The Use of electric Vehicles for optimal Energy Procurement and Grid Support in local Energy Communities

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***Abstract*—In the course of the ongoing transformation of the energy supply towards a renewable and decentralized system, the share of volatile renewable infeeders, as well as high power consumers like plug-in electric vehicles (PEVs) in the German distribution grid is steadily increasing. Challenges in that context are likely to manifest mainly through asset overloads in urban distribution grids. Since charging processes of PEVs rarely require the maximum charging power over the entire parking time, they offer a high level of flexibility, which may be used to counteract grid overloads via controlled charging. Therefore, comparatively expensive grid enhancement could be avoided. Additionally, the integration of renewable energy sources could be supported by exploiting the PEVs' charging flexibility (i.e. to match volatile infeed). A further increase in added value may be achieved through a suitable energy procurement strategy at the spot market for energy, which should also take into account forecast deviations.**

In this paper a procurement optimization strategy for a car park with 40 PEV charging stations and decentralized infeeders is presented. In that context an automated temporal shift of the PEV charging power is carried out several times in order to adapt the charging schedule to the relevant energy prices and occurring forecast deviations. The corresponding grid-related power limit is constantly adhered to.

Keywords—demand-side management, aggregation, optimal scheduling, plug-in electric vehicles, grid-support, energy market, smart grid, decentralized feed-in, self-sufficiency

I. INTRODUCTION

In the National Development Plan for Electric Mobility, the German government defined the target of one million electric vehicles on German roads in 2020. Correspondingly, a clear trend in favour of electric mobility has been noticeable in Germany for several years now. According to a survey carried out by the National Platform Electromobility (NPE) in 2018, the actual market development shows that if the current market dynamics continue, this goal will probably be achieved by 2022. Furthermore, the market share of plug-in electric Vehicles (PEVs) in Germany may grow more than threefold within the next six years, leading to a total number of up to three million PEVs on German streets by the year 2025 [1]. This mobility transition initiated by the German federal government is expected to have an increasing impact on the structures and energy supply tasks in today's distribution grids [2]. For the consideration of electromobility, this paper focuses on urban grids, since there (among other things due to the range limitation of PEVs) higher market penetration rates are to be expected than in rural areas [3]. PEVs offer high flexibility in many cases, as the parking time is often longer than the actual charging process, allowing them to follow load profiles in a controlled manner [4] [5].

If the flexibility of charging processes is accessible, different purposes could be pursued with the help of a charging management system. In general, possible objectives can be subdivided into market, system and local grid-related as well as ecological purposes. Thus, the deployment of charging flexibility can facilitate the grid integration of electromobility on the one hand, as well as the integration of decentralized infeeders at the distribution grid level on the other hand [2] [3] [6]. In addition, this also offers the possibility of cost-optimized energy procurement at short-term energy markets [5]. Since in many cases several charging stations for electric vehicles are installed in the immediate vicinity (e.g. in a car park [8]) and thus have a bundled influence on certain grid sections [7] aggregated consideration of such constellations is beneficial [9].

Within the scope of the research project WIKI (Virtual Power Plant Iserlohn), in which a car park with several charging stations as well as a photovoltaic (PV) system and a combined heat and power (CHP) unit (as decentralised feed-in) is to be integrated into a regional virtual power plant (VPP), research and development efforts are being made in this context.

In the context of the investigations presented here, both grid- and vehicle-dependent restrictions as well as energy costs are taken into account. In addition, the corresponding PV and CHP feed-in is considered in terms of energy costs, renewable energy utilization and the rate of self-supply.

II. Assumptions and Theoretical Fundamentals

A. Simulation of car park utilization

In order to analyze and optimize the conventional charging behaviour of PEV users, a simulation of the car park utilization, as described in [10], is carried out. The necessary data were provided by the study "Mobility in Germany" (MiD) [11] and the parking statistics of an exemplary car park. For this contribution it was also assumed that the behaviour of PEV users more or less resembles the mobility pattern of consumers using conventional vehicles with combustion engines. Output parameters of the simulation are the time-series of the car park occupancy, the arrival and departure times, as well as the state of charge (SOC) of the parking vehicles at the time of arrival. The battery capacity of all vehicles is assumed to be 40 kWh and the energy consumption per 100 km to be 20 kWh. A one-minute solution was chosen and a total period of one month is simulated. Fig. 1 shows the average occupancy of the car park over its opening hours of a day, which is computed by using data of the entire simulation period.

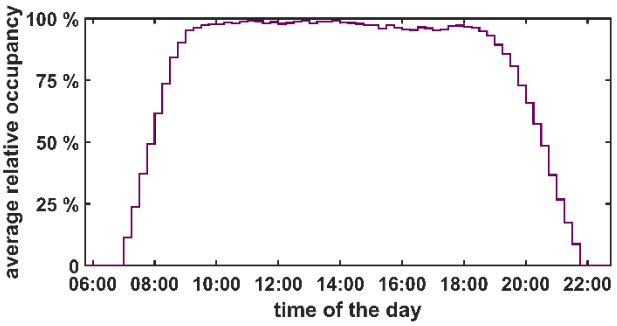

Fig. 1. Average car park occupancy

It can clearly be seen, that the occupancy starts to rise relatively fast right after the opening of the car park, then stays on a high level for several hours and starts to decline steadily around three hours before the car park is closing. Furthermore, it is to mention that the highest occupancy is around noon. The occupancy simulation showed that all charging stations are occupied in 38.45 % of the car park opening time and that on average a total number of about 196 charging processes take place each day. The parking time varies between about 0.5 and 10.25 hours with an average value of about 2.26 hours and an energy requirement on arrival between 0.2 and 38.5 kWh. The average energy demand is about 4 kWh.

B. Grid-related Assumptions

Due to mostly short cables and high load density in urban distribution grids, equipment overloads are considered to be the major type of limit violations [3]. Therefore, investigations presented here focus on transmission capacity restrictions. Reactive power and voltage limit violations are not taken into account. According to that the main grid-related restriction results from the power transmission limits of the supplying grid section.

C. Considered Energy Market Platforms

Since the energy provided for or by all technical units must be traded in advance, but the energy demand of PEVs can hardly be forecasted in the longer term, the possibility of medium to long-term portfolio optimization at the EEX derivatives market remains unconsidered. The reasons for this include insufficient empirical data and a potentially low loading simultaneity, which in turn results in a high volatility [2]. It is therefore assumed that energy trading for the car park will take place entirely on the short-term EPEX SPOT SE markets. The European Power Exchange EPEX SPOT SE provides service to most of the central european countries. In the scope of this work three different markets at the EPEX SPOT SE are considered: the day-ahead auction, the intraday auction and the continuous intraday market. Generally, all three short-term energy markets mentioned above offer the opportunity for operators of flexible technical units to optimize their energy costs by shifting the energy in time [12], which accordingly applies for the charging processes of PEVs [5].

The day-ahead auction takes place daily at 12:00 noon and sets a market clearing price for energy for each hour of the following day. The existing option of buying block products consisting of several hours is not considered. Contrary to what its name suggests, the intraday auction is held one day before the physical delivery of the traded energy following the day-ahead auction. At 15:00 a market clearance price is determined for each of the 96 quarter hours of the following day. The order details correspond to those of the day-ahead auction. The intraday auction is usually approached by traders who require a resolution higher than one hour, for example to match power ramps of solar or conventional power plants [12]. The intraday continuous market offers the opportunity to trade energy for the current day in units of 1-hour, 30-minute and 15-minute time blocks. From 15:00 the previous day for hours (15:30 for 30-minute products and 16:00 for 15-minute) energy can be traded up to 30 minutes before physical delivery (up to 5 minutes before delivery within the same control area). The moment when a certain time slice stops being tradable is generally called “gate closure”. For further examination only 15-minute products which can be traded up to 30 minutes before physical delivery are relevant. All input data with a time reference used in the computations for the present paper are supposed to be available with an hourly resolution for the day-ahead market and also with a quarter-hourly resolution for intraday auction and intraday continuous optimizations. The car park utilization data generated by the simulation mentioned before was therefore converted from a one-minute-resolution to hourly and quarter-hourly resolution.

In this way, the intraday continuous market for example allows participants to counteract forecast deviations, resulting in more accurate energy coverage within their balancing group [12]. Unlike the other two described platforms, there is no market clearing price on the intraday continuous market as each order that is placed and every transaction that is executed has a different price (so-called pay-as-bid principle). All bid- and ask-orders are listed in a so-called order book and can be matched, which means that an actual transaction takes place and the order is either reduced (if partially matched) or entirely deleted from the order book [13] [14]. Since several offers with different prices and different volumes for the same delivery interval can occur in each trading interval, it is common to use different price indicators (like best-bid/ask prices or volume-weighted average prices) when analyzing such volatile markets [5]. In this contribution best prices are used. While the energy prices of the day-ahead and intraday auction are publicly available, the price data for the intraday continuous market were obtained from a local energy supplier.

D. Chosen Procurement Strategy

By exploiting the flexibility of charging processes and applying a suitable procurement strategy, all short-term market platforms are to be optimally combined in this paper. In addition, the energy fed in by the decentralized units is taken into account at a price of 0€ per MWh, since it is assumed that the feed in is independent from the needs of the parked electric vehicles and is therefore not associated with any additional financial expense. By this means, the secondary objective is to maximize the degree of self-sufficiency. It should be mentioned that the feed-in of the PV and the CHP plants is reduced by the inflexible consumption of the building, which is assumed to be satisfied preferably. The main advantage of the day-ahead auction lies in the liquidity through a single auction per day with a unique market clearing price. In connection with this, the spreads between low and high energy prices on the day-ahead market are significantly lower than on the intraday continuous market. Due to the continuity of trading, the trading volume is spread over all hours of the trading period and is not concentrated on a single auction, as is the case of the day-ahead market. It can be said that the vast majority of trades, when looking at a single delivery period, are concentrated on only a few hours before physical delivery. Based on the trading method developed at the University of Wuppertal called “Intraday Redispatch”, all marketplaces described above as well as the feed-in of the PV system and the CHP are combined optimally [15]. The entire amount of energy that is required should already be covered at the day-ahead market and at the intraday auction. As mentioned before, the energy provided by the two decentralized plants will be modelled from the operators or aggregator’s point of view as a costless alternative, but with a limited trading volume. In these two steps the flexibility of the charging processes of electric vehicles is already used to possibly shift the charging profile in the times of available decentralized energy or in times of low energy prices at the two markets. Accordingly, it is expected that only the energy amount that cannot be provided by the decentralized units will be procured at the energy auctions. Besides that, it is noticeable that already at this point the overall energy costs can be reduced by using the charging flexibility in comparison to the energy procurement of uncontrolled charging.

After the obtaining of the total required energy amount at the auction platforms and thereby reducing the risk through ensuring a market compliant energy price for the corresponding time intervals, the prices at the continuous intraday market are monitored periodically every quarter hour. According to the Intraday Redispatch trading strategy introduced in [15], further energy shifts and additional restructuring of the charging processes are only carried out if they are accompanied by additional savings in energy cost. In contrast to that and also to the implementation of this strategy in [5], in this contribution transactions at the intraday continuous market can occur even without reducing the overall energy costs. The reason for this variation from the original concept is, that in this paper forecast deviations are considered. This detail can under certain circumstances lead to the situation, that the actual charging schedule will differ from the consumption profile purchased at the day-ahead and intraday auction, forcing the operator (or the aggregator respectively) to counteract them by adjusting the energy procurement at short notice.

E. Aggregated PEV Flexibility Approach

As mentioned before, most charging processes are flexible due to high maximum charging power and often comparatively small required energy amount leading to the condition that the parking duration is most likely higher, than the time actually needed for charging at maximum speed (using the maximum charging power) [2] [5] [7] [10]. The actual flexibility results from the opportunity to either shift the charging power in time or even lower it to a certain value and for a certain period, without violating relevant restrictions. The amount of flexibility provided by every charging process therefore primarily depends on the times of arrival and departure, as well as the required energy amount of the corresponding PEV. This certain energy amount in turn depends on the initial battery level as well as on the desired final battery level. While different determination criteria for the final battery level are conceivable depending on the purpose of a study, for the examinations presented here it was assumed that the required amount is equal to the difference between the maximum and the initial battery level of a PEV. Fig. 2 visualizes the flexibility of a single charging process as it is described in [10]. The green area in the upper part of the figure, hereinafter reffered to as corridor, includes all states the battery level of this certain PEV is allowed to have in every moment. The possible course of the SOC is additionally restricted by the maximum possible charging power shown below in Fig. 2, which determines the SOC gradient. Due to the fact that the highest resolution used in this contribution is quarter-hours and in order to avoid unnecessary complexity the SOC course can be linearized [16].

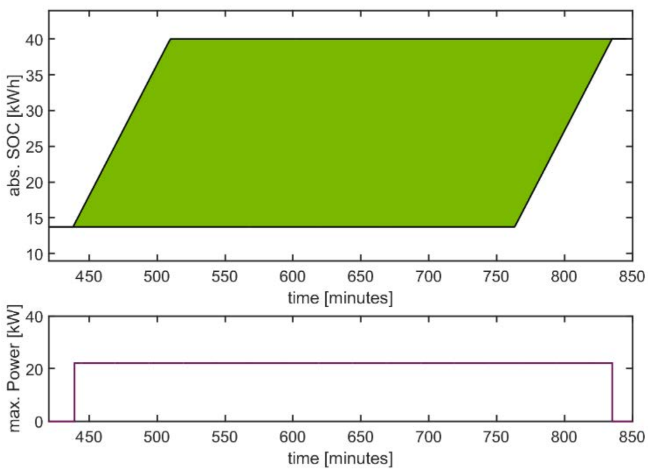

Figure 2. SOC corridor and maximum charging power of a single PEV [10]

The flexibility of a charging process can be described mathematically as the ratio between the area of the parallelogram (between the lower and the upper SOC bound) and the required energy amount or optionally the ratio between the maximum possible and the average charging power needed over the whole parking time (which is equal to the ascending gradient of the straight connecting the lower left and the upper right corners of the flexibility parallelogram). Depending on the number of units, an aggregated approach is advisable when examining a PEV fleet. Therefore, charging processes of PEVs are treated in an aggregated manner. Above all the aggregation of a comparatively high number of individual units to a single entity is an effective strategy to minimize the complexity and therefore the scope and the computation time of according calculations and optimizations [17]. In addition, regarding flexibility, the aggregation leads to a better forecasting of the so called “system response” at a higher aggregation level, because individual effects are smoothened [10] [18]. Generally, due to energy volume related market participation criteria [19] and cost-effective operating [20] smart charging concepts are likely to be implicated by aggregators providing service to a compound of several PEV units. As it is described in [10] the corridor and the maximum power defining the boundaries of the aggregated flexibility of a whole compound of charging stations are determined by cumulating the relevant values of every single PEV in every time step respectively. The output of that operation are the maximum charging power $\overline{P}_k$, as well as the upper and lower bounds of the SOC, $\overline{SOC}_k$ and $\underline{SOC}_k$. Other than usual, in the present contribution “SOC” is equal to the absolute amount of energy stored in a battery, thus measured in kWh.

III. Energy Procurement Optimization

The aim of the present contribution is to evaluate the opportunity of using the aggregated flexibility of PEV charging processes to minimize energy procurement costs based on the spot market platforms mentioned above. Additionally, the objective of self-sufficiency is implicitly pursued by applying an energy price of 0 € to the considered decentralized feed-in. Furthermore, the optimization has to comply strictly with grid- and PEV-related power and capacity limits, while fully ensuring the mobility needs of PEV users. The energy procurement optimization is modelled as a mixed-integer linear programming (MILP) problem. YALMIP is chosen as the optimization framework, which is a modelling and optimization toolbox for MATLAB [21]. While forecast deviations related to PEV user behavior are considered for the continuous intraday market, the car park energy consumption and the day-ahead respectively the intraday auction perfect prices forecasts are suggested.

A. Input Data

Several aforementioned information is provided to the optimization model as input data. As stated previously all time-related data has to be provided with an hourly resolution for the optimization based on the day-ahead market and with a quarter-hourly resolution to be processed in context with the intraday-auction and the continuous intraday market. For the energy prices, the necessary data is already provided in the appropriate time resolution, while PV and CHP feed-in as well as aggregated flexibility data and car park consumption has to be processed accordingly. Forecast deviations are simulated with a quarter-hourly resolution, as they are only considered for the continuous intraday market.

B. Variables

The total power of all aggregated PEVs in every time step $k \in \{1 \dots K\}$ is in the following represented by the decision variable P_k. The actual total battery level of the PEV pool for the same time step k is stored in the variable SOC_k. The total number of time steps is $K = 96$, with every time unit k covering one quarter hour, as that is the minimum resolution used for this contribution and hours can be formulated by adding the appropriate four quarter hours to $h \in \{0 \dots H\}$, with $H = 23$, for the day-ahead auction. In that context the variable $\tilde{P}_h$, which contains the hourly constant charging power resulting from the day-ahead trading, is introduced. The power purchased from the corresponding market platform is represented by P_k^{trade} while the self-supply from decentralized infeeders is determined by $P_k^{feed-in}$, both valid for every time interval k. For the formulation of constraints for the continuous intraday market the count variable $v \in \{1 \dots V\}$ is introduced. In the context of the optimization model presented here v is used for indexing the tradable quarter hours from 16:00 of the day before delivery until the last tradable quarter hour of the delivery day less the lead time of 30 minutes, with the maximum amount of trading quarter hours considered being $V = 125$.

C. Constraints

The restrictions and conditions, whether they are resulting from technical factors or PEV-user mobility needs, have to be formulated through logical expressions, in order to be implemented in the optimization model. As a result of the market structures there are both those constraints that apply for all optimization steps and those that differ depending on the market platform. The following four conditions are consequently applying for all considered market platforms.

$$\underline{P}_k \leq P_k \leq \overline{P}_k \text{ , } \forall k \quad (1)$$

$$\underline{SOC}_k \leq SOC_k \leq \overline{SOC}_k \text{ , } \forall k \quad (2)$$

$$SOC_k = SOC_{(k-1)} + P_k \cdot \Delta k \text{ , } k > 1 \quad (3)$$

$$0 \leq P_k^{feed-in} \leq min\left(\overline{P}_k, \overline{P}_k^{feed-in}\right) \text{ , } \forall k \quad (4)$$

Expression (1) ensures that the value of the aggregated charging power P_k is between its upper and lower bounds in every moment k, which are $\underline{P}_k$ and $\overline{P}_k$ respectively. For this contribution $\underline{P}_k$ is assumed to be constantly 0 kW as bidirectional charging technologies are not considered. Similarly, through (2) the absolute SOC of the PEV compound is limited to an according range. With equation (3) it is ensured that the SOC can only change as a result of charging power that is applied for a certain period of time. While (3) is valid for all time steps $k > 1$, in $k = 1$ the aggregated SOC equals its initial value provided as part of the input data. This relation is covered by (2), as initially the upper and lower SOC bounds are equal. In (4) it is determined, that the self-supply related power can only be positive and not higher than the maximum charging power or the total decentralized feed-in $\overline{P}_k^{feed-in}$. The following constraints apply exclusively in context with the appropriate market platform.

1) Day-Ahead Auction

Since it is only possible to trade energy with an hourly resolution at the day-ahead market, for this part of the optimization (5) forces the quarter-hourly charging power P_k within every hour h to be of the same value $\tilde{P}_h^{trade}$.

$$\left.\begin{matrix} P_{k=(1+h*4)} \\ P_{k=(2+h*4)} \\ P_{k=(3+h*4)} \\ P_{k=(4+h*4)} \end{matrix}\right\} = \tilde{P}_h^{trade} \text{ , } \forall h \quad (5)$$

In (6) P_k is restricted to exclusively be composed of the combination of power purchased at the day-ahead market and the decentralized feed-in. Expression (7) additionally specifies that the upper limit of the power purchased at the day-ahead market is the maximum charging power, while negative values are excluded.

$$P_k = P_k^{trade} + P_k^{feed-in} \text{ , } \forall k \quad (6)$$

$$0 \leq P_k^{trade} \leq \overline{P}_k \text{ , } \forall k \quad (7)$$

2) Intraday Auction

As the hourly constant power $P_{60,k}$ already bought at the day-ahead auction has to be considered for the intraday auction optimization, (8) determines, that the charging power in every time step k has to be equal to the sum of P_k^{trade} (which here is the power purchased at the intraday auction), $P_k^{feed-in}$ and the power already purchased at the day-ahead market $P_{60,k}$ (which is an output of the day-ahead optimization step). Additionally, the restriction formulated through (9) applies to the intraday auction optimization, whereby the negative value of the charging power computed in the course of the day-ahead is the maximum power value that can be sold for the current time step within the intraday auction optimization.

$$P_k = P_{60,k} + P_k^{trade} + P_k^{feed-in} \text{ , } \forall k \quad (8)$$

$$-P_{60,k} \leq P_k^{trade} \leq \overline{P}_k \text{ , } \forall k \quad (9)$$

3) Continuous Intraday Market

Restrictions added in the context of the continuous intraday market are concerning the relation of different trading quarter hours. Equation (10) ensures that rescheduling of the aggregated charging profile can exclusively result from trading actions at the continuous intraday market. Furthermore, according to (11) the tradable amount of energy for every physical delivery quarter hour k in every trading quarter hour $v > 1$ is limited by $\overline{P}_k$ as the upper bound and the negative value of the charging power, that was the output of the previous iteration of the continuous intraday optimization, $P_{k,(v-1)}$ as the lower bound. Accordingly, for $v = 1$ in both (9) and (10) the variable $P_{k,(v-1)}$ is replaced by the charging power in the corresponding time step k, that was the output of the intraday auction optimization, as there is no trade quarter hour in the continuous intraday optimization previous to $v = 1$.

$$P_{k,v} = P_{k,(v-1)} + P_{k,v}^{trade} \text{ , } \forall k, v > 1 \quad (10)$$

$$-P_{k,(v-1)} \leq P_{k,v}^{trade} \leq \overline{P}_k \text{ , } \forall k, v > 1 \quad (11)$$

In order to be able to consider forecast errors the deviations $\Delta\overline{P}_{k,v}$, $\Delta\overline{SOC}_{k,v}$ and $\Delta\underline{SOC}_{k,v}$ are added to the appropriate input data $\overline{P}_k$, $\overline{SOC}_k$ and $\underline{SOC}_k$ respectively. This relation is described in (12) to (14). In order to imitate changing level of knowledge and therefore time-dependent forecasts, the values of the forecast deviations differ in every trading quarter hour, leading to changing input variables.

$$\overline{P}_{k,v} = \overline{P}_k + \Delta\overline{P}_{k,v} \text{ , } \forall k, v \quad (12)$$

$$\overline{SOC}_{k,v} = \overline{SOC}_k + \Delta\overline{SOC}_{k,v} \text{ , } \forall k, v \quad (13)$$

$$\underline{SOC}_{k,v} = \underline{SOC}_k + \Delta\underline{SOC}_{k,v} \text{ , } \forall k, v \quad (14)$$

D. Optimization Objectives

The overall objective of this paper is to minimize the cost of energy procurement for PEV charging processes. Though every optimization step aims to minimize energy procurement costs, the formulation of the objectives differs depending on the market platform. In a first step, the flexibility of the charging processes is used to minimize the energy costs based on the day-ahead auction. The result of this optimization step is, combined with additional input information, used as the input data for the intraday auction, where the aggregated charging schedule is restructured based on intraday auction prices and with a quarter-hourly resolution. As mentioned before, subsequently the continuous intraday optimization is carried out periodically every 15 minutes, where the aim is to generate additional benefit by rescheduling the given charging profile based on the frequently changing prices.

1) Day-Ahead Auction

The day-ahead objective function (which is the total energy cost) is computed by summing up all products of the hourly day-ahead prices c_h^{da} and the energy purchased in that hour, which, in turn, is determined by multiplying the hourly purchased charging power $\tilde{P}_h^{trade}$ and the appropriate time interval Δh. The minimization problem is presented by (15).

$$min\left\{\sum_{h=0}^{H} c_h^{da} \cdot \tilde{P}_h^{trade} \cdot \Delta h\right\} \quad (15)$$

2) Intraday Auction

The hourly constant charging power $P_{60,k}$ resulting from the day-ahead optimization has to be considered for the intraday auction optimization. The minimization problem presented in (16) is formulated similarly to (15), with the difference, that the energy already scheduled during the day ahead optimization is subtracted in every time step k. For that purpose $c_k^{id\_a}$ represents the energy price for every quarter hour interval Δk at the intraday auction. The objective function is again the total energy cost.

$$min\left\{\sum_{k=1}^{K} c_k^{id\_a} \cdot \left(P_k^{trade} - P_{60,k}\right) \cdot \Delta k\right\} \quad (16)$$

3) Continuous Intraday Market

As introduced in [5], for the continuous intraday optimization the goal is to maximize additional revenue by rescheduling the initial charging process in every optimization iteration. Basically, rescheduling in that context means, that the charging power is shifted without changing the total energy amount provided to the PEV compound, while the energy $E_{k,v}$ of a single time interval Δk (which is defined in (17)) may very well change depending on the energy prices in every iteration v.

$$E_{k,v} = P_{k,v} \cdot \Delta k \text{ , } \forall k, v \quad (17)$$

Rescheduling is only carried out if the trade maximizes additional revenue or minimizes the costs of counteracting forecast deviations, as it is described in (18) for $v > 1$. In iteration $v = 1$ for the objective of the first continuous intraday optimization $E_{k,(v-1)}$ is replaced by the energy in the time step k resulting from the intraday auction optimization.

$$max\left\{\sum_{k=1}^{K} c_{k,v}^{id\_c} \cdot \left(E_{k,(v-1)} - E_{k,v}\right)\right\} \text{ , } v > 1 \quad (18)$$

IV. Scenario and Scope of Investigations

The chosen scenario is based on real conditions where the car park under investigation is supplied with electricity via a single cable from a local network station limited to a power of approximately 87 kW. In addition to the regular electricity consumption of the car park and the observed charging stations, a PV system with a peak power of 40 kW and a heat-guided CHP plant with a nominal power of 150 kW are considered. As input data for the consumption of the car park and the feeds time-series with quarter-hour resolution are available. The car park examined is located in the German city of Iserlohn, is open from 7:00 a.m. to 10:00 p.m. and has a total number of 600 parking spaces. Since the current state of development of electric mobility does not allow a meaningful investigation of the situation, 2030 is set as the projection year. With the help of an available software tool that predicts the level of electrification in the mobility sector, a total of 40 electrified parking spaces with a maximum charging power of 22 kW each are assumed to be available at the car park. To determine the degree of electrification, 12 different studies on the market penetration of electric mobility and some region-related parameters were considered. A total period of one month is simulated for this contribution. February 2018 was chosen as the investigation period, which is why the PV feed-in is comparatively low. The uncontrolled charging is chosen as the benchmark; therefore, the optimization results are analyzed in comparison to it.

V. Optimization Results

In order to determine the actual effects of the described optimization, as mentioned above, the optimization model was applied for a simulation period of a full month. The output data has then been analyzed based on several relevant criteria. Generally, the continuous intraday optimization was analyzed separately, as it was assumed that the continuous intraday market will not be considered for the energy procurement for uncontrolled charging processes. Additionally, forecast deviations are taken into account only for the continuous intraday optimization of controlled charging processes. Concerning the day-ahead market and the intraday auction the optimization results are always compared to the energy procurement and scheduling for uncontrolled PEV charging processes. The following comparison focuses on the grid-serving aspect, the self-sufficiency and the energy procurement costs of the optimization and its chosen benchmark.

A. Grid-serving Aspect

As mentioned above, in terms of grid-support the focus for the investigations presented here lies on the maximum capacity of the relevant grid section, namely the supplying cable's upper power limit of 87 kW. Furthermore, the decentralized feed-in has to be considered here, as it increases the maximum charging power of the PEV compound, by providing additional energy, that does not have to be provided via the supplying cable. The analysis shows that in the observed period power limit violations occurred in 53 quarter-hours in the case of uncontrolled charging processes. Compared to that no limit violations can be determined when the optimization is used. The uncontrolled and optimized charging schedules, as well as the power limit in each quarter-hour, can be seen in Fig. 3 for one exemplary day. In case of the optimization the charging power of the PEV compound was scheduled in a way, that it doesn't exceed the power limit

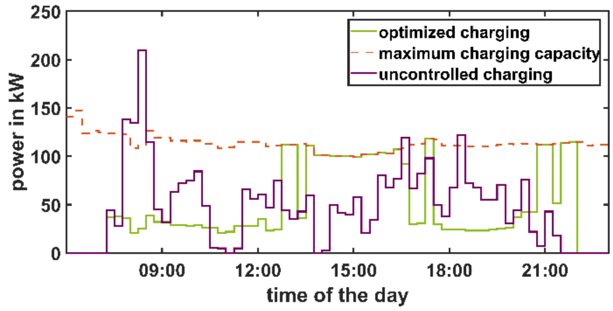

Fig. 3. Violation of grid-related power limits

in each time step, while that happened in several quarter-hours with uncontrolled charging in this example.

B. Self-sufficiency

In case of uncontrolled charging the timing of the energy consumption only depends on the time of arrival and the energy demand and starts right after the PEV is connected to the charging infrastructure and ready to charge. It is therefore expected that optimized charging leads to a higher self-sufficiency if the according incentives are given. As mentioned before, for the method presented here this is the case, as the decentralized feed-in is modelled as a costless but finite energy source. In line with this assumption the overall self-sufficiency level for optimized charging processes is approximately 81.09 %, while it is about 65.11 % for uncontrolled charging. The uncontrolled and optimized charging schedules of the same exemplary day are shown in Fig. 4 and Fig. 5 respectively. Obviously, the energy consumption of optimized charging processes (see Fig. 4) is significantly more adjusted to the decentralized feed-in than the uncontrolled charging schedule (see Fig. 5).

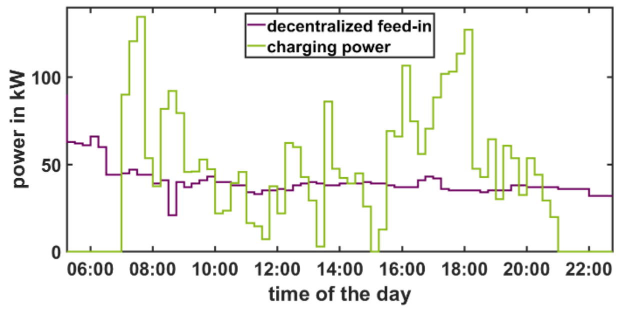

Fig. 4. PV- and CHP-feed-in and uncontrolled charging power

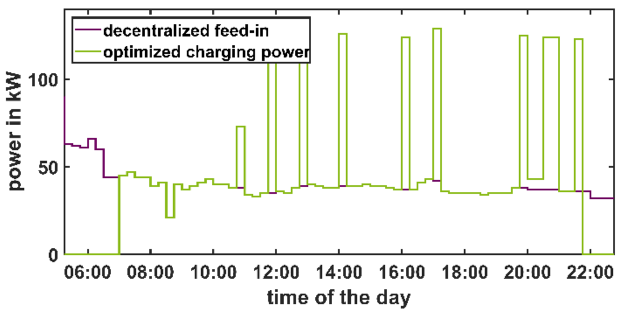

Fig. 5. PV- and CHP-feed-in and optimized charging power

C. Energy Procurement Costs

As already mentioned, the main objective of the optimization is to minimize the energy procurement costs compared to those of uncontrolled charging processes. For uncontrolled charging processes the energy was purchased as follows: The hourly average power is procured at the day-ahead market while the differences to the actual charging schedule are equalized at the intraday auction. The hourly constant power purchased at the day-ahead market and the actual uncontrolled charging power with quarter-hourly resolution of one certain day are shown in Fig. 6.

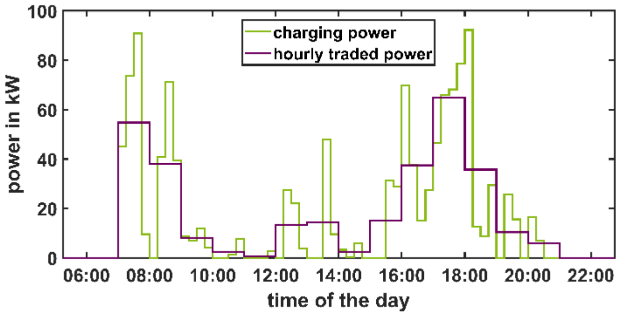

Fig. 6. Trading strategy for uncontrolled charging

Though in Fig. 4 and Fig. 6 data of the same day is presented, differences concerning the uncontrolled charging power can be seen. The reason for that is that Fig. 6 shows only the amount of the charging power in every time step, that is not covered by the feed-in and therefore has to be purchased at the energy market. Furthermore, the earnings related to the decentralized feed-in that potentially would have been consumed by the PEV compound (if using the flexibility) are determined to quantify the opportunity costs and to assure a proper comparison.

1) Day-Ahead and Intraday Auction

In case of the uncontrolled charging processes the costs of the energy that was not covered by the decentralized feed-in and therefore had to be purchased at the day-ahead and intraday auction amount to 433.02 €. When considering the sale of the unconsumed decentralized feed-in, the energy costs that can be used as a benchmark for the optimization are approximately 182.24 €. Since after the optimization, approximately additional 16 % of the required energy for the PEV compound is covered by the decentralized feed-in and the rest is shifted in times of comparatively low energy prices, the energy procurement costs can be lowered to an amount of 59.35 € already after the day-ahead and intraday auction optimization steps.

2) Continuous Intraday Market

After the deployment of charging flexibility for the continuous intraday optimization, additional savings or even earnings resulting from rescheduling the charging processes are expected. The average number of redispatches per day is about 65 with average savings of approximately 0.06 € per redispatch, leading to cumulative savings of about 109 € for the simulated period. Accordingly, the continuous intraday optimization is eventually resulting in negative energy procurement costs of -50.59 €. On the other hand, the rescheduling of the charging process can lead to a lower self-sufficiency level while reducing the energy costs. In Fig.7 the charging schedule after continuous intraday optimization of the same example day as in Fig. 4 to 6 is depicted.

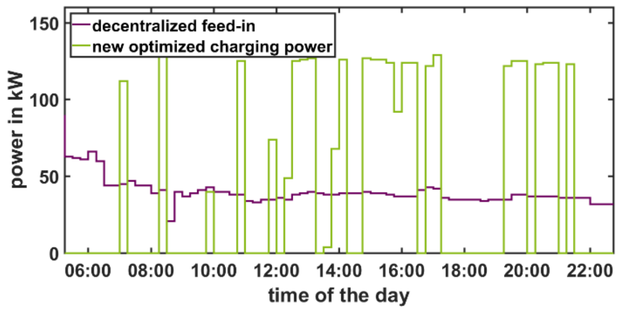

Fig. 7. Charging power after the continuous intraday optimization

Compared to Fig. 5 it can clearly be seen that a significantly lower amount of the energy demand of the PEV compound is covered by the decentralized feed-in for that specific day. In total the continuous intraday optimization is leading to a self-sufficiency level of only 40.14 % (about 25 % lower than in case of uncontrolled charging) while reducing the energy procurement costs.

3) Handling Forecast Deviations

As indicated before, besides cost reduction, an intraday redispatch can also be activated by anticipated SOC limit violations resulting from forecast deviations. Concerning the investigations presented here, this was the case for approximately 19 % of all redispatches. An example for rescheduling of the charging process of the PEV compound is shown in Fig. 8.

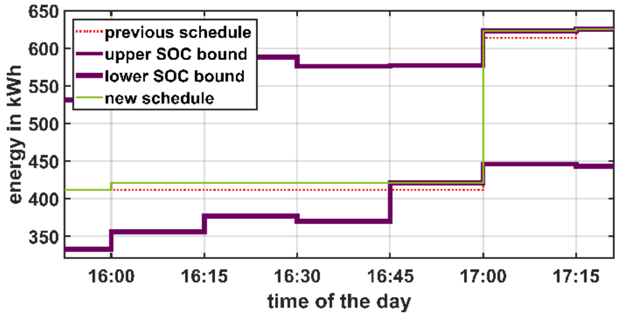

Fig. 8. Forecast deviations based intraday-redispatch

As it can be seen in Fig. 8 the previous charging schedule (red dotted curve), that was computed in the prior redispatch, would violate the lower SOC bound in the quarter-hour between 16:45 and 17:00. To counteract this limit violation an energy amount of 9 kWh is bought for the delivery quarter-hour between 16:00 and 16:15. Additionally, 9 kWh were sold for the delivery quarter-hour between 17:15 and 17:30 during the same redispatch, as otherwise the upper SOC bound would have been violated in this quarter-hour.

VI. Conclusion and Outlook

In this paper a modelling method for a combined energy procurement optimization for aggregated PEV charging stations on the base of the EPEX SPOT SE market platforms is presented, which also takes into account local decentralized feed-in and grid-related restrictions. In the course of a case study the operation and energy procurement of a car park with 40 PEV charging stations, a PV system and a CHP plant was simulated for both, uncontrolled and optimized charging processes over the period of an entire month. The results of the calculations for both cases were analyzed and compared regarding grid-related power limits, level of self-sufficiency and energy procurement costs based on the day-ahead and intraday auction. Furthermore, an additional optimization based on the continuous intraday market was carried out for the charging processes (which were already optimized based on the aforementioned market platforms), after which the costs for energy procurement and the level of self-sufficiency are analyzed again. A further analysis criterion in this case is the handling of forecast deviations. The results of the described investigations show that the energy procurement costs can be reduced to a third already by optimizing the charging schedules based on the day-ahead and intraday auction, while significantly increasing the level of self-sufficiency. Concerning the continuous intraday optimization, the optimization model is suitable for eliminating the energy costs and also handling the forecast deviations. On the other hand, it has to be mentioned, that the level of self-sufficiency was reduced by half, as this was apparently necessary to increase the savings to the resulting value and no additional incentive to purchase the decentralized feed-in was applied in this optimization step. The presented concept could potentially be applied for other parking facilities. Though for market maturity further development, research and analysis have to be carried out. Especially in the context of the acquisition of PEV user information further effort is needed, as it is, amongst other publications, described in [10]. Furthermore, concerning the continuous intraday optimization more achievable price signals than best-bid and ask prices could be used for following investigations. Also the simulation and handling of forecast deviations offers additional research opportunities.

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