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Incentivizing smart charging: Modeling charging tariffs for electric vehicles in German and French electricity markets

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ABSTRACT

Over the past few years, registration figures of plug-in electric vehicles have increased rapidly in industrialized countries. This could cause considerable mid- to long-term effects on electricity markets. To tackle potential challenges specific to electric power systems, we develop a load-shift-incentivizing electricity tariff that is suitable for electric vehicle users and analyze the tariff scheme in three parts. First, acceptance is analyzed based on surveys conducted among fleet managers and electric vehicle users. Corresponding results are used to calibrate the tariff. Secondly, load flexibilities of electric vehicle charging are used in an agent-based electricity market simulation model of the French and German wholesale electricity markets to simulate corresponding market impacts. Thirdly, the charging manager's ('aggregator') business model is analyzed. Our results reveal that the tariff is highly suitable for incentivizing vehicle users to provide load flexibilities, which consequently increase the contribution margins of the charging managers. The main drawback is the potential for 'avalanche effects' on wholesale electricity markets increasing charging mangers' expenditures, especially in France.

1. Introduction

Since 2008, the registration figures of plug-in electric vehicles (PEV[1]) have increased continuously in industrialized countries [1], particularly in countries with pricing incentives and widespread access to charging stations [2,3]. Rising electricity consumption due to a growing PEV fleet might challenge future electricity systems on the mid- and long-term horizon [4]. The additional electricity demand during peak hours can potentially result in higher wholesale electricity market prices or even scarcity in relation to generation capacity and an electricity demand that cannot be entirely met by supply. In Germany, PEV-specific demand for electricity should be considered with regard to the energy transition with a more volatile, less controllable but increasingly decentralized generation of electricity (e.g. from wind turbines and photovoltaic systems), which is driven by political objectives to reduce greenhouse gas emissions [5]. The growing share of fluctuating renewable energy sources cannot be synchronized with the demand for electricity as easily as before. This leads to an increased need for flexibility mechanisms such as peak-load power plants, storage systems or demand response measures [6,7].

In Germany, electricity demand is served in a static manner, i.e. private households are usually offered an electricity supply contract with a constant energy price over a certain period. Suppliers ensure that the expected electricity demand is satisfied independent of actual wholesale market prices. In contrast, the idea of demand response involves load shifting by deviating from the typical electricity consumption in response to changes in the electricity price offered to consumers [8]. While the concept has long been established [9], its implementation has been slow, though increasing in recent years [10,11].

Demand response requires an adequate technical integration of consumers into electricity systems and can be stimulated through different approaches, generally called demand response programs.

Demand response can, on the one hand, help to reduce price volatility in wholesale electricity markets and to limit required investments in generation and grid capacities. On the other hand, demand response programs also involve considerable challenges and costs [8,12]. Comprehensive reviews exist concerning smart grid business models [13] and agent-based modelling of smart electricity grids and markets [14].

One stream of research points to the issue of potential overreactions of demand response, also referred to as avalanche effects [15–20]. Avalanche effects are sudden increases of load induced by the optimal price-sensitive behavior concerning demand allocation in time periods in which low electricity prices are offered to consumers [21]. This can potentially result in an undesired increase of wholesale electricity market prices.

Roscoe and Ault [15] reveal that real time pricing of demand

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[1] PEV consist of battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and range extended electric vehicles (REEV).

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response programs in the UK domestic electricity market could reduce peaks by 8–11 GW. However, since the same price signal is received by all domestic controllers, all the shifted events are rescheduled according to the same forecast, resulting in undesired spikes of demand. Such avalanche effects are also observed by Gottwalt et al. [16] who analyze the effects of demand response based on time-of-use tariffs. According to Flath et al. [20], the sole use of time-based electricity prices for the coordination of PEV charging produces high load spikes independent of the charging strategies and power levels. To avoid such avalanche effects, Ramchurn et al. [17] develop a decentralized demand side management mechanism that allows consumers to coordinate the deferments of their loads based on grid prices. They reveal that the peak demand of UK domestic consumers can be reduced by up to 17%. To avoid avalanche effects of automated control, Dallinger and Wietschel [18] include feedback on transformer utilization, providing access to information about the reaction of other PEVs in the same distribution network. Their results show that peak load can be limited and renewables better integrated. For the German 2030 scenario, the negative residual load is reduced by 15–22%. Flath et al. [20] introduce price signals that reflect the utilization of locally available capacities to avoid avalanche effects. Boait et al. [19] use different indirect demand response control signals for various types of households to incentivize load shifting to receive the desired load curves.

In future energy systems, aggregators (e.g. PEV charging managers) with centralized control mechanisms could contribute to avoid such avalanche effects by controlling the loads of PEV charging processes directly.

Social barriers are preventing social acceptance of controlled charging [23]. Despite these concerns, support for unidirectional controlled charging among potential PEV buyers can be observed [22]. According to Bauman et al. [24], the possibility of setting minimum ranges is important for user acceptance in the early adoption period of controlled charging. Because user acceptance [25] and framework conditions for industrial stakeholders [26] are crucial for successful smart PEV charging services [27] and corresponding business models [28], our research design intersects **social, technical** and **economic** aspects.

Most studies on potential effects of PEV-specific demand response on power systems focus on the analysis of one specific country at a time, such as the Danish energy system [6], China [29], Spain [30], the United States [31], as well as Germany [4,32,33]. Studies that compare demand response effects of PEV in different regions are rare. Dallinger et al. [34] provide an exception with a comparison of California and Germany.

The power plant portfolio of France differs to that of Germany as it is predominantly based on nuclear power. Therefore, potential future effects of an increasing PEV stock on wholesale electricity markets might also be different. Our focus is on potential effects of charging managers on wholesale electricity markets in France and Germany by 2030.

The charging managers are expected to provide demand response services through controlled charging while accounting for avalanche effects and a minimum range (i.e. a minimum range requested by customers that will always be recharged instantaneously after plugging-in) and guaranteeing for a complete recharge at the end of the charging event if time for recharging is sufficient. Between the time of achieving minimum range and the end of the charging event, the charging managers can use the remaining degrees of freedom to control the load and time of the charging process, if parking times exceed minimum charging times (CC charging phase). Aspects of controlled charging acceptance, i.e. stated preferences of PEV users regarding the required minimum range and their willingness to pay, as well as French and German specificities of wholesale electricity markets, are considered in our agent-based simulation model.

To the best of our knowledge there are no studies published so far which comprehensively describe and evaluate a controlled charging business model focusing on France and Germany with a value proposition incentivizing PEV users to provide load flexibilities to charging managers considering PEV user requirements and corresponding effects on profitability potentials. The following research questions are answered:

RQ1: What are the expectations of PEV users and organizational fleet managers concerning the prices of controlled charging programs and what are their minimum range requirements?

RQ2: How are French and German load profiles affected by controlled charging programs with regard to minimum range requirements and avalanche effects?

RQ3: What are the effects of these controlled charging programs on the profitability of charging managers, i.e. expenditures, revenues and contribution margins?

To answer RQ1, web survey data collected from PEV users and fleet managers is used. Web surveys have similar levels of measurement quality as other methods of survey data collection [35]. Data from PEV users and fleet managers is used in order to consider the effects that experiencing technology as well as social influences have on technology acceptance [36]. We use agent-based modelling to answer RQ2 and RQ3 as it is suitable for analyzing interactions and dependencies in complex systems, such as electricity systems, while still considering **economic**, **technical** and **social** aspects [37]. An agent-based approach provides a simulation framework within which different agent decision models as well as possible agent interactions (e.g. via markets) are explicitly formulated.

This paper has the following structure: Section 2 describes the research design. The used data is briefly described in Section 3. Results are provided in Section 4 and discussed in Section 5. Conclusions are provided in Section 6.

2. Research design

In Section 2.1, a description of the simulation framework is provided. The charging manager and its value proposition is described in Section 2.2. Section 2.3 focuses on the specific methods applied to answer the research questions.

2.1. PowerACE as a simulation framework for electricity markets

We assume that the charging manager utilizes spot electricity markets to procure the required charging energy in each hour of the time horizon under consideration. Given our problem statement, we sought to simulate the development of the underlying electricity markets with the charging manager as an additional key market participant between today and 2030 in an hourly resolution.

We extend and apply the PowerACE model, an agent-based, bottom-up simulation model for wholesale electricity markets, in order to estimate the electricity procurement costs of the charging manager. The model has been used for various research issues, e.g. the impact of an increasing feed-in from renewable energy sources on spot prices [38], the existence of market power in electricity markets [39], generation adequacy in interconnected electricity markets [40], and design options for electricity markets [41]. In this analysis, we improve the charging managers' methodological approaches based on a model version presented in Ensslen et al. [42] and add the French market area while building on an up-to-date PowerACE model version [43,41].

The PowerACE model represents the main elements of the wholesale market design of the market areas under consideration. On the agent level, key market participants are modelled separately as software agents [44]. Given the model's focus on supply, major generation companies are represented by individual agents, thereby emulating the structure in the respective market area. Electricity demand, generation from renewable energy sources, pumped storage operations, and exchange flows with neighboring market areas are modelled in an aggregated form. Besides the short-term spot market operations, generation agents also perform investment planning with regard to conventional power plants.

The simulation flow in PowerACE follows several generic steps in the form of discrete events. After the model initialization, the day-ahead market is executed on a daily basis. All market participants are called by the spot market operator to submit hourly bids according to their demand profile and generation costs respectively. Bid volumes and prices are defined based on the underlying agent model. Generation companies consider marginal generation costs, including the expected start-up costs when offering conventional power plants [45]. The market operator clears the market by intersecting the demand and supply curves and publishes the results to the market participants. If the demand cannot be fully satisfied by the available generation capacity, a loss-of-load event referred to as a generation capacity deficit is registered. In such situations of scarcity, the market price is set synthetically. As a first step, the market operator checks to see whether interruptible load contracts are available, setting the price to the respective activation costs. A remaining shortfall will finally result in a situation where supply cannot meet demand with an hourly market price equal to the maximally allowed price. The respective parameters for the diffusion of interruptible load contracts, their costs, and the maximum market price are set exogenously. These model conventions are intended to reflect the function of electricity spot prices in a simplified manner to provide signals for investments. The other extreme, fully meeting the demand with renewable energy sources, will yield a market clearing price of 0 EUR/MWh or below in the case that power plants bid avoidable start-up costs. At the end of each simulation year, the investment planning module is called. Generation companies then decide based on a net present valuation of different new-build options for flexible power plants. These generic simulation steps are repeated according to the timeframe that is to be investigated. Fig. 1 provides a schematic overview of the PowerACE model.

2.2. Value proposition of a PEV charging manager

The charging manager included in Fig. 2 offers a PEV-specific controlled charging tariff to incentivize customers to provide flexibility potentials. The charging manager targets to schedule individual charging events in a cost-minimizing manner based on price forecasts for day-ahead market prices.

2.2.1. A PEV-specific controlled charging tariff

The development of the e-mobility controlled charging value proposition is inspired by Dütschke and Paetz [46] who recommend dynamic electricity pricing programs to be simple, transparent and predictable. In addition, the investigations of Bailey and Axsen [22], as well as Parsons et al. [47], who clearly mention that acceptance levels of controlled charging programs decrease with regard to restrictions concerning range, are considered in the controlled charging tariff proposed. Therefore, the charging manager's value proposition urges that PEV are fully charged before the start of the next trip. Furthermore, the value proposition in charging Scenarios 1–3 and 5 (c.f. Section 3.3) covers the minimum range requirements of PEV users, i.e. the range that should always be available, e.g. in case of emergencies [24].

The charging manager receives the following information when the PEV are plugged in to be recharged: (1) The state of charge of the battery of a charging event x at arrival time $SoC_x^{arrival}$, (2) the battery capacity of the PEV which equals the final state of charge at departure $SoC_x^{departure}$, (3) the current state of charge during the charging process $SoC_{t,x}$, (4) the requested minimum range SoC_x^{MR}, (5) the limited charging power $P_x^{\max}$ as well as (6) the time in which the PEV is plugged in $t_x^{arrival}$ and (7) the time the PEV is supposed to leave $t_x^{departure}$. t_x^{CC} represents the point of time in which the charging manager can start load control during the charging event. At this point, the PEV's state of charge is at least SoC_x^{MR}, and the remaining time allows for load shifts (i.e. if $t_x^{LSP} > 0$, Eq. (2)). Based on this information, the developed load-shift-incentivizing pricing tariff scheme is defined. Formally, this tariff, i.e. $p_{t,x}$ being the charging event and time-specific price per kWh, can be described as follows (Eq. (1)):

$$p_{t,x} = \begin{cases} p^{\max} & , \; t_x^{arrival} < t \le t_x^{CC} \\ p^{\min} + \left((p^{\max} - p^{\min}) \left(1 - \frac{\min(t_x^{LSP}, T)}{T} \right) \right) & , \; t_x^{CC} < t \le t_x^{departure} \end{cases} \quad \forall \, x \tag{1}$$

The time available to the charging manager for load shifting activities, i.e. the period the PEV is plugged-in but no charging is required to take place t_x^{LSP}, is calculated by subtracting the active charging time from the plug-in time $d_{t,x}$ (Eq. (2)):

$$t_x^{LSP} = \sum_{t=1}^{24} d_{t,x} - \frac{SoC_x^{departure} - SoC_x^{arrival}}{P_x^{\max}} \quad \forall \, x \tag{2}$$

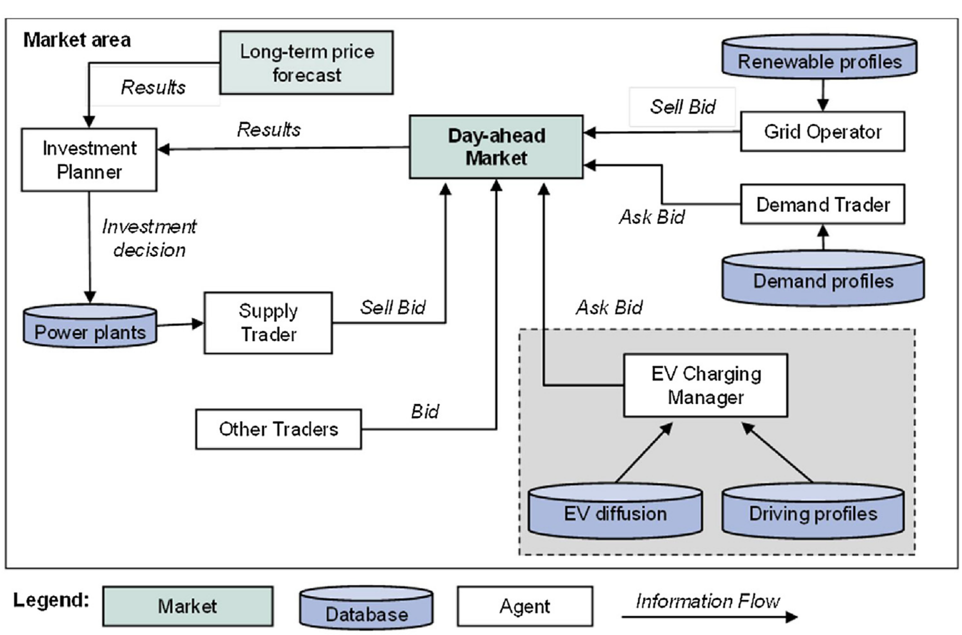


Fig. 1. Schematic overview of the PowerACE model.

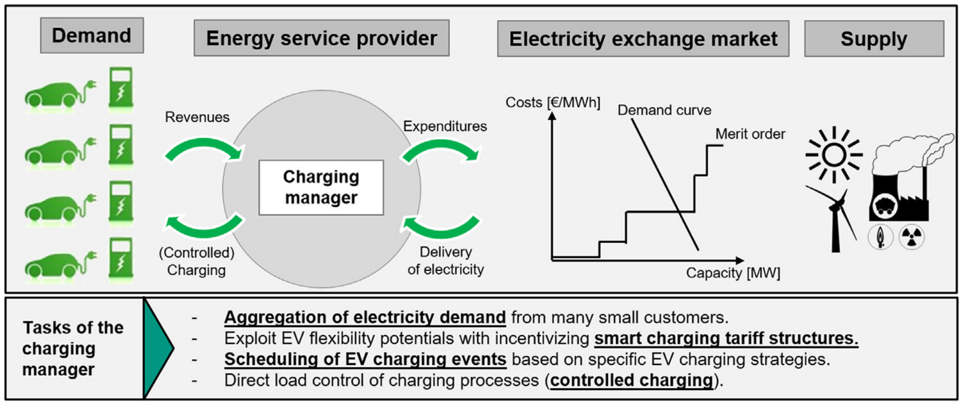


Fig. 2. Overview on the activities of the charging manager.

The parameter T represents the minimal flexible time for load shifting activities provided by a customer to the charging manager so the lowest possible price $p^{\min}$ is paid between t_x^{CC} and $t_x^{departure}$. $p^{\min}$ will be charged only if $t_x^{LSP} \geq T$.

Fig. 3 illustrates how a potential charging process controlled by the charging manager and corresponding price levels of the controlled charging tariff could look like. Furthermore, the charging manager's optimization potential to minimize expenditures for PEV charging is illustrated (dotted rhomboid).

In this study the minimal flexible time T that has to be provided by the customers so they pay $p^{\min}$ is set to a very short time to avoid dividing by zero (Eq. (1)). Hence, we do not account for varying charging event specific, load-shifting dependent charging price levels during the controlled charging phase (CC phase) (Eq. (1)). Accordingly, the tariff offered to the PEV using customers has the following structure (Eq. (3)):

$$P_{t,x} = \begin{cases} p^{\max}, & t_x^{arrival} < t \leq t_x^{CC} \\ p^{\min}, & t_x^{CC} < t \leq t_x^{departure} \end{cases} \quad \forall\, x \tag{3}$$

2.2.2. Load scheduling algorithm

To charge PEV, the charging manager purchases electricity on the day-ahead market. We use the PowerACE model as a simulation framework to analyze the effects of different controlled charging programs on wholesale electricity markets, i.e. the effects on the load profiles and prices of the day-ahead market in France and Germany. In the instantaneous charging scenario (Scenario 1, c.f. Section 3.3), households with PEV do not enter into flexible contracts. Their static load profiles need to be covered by flexible supply. In more advanced scenarios, the charging manager can use the charging event specific flexibilities to shift charging volumes to hours with lower expected spot prices (Scenarios 2–5, c.f. Section 3.3).

The algorithm for generating bids on the day-ahead market comprises different steps. Each simulated day, the charging manager generates a price forecast for all 24 h of the following day. The forecast is based on a merit order model of the respective market area using the information available to the agent. As charging managers intend to minimize expenditures for purchasing electricity, they try by respecting PEV-specific constraints to shift PEV-specific loads into hours with low residual loads. Expenditure minimizing charging strategies so contribute to flatten net-load curves.

The expected consumption of PEV ($\Sigma_{x=1}^{X} Q_x^{IC} + Q_x^{CC}$) is included iteratively in the iterations $i = 1...I$ based on the expected load considering PEV-specific flexibility potentials. The agent uses additional iterations of price forecasts to shift PEV-specific charging events into hours with low forecasted spot prices (cf. Fig. 4).

The total load shift potential is given by a combination of different factors. The potential is determined by the expected PEV usage, including consumption as well as start and end times of daily trips (cf.

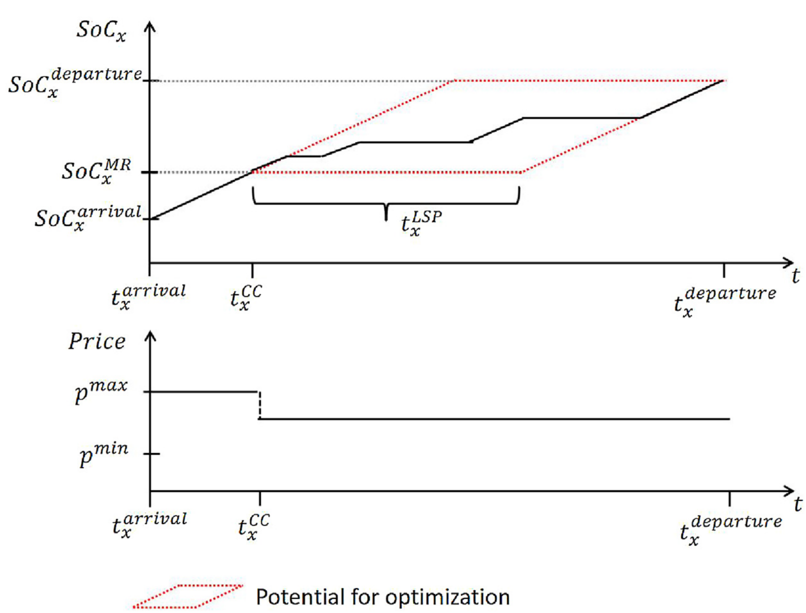


Fig. 3. Illustration of the charging process with controlled charging.

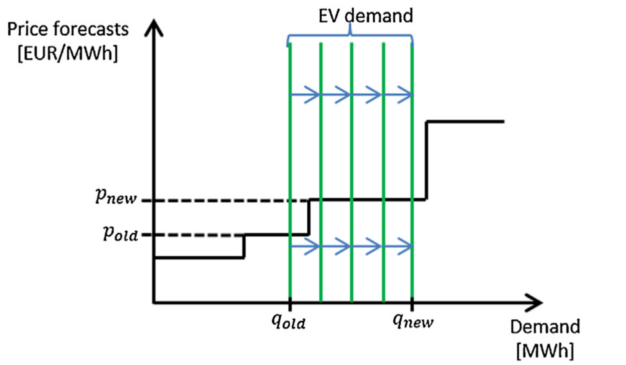


Fig. 4. Schematic overview of the charging managers' iterative scheduling of PEV-specific demand.

Section 3). A guaranteed minimum range means that the battery needs to be charged instantaneously to SoC_x^{MR} (instantaneous charging phase). The remaining energy to fully charge the PEV up to $SoC_x^{\max}$ can be provided through controlled charging according to the charging manager's algorithm. The maximum charging power of $P_x^{\max}$ is an additional technical limitation. Within these limits, the charging manager generates an iteratively optimized load profile for each PEV under contract (cf. Fig. 5).

Initially, the energy needed to instantaneously charge the PEV to the minimum range (IC phase) Q_x^{IC} is calculated:

$$Q_x^{IC} = \sum_{t=1}^{24} \max\{0, \min\{SoC_x^{MR} - SoC_{t,x}^{start}, P_x^{\max} d_{t,x}\}\} \quad \forall\, x \tag{4}$$

The remaining energy to be charged is calculated by subtracting Q_x^{IC} from the energy required for the whole charging process (CC phase):

$$Q_x^{CC} = \min\left\{SoC_x^{departure} - SoC_x^{arrival}, P_x^{\max} \sum_{t=1}^{24} d_{t,x}\right\} - Q_x^{IC} \quad \forall\, x \tag{5}$$

After SoC_x^{MR} has been reached, the charging manager schedules the equally distributed incremental loads $\frac{1}{I}Q_x^{CC}$ for the iterations $i = 1...I$ in a cost-minimizing manner based on price forecasts $p_{i,t}$ (Fig. 4). We use $I = 10$ for scenarios in which avalanche effects are accounted for and $I = 1$ for scenarios in which avalanche effects are neglected (cf. Section 3.3). After the loads of the charging events of iteration i, $\frac{i}{I}Q_x^{CC}$ are scheduled, a new price forecast is made based on the schedule of the last iteration. The new price forecast $p_{i+1,t}$ is used to schedule the load $\frac{i+1}{I}Q_x^{CC}$ of the next iteration. After the loads of all iterations are scheduled, i.e. $i > I$, the heuristic stops.

The linear optimization problem solved in each iteration i of the scheduling problem is formulated as follows:

$$\min \sum_{t=1}^{24} \sum_{x=1}^{X} p_{i,t}\ e_{t,x} \tag{6}$$

s.t.

$$\sum_{t=1}^{24} e_{t,x} = Q_x^{IC} + \frac{i}{I} \cdot Q_x^{CC} \quad \forall\, x \tag{7}$$

$$e_{t,x} \le P_x^{max} d_{t,x},\ e_{t,x} \ge 0 \quad \forall\, t\ \ \forall\, x \tag{8}$$

$$e_{t,x} \ge \min\{SoC_x^{MR} - SoC_{t,x}^{start},\ P_x^{max} d_{t,x}\} \quad \forall\, t\ \ \forall\, x \tag{9}$$

$$\sum_{x=1}^{X} e_{t,x} \ge e^*(t, i-1) \quad \forall\, t \tag{10}$$

$$t \in \{1, \dots, 24\} \tag{11}$$

$$x \in \{1, \dots, X\} \tag{12}$$

The first constraint (Eq. (7)) represents the energy balance for each charging event, the second constraint (Eq. (8)) the power constraint, and the third constraint (Eq. (9)) the constraint that the PEV is instantaneously charged up to SoC_x^{MR} after being plugged-in. The fourth constraint (Eq. (10)) ensures that the hourly energy charged $e^*(t, i)$, which is determined during iteration i, cannot fall below $e^*(t, i-1)$. The fifth and sixth constraints (Eqs. (11) and (12)) ensure that this is done for every hour per day and for all charging events considered.

The price forecast per market area in iteration i is identical for all PEV considered. As new price forecasts are made within each iteration i, the effects of the charging manager's bids on prices within the scheduling algorithm are considered.

The day-ahead bids are submitted in a price-independent manner. Thereby, the simulated charging manager ensures that PEV-specific demand can be procured with certainty on the day-ahead market. Because the charging manager has complete information on the day-ahead demand of households' PEV, there is no need to adjust the schedule before physical delivery, i.e. on intra-day or reserve markets.

2.3. Overview of methods applied to answer the proposed research questions

2.3.1. Parameterization of charging tariff and minimum range (RQ1)

We use stated willingness to pay to set the controlled charging tariff's price parameters for $p^{\max}$ and $p^{\min}$. In addition, we use stated requirements of PEV users for minimum ranges SoC_x^{MR}. Willingness to pay is measured by applying van Westendorp's price sensitivity meter [48]. Furthermore, descriptive statistics of survey results concerning minimum range requirements are calculated. The survey questions

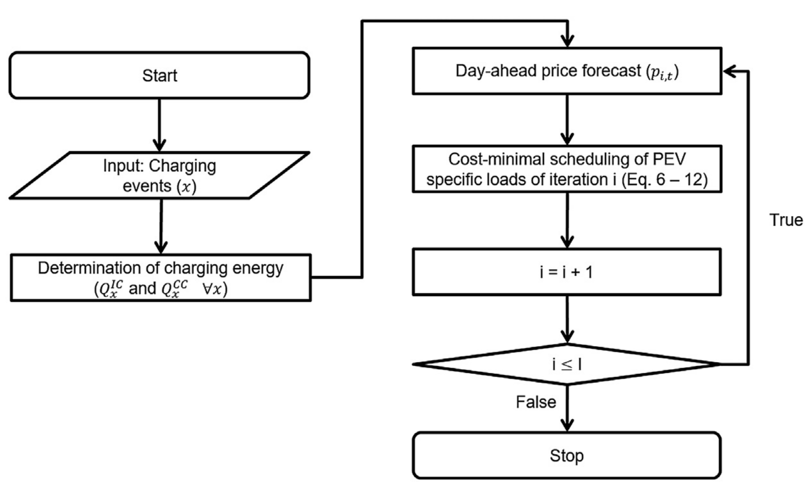


Fig. 5. Flowchart of the PEV load scheduling algorithm of the charging manager.

Table 1
Overview of key input data and sources.

Input data type	Resolution	Main data sources	
		Germany	France
Conventional power plants	Plant/unit level, various techno-economic characteristics	Based on Platts with own assumptions [61]	
Feed-in from renewable energy sources	Hourly feed-in, aggregated for each market area	Vita et al. [62]	
Demand	Hourly load, aggregated for each market area	ENTSOE [63], Vita et al. [62]	
Fuel and carbon spot market prices	Daily/yearly	Vita et al. [62]	
Mobility data	Daily trip profiles	infas [57]	MEEDDM [58]
Survey data	Stated preferences of PEV using organizations' fleet managers and PEV users	Primary data collected during a fleet test with PEV in the south-western part of Germany [64]	

provided to the users and fleet managers are presented in Appendix A and Appendix B.

2.3.2. Analyzing the charging tariff's effects on day-ahead markets (RQ2)

To calculate the hourly load profiles of the charging scenarios considered, PEV-specific flexible loads are aggregated and added to the static hourly electricity demand (D_t^{static}) for every hour of the year (Eq. (13)).

$$D_t^{total} = \sum_{x=1}^{X} e_{t,x} + D_t^{static} \quad \forall\, t \tag{13}$$

2.3.3. Charging tariff's effects on charging manager's profitability (RQ3)

To estimate the profitability of different controlled charging programs, corresponding costs for purchasing electricity on energy markets are compared to potential revenues from selling the electricity to customers.

The charging manager's expenditures are calculated by multiplying the aggregated PEV-specific loads scheduled with the day-ahead market prices p_t (Eq. (14))

$$\mathrm{E} = \sum_{t=1}^{8760} \sum_{x=1}^{X} p_t \cdot e_{t,x} \tag{14}$$

The charging manager's revenues $r_{t,x}$ for charging a PEV during t are calculated as follows (Eq. (15)):

$$r_{t,x} = \begin{cases} (1+z^{IC}) \cdot p^{ref} \cdot (SoC_x^{MR} - SoC_x^{arrival}), & t_x^{arrival} < t \le t_x^{CC} \\ (1+z^{CC}) \cdot p^{ref} \cdot (SoC_x^{departure} - SoC_x^{MR}), & t_x^{CC} < t \le t_x^{departure} \end{cases} \quad \forall\, x \tag{15}$$

p^{ref} is set equal to the average expenditures for purchasing electricity if PEV are instantaneously charged (Eq. (16)).

$$p^{ref} = \frac{\sum_{t=1}^{8760} \sum_{x=1}^{X} p_t \cdot e_{t,x}}{\sum_{t=1}^{8760} \sum_{x=1}^{X} e_{t,x}} \tag{16}$$

z^{IC} represents the willingness to pay more for instantaneous PEV charging up to the minimum range (IC phase) compared to a single price level reference tariff p^{ref} with $p^{\max} = (1+z^{IC}) \cdot p^{ref}$. z^{CC} represents the willingness to pay more for controlled charging compared to p^{ref} with $p^{\min} = (1+z^{CC}) \cdot p^{ref}$, if the charging manager schedules the charging events in a cost-minimizing manner.

The aggregation of the revenues from all charging processes $x \in \{1,\ldots,X\}$ is presented in Eq. (17):

$$\mathrm{R} = 365 \cdot \sum_{t=1}^{24} \sum_{x=1}^{X} r_{t,x} \tag{17}$$

Only trip data of individual days is represented in the mobility data we use. Therefore, potential charging times are assumed to remain the same for every day within a year, i.e. potential periodical and seasonal variations of driving patterns, particularly between weekdays and weekends [4,49], are not accounted for. However, weighting factors ensure that the trip data at hand represents the national average daily mobility patterns. Revenues are the same for every day within a year. Expenditures depend, however, on daily prices on the day-ahead market and are therefore calculated individually for each day of the year. Contribution margins are calculated by subtracting the aggregated annual expenditures from the aggregated annual revenues ($R - E$).

3. Data and assumptions

Section 3.1 provides an overview of the data used, Section 3.2 a description of crucial assumptions, and in Section 3.3, charging scenarios are described.

3.1. Data sources

Generally, the PowerACE model relies on different types of exogenous input data. Time series data typically has an hourly resolution. As far as available, official sources are used for historical data, while scenario data is based on various existing studies (Table 1). Additionally, PEV-specific electricity demand is derived from representative mobility studies carried out in France and Germany. The data used to set the parameters for the two price level controlled charging tariff, as well as the minimum range, is derived from two surveys (among organizational fleet managers and PEV users) conducted during a fleet test with PEV in the south-western part of Germany between 2013 and 2015 [50].

3.2. Assumptions

In order to compare PEV-specific effects on French and German wholesale day-ahead electricity market prices, the same PEV diffusion scenario based on a Bass diffusion model as introduced in Ensslen et al. [42] is used for France and Germany, assuming a PEV stock of five million cars in both countries in 2030 (i.e. a market share of 15% and 12%, respectively). Households adopting PEV within representative mobility datasets are identified by applying a binary logit model yielding probabilities for purchasing PEV, i.e. substituting the households' old cars [65,42].

From this PEV stock data, together with the vehicle operation data from infas [57] and MEEDDM [58], corresponding electricity demand as well as load shift potentials can be drawn. We assume that PEV can be charged during the time they are parked at home and at the premises of the workplace, since these are the places PEV are parked most frequently for longer time periods [66]. We assume that charging facilities are equipped with smart devices permitting controlled charging.

To simulate day-ahead wholesale electricity markets, we assume that there is only one charging manager in each market area. The energy volume allocated by the charging managers is therefore equal to the total PEV-specific energy demand in the respective market area. Expenditures of the charging managers should therefore be considered as lower bounds, since no competition for PEV-specific flexibility potentials is assumed. In order to obtain robust results on expenditures, we analyze the simulation results for the whole year 2030.

The calculations concerning electricity consumption are based on a PEV-specific consumption of 0.15 kWh/km, a battery capacity of 25 kWh, and a maximum charging power of 3.7 kW. Since this battery capacity is insufficient for certain trips, we assume that any remaining distance is covered by gasoline (by PHEV or REEV).

Because the PEV users' and fleet managers' willingness to pay may not be the same today as it will be in 2030, we set the reference electricity price equal to the average expenditure of the charging manager in the instantaneous charging scenario (Scenario 1, cf. Section 3.3). The price levels of the smart charging tariff described in Section 2.2 are set according to the fleet managers' and PEV users' relative stated willingness to pay more compared to the reference tariff for instantaneous charging.

3.3. Charging scenarios

Five different charging scenarios are considered. These are parameterized by four different factors. PEV can either be charged instantaneously after they have been plugged in or by controlled charging. Potential avalanche effects can either be considered or not by iteratively or directly scheduling PEV-specific demand (Section 2.2). Range anxiety can or cannot be encountered by guaranteeing or not guaranteeing the instantaneous charge of the PEV up to a certain minimum range threshold. Concerning charging locations, the possibilities to charge at home and at work are considered (Table 2).

- Scenario 1 (Instantaneous PEV charging) focuses on charging PEV directly after they are plugged-in with the maximum charging power possible.
- In Scenario 2, loads for charging PEV are scheduled in a way that considers avalanche effects of demand flexibilities (Section 2.2). Furthermore, minimum range requirements SoC_x^{MR} are taken into account.
- Scenario 3 incorporates SoC_x^{MR} but does not consider potential avalanche effects.
- Scenario 4 accounts for potential avalanche effects of demand flexibility without considering SoC_x^{MR}, i.e. theoretically available flexibility potentials can be fully exploited. Please note that not considering SoC_x^{MR} is not a perceived significant risk to the convenience or safety of the driver since this scenario also assumes that PEV are fully charged when needed for the next trip. Only unplanned trips starting earlier than the next planned trip could be affected by lower state of charge levels.
- In Scenario 5, PEV are charged as in Scenario 2, but only home charging is allowed.

4. Results

To parameterize the proposed controlled charging tariff and minimum range requirements, Section 4.1 presents results from surveying PEV users and fleet managers. In Section 4.2, aggregated load profiles of considered charging scenarios are described. In Section 4.3, results regarding profitability of charging managers are presented and discussed.

Table 2
Considered scenarios of the charging managers' charging strategies.

Scenario	Cost minimizing controlled charging	Consideration of avalanche effects	Instantaneous PEV charging to minimum range SoC_x^{MR}	Charging locations	
				At home	At work
1	–	–	✓	✓	✓
2	✓	✓	✓	✓	✓
3	✓	–	✓	✓	✓
4	✓	✓	–	✓	✓
5	✓	✓	✓	✓	–

4.1. Parameterization of controlled charging tariff and minimum range (RQ1)

The survey data for these analyses were collected during a fleet test with 109 organizations using 327 PEV. The fleet test was carried out in 2014 and 2015 in the south-western part of Germany. Further details on the fleet test, including information on the participating organizations, are available in Sachs et al. [50] and Ensslen et al. [64].

Survey answers were collected from 109 organizational fleet managers between January and September 2015 and from 122 other employees using the organizations' PEV between April and August 2015. Fleet managers were asked questions concerning charging the PEV at the organizations' premises. In addition, PEV users were asked about charging these PEV at home and at the organizations' premises. According to Table 3, most of the participating fleet managers and PEV users were between 30 and 60 years old, male and had a high level of education, i.e. almost half of the respondents completed their academic studies.

Fleet managers and PEV users were asked how many kilometers PEV should always be able to travel in unprojectable cases, e.g. in cases of emergencies. The arithmetic average for SoC_x^{MR} at home and at work is about 100 km. This is considered sufficient by most of the PEV users and fleet managers who participated in the survey (Table 4). Detailed information on the questions asked are provided in Appendix A.

Fleet managers and PEV users were asked about their willingness to pay for a conventional single price level reference tariff, for instantaneous PEV charging to SoC_x^{MR}, and for controlled charging if individual minimum range preferences are accounted for. The questions are provided in Appendix B.

To assess potential revenues, we set the parameters for SoC_x^{MR} based on the survey results (on average about 100 km). Concerning willingness to pay, Table 5 shows that PEV users are willing to pay slightly more during IC phase. However, as charging during IC phase equals charging in Scenario 1, we set $z^{IC} = 0$. During CC phase, PEV users and fleet managers are willing to pay slightly less (Table 5). We use $z^{CC} = -5\%$ compared to p^{ref} in the profitability calculations (Section 4.3).

4.2. Effects of controlled charging on load profiles (RQ2)

Results of the simulation reveal that the electricity demand generated by five million PEV on the roads in 2030 sums up to a daily amount of about 55 GWh in France and 49 GWh in Germany. Only having the possibility to charge at home results in a daily PEV-specific demand of about 48 GWh in France and about 47 GWh in Germany. The availability of charging infrastructures at the workplace hence increases the share of electric vehicle kilometers travelled. Due to the binary logit model used, the households that procure PEV are mainly those with a high daily mileage. This is reflected in the above-average daily electric vehicle kilometers travelled (France: 73 km, Germany: 65 km) [67,68]. Average load profiles of the different charging scenarios in 2030 considered are presented in Fig. 6.

On average, PEV-specific electricity demand is responsible for 4.3% of the total demand in France and 3.2% of the total demand in Germany. The projected hourly electricity demand in 2030, excluding PEV, ranges from 30 GWh to 90 GWh in France and from 37 GWh to 89 GWh in Germany. In the instantaneous charging scenario (Scenario 1), PEV are responsible for up to 12% of the total hourly electricity demand in France and up to 8% in Germany. PEV load curves in case of instantaneous charging (Scenario 1) are an immediate consequence of the driving profiles at hand. Here, the predominant factor for most PEV

Table 3
Sociodemographic characterization of samples used.

		Fleet managers (N = 109)	EV users (N = 122)
Age	Respondents providing information on their age	n = 77	n = 107
	Distributions' location parameters	M = 45.6; SD = 11.2; SE = 1.3; Min = 18; Max = 70; $q_{0.25}$ = 38.5; $q_{0.5}$ = 46; $q_{0.75}$ = 54	M = 42.8; SD = 11.1; SE = 1.1; Min = 20; Max = 65; $q_{0.25}$ = 34; $q_{0.5}$ = 45; $q_{0.75}$ = 53
Gender	Respondents providing information on their gender	n = 99	n = 104
	Female	n = 11 (11.1%)	n = 16 (14.4%)
	Male	n = 88 (88.9%)	n = 88 (85.6%)
Level of education	Respondents providing information on their level of education	n = 96	n = 108
	(General) Certificate of Secondary Education	n = 2 (2.1%)	n = 10 (9.3%)
	Completed vocational education	n = 10 (10.4%)	n = 11 (10.2%)
	Advanced technical college entrance qualification; university entrance diploma; title of a master craftsman	n = 38 (39.6%)	n = 32 (29.6%)
	Completed academic studies	n = 43 (44.8%)	n = 51 (47.2%)
	Others	n = 3 (3.1%)	n = 4 (3.7%)

owners is the commute between their home and their workplace. Many parallel charging processes take place in the late morning after the commuters' arrival at work and again, however less synchronously, after their arrival at home in the evening.

In Scenario 2, in which avalanche effects and minimum range requirements are considered, the load shift potentials are used to avoid charging during peak price periods and to increase demand in cheaper periods, e.g. during the night and during noon hours with high PV feed-in. In Germany as well as in France, average loads are shifted from early morning hours to noon, and from afternoons and evening hours to late-night hours. Charging volumes between 11 p.m. and 6 a.m. are almost doubled. However, the load shift potential is limited by the minimum range and the constraint of a required state of charge of 100% at the end of each charging event.

Average load shifting activities in the scheduling algorithm without accounting for avalanche effects (Scenario 3) are similar to the load shifting activities in Scenario 2. However, slight differences concerning the allocation of loads can be observed. PEV-specific loads are scheduled somewhat later around noon in both countries (Fig. 6).

In Scenario 4, more charging takes place at night compared to the Scenarios 1–3 (Fig. 6). On average, 41% of the total PEV load in Germany occurs between 11 p.m. and 6 a.m. In France, this number ranges slightly below 31%. However, the load shift potential is limited by the full capacity constraint preventing the shift of charging events at the workplace to night-time charging windows at home as in all other scenarios considered.

In Scenario 5, only home charging is permitted. Daytime peaks are reduced in both countries and nighttime charging increases despite minimum range requirements, i.e. 38% of overall French and 43% of overall German charging volumes are shifted to the time period between 11 p.m. and 6 a.m.

4.3. Effects of controlled charging on profitability (RQ3)

4.3.1. Electricity procurement costs

Simulation results for Scenario 1 determine annual electricity procurement costs of about 1.5 EURbn in France and about 2.1 EURbn in Germany for the year 2030. Over the entire year of 2030, as much as 133 and 192 h go by in which demand can not be met by supply in France and Germany. 91 and 27 of these are occasions in which the interruptible load is exceeded. Such situations result in high scarcity prices of 700 EUR/MWh and 3,000 EUR/MWh. The instantaneous scheduling of PEV is a major reason for capacity deficits observed. According to the baseline scenario without PEV capacity, deficits occur only in 61 h in France and 101 h in Germany. The electricity costs for charging PEV at scarcity prices increase the total bill of PEV users by 0.54 EURbn (26% of total) in Germany and by 0.46 EURbn (31% of total) in France. On the other hand in Scenario 1, 19 and 51 h of charging take place with electricity only provided by renewable energy in both France and Germany. The wholesale electricity prices are consequently at 0 ct/kWh.

Considering price-elastic, cost-minimizing charging strategies and accounting for a 100 km minimum range (Scenario 2) reduces costs by 0.76 EURbn or 51.5% in France and by 0.44 EURbn or 20.9% in Germany as compared to Scenario 1. Expenditures can particularly be saved when charging during high price periods can be reduced by controlled charging. The reduction of PEV load during peak hours, i.e. during hours with a high share of residual thermal loads and corresponding high prices, leads to decreasing peak prices and has a leveling effect (Fig. 7).

In Scenario 3, in which a price-inelastic cost minimization strategy is pursued and minimum ranges are considered, expenditure savings of the charging manager in the French market area drop from 51.5% to 46.6% as compared to Scenario 1. In Germany, results for both scenarios are alike (20.4% vs. 20.9%). Inelastic minimization causes unexpected price increases as high additional demand is allocated to the periods with the cheapest inelastic price forecasts. This is particularly true for higher charging powers. Assuming PEV are charged in an inelastic manner with 15 kW results in a 30% cost increase in France and a 14.3% cost increase in Germany as compared to Scenario 2. Therefore, pursuing strategies that avoid avalanche effects to avoid undesired new demand peaks and price increases (Fig. 7) due to high price sensitivities specific to merit orders (Fig. 8) would seem of particular interest to France. In general, higher charging powers can

Table 4
Stated preferences for minimum range requirements SoC_x^{MR}.

Sample	Parking location	Number of persons providing information on SoC_x^{MR}	[in km] M	SD	SE	Min	Max	$q_{0.25}$	$q_{0.5}$	$q_{0.75}$
Fleet managers	At work	109	103	78	7.4	0	500	50	100	150
EV users	At home	122	111	125	11.4	0	700	50	60	100
	At work	122	108	97	8.8	0	500	50	80	128

Table 5
Willingness to pay for PEV charging to travel 100 km.

Sample	Tariff		Number of persons providing consistent information	[in EUR/100 km]			
				IDP[a]	OPP[b]	MGP[c]	MDP[d]
Fleet managers (parking at work)	Single price level reference tariff		56	3.55	2.65	1.40	5.20
	Two price level tariff	IC phase	60	3.80 (+7%)	2.95 (+11%)	1.70	5.85
		CC phase	60	3.30 (−7%)	2.60 (−2%)	1.40	4.95
EV users parking at home	Reference tariff		54	4.00	3.65	1.95	5.55
	Two price level tariff	IC phase	59	4.30 (+8%)	3.50 (−4%)	1.95	5.80
		CC phase	54	3.65 (−9%)	3.30 (−10%)	1.95	4.95
EV users parking at work	Reference tariff		46	3.70	3.00	1.90	4.95
	Two price level tariff	IC phase	49	3.80 (+3%)	3.10 (+3%)	1.50	5.50
		CC phase	50	3.65 (−1%)	3.10 (+3%)	1.90	4.95

[a] IDP: Indifference price point – The IDP refers to the price at which an equal number of respondents rate the price point as either “cheap” or “expensive”.
[b] OPP: Optimal price point – This is the point at which an equal number of respondents describe the price as exceeding either their upper or lower limits.
[c] MGP: Point of marginal cheapness – The number of people who experience a product as “too cheap” is larger than the number who experience it merely as cheap.
[d] MDP: Point of marginal expensiveness – The number of people experiencing the product as “too expensive” is larger than the number of those experiencing the product merely as expensive.

drastically increase the risk of capacity deficits and hence increase charging costs. This risk can only partly be alleviated by controlled charging as long as PEV users continue to insist on certain constraints such as minimum range.

Differences observed concerning avalanche effects can be explained by country specific merit orders. While the French merit order is rather stable up to about 53 GW of thermal capacity (due to a high capacity of nuclear power), the merit order in Germany is characterized by slighter price increases up to about 53 GW due to a higher heterogeneity of technologies and corresponding heterogeneous marginal price levels. This results in comparably stable price elasticities on the supply side of the German wholesale electricity market. The French merit order is completely elastic up to about 53 GW of installed thermal capacities. Here, the French merit order escalates. An overview on the power plants and their marginal costs is provided in Fig. 8.

Hourly fluctuating renewable feed-in in the year 2030 ranges between 8 GW (9 GW) and 58 GW (80 GW) in France (Germany), i.e. 24 GW (30 GW) on average. In general, decreasing minimum ranges as well as accounting for avalanche effects result in decreasing hours with capacity deficits, more notably in France where situations of scarcity occur more frequently (Fig. 9).

In Scenario 4 accounting for these avalanche effects but neglecting potential minimum range requirements even more load can be shifted by the charging managers. Annual cost savings as compared to Scenario 2, in which minimum range requirements and avalanche effects are accounted for, increase by up to 85 EURmn in France and 79 EURmn in Germany.

As a higher share of load is shifted to evening and night hours in Scenario 5 prices increase slightly more during early evening peak hours than in the other load shifting scenarios considered.

In addition to electricity procurement costs, other operational costs, including personnel expenses, trading fees, rent and forecast costs need to be considered. According to Reeg et al. [70], the overhead and fix costs of a charging manager excluding infrastructure would amount to less than 10 EURmn per year and thus make up only a negligible part of the total costs.

Overall these results show that increasing load shift potentials provided by PEV users would decrease electricity procurement expenditures substantially in France and Germany.

4.3.2. Revenues

In Scenario 1, revenues are calculated with a single price level reference tariff. Its price is set to a value so that revenues equal expenditures in Scenario 1. The charging manager of the German market

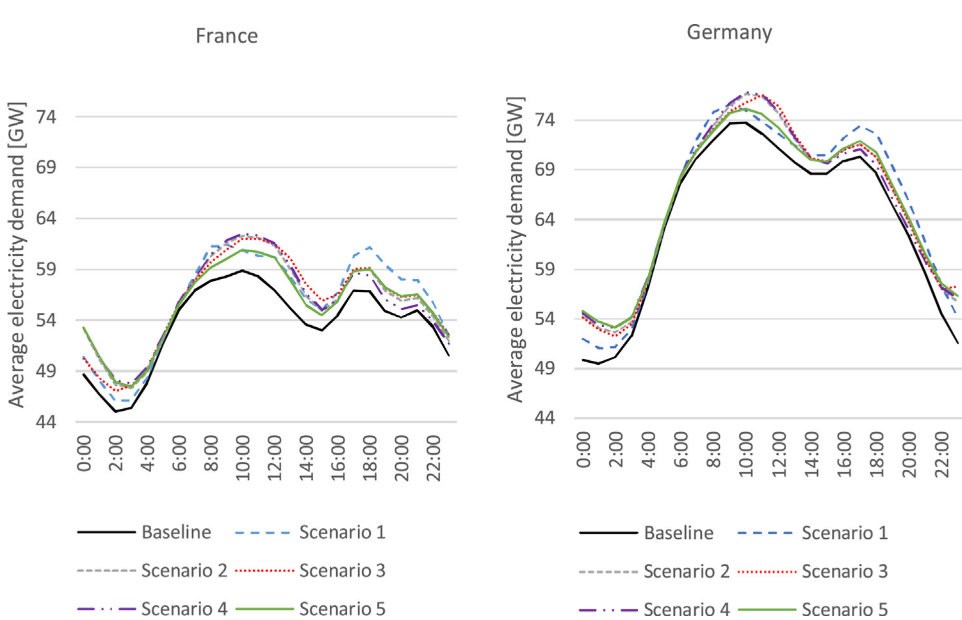


Fig. 6. Average load profiles in 2030 of the different charging scenarios considered.

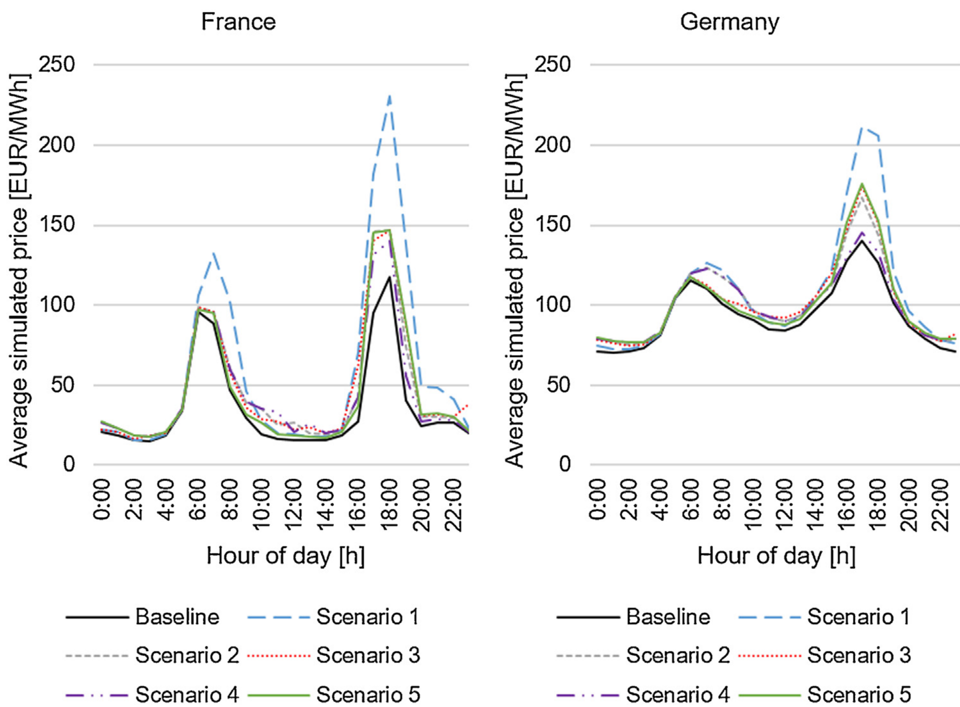


Fig. 7. Wholesale day-ahead electricity market prices in 2030 in the different scenarios considered.

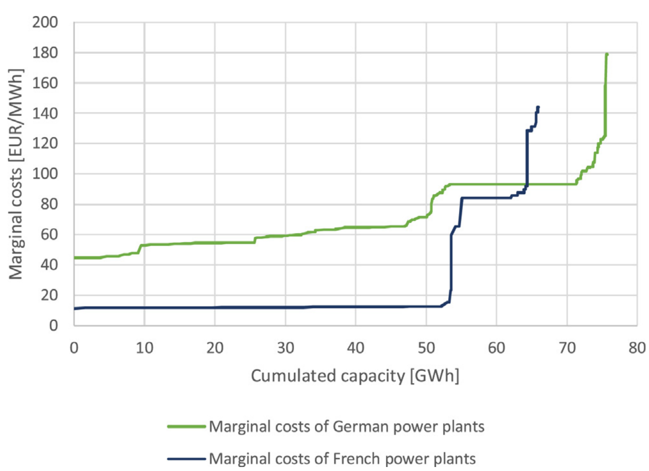


Fig. 8. Merit order of the French and German power plant portfolios in 2030 (thermal power plants only).

area sets the price to 0.117 EUR/kWh, the French to 0.073 EUR/kWh. Revenues in Scenario 1 amount to 1,481 EURmn in France and up to 2,082 EURmn in Germany. In scenarios considering the minimum range of 100 km, revenues decrease by 3.7% and amount to 1,426 EURmn in France and 2,006 EURmn in Germany (Scenarios 2 & 3). Assuming no minimum range, revenues reveal similar values (−1%), i.e. 1,414 EURmn in France and 1,985 EURmn in Germany (Scenario 4). In scenarios where only home charging is allowed, revenues are slightly lower, i.e. 1,243 EURmn in France and 1,980 EURmn in Germany. Although the French and German trading volumes for PEV charging are at a similar level, charging managers' revenues still differ substantially: they are about 30% higher in Germany (Fig. 10).

These findings might encourage utility companies to develop specific e-mobility charging tariffs, such as the tariff presented in this study. Particularly considering the special requirements of controlled charging, specifically the consumers' demand for minimum range, the long idle periods of PEV, as well as acceptable incentives for load shifts, could contribute to convince PEV users to provide load shift potentials to charging managers.

4.3.3. Contribution margins

Increasing flexibility by a decreasing minimum range and accounting for avalanche effects result in higher contribution margins of the charging managers (Fig. 10). Comparing contribution margins between instantaneous charging (Scenario 1) and price-elastic, cost-minimizing charging considering minimum range requirements (Scenario 2) reveals that the contribution margins for French charging managers would increase by 708 EURmn and by 359 EURmn for German charging managers. Neglecting consumer preferences concerning minimum range leads to a further increase of contribution margins as compared to Scenario 1 (781 EURmn for French and 418 EURmn for German charging managers). Selling e-mobility specific controlled charging tariffs that incentivize PEV users to provide high amounts of flexibility could significantly increase the profitability of controlled charging for both the users and electricity providers.

Comparing the costs and contribution margins between France and Germany in the different scenarios shows that differences between the price-elastic (Scenario 2) and price-inelastic (Scenario 3) scheduling procedures can rather be observed in France (73 EURmn). This effect can be explained by the higher share of hours with generation capacity deficits in Scenario 3 (Fig. 9) that lead to higher average market prices (Fig. 7), higher costs, and lower contribution margins (Fig. 10). Differences between the costs and corresponding contribution margins of these two scenarios in Germany only amount to 11 EURmn.

In all controlled charging scenarios, contribution margins increase as compared to the instantaneous charging scenario as demand during peak hours is flattened. These findings underline substantial potentials for increasing contribution margins by controlled charging in the future.

5. Discussion and limitations

Our holistic approach to evaluate profitability potentials of controlled PEV charging comprises several large assumptions. We simulated potential effects of different PEV charging strategies on electricity markets in the year 2030. The model derives PEV charging profiles from

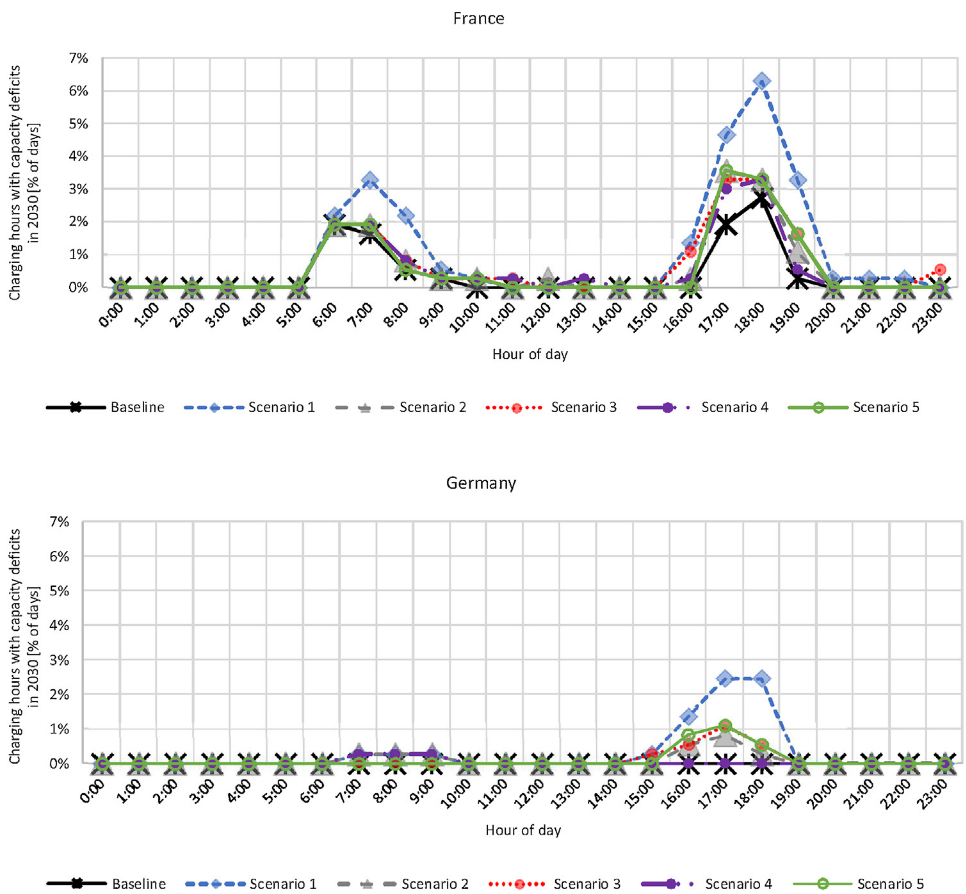
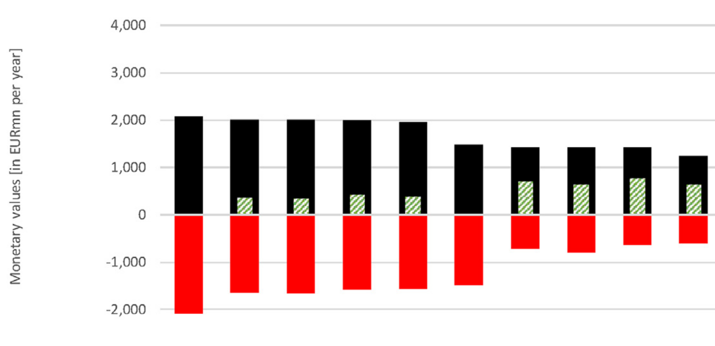


Fig. 9. Hours with capacity deficits in different PEV charging scenarios over the year 2030.



	Scenario 1, 3.7 kW (GER)	Scenario 2, 3.7 kW (GER)	Scenario 3, 3.7 kW (GER)	Scenario 4, 3.7 kW (GER)	Scenario 5, 3.7 kW (GER)	Scenario 1, 3.7 kW (FR)	Scenario 2, 3.7 kW (FR)	Scenario 3, 3.7 kW (FR)	Scenario 4, 3.7 kW (FR)	Scenario 5, 3.7 kW (FR)
Variable costs [in EURmn]	-2,082	-1,647	-1,658	-1,567	-1,560	-1,481	-718	-790	-633	-608
Revenues [in EURmn]	2,082	2,006	2,006	1,985	1,946	1,481	1,426	1,426	1,414	1,243
Contribution margins [in EURmn]	0	359	348	418	386	0	708	635	781	635

Revenues [in EURmn] Variable costs [in EURmn] Contribution margins [in EURmn]

Fig. 10. Overview of annual costs, revenues and contribution margins for the charging managers' charging activities.

today's car usage patterns based on the assumption that mobility patterns of PEV adopting households remain the same in 2030. Nevertheless, we account for PEV user acceptance by identifying early PEV adopting households based on a binary logit model [65,42]. This results in a quicker substitution of conventional vehicles with above-average vehicle kilometers travelled.

Bailey and Axsen [22], Tan et al. [23], Bauman et al. [24], and Will and Schuller [25] show that despite social barriers such as range anxiety, there is potential for controlled charging, particularly if minimum ranges are accounted for and the individual need for flexible mobility is not limited through charging control. All these aspects are considered in the PEV charging tariff proposed in this paper. In addition to prior studies, we analyze willingness to pay and PEV users' minimum range requirements for the controlled charging tariff proposed, parameterize the PEV-specific demand accounted for in the electricity market model according to these findings, and evaluate future profitability potentials of charging managers' in the two countries considered.

The phenomenon of avalanche effects as a result of the decentralized indirect control of load has been widely addressed [15–17]. Dallinger and Wietschel [18], Flath et al. [20], and Boait et al. [19] presented approaches to avoid avalanche effects based on signals that are to be interpreted in a decentralized manner. Contrary to that, this study focuses on the direct control of PEV-specific loads by charging managers. As day-ahead market participants, charging managers have adequate information available to make informed decisions on how to best allocate loads to avoid avalanche effects with new price peaks. Just like in prior studies, our study shows that prices for PEV charging can be reduced. This study additionally points out that the differences between the merit orders of the two countries comprises higher potentials to reduce expenditures by controlled charging in the French market area.

Survey results (**RQ1**) are based on answers provided by a non-representative sample of early PEV adopters who might have had an increased willingness to pay for innovative products or different range requirements as compared to those provided by a representative sample. However, we assume that it would be rather challenging for individuals of representative samples who were not actively using PEV to provide answers to the questions asked (Appendix A and Appendix B). Only about half of the respondents could be used to estimate willingness to pay as some participants did not complete the surveys or provided inconsistent answers. Survey participants who did not provide answers on willingness to pay for charging during IC or CC phase were not considered in the willingness to pay assessment. As survey data was collected in 2015, the results (Table 5) reflect PEV users' perceptions in the year 2015. However, as we intended on calculating an estimate on what PEV users and fleet managers would be willing to pay more for the two price level controlled charging tariff presented in this paper compared to the conventional single price level reference tariff today, we explicitly neglected creating scenarios for 2030 in the survey.

The results of the simulation (**RQ2**) are likely to overestimate PEV-specific price increases. Agents representing the power plant operators in the electricity market simulation model do not consider the additional electricity demand which is induced by PEV in their long-term price forecast and thus, in their investment decisions. This leads to a higher level of electricity prices in our simulation results given a steadily rising number of PEV in the system. However, the beneficial effects of controlled charging in general do not depend on this simplification. Load shifting potentials would also be exploited if price spreads were lower, though with a lower absolute impact. Moreover, it is challenging and uncertain how utilities might value such structural developments with regard to the electricity demand within their investment valuation approach. Since the simulation is based on hourly time intervals, power peaks might be underestimated. A higher time resolution might even lead to higher avalanche effects. Furthermore, we do not assume coupled markets. Therefore, trading possibilities between France and Germany are not considered by the load scheduling algorithm. Competition among charging managers for flexibility potentials is not part of the simulation. Results are based on the assumption that there is one central charging manager per market area. In a scenario with more than one charging manager, charging strategies for all PEV can no longer be coordinated centrally. Hence, market power of all charging managers would be diminished. New demand peaks can follow the decentral charging schedules. In addition, our results are based on a market-driven analysis which does not consider any of the physical constraints of electricity distribution as potential bottlenecks in the electricity grid [71].

Charging managers' profitability potentials (**RQ3**) predominantly depend on expenditure savings. The simulated spot market price levels in the baseline scenario, not including PEV with simulated average prices of about 93 EUR/MWh in the German market area in 2030 (Fig. 7), are comparably high compared to today's wholesale electricity market prices of about 30 EUR/MWh in Germany [72]. The simulations' price level of 36 EUR/MWh in the French market area fits fairly well to the price level today of 35 EUR/MWh [73]. The charging managers could further decrease expenditures by using the flexibility potentials of the PEV charging processes for trading activities after day-ahead market clearance on intra-day markets. Alternatively, participating on balancing markets by providing negative balancing energy could be an option for the charging managers to increase revenues [74]. Further limitations include additional investments necessary in smart charging infrastructure solutions that permit controlled charging. Revenue calculations are based on the assumption that relative willingness to pay for the controlled charging tariff is more or less the same for France and Germany. Only one single tariff offer with two price levels that does not vary dependently on the flexibilities provided is assumed per scenario. Driving patterns are assumed to be the same every day. The different charging strategies' impacts on the profitability of charging managers are based on the assumption that the expenditures for instantaneously charging the PEV (Scenario 1) would equal corresponding revenues. Surcharges for grid usage, taxes and fees are not accounted for in the revenue assessment.

6. Conclusions and future work

We analyzed the effects of different charging scenarios on potential revenues and expenditures of PEV charging managers in France and Germany in 2030 by considering aspects of user acceptance accounted for by an innovative load-shift-incentivizing tariff for PEV users. The results show that intelligent provisioning of electricity by charging managers can help to substantially improve the contribution margins of controlled charging schemes in 2030. Revenues of the charging managers based on the two-price level controlled charging tariff introduced are only slightly lower compared to the revenues of instantaneously charging PEV. Profitability aspects of controlled charging majorly depend on potential savings of provisioning electricity on wholesale electricity markets. The analyses of the charging managers' expenditures show that increasing flexibility potentials provided by PEV users in the different charging scenarios considered lead to decreasing expenditures as well as a decrease of hours with capacity deficits. This relationship can be observed for the charging managers in France as well as in Germany.

However, differences can be observed concerning potentials for avalanche effects in the two countries. Expenditures for purchased electricity by the German charging manager increase by a lower degree than expenditures for electricity purchased by the French charging manager if charging events are scheduled in a manner that does not take into account undesired demand response overreactions, i.e. potentials for undesired avalanche effects are higher in the French market area. The French merit order is characterized by large steps during periods with high residual loads. Increments of variable costs between the power plants of the German market area are comparably low.

The future share of PEV could severely affect wholesale electricity market prices, i.e. increasing electricity prices and challenges concerning security of supply. Controlled charging is effective in mitigating these effects. Therefore, incentives for PEV adopters to install smart and connected charging infrastructure components that enable controlled charging and to participate in demand response measures could be supportive. Table 6 summarizes the major findings and implications of this study.

Future analyses on the effects of controlled charging could compare differences for France and Germany and further countries. As assumptions concerning the degrees of flexibility concerning PEV charging could have an impact on power plant portfolio investment decisions, future work could focus on this. In addition, multi-objective, controlled charging strategies intending to minimize PEV-specific carbon dioxide emissions and to maximize the share of renewable energy sources or self-generated electricity while also considering grid bottlenecks could be analyzed. As perspectives for business models of controlled charging on day-ahead wholesale electricity markets seem limited, the profitability potentials of integrating a large number of PEV on different

Table 6
Summary of results.

Research questions	Major findings and implications
What are PEV users' and organizational fleet managers' expectations concerning prices of controlled charging programs and their stated minimum range requirements?	The willingness to pay for the controlled charging tariff incentivizing PEV users to provide load flexibilities proposed in this paper that accounts for minimum range preferences is comparable to the willingness to pay for a single price level reference tariff. Stated minimum range requirements of PEV users are on average 100 km. Considering the results of Bauman et al. [24], the load-shift-incentivizing controlled charging tariff proposed could result in decreasing minimum ranges asked for by PEV users. This could lead to significantly increasing load shift potentials provided to charging managers.
How are French and German load profiles affected by controlled charging programs with regard to minimum range requirements and avalanche effects?	On average, load is shifted from afternoon and evening hours into night hours as well as from morning to noon hours in both market areas and all controlled charging strategies considered. Increasing load shift potentials provided by PEV users with strategies that avoid avalanche effects and include low minimum ranges result in decreasing prices. Controlled PEV charging can therefore significantly contribute to balancing supply and demand.
What are the effects of these controlled charging programs on charging managers' profitability, i.e. expenditures, revenues and contribution margins?	Contribution margins majorly depend on the savings for provisioning electricity on wholesale electricity markets, as controlled charging programs reduce electricity market prices and therefore the charging managers' expenditures. Charging managers' revenues are hardly affected because willingness to pay for the controlled charging tariff proposed is high.

markets (intra-day and balancing energy markets) could be addressed in future analyses. Furthermore, future studies could differentiate between different weekdays as charging profiles might be considerably affected by different mobility needs and corresponding electricity demand.

Acknowledgements

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Appendix A. Survey questions for the assessment of minimum range requirementsSoC_x^{MR}:

Survey questions for the assessment of minimum range requirementsSoC_x^{MR}:

1. Question for fleet managers:
How many kilometers should the organizations' PEV parked at the factory premises always be able to travel in unprojectable cases, e.g. in cases of emergencies?
[ ] kilometers.
2. Questions for PEV users:
How many kilometers should your car parked at the following places always be able to travel in unprojectable cases, e.g. in cases of emergencies?

At home	[ ] kilometers.
At the workplace	[ ] kilometers.

Appendix B. Survey questions for the assessment of willingness to pay for a conventional single price level reference tariff:

Survey questions for the assessment of willingness to pay for a conventional single price level reference tariff:

1. Question for fleet managers:
At what price per 100 km would your organization consider charging as…
2. Questions for PEV users:
2.1 Imagine you own a PEV. Which price per 100 km **for charging at home** would you consider as…
2.2 Assume your employer provides charging infrastructure so you can charge your PEV. You can authenticate an access at the charging station in a user-friendly way. The billing process for charging your PEV that you exclusively use for commuting purposes is done independently of your employer. At what price per 100 km would you consider **charging at the workplace** as…

a) …too expensive?	[ ] Euros per 100 km range
b) …expensive, i.e. you would charge the PEV after giving it some thought?	[ ] Euros per 100 km range
c) …cheap, i.e. charging the PEV would be a bargain?	[ ] Euros per 100 km range
d) …too cheap, i.e. you would question the reliability of the offer?	[ ] Euros per 100 km range

Survey questions for the assessment of willingness to pay for charging PEV before the charging manager starts controlled charging (IC phase):

Suppose there is a charging manager providing a charging service with a special, two price level charging tariff. The charging manager promises that the PEV will be fully recharged at the time you individually prescribed. In the first charging phase, the charging manager charges the PEV up to the minimum range you are comfortable with as quickly as possible.

1. Question for fleet managers:

Assuming that the battery of the PEV is empty when the vehicle is parked, at what price per 100 km would your organization consider charging the PEV up to the minimum range you provided as…

2. Question for PEV users:

2.1 Assuming that the battery of the PEV is empty when the vehicle is parked after coming home, at what price per 100 km would you consider charging the PEV up to the minimum range **at home** as…

2.2 Assuming that the battery of the PEV is empty when the vehicle is parked at the workplace, at what price per 100 km would you consider charging the PEV up to the minimum range **at the workplace** as…

e) …too expensive?	☐ Euros per 100 km range
f) …expensive, i.e. you would charge the PEV after giving it some thought?	☐ Euros per 100 km range
g) …cheap, i.e. charging the PEV would be a bargain?	☐ Euros per 100 km range
h) …too cheap, i.e. you would question the reliability of the offer?	☐ Euros per 100 km range

Survey questions for the assessment of willingness to pay for controlled charging (CC phase):

After charging the PEV up to the minimum range you defined, the second price level of the charging tariff is effective. During this charging phase, the charging manager controls the charging process of the PEV in a self-serving optimal manner, but ensures that the PEV is fully charged again the next time it is needed.

1. Question for fleet managers:

At what price per 100 km would your organization consider controlled PEV charging by the charging manager as…

2. Question for PEV users:

2.1 At what price per 100 km would you consider controlled PEV charging by the charging manager **at home** as…

2.2 At what price per 100 km would you consider controlled PEV charging by the charging manager **at the workplace** as…

a) …too expensive?	☐ Euros per 100 km range
b) …expensive, i.e. you would charge the PEV after giving it some thought?	☐ Euros per 100 km range
c) …cheap, i.e. charging the PEV would be a bargain?	☐ Euros per 100 km range
d) …too cheap, i.e. you would question the reliability of the offer?	☐ Euros per 100 km range

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