Aggregated Approach to use the Flexibility of PEVs for Grid Support in local Energy Communities

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***Abstract*—Current changes in the energy sector towards a more decentralized and renewable supply system are especially noticeable in the form of voltage range and utilization-limit violations in the distribution grid. Conventional low-voltage networks are not designed for a rapid increase of uncontrolled energy consumption by power-intensive consumers such as plug-in electric vehicles (PEVs). In this context the rising share of electrical vehicles could both intensify grid issues but also, if equipped with automation technology, provide the opportunity to counteract network congestions without being dependent on the comparatively expensive grid expansion.**

This paper presents an aggregated approach to control a compound of charging stations with respect to network congestions. The main focus of the paper will be on the automated temporal shift of the charging power of pooled charging stations in order to avoid limitation violations of the corresponding network section.

Keywords - Plug-in electric vehicle (PEV); aggregated charging; charge optimization; parking behavior; grid serving deployment; car parks; smart grids; load management

I. Introduction

Electromobility is slowly picking up speed. This also increases the stress on the energy supply grid. There are network areas which, for example, through the earlier use of night storage heaters and their dismantling, offer sufficient reserves to accommodate a comparatively large number of charging stations. In network areas, however, which are already reaching their limits today, the construction of an additional charging infrastructure can entail serious risks [1]. The associated network expansion requirements, as well as the corresponding costs, can be partially reduced by an intelligent charging infrastructure, while still preventing bottlenecks and limit violations in general [2] [3]. Regional differences require different approaches. In rural areas with a large number of vehicles charging at home, for example, intelligent linking of the charging infrastructure with grid management at peak load times can help reducing the load. In the urban area, a more central collection of charging points can be expected. Many people in these areas will not be able to use the opportunity of charging their PEVs at home and are dependent on public charging facilities. These can be found, for example, in public car parks, or parking lots at shopping centers. Since in many cases several charging stations for electric vehicles are installed in immediate vicinity and thus have a bundled influence on specific network sections [4] [5], an aggregated consideration of charging points is advantageous [6].

Depending on variables like the parking duration, the power limits and the energy demand the respective charging process of a PEV is flexible to a certain extent and can be theoretically shifted in time. Considering this opportunity, a charging management system can be used to prevent congestions for example by minimizing the simultaneity of the charging processes. The chosen control strategy must be non-discriminatory and should, if possible, not restrict the mobility of PEV users. This requires some information from the PEV users, such as the state of charge, the planned departure time and the respective energy demand. In order to subsequently validate the developed concept in the following, the occupancy of the charging stations of the car park is simulated over a representative time period on the basis of a German mobility study. The described control strategy is then applied to the corresponding charging processes and subsequently compared with an uncontrolled charging scenario with respect to limit violations.

In the course of the investigations presented here, an actual car park with 20 charging points is considered. Both grid- and vehicle-dependent restrictions, such as power and capacity limits, parking times and energy demand as well as charging costs, will be taken into account. The flexibility of the aggregated and controlled pool of charging stations offers the possibility to react at short notice to unexpected events within the defined constraints and limitations.

After accordingly comprehensive investigations, the resulting model will be applied to the WIKI (Virtual power plant Iserlohn) project, leading to a field test, in order to test the concept under real operating conditions. Once a certain level of concept maturity is reached, this general approach may be transferred to other research projects in the field of grid supporting charging management accordingly.

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II. Generation of Parking Profiles and Description of aggregated Flexibility of PEVs in a Car Park

The need for flexibility within the energy sector is increasing steadily [7]. To estimate the flexibility of the charging processes a simulation of the car park usage was carried out. The necessary data was provided by the "Mobilität in Deutschland" (MiD) study and parking-statistics of the car park under investigation [8]. For this contribution it has been assumed, that the behaviour of EV users will be more or less similar to the mobility pattern of consumers, who use conventional vehicles with combustion engines.

A. Generation of Parking Profiles

In order to be able to analyse and optimize the charging behaviour of PEV users the car park occupancy has to be simulated. Therefor a multistage algorithm, which is based on the mobility study mentioned above [3], is used to generate individual driving profiles of several PEVs to be able to "fill" a modelled car park with a limited number of parking bays. Depending on its arrival time, the defined opening hours of the car park and the current car park occupancy, a vehicle could simulatively enter the car park and occupy an available parking space. In addition, the occupancy of a parking space is provided with a probability depending on the respective parking time in order to stochastically take into account the frequencies of individual parking durations of the car park actually examined. The output parameters of the simulation are the variation of the car park occupancy over time, the arrival and departure times (T_{arr} and T_{dep}), the state of charge (SOC), as well as the next planned route of the parked vehicles.

B. Description of aggregated Flexibility of PEVs

In most cases the charging processes of PEVs are flexible due to the fact that the parking duration often exceeds the time needed for the actual charging. However, this amount of time primarily depends on the appropriate power limits, the capacity of the cars battery, it's SOC at T_{arr} and the required quantity of energy, which itself depends on the mobility needs of the respective PEV user [10]. It has to be mentioned, that the charging station operator usually has no automatic access to this information [8]. The charging flexibility ($flex$) of a single charging process can be described with the following equation [11]:

$$flex = SOC \cdot C + (T_{dep} - t) \cdot P - d \cdot E \qquad (1)$$

Where C is the capacity, T_{dep} represent the departure time and t the current time step, P is the current power of the charging car, d is the next driving distance and E is the amount of energy the car consumes per km. Due to the fact that the simulated time span won't fall below 1 minute and in order to avoid unnecessary complexity of the simulation model the charging process can be linearized [12].

For the following investigations an aggregated approach is applied for several reasons. This pre-eminently minimizes the complexity of the optimization [10], since a smaller amount of restrictions and variables leads to a lower calculation effort.

The aim of aggregation is to combine the loading processes of the individual PEVs to a single process that can be optimized in order to compress the scope of the problem to be solved. For this purpose, it is necessary to describe the PEV pool as a single accumulator by appropriate constraints, but with respect to the individual PEVs' restrictions. For this purpose, the upper and lower battery filling limits as well as the corresponding power limits of the individual vehicles are first determined in order to aggregate them afterwards. For the following description of the aggregation approach, the absolute battery level of the individual PEVs should be used. This is hereinafter referred to as SOC_{abs} and can be described as follows:

$$SOC_{abs} = SOC \cdot C \qquad (2)$$

The SOC_{abs} of every vehicle i in every time step k is generally constraint by the corresponding upper and lower limits, which is described in (3).

$$\underline{SOC_{abs,i}} \leq SOC_{abs,i,k} \leq \overline{SOC_{abs,i}} \qquad (3)$$

The next step is to define the upper and lower bounds of $SOC_{abs,i,k}$ for each time step of the simulation. If in addition the maximum SOC_{abs} change per time step ($\Delta SOC_{abs,i}^{max}$), which is composed as:

$$\Delta SOC_{abs,i}^{max} = P_i^{max} \cdot \Delta T \qquad (4)$$

is considered, the earliest possible time ($T_{early,i}$) for the PEV to be fully charged and the latest possible time ($T_{late,i}$) for the PEV to start charging can be determined as follows:

$$T_{early,i} = T_{arr} + \frac{\underline{SOC_{abs,i}} - \overline{SOC_{abs,i}}}{P_i^{max}} \qquad (5)$$

respectively

$$T_{late,i} = T_{dep} - \frac{\underline{SOC_{abs,i}} - \overline{SOC_{abs,i}}}{P_i^{max}} \qquad (6)$$

Assuming that the battery of the respective vehicle has to be fully charged in T_{dep}, the following two restrictions can be formulated:

$$SOC_{abs,i,k} = \underline{SOC_{abs,i}}\ , \text{for } k \leq T_{arr} \qquad (7)$$

$$SOC_{abs,i,k} = \overline{SOC_{abs,i}}\ , \text{for } k \geq T_{dep} \qquad (8)$$

Consequently, the upper and lower bounds are linearized during the time spans of the earliest and latest possible charging. This causal relation is described with equations (9) and (10).

$$\overline{SOC_{abs,i,k}} = \underline{SOC_{abs,i}} + \Delta SOC_{abs,i}^{max} \qquad (9)$$

$$, \text{for } T_{arr} < k < T_{early,i}$$

$$\underline{SOC_{abs,i,k}} = \underline{SOC_{abs,i}} + \Delta SOC_{abs,i}^{max} \qquad (10)$$

$$, \text{for } T_{late,i} < k < T_{dep}$$

After $T_{early,i}$ the $\overline{SOC_{abs,i,k}}$ constantly equals its highest possible level, whereas the $\underline{SOC_{abs,i,k}}$ stays at its lowest possible value until $T_{late,i}$ is reached. An example of the course of $\overline{SOC_{abs,i,k}}$ and $\underline{SOC_{abs,i,k}}$ over time, which is restricted by equations (2) – (10), is shown in Fig. 1.

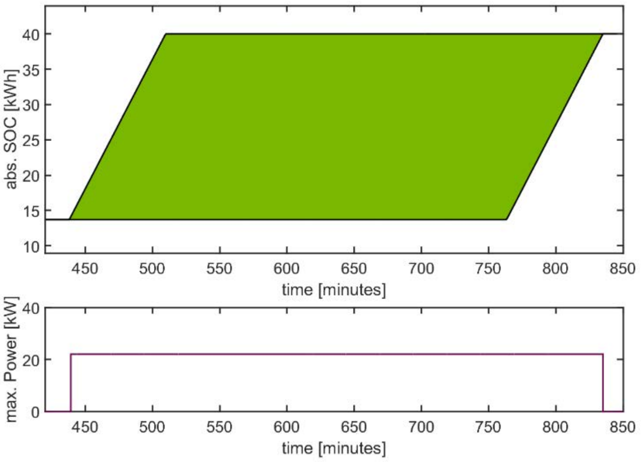

Figure 1. SOC corridor and maximum charging power of a single PEV

The course of the SOC_{abs} of this single PEV can be “chosen” freely within the green parallelogram with the additional restriction of the corresponding maximum charging power P_i^{max}, which is shown in the same figure right beneath the SOC corridor.

In order to describe the SOC corridor for the whole pool in an aggregated manner, the corresponding $\overline{SOC_{abs,i,k}}$ and $\underline{SOC_{abs,i,k}}$ values of each parking process i are cumulated for every time step k. The according P_i^{max} values of all PEVs are also summed up for the entire period under review. The resulting upper and lower bound, $\overline{SOC_{agg,k}}$ and $\underline{SOC_{agg,k}}$ respectively, as well as the aggregated maximum charging power $\overline{P_{agg}}$ are visualized in Fig. 2.

C. Handling Information Loss

After this first aggregation step, the energy purchase of the PEV pool is not yet ready to be optimized due to aggregation-related information loss. After the aggregation it is no longer possible to assign the appropriate parking time, the energy demand or the maximum charging power to a certain PEV. This can for example result in a scenario where the optimization algorithm is assuming a higher P_{agg}^{max} than practically applicable, because one PEV is fully charged before its T_{dep} is reached and therefore doesn’t offer any more charging power until its departure.

Thus, to avoid infeasible solutions, further steps have to be taken to counteract the information loss. In general, it is possible to either determine the cases and conditions in which the solution for the pool is not valid for the individual PEVs and define corresponding constraints in addition, or to apply the feasible part of the solution and start another optimization iteration with new values until the outcome is applicable to all individual PEVs. For the presented paper a combination of the two named opportunities was chosen. Some frequently appearing conditions, like the one explained in the example, were considered in appropriate restrictions, while the remaining discrepancies are eventually reconciled by further iterations.

III. Investigation Scenario

In the present paper, the applicability of the aggregated approach described above is examined in the context of grid serving flexibility deployment. Due to the fact, that the main focus of this paper is on the aggregation approach, following investigations are limited to power-related utilization limits as the decisive factor. Thereby the reactive power is not considered. The chosen scenario is based on real conditions, where the car park examined is powered via a single cable from a transformer station, which is limited to an output of about 70 kW. Besides the regular power consumption of the car park and the observed charging stations, a PV system with a peak power of 13 kW is considered. While the lighting and heating of the modelled car park mainly vary as a function of the time of the year and day, the PV feed-in is simulated using a more detailed tool, which for example takes cloudiness into consideration.

A. Car Park Simulation

For the simulation of the occupancy, it was assumed that the car park is open from 7:00 am to 10:00 pm. 20 charging stations with a maximum charging power of 22 kW each, are available. The battery capacity of the vehicles was set to 40 kWh and the energy consumption per 100 km to 20 kWh. A one-minute resolution was selected and a total period of 4 weeks, each of them representing one season of the year, was simulated. The occupancy simulation showed that all charging stations are occupied in 61.3 % of the time (not considering the time span when the car park is closed) and that on average a total of about 103 charging processes are distributed over one single day. Parking durations vary between 0.65 and 9.98 hours and the energy demand at arrival time varies between 0.2 and 39.8 kWh.

B. Observed Charging Strategies

To be able to detect congestions and limit violations that may occur and furthermore to have a reference, three different charging strategies are simulated and analysed in the context of the same scenario:

- uncontrolled charging
- first-come-first-serve (FC-FS)
- optimized charging

While the first two strategies only depend on the energy demand and the simultaneity of the charging processes (with the difference, that charging processes, which would violate the power limit are not executed with the second strategy), only the third strategy requires an optimization. The preparatory analysis revealed that uncontrolled charging violated the utilization limit in about 6 % of the time (also only considering the time span when the car park is open). The maximum value was 190 kW, which is approximately 2.6 times higher than the permitted 74.58 kW (4.58 kW was provided by the PV system in that time step). The FC-FS strategy left 11 of 2894 charging processes uncompleted, preventing all limit violations. The maximum denied energy for one of those 11 cars was about 60 % of the demanded amount.

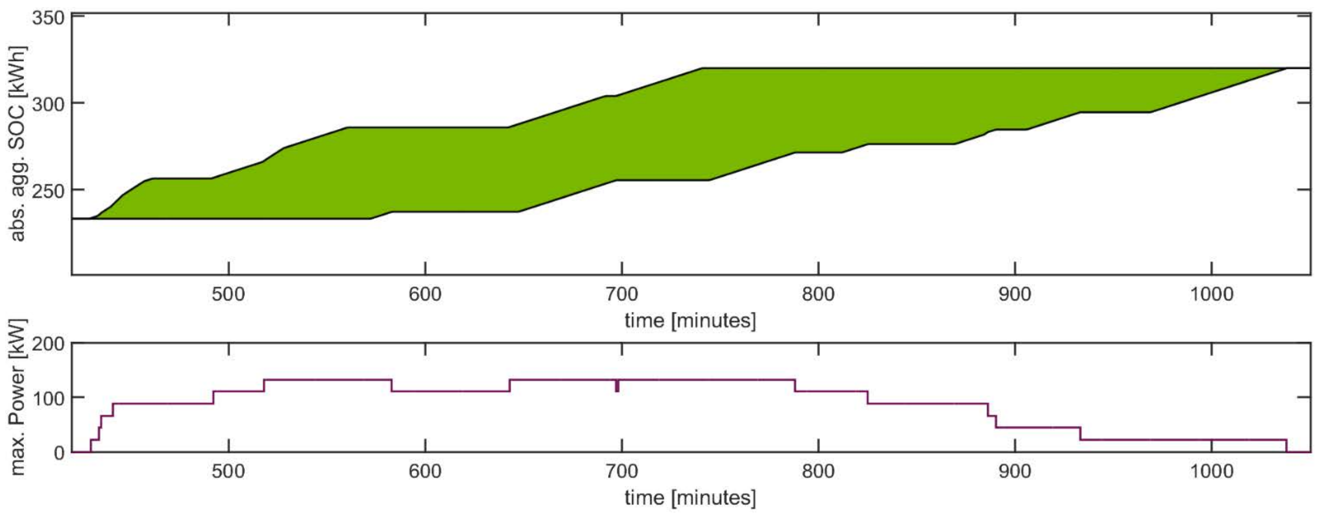

Figure 2. SOC corridor and maximum charging power of aggregated PEVs

IV. Grid Serving Aggregated Charging Optimization

The grid serving based optimization is modelled as a mixed-integer linear programming (MILP) problem and is then solved using YALMIP, which is a toolbox for modelling and optimization in MATLAB [13]. Since the focus of this paper is on the aggregated charging approach, a perfect forecast for the PV system feed-in and the PEV users' behavior is assumed. Furthermore, the optimization is based on the premise of full-user-information, though with the restriction that all vehicles should be fully charged at the end of the indicated parking time. Full-user-information means, that the parking duration, the energy demand and next planned driving distance of the vehicles are known. In consistence with the general scenario that is introduced in section III, a one-minute resolution was chosen for the optimization.

A. Variables and Constants

The total power of the PEV pool in every time step $k \in \{1 \dots K\}$ is in the following represented by the decision variable $P_{agg,k}$. The charge level of the whole pool for the same time step k is stored in the variable $SOC_{agg,k}$. The generated parking profiles, the feed-in profile of the PV system, as well as the results of the aggregation of the observed pool are provided to the optimization as constants, quantitatively describing the conditions of the modelled optimization scenario.

B. Constraints

The $SOC_{agg,k}$ of the whole pool should, at best, be within the range limited by its upper and lower bound, $\overline{SOC_{agg,k}}$ and $\underline{SOC_{agg,k}}$ respectively, at every time step k. Due to the fact, that the total charging power of the pool is restricted by the cable and the PV feed-in, the PEV's cannot be expected to be charged completely in every case. To consider this aspect and to ensure the solvability of the model, $SOC_{sl,k}$ has to be added as substitute variable, which is not connected to the charging power of the PEV pool. According to that the following restriction is implemented:

$$\underline{SOC_{agg,k}} \leq SOC_{agg,k} + SOC_{sl,k} \leq \overline{SOC_{agg,k}} \quad (11)$$

$$, \forall k$$

Here, $SOC_{sl,k}$ represents the deviation of $SOC_{agg,k}$ from its desirable range in every time step.

A related constraint concerning the power consumption of the pool has to be formulated as follows:

$$\underline{P_{agg,k}} \leq P_{agg,k} \leq \overline{P_{agg,k}}, \forall k \quad (12)$$

The change of the energy consumed by the pool within a certain period of time (e.g. between k and $k + \Delta T$) must always correspond to the cumulated product of the obtained power P_k and the respective time steps of the interval ΔT. This relation is given by equation (13).

$$SOC_{agg,k+\Delta T} = SOC_{agg,k} + \sum_{t=k}^{k+\Delta T} P_t \cdot t, \forall k \quad (13)$$

In addition, according to the example presented in section II.C, in the case that a certain $SOC^{*}_{agg,k}$ is reached in time step t, which is before a certain time k^{*}, equation (14) forces the further course of the maximum power to be adjusted:

$$\overline{P_{agg,t,new}} = \overline{P_{agg,t,old}} - P_{single} \quad (14)$$

$$, \text{for } t < k < k^{*}$$

P_{single} is equal to the maximum power of a single vehicle, which is set to $22\ kW$ in that context. The required $SOC^{*}_{agg,k}$ and k^{*} values for the according time step are determined based on the energy demand and the departure time of the single PEVs during the aggregation process and are then available amongst its outputs.

With a last restriction which covers the grid serving aspect and therefore considers the constant utilization limit of the cable P_{cable} as well as the PV system feed-in $P_{PV,k}$, the aggregated power is furthermore forced to be lower than a certain limit $\overline{P_{grid,k}}$.

$$P_{agg,k} \leq \overline{P_{grid,k}}, \forall k \quad (15)$$

$$\overline{P_{grid,k}} = P_{cable} + P_{PV,k}, \forall k \quad (16)$$

Considering both constraints (12) and (15) eventually the valid upper limit in every time step is always the one with the lower value.

C. Optimization Objective

As mentioned above, due to the power consumption limitation of the pool it cannot be assumed, that every charging process can be fully completed, especially in case of a high simultaneity. The objective of the optimization is therefore to minimize the summation of the occurring SOC_{agg} deviation from its desired spectrum, which is $SOC_{sl,k}$. The corresponding target function depends on the decision variables P, SOC_{agg} and SOC_{sl} and is formulated in (17).

$$\min_{P,SOC_{agg},SOC_{sl}} \left\{ \sum_{k=1}^{K} SOC_{sl,k} \right\} \quad (17)$$

V. OPTIMIZATION RESULTS

To show the functionality and the concrete effects of the aggregated charging optimization approach, it was simulatively compared to uncontrolled charging and to the FC-FS strategy in the context of the scenario described before. With the optimized charging strategy all possible limit violations were prevented. Fig. 3 shows the optimization results of one simulated day. In particular, the total power limit (dotted red line), the uncontrolled charging power (yellow line) and the optimized charging power (blue line) are displayed. As it can be seen, unlike the charging power that occurred with the uncontrolled charging, the total charging power of the pool, that was computed by the optimization, didn't exceed the permitted consumption power level at any time step.

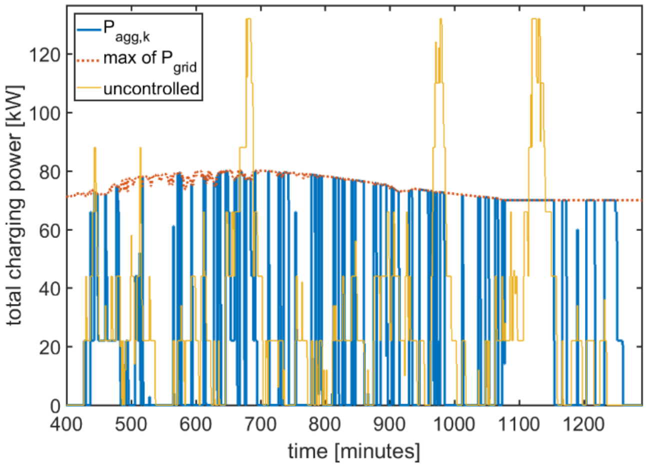

Figure 3. Charging strategy comparison: $\overline{P_{grid}}$ (red), $P_{agg,k}$ (blue) and the uncontrolled charging power (yellow) of the PEV pool

Though to maximize the charge level of the PEVs while ensuring the charging power to be below or equal to its upper bound, the energy consumption was shifted in time by the optimization. In Fig. 4 it can be seen, that in exchange for the lower power peeks the power computed by the optimization has consequently to be higher in other time steps, for the PEVs to be able to consume the same amount of energy.

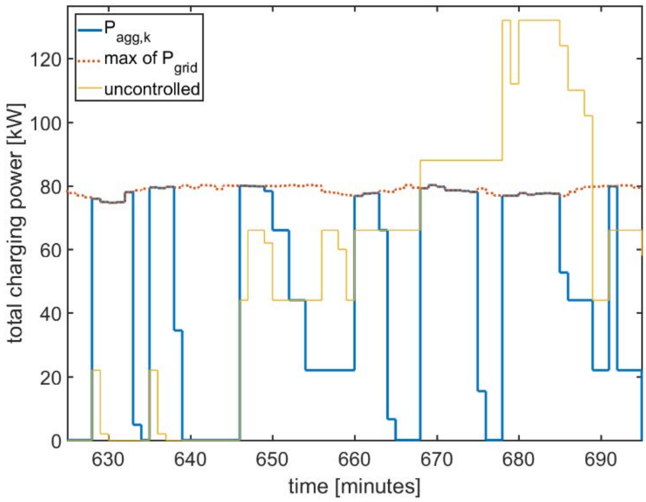

Figure 4. Cutout displaying $\overline{P_{grid}}$ (red), $P_{agg,k}$ (blue) and the uncontrolled charging power (yellow) of the PEV pool

With the optimized charging strategy, a total number of 3 charging processes couldn't deliver the whole demanded amount of energy, which is 72.73 % less than in the case of the FC-FS strategy. The highest relative energy amount that was not delivered by the optimized charging strategy was 27.87 %. In only one single case the optimized charging strategy showed worse results by not completing 2 of 91 charging processes of one simulated day, while the FC-FS strategy managed to charge all PEVs completely. This most probably results from the fact that the optimization usually consists of several separated partial optimizations, which itself is a consequence of the aforementioned information loss during the aggregation process.

VI. CONCLUSION AND OUTLOOK

In this paper, the functionality of an aggregated optimization approach was presented and validated by comparing it to other possible charging strategies in the context of grid support. Regarding sections III.B and V, it can be seen, that -of all three considered charging strategies- the most satisfying results can be attained by optimizing the aggregated power consumption in nearly all respects. Although by using the presented approach it was possible to prevent grid-related limit violations and while providing a higher percentage of demanded energy than with the described FC-FS concept. At this point it is an initial draft concept and requires further proof and development. Especially in the context of the aforementioned issue of information loss more extensive research is needed.

For a more comprehensive concept validation in the context of grid serving flexibility deployment, a rather complex grid topology and the consideration of additional grid-related limit criteria, for example voltage limits, might be useful. Furthermore, a comparison to an optimization of the same number of fully individual charging processes should be carried out with regard to the difference in optimization duration, to be able to detect the quantitative extent of the advantage provided by the aggregated approach. To enhance the realism of the scenario and thus to prove the applicability of the concept furthermore, the integration of different forecast deviations, based for example on the weather or on PEV user behavior, should be realized. The aggregated approach should also be used particularly for forecasting the PEV pool, as the stochastic forecast of individual PEVs could lead to comparatively strong fluctuations in value, which can be smoothened with an aggregated forecast. Aside from that, as a crossover to the energy procurement optimization, the aim of energy cost minimization can be added as a secondary objective.

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