore, the limitation that NEXT only trades from 20:00h to 06:00h falls into the time where most of the flexibility is available. Further, looking at the price fluctuation the mean price follows two high low patterns over the whole day. High prices occur in the morning and evening due to high demand. Low prices can be observed in the night and noon due to low demand and additional high PV generation during noon. The hourly intraday price fluctuations can be explained by 1-hour trades in the day-ahead market. Since these day-ahead trades are based on hourly averages, e.g., the first 15 minutes of an hour in the morning are usually more expensive than the following due to increasing PV generation, and vice versa in the afternoon. These hourly fluctuations of the prices are taken advantage of as the discharging power is large in times of high prices and the charging power is large in times of low prices. The discharging power of the fleet increases after multiple charging periods again showcasing the low SoCs of the EVs at the beginning of the trade period resulting in smaller flexibility of the fleet. Outside of the trading period, the mean charging power only shows one additional peak around 6:00h. Multiple EVs often charge to their target SoC at this time as their departure time is shortly after. Simultaneously, the peak of the discharging power implies that EVs discharge so that the EV pool follows the forecasted schedule.

There is still revenue potential left open as the largest price difference between the afternoon and the early evening is not utilized. This could be taken advantage of if multiple EVs are able to discharge during this time. In the field trial, this could have been achieved by scheduling charging trades in the afternoon. However, the focus of the field trial was on the period with the largest flexibility at night. For larger fleets with diverse customers the prediction of the flexibility becomes easier as a single vehicle plugged in or out makes a smaller difference. Hence, these larger fleets can more reliably plan and take advantage of these regular price fluctuations during each day. The correct prediction of the forecast and the control of the pool is highly complex and needs experience and time to optimize.

Fig. 7 shows the development of the share of lost energy, the discharged energy, the energy used for driving and the total energy in black.

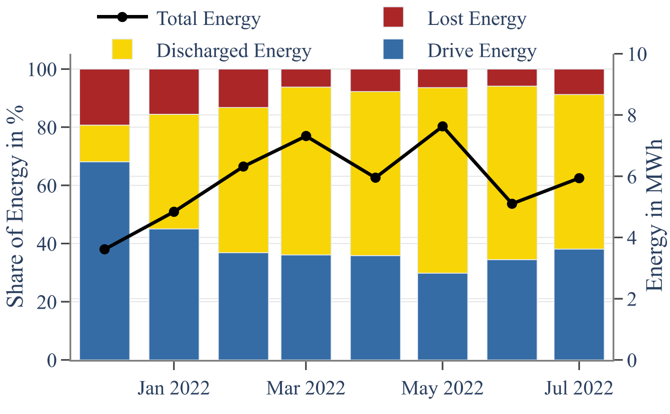

Fig. 7 Development of the total energy on the secondary y-axis and on the primary y-axis the share of the drive energy, discharged energy and lost energy

The intraday trades lead to increased energy flows in and out of the EV battery. Therefore, the charged energy was separated into three parts: the energy possibly used for driving, the energy that was discharged and the energy lost by the round-trip efficiency (see Fig. 7).

The energy used for driving is indirectly calculated since the driving distance is not measured in the field trial. Hence, the drive energy was measured by comparing the plug-in SoC of the EV with the plug out and calculating the net positive charged into the EV's battery. A potential surplus of discharged energy is forgotten at the plug-out of the EV and will not be considered at the next plug-in. To be precise the so-called energy request is used for the calculation. The energy request is measured in Wh, is more accurate than the SoC, and is highest when the battery is empty, therefore behaving inverse to the SoC. Further, the one-way efficiency is included to estimate the drive energy charged. Therefore, the lost energy is only the lost energy which arose due to the intraday UC. Accordingly, the round-trip efficiency cannot be read by from the share of the lost energy of the total energy.

In December, most of the customers are added to the intraday use case. However, only a few trades are scheduled in December resulting in a low amount of discharged energy. Here the amount of lost energy caused by the trades was higher than the amount discharged. Thereafter, the lost energy share decreases while the share of discharged energy increased significantly. This is due the improved charge management of the fleet. In December and January, the pool could rapidly switch from charging to discharging and even short deviations from the scheduled forecast were equalized by charging or discharging. Furthermore, once the EVs were fully charged some energy may be drained while they are plugged in. This energy was then repeatedly recharged leading to continuous charging spikes and thus more lost energy. These adjustment to the pool control were successful, therefore the share of lost energy decreased. Another important metric for the intraday pool is the round-trip efficiency, which for simplicity will be called efficiency. The efficiency η can be calculated by

$$\eta = \frac{E_D}{E_C} \tag{1}$$

with E_C being the charged energy for the EV to reach a certain SoC and E_D the discharged energy to return to the initial state. In the intraday UC, a mean efficiency of η = 80% was observed for the EVs. For a detailed description how the efficiency is calculated see [17]. The improved efficiency during the field trial by the implementation of the control updates led to a smaller amount of lost energy compared to the discharged energy. The efficiency of the intraday UC in the BCM field trial is significantly higher than for the PV UC which is 54%. Furthermore, the efficiency is competitive with conventional storage methods such as pumped storage power plants, which have a reported efficiency between 70% and 90% [18] [19].

The additional usage of the intraday UC leads to an increased energy turnover of the EVs. On average 15 kWh per EV and day were charged and 9 kWh per EV and day discharged. The execution of the trades led to an additional operating time of 1006 hours per EV and year. Furthermore, the intraday use case caused 79 additional full battery cycles per year and EV. The additional operating time and full load circles for the months of February to July were extrapolated to calculate the values of the year. Comparing these values to the warranted lifetime values of lithium-ion batteries (5.000 full cycles of residential storage units [20] and 10.000 operating hours in automotive applications [21]) the additional energy resulting from the intraday UC leads to more utilization for the EVs battery but is not the main limiting factor for the lifetime of the EV. Simulations optimizing the full potential of an intraday fleet with similar system configuration led to 450 to 570 full cycles per year [14]. However, one major difference is that Kern et al. [14] assume a significant higher EV availability. Hence, the BCM field trial successfully executed the intraday UC, but further optimization is possible.

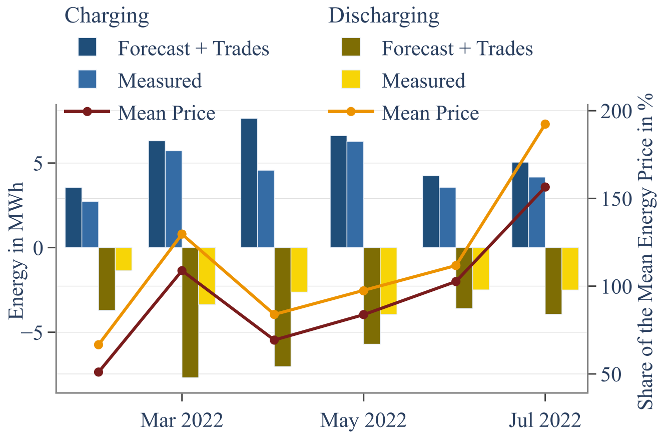

Fig. 8 Amount of energy scheduled by the trades and forecast and the measured energy for the fleet, while a load is scheduled, separated into charging and discharging on the primary y-axis with the mean price for the scheduled loads on the secondary y-axis

Fig. 8 shows the amount of scheduled and measured trades differenced by charging and discharging per month. Further, the mean price of each charging and discharging trade is displayed. The wider the gap between these two lines the higher the revenues. Comparing the scheduled and measured trades higher deviations occur in the first months. Further, at first the discharging discrepancy are considerable higher than the charging mismatches. Additionally, in March, more energy was scheduled to be discharged than charged which is a system error. As the fleet cannot discharge more energy than it has charged the scheduling changed afterwards. Despite less scheduled trades in May than in March more energy was discharged by the fleet due to optimized control strategy. Furthermore, both the scheduled charging and discharging energy decreased but the measured energy aligned closer to the schedule. In April, only 58% of the scheduled charged and 36% of the scheduled discharged energy was fulfilled. Comparing this to July the shares rose to 79% for charging and 61% for discharging. As the field trial continues these trends are promising for the following months. The price spreads also rose from only 13% difference in share of the mean price in June to 38% in July. This implicates a larger potential for the revenues. This trend continued in August and September. With the schedule optimization and higher spreads in the months of August and September are the revenue prospects of the field trial are promising.

4 Conclusion

In line with previous studies, the present findings confirm that customer behavior is a key aspect for the success of the intraday use case [22] [14]. This conclusion follows from the fact that without enough provided flexibility trades cannot be successfully realized, resulting in less revenues. Therefore, it is recommended to encourage customers to plug in their EVs frequently and for a long time. Furthermore, customers should be informed that a low target SoC results in more flexibility and thus increases profits. Customer behavior that has a positive impact on the use case can be influenced by gamification approaches, for example. The University of Passau conducts extensive research on this in BCM.

Importantly, our results demonstrate that the pool scheduling has a major influence on the system efficiency. Our data shows that it is not feasible to trade every spread. By adapting the control, lost energy can be kept to a minimum. Additionally, compared to other bidirectional charging use cases (e.g. increase of self-consumption), the intraday use case has the advantage that it discharges and charges at high power, resulting in a high round trip efficiency. With a round trip efficiency of 80%, the performance of the system is similar to that of a pumped storage power plant [19]. Another advantage that reliable user behavior entails is that the pool's energy prediction becomes more accurate. Especially with large pool sizes, variations statistically equalize. The algorithm also benefits from more historical data on which it can base its prediction. However, the individual prediction is significantly improved by the customer data, given that they are reliable.

One limitation of this study is that at this point we cannot provide realized revenues in the intraday use case. With the current market situation and occurring spreads, the last months seem promising regarding the revenues. One limiting factor will be that trades are only made during the night. However, the greatest influence on the economic viability of the intraday use case is the levies and charges on consumed electricity. If there is no strong exemption here, the use case is not economically feasible [22]. Another point not to be neglected is that bidirectional EVs trading in the electricity market have a smoothing effect on electricity prices. Therefore, the revenue potentials decrease the more EVs participate in the market. The calculation and analysis of the revenues of the intraday use case will be part of the final project phase.

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