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Optimized Charging of Electrical Vehicles Based on the Day-Ahead Auction and Continuous Intraday Market

Using the flexibility of electrical vehicle’s charging process for reducing energy costs

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Abstract— **The raising share of electrical vehicles opens up new possibilities for an optimized charging strategy using the Day-Ahead Auction and the continuous Intraday market. Based on the simulation of the mobility needs of a huge set of customers the available flexibility of charging processes has been identified. A mixed integer linear optimization problem determines the optimal charging schedules by shifting the charging processes to the cheapest hours. A case study with 50 vehicles was carried out to demonstrate the effects.**

Index Terms: Batteries, Demand-side management, Electrical engineering, Energy consumption, Load management, Optimal scheduling, Optimization, Smart transportation, Vehicles

I. INTRODUCTION

Electrical vehicles have a rising share among the sold new cars in the recent past– for the next years a further increase is predicted. The electrification of the mobility seems to be the only way to decrease the dependency on imported resources and to reduce the CO_2 and NO_2 emissions especially in larger cities [1], [2], [3].

As the simulation presented in the following shows, most charging processes of electrical vehicles have a high flexibility concerning the actual charging time. This flexibility may be used for different purposes: the charging processes can be shifted to times where energy prices at the spot market are low to reduce the total energy costs. The other field of application is the relief of the distribution grid by reducing the required power due to a load shift of single charging processes.

In this paper, a mobility simulation framework is presented which generates driving profiles of electrical vehicles. The simulation is based on the mobility behaviour in Germany [4], which will be used as constraints for the optimization of the charging process. The determined flexibility will be used to reduce the electricity costs of the charging processes based on a three-step optimization. In the first step, an optimization regards the Day-Ahead Auction to find the cheapest hours to charge the vehicle without violating any constraints. The quarter-hour structuring is done in the Intraday Auction as a second step. The third step is carried out periodically within the current day and uses price signals of the continuous Intraday market for rescheduling the charging process – this will be called Intraday Redispatch in the following.

II. USING FLEXIBILITY OF ELECTRICAL VEHICLES

The charging of electrical vehicles can be performed with different charging power, depending on the supported plug-type of the vehicle and the charging station. The charging power ranges from 3.7 kW up to fast charging stations with 350 kW [5]. The most common system is AC loading with type-2 plugs with a charging power of 22 kW.

Based on a charging power of 22 kW the required energy for driving the typical daily distances can be charged within a short time, mostly less than one hour. Combined with the fact, that most vehicles are being used only a few hours a day, it offers the possibility to shift the loading process in time. If the mobility needs of the vehicle’s user are known, smart charging systems could postpone the charging process. The most important constraint for such smart charging systems is that the user must not be limited in the use of his vehicle, i.e. the vehicle must always be charged at least to such an extent that the user can drive the next journey.

A. Underlying mobility statistics

To determine the charging power and the flexibility potential, the mobility behaviour of the vehicle’s user is required. Therefore, a simulation of the usage of electrical vehicles was carried out. In order to obtain valid results the simulation is based on data of a study on mobility in Germany [4]. Based on the provided data, probabilistic driving profiles are generated by means of a multistage algorithm that was customized for utilizing data available in this specific mobility study [6]. The main aspects of the algorithm are depicted in Figure 1.

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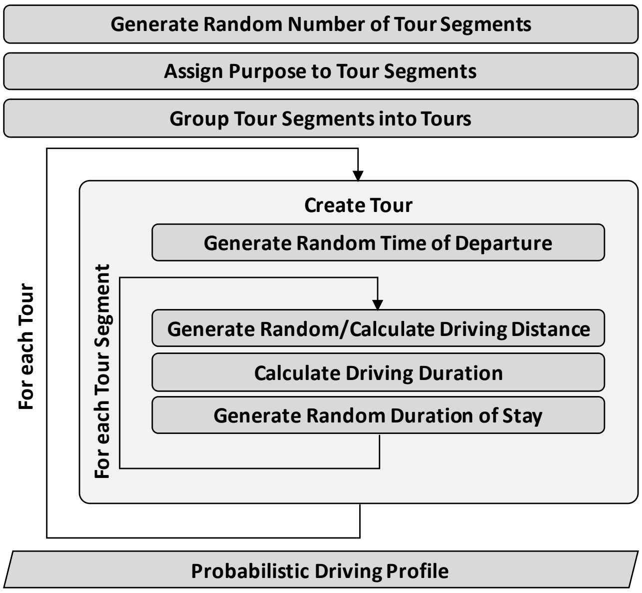

Figure 1: Simulation algorithm for generating probabilistic driving profiles

For the case study, driving profiles of 50 electrical vehicles with a 40 kWh battery and a consumption of 20 kWh/100 km have been simulated. The peak power of the charging stations is assumed to be 22 kW.

The driving profiles that have been generated for a single day sum up to the driven distances shown in Figure 2.

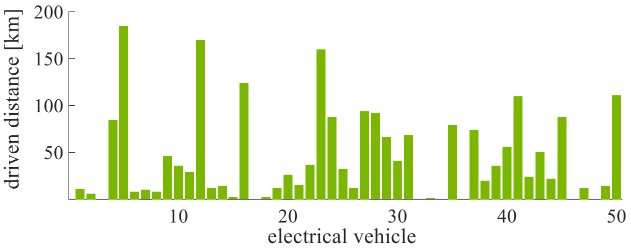

Figure 2: Driven distance of all electrical vehicles at one single day

The median driving distance of this day is 43.76 km, the maximum is 185 km, and with a 25 % quantile of 8 km and a 75 % quantile of 74 km. With these statistical values, the generated driving profiles are reflecting a realistic use of electrical vehicles.

The resulting traveling times for the exemplary driving profiles are displayed in Figure 3. Most time a day the electrical vehicles are parking (green bar), on average 75.2 % of the time.

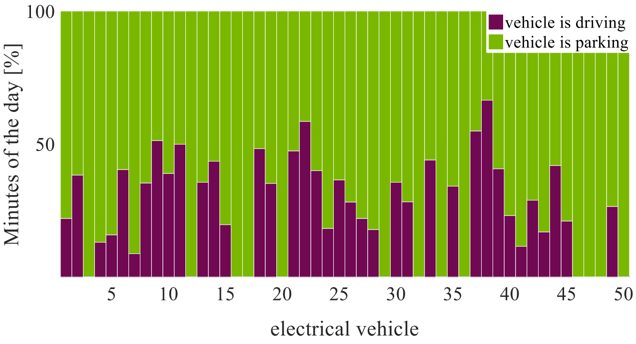

Figure 3: Available charging flexibility within the generated driving profiles

When combining the information about the parking time with the time needed for charging it for the next journey, one gets the flexibility presented in Figure 4. When charging with a power of 22 kW, the vehicles need in median 2.25 % (10.1 % maximum) of their parking time to get their batteries charged. This combination of high charging power and comparatively short driven distances opens up a huge flexibility potential.

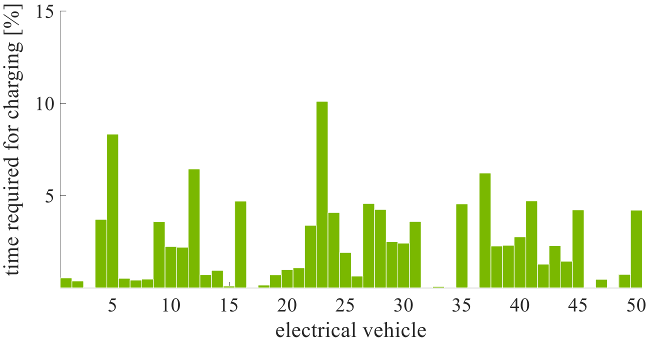

Figure 4: Share of parking time required for charging the vehicle for the next journey

B. *Assumptions and general requirements*

For this study, a perfect forecast for the Day-Ahead Auction and for the mobility requirements of all users is assumed. The state of charge for all batteries will be assumed to be 100 % at the beginning of the observed year; the constraint defined in (5) forces the state of charge to be 100 % at the end again. The charging of the batteries is assumed to be linear with the provided power; the batteries are modelled without any losses.

C. *Applied price signals*

Due to the design of the different markets, different price signals can be used. The Day-Ahead Auction and the Intraday Auction require a single bid, whereas the continuous Intraday market offers ongoing prices at every moment.

1) *Prices at Day-Ahead and Intraday Auction*

Precise forecasts for the Day-Ahead and Intraday Auction are already available, which can be used for the described optimization. Using the perfect-foresight approach the following case study is based on historical prices for both markets.

2) *Prices at the continuous Intraday Market*

The prices in the continuous Intraday market are very volatile. Although there are first approaches, they cannot be forecasted precisely so far. In the case study, the price at the continuous Intraday market was generated based on all transactions of the year 2016. For reflecting the course of the prices within the day, volume-weighted average prices for every 15-minute product have been generated for every 15-minute trading interval based on the real transactions in this interval.

The distribution of prices for a single quarter-hour depending on the trading time is shown in Figure 5. It can be seen, that the prices vary within the day, but also the minimal and maximal prices for the same quarter-hour show a significant spread.

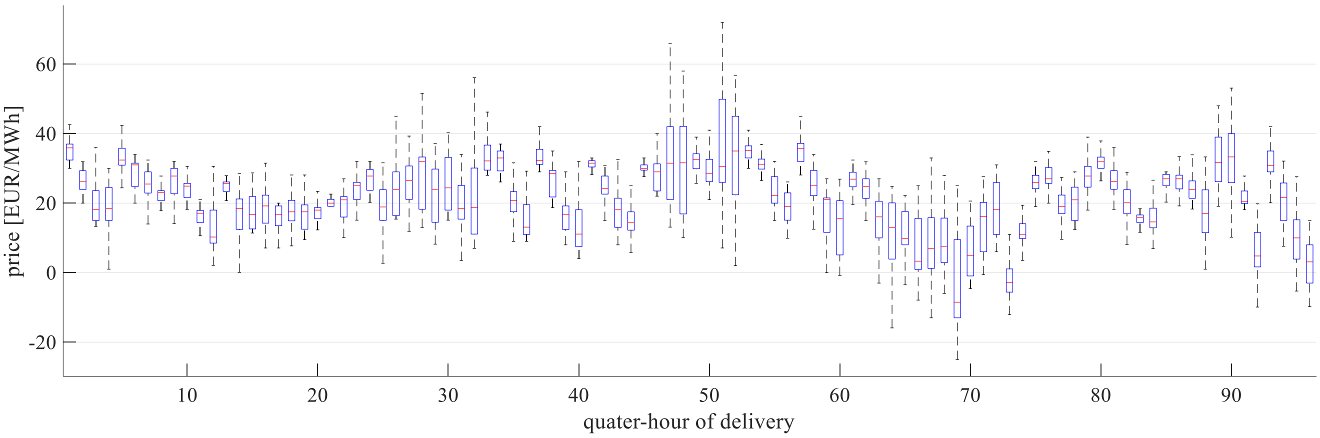

Figure 5: Prices of the continuous Intraday market for July the 5th 2016

Using the volume-weighted average price for every trading quarter-hour is a good approximation. It can be used like the mid-price, which is half the bid-ask spread. The change of the best bid/best ask prices of a single delivery quarter of an hour at the continuous Intraday market is shown for an exemplary trading day in Figure 6.

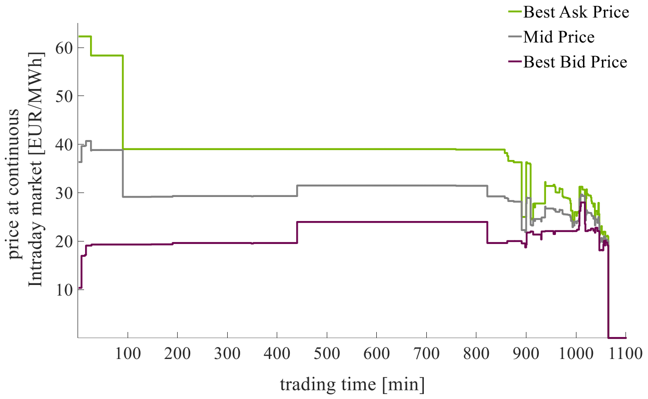

Figure 6: Trading curve for one exemplary quarter of an hour

D. *Intraday Redispatch – Coupling the spot markets*

Combining the advantages of all spot products, especially the Day-Ahead Auction and the continuous Intraday market to a method called *Intraday Redispatch* [7], yields to the greatest savings via shifting the charging process of electrical vehicles in time.

The main advantage of the Day-Ahead Auction is its liquidity due to one single auction per day with a unique market-clearing price. On the other hand, the spreads between cheap and expensive moments are much bigger at the continuous Intraday market, as it is shown exemplarily in Figure 5. At the continuous Intraday market, though the most transactions are only concluded in the short term, the main activity is cumulated to the last hours before delivery. A trading strategy based only on the continuous Intraday market would therefore be risky. With the developed trading method *Intraday Redispatch,* the advantages of both market places can be combined. The whole required energy will be purchased within the Day-Ahead Auction, leading to big savings compared to average prices, as it will be shown in section IV. The Intraday Auction is used to realize first savings by rescheduling the charging and for structuring the schedule to the required quarter-hour interval. After the opening of the continuous Intraday market at 4pm at the day before the course of prices will be observed and Intraday Redispatch optimizations will be carried out periodically as shown in Figure 7.

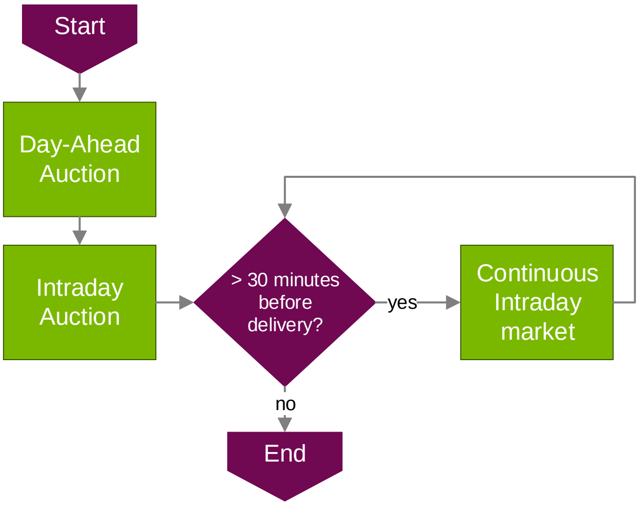

Figure 7: Trading course for coupling the spot markets

The objective of the Day-Ahead Auction therefore is to minimize the energy costs with respect to the constraints defined in Section III.A. The objective of the Intraday Auction and the Intraday Redispatch is to maximize the earnings of shifting the load. A load shift results in two energy blocks, exemplarily shown in Figure 8. The result of the Day-Ahead auction respectively the previous optimization result is referenced as initial schedule and the result of the Intraday Auction respectively the Intraday Redispatch is called new schedule. The result of the load shift is an amount of energy (green block "sell") that is no longer required and a second block of energy (purple block "buy") that has to be bought. The objective is to maximize the difference between the costs for these both energy blocks. As long as a load shift results in a positive revenue, it will be carried out.

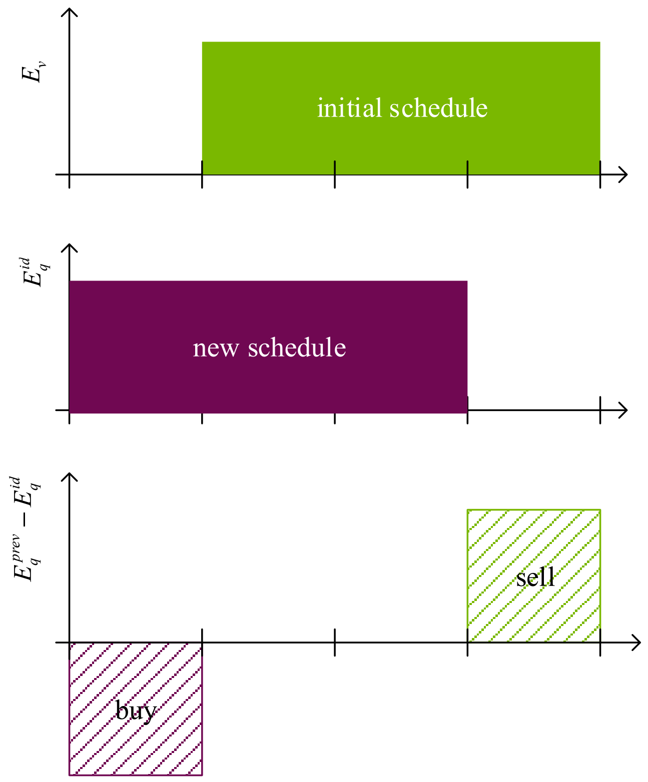

Figure 8: Schematic diagram of the Intraday Redispatch trading method

Due to the high flexibility of the charging processes, the load shift does not have to result in a shifting of the whole charging process; it is also possible to interrupt the charging process for single time steps.

III. MIXED INTEGER LINEAR OPTIMIZATION PROBLEM

The aim of this paper is to show the effect of using the flexibility of the charging process of electrical vehicles to reduce the electricity costs based on the different spot markets. The charging process is modelled as a mixed integer linear optimization problem in YALMIP [8]. The optimization is carried out in a one-minute resolution to obtain also the effect of short charging processes to the needed power, for example for regarding effects on the distribution grid.

The required power for charging all $i \in \{1 \dots N\}$ vehicles in every minute $k \in \{1 \dots m\}$ of every hour $v \in \{1 \dots V\}$ is described in the decision variable P_{ik}, the resulting energy in every hour is summarized in E_h, the actual state of charge of every vehicle in every minute is stored in SOC_{ik} and the binary information whether a vehicle is loading or not is referenced in α_{ik}. The time resolution for k is $\Delta k = 1\,min$, the time resolution for the hours v is $\Delta v = 60\,min$. The quarter-hours of a single day are described with $q \in \{1 \dots Q\}$. The time resolution for quarter-hours q is $\Delta q = 15\,min$.

A. Constraints

For getting the required energy of every hour *v*, the resulting power P_{ik} within this time span is summarized for all *N* vehicles as shown in (1).

$$E_v = \sum_{k=(v-1)\cdot\Delta v+1}^{v\cdot\Delta v} \sum_{i}^{N} P_{ik} \cdot \Delta k \ , \forall\, v \qquad (1)$$

Referring to the assumption that a vehicle is always plugged in at a charging station while it is not traveling ζ_{ik} is only zero while vehicle i is traveling, one otherwise. Equation (2) defines the link to the binary decision variable α_{ik}.

$$\alpha_{ik} \le \zeta_{ik},\ \forall\, i,k \qquad (2)$$

The state of charge SOC_{ik} of every vehicle is defined by the state of charge in the previous time step and the deployed power in this time step. Equation (3) shows the relation in the first time step, where the initial state of charge is used instead of the previous one, (5) defines the last state of charge to be the initial one and (4) is used for all other time steps. The energy retrieved from the battery for driving is described with ξ_{ik}.

$$SOC_{ik} = SOC_{init} + P_{ik} \cdot \Delta k - \xi_{ik},\ k = 1, \forall\, i \qquad (3)$$

$$SOC_{ik} = SOC_{i(k-1)} + P_{ik} \cdot \Delta k - \xi_{ik},\ \forall\, i, k > 1 \qquad (4)$$

$$SOC_{ik} = SOC_{init},\ k = m, \forall\, i \qquad (5)$$

The state of charge SOC_{ik} of every vehicle is constrained by the minimal state of charge $\underline{SOC_{ik}}$ and the maximal state of charge $\overline{SOC}_{ik}$. This constraint is defined in (6).

$$\underline{SOC_{ik}} \le SOC_{ik} \le \overline{SOC}_{ik} \ , \forall\, i,k \qquad (6)$$

Equation (7) sets the limit for the minimal power $\underline{P_i}$ and the maximal power $\overline{P}_i$ obtained of every vehicle. Combined with the binary decision variable α_{ik}, which regards the loading times for each vehicle, the resulting power P_{ik} in every time step is defined.

$$\underline{P_i} \cdot \alpha_{ik} \le P_{ik} \le \alpha_{ik} \cdot \overline{P}_i \ , \forall\, i,k \qquad (7)$$

B. Optimization Objectives

Within this contribution, different objectives will be used. In a first step, the vehicles' flexibility is used for minimizing the energy costs based on the Day-auction. The result of this Day Ahead Optimization is structured to quarter-hours regarding the Intraday Auction. Afterwards the continuous Intraday market is used repeatedly every 15 minutes for generating additional revenues by shifting the charging process.

1) Day-Ahead Auction

The objective is to minimize the total costs for charging all electric vehicles by using the hourly prices of the Day-Ahead Auction at the spot market. Equation (8) shows the sum of the Day-Ahead prices c_v for all *M* hours per day multiplied with the actual bought amount of energy E_v.

$$\min_{P,SOC,E,\zeta} \left\{ \sum_{v=1}^{M} c_v \cdot E_v \right\} \qquad (8)$$

2) *Intraday Auction*

For getting the required energy of every quarter-hour q, the resulting power P_{ik} within this time span is summarized for all *N* vehicles as shown in (9).

$$E_q^{id\_a} = \sum_{k=(q-1)\cdot\Delta q\,+\,1}^{q\cdot\Delta q} \; \sum_{i}^{N} P_{ik} \cdot \Delta k \ , \ \forall\, q \qquad (9)$$

The Intraday Auction is not only used for structuring the result of the Day Ahead optimization to quarters of hours but also for a first Redispatch by means of an additional load shifting. The result of the Day Ahead optimization is split up in similar values for every quarter of an hour E_q^{da} and used as an input value for the Intraday Auction optimization as shown in (10).

$$\max_{P,SOC,E,\zeta} \left\{ \sum_{q=1}^{Q} c_q^{id\_a} \cdot \left(E_q^{da} - E_q^{id}\right) \right\} \qquad (10)$$

The result of the Intraday Auction optimization is a schedule for the required charging power P_{ik} in a 1-minute resolution and a schedule for the required energy E_q^{id} in a 15-minutes resolution.

3) *Continuous Intraday market*

Every optimization run of the continuous Intraday market is based on the previous schedule, which is the result of the Intraday Auction optimization or the previous continuous Intraday market optimization. The previous schedule is referred as E_q^{prev} in (11).

$$\max_{P,SOC,E,\zeta} \left\{ \sum_{q=1}^{Q} c_q^{id\_c} \cdot \left(E_q^{prev} - E_q^{id}\right) \right\} \qquad (11)$$

The resulting schedule will be discarded if the objective defined in (11) is negative. Only new schedules leading to a positive revenue will be executed.

IV. CASE STUDY

For showing the effects of the price-optimized charging strategy, a simulative case study with 50 vehicles has been carried out. The optimization is based on the perfect-foresight assumption for the mobility behavior of the vehicles. It is assumed, that the times of arrival, departure and the driven distances are known one day ahead. With this information, the optimization algorithm can calculate the optimal charging behavior – without any limitations for the vehicle's user.

The results can be seen in TABLE I. Comparing the first column, which shows the costs based on average Day-Ahead prices, and the second column, which presents the costs after the Day-Ahead optimization, it can be seen, that huge savings can be realized – in mean 65 %. Considering the continuous Intraday market leads to even greater savings, in mean 46.62 EUR/a, which equals 56 % of the result of the Day-Ahead optimization.

It can be seen, that a combination of the advantages of all market places could be realized by the developed method called Intraday Redispatch. The extensive liquidity of the Day-Ahead auction can be used for a hedge at the day before; the large price fluctuations within the continuous intraday market could be used for additional savings.

TABLE I: RESULTS OF THE CASE STUDY

	Average costs [EUR/a]	***Costs Day-Ahead [EUR/a]***	***Savings Cont. Intraday Market [EUR/a]***	***Final Costs [EUR/a]***
Minimum	74.56	20.00	42.63	-46.86
Maximum	91.14	34.42	71.19	-13.89
Mean	82.80	28.82	46.62	-17.97

Optimizing a larger amount of electrical vehicles against the same price signals could result in problems for the electrical grid, especially for the distribution grid within areas of a local accumulation of electrical vehicles. In such situations of equipment overload or violations of the voltage band local flexibility markets (described e.g. in [9], [10], [11]) could use the flexibility of the charging process to counteract network congestions, thus helping to avoid or postpone conventional grid enforcement.

V. SUMMARY AND CONCLUSION

This contribution shows a method for a combined trading of the flexibility of electrical vehicle's charging process at short-term markets for energy. A case study presents results for the mixed-integer linear optimization program for 50 electrical vehicles using a perfect-foresight approach for the mobility needs of the user. This could be appropriate for example within a car-sharing system or a corporate fleet, where the start and end-times of each journey and the planned next distance is known before. Otherwise, a precise forecast is needed.

Combining the advantages of the different products offered at the EPEX SPOT energy-trading platform, especially the Day-Ahead auction and the continuous Intraday market, savings greater than 50% compared to average prices could be realized. In the case study, the costs for all 50 electrical vehicles could be lowered to negative values with an intelligent shifting of the charging process.

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