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Effects of electric vehicles on the spot market price

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ABSTRACT

In this paper we investigate the impact of different electric vehicle charging strategies on spot market power prices for the case of Germany. We also provide a detailed analysis of uncertainties resulting from vehicle-to-grid (V2G), the most flexible charging option. Since the integration of renewable energy sources requires flexibility, we compare V2G with two competing systemic flexibility options provided by highly flexible power plants and resulting from EU high voltage grid expansion, respectively. In all cases we find that V2G has by far the most significant impact on prices, mainly smoothing them, while reducing, for example, the surplus electricity from renewable energy sources. V2G also has the strongest influence on prices compared to the systemic flexibility options of more flexible power plants or network expansion. In addition, we show that it is important to take the structural difference between working days and weekends into account. Especially on weekend days, which are usually characterized by low power demand, V2G raises power prices the most. Finally, the price effects are accompanied by a saturation effect, which is already noticeable in the German case at two million vehicles.

1. Introduction

At the 21st conference of the parties (COP21) to the United Nations Framework Convention on Climate Change 2015 (UNFCCC) in Paris, the participating nations settled an agreement to reduce global CO_2 emissions [1]. In this process, the transportation sector has an important role to play. With a transformation to electric vehicles (EVs) emissions may be significantly reduced as long as the required electricity is produced by renewable energy sources (RES) [2]. In 2016, for the first time, the global number of EVs exceeded one million [3]. To emphasize its goal of six million EVs by 2030 [4], the German government initialized a purchase premium.

Although EVs might contribute to the overall goal of emission reduction, their roll out will affect the power system. Quantifying the expected impact requires an understanding of the resulting energy demand that is challenging due to a current lack of empirical data. Nevertheless, there is a wide range of modeling approaches to generate deterministic load curves for uncontrolled charging (UNC) of EVs from the immediate moment they are connected to the grid [5–8]. In contrast to UNC, the feasible charging strategies of price driven and bidirectional charging offer a significant degree of freedom. In the first case, the exploitation of power price differences result in some form of demand-side management. We therefore abbreviate this loading variant with DSM. In addition to potential load shifting, batteries can be occasionally discharged with bidirectional charging, which often is referred to as vehicle-to-grid (V2G). In consideration of the energy demand for driving purposes, effectively, EVs then act as mobile energy storage plants. As a consequence, different EV charging strategies lead to a different power plant dispatch, different overall power system operation cost, and different CO_2 emissions. These impacts were studied for a variety of countries in Refs. [5,9–14]. Although the structures of the power systems differ, with respect to costs and the possible integration of RES all studies prefer flexible charging strategies over uncontrolled charging. Other flexibility options through EVs are discussed in Refs. [15–18].

Nonetheless, none of the aforementioned studies analyzed the direct effects on spot market prices. To the best of our knowledge, there has been very little research regarding to this topic. Schill [19] applied a hypothetical car fleet to the estimated German power plant fleet of 2020 and found that increased charging flexibility leads to decreasing peak prices. Due to the selected year this work considers a rather moderate share of renewable energy sources and ”only” one million EVs. Razeghi and Samuelsen [20] compare the two strategies of UNC and DSM. They obtain a price increase in the case of charging at peak demand and decreased average prices when charging is incentivized by electricity prices which are time dependent on the spot market prices.

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Hence, we extend previous work by a comprehensive analysis of the impacts resulting from EV charging strategies on the spot market power price for the case of Germany in 2030. At that time, the power system will be characterized by a large share of RES, the absence of nuclear power plants, and increased share of EVs. Since intermittent RES require some degree of flexibility for their integration, we focus on possible uncertainties resulting from V2G as the most flexible charging option. Moreover, we compare V2G with two other systemic flexibility options (1) highly flexible power plants and (2) grid expansion, i.e. increased net transfer capacities between the countries.

The rest of the work is structured as follows: The next section describes the applied model with a particular focus on the resulting spot market prices as well as the investigated sensitivities and scenarios. Sections 3 and 4 present the results and a discussion of potential limitations, respectively. A summary of the work is given in Section 5.

2. Methodology

First, we will describe the applied model. Subsequently, we focus in particular on the description of the retrieval of spot market prices within the model, since they constitute the core of this work. Furthermore, we illustrate the impact of renewable energy sources (RES) on prices, because they will make up a significant share of future electricity production. Finally, we give an overview on investigated scenarios and sensitivities.

2.1. EVs within a unit commitment model formulation

To quantify the effects of EVs on the spot market price, the large scale unit commitment[1] model MICOES [23] was applied. The model's objective is to minimize the system's operation cost, which is schematically represented by equation (1). Therein, the decision variables for each unit pp are the power plant production $sup_{t,pp}$ and the option to start-up $su_{t,pp}$ at time step t. The associated variable and start-up costs are C_{pp}^{var} and C_{pp}^{su}, respectively. Since start-up variables are binary, the model belongs to the class of mixed-integer problems.

$$\min \sum_t \sum_{pp} \Big\{ C_{pp}^{var} \cdot sup_{t,pp} + C_{pp}^{su} \cdot su_{t,pp} \mid sup_{t,pp} \in \mathbb{R}^+, su_{t,pp} \in \{0,1\} \Big\} \tag{1}$$

Additionally, the model includes typical unit commitment constraints, such as ramp rates, minimum run and down times or capacity restrictions. Each unit belongs to a specific region, which corresponds to a certain country. Within these regions, system constraints ensure the balance between energy supply and demand. Finally, energy flows between regions are restricted through net transfer capacities. To properly account for cross border trades, the considered countries are Germany and the directly adjacent countries. A detailed model description can be found in Böttger et al. [23]. Its structure is displayed in Fig. 1.

In this paper, we use the model extension for EVs, described in detail in Hanemann et al. [5]. There, the charging strategies UNC, DSM and V2G are implemented in such a way that UNC charges at fixed times, DSM has a certain load shifting potential and V2G also has the flexibility to feed power back into the grid.

For a better understanding of the results presented in this study, we will summarize the important equations below.

The coupling of the EVs to the unit commitment model is captured by a balance equation:

$$\sum_{pp} sup_{t,pp} + \sum_i out_{t,i} = Dem_t + \sum_i in_{t,i} \quad \forall t. \tag{2}$$

Within the equation $sup_{t,pp}$ and Dem_t represent the usual balance between power plant production and the residual grid load after substracting feed-in from RES. Each EV i contributes to the grid balance via discharging $out_{t,i}$ and charging $in_{t,i}$ of energy. It is assumed that there exists a grid connection between the last ride of the day and the first ride on the consecutive day. In the cases of UNC and DSM, EVs are restricted to charging mode only, implying that $out_{t,i}$ is equal to zero. Furthermore, UNC charging is deterministic. In this case, $in_{t,i}$ is a fixed parameter instead of a decision variable.

The upper and lower bound of each vehicle's state of charge $soc_{t,i}$ is given by a minimum ($CAP_{t,i}^{min}$) and maximum storage capacity ($CAP_{t,i}^{max}$):

$$CAP_{t,i}^{min} \leq soc_{t,i} \leq CAP_{t,i}^{max} \quad \forall t, i. \tag{3}$$

Here, $CAP_{t,i}^{min}$ can be interpreted as an emergency reserve. Additionally, intertemporal dependencies are ensured by equation (4). There, the state of charge $soc_{t,i}$ of one time period is the sum of the state of charge of the previous period $soc_{t-1,i}$, the charged energy, and an additional delta term $\Delta SOC_{t,i}$ minus the discharged energy. The coefficients η^{in} and η^{out} capture the losses for energy transfer from and to the grid. The parameters $\Delta SOC_{t,i}$ are used to model the energy contained in the EV battery which is brought back after the EV connects with and taken away once the EV disconnects from the grid. From the power systems perspective, the effectively usable state of charge drops to zero at EVs' departure. At EVs' arrival it jumps to the energy remaining after driving.

$$soc_{t,i} = soc_{t-1,i} + \eta^{in} \cdot in_{t,i} - \frac{1}{\eta^{out}} \cdot out_{t,i} + \Delta SOC_{t,i} \forall t, i \tag{4}$$

Both energy flow variables are bound by some power limit P_i multiplied by the width of the modeled time steps Δt:

$$in_{t,i} + out_{t,i} \leq P_i \cdot \Delta t \quad \forall t, i. \tag{5}$$

It is assumed that the vehicles are fully recharged before departure:

$$soc_{t_d-1,i} = CAP_i^{max} \quad \forall i. \tag{6}$$

In case that a rolling horizon approach is used as in Ref. [5], the vehicles last departure d_2 might take place after the optimization horizon T. Then, the charging requirements are ensured by equation (7).

$$CAP_{T,i}^{min} = CAP_i^{max} - max(d_2 - T, 0) \cdot P_i \cdot \Delta t \quad \forall i, \tag{7}$$

Finally, equations (8) and (9) implement boolean logic to prohibit the case of simultaneous charging and discharging. Therein, $bin_{t,i}$ are binary variables and M is a parameter, to be chosen sufficiently large.

$$0 \leq in_{t,i} \leq bin_{t,i} \cdot M \quad \forall t, i \tag{8}$$

$$0 \leq out_{t,i} \leq (1 - bin_{t,i}) \cdot M \quad \forall t, i. \tag{9}$$

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[1] Such unit commitment models belong to the broad class of mathematical optimization problems. They are typically used in conjunction with power generators either to minimize production costs while meeting a specific energy demand or to maximize the benefits from energy generation. One of the main advantages of these models is that they ensure that the multitude of technical restrictions, as they occur in reality, are met. A comprehensive overview of the progress of unit commitment problems can be found in Refs. [21,22].