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Original research article

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