Journal of Power Sources 390 (2018) 20–29

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

The load shift potential of plug-in electric vehicles with different amounts of charging infrastructure

Till Gnann*, Anna-Lena Klingler, Matthias Kühnbach

Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Str. 48, 76139 Karlsruhe, Germany

HIGHLIGHTS

- We model the market diffusion of electric vehicles and their load shifting potential.
- We analyze private and commercial PEVs in Germany in 2030 with 50% renewables.
- Commercial electric passenger cars charge different to private ones.
- We find large load shifting potentials if charging at home and at work is possible.
- 25–30% more excess renewable electricity can be integrated with PEV load shifting.

ARTICLE INFO

Keywords:
Plug-in electric vehicles
Charging infrastructure
Load shifting potential
Market diffusion

ABSTRACT

Plug-in electric vehicles are the currently favoured option to decarbonize the passenger car sector. However, a decarbonisation is only possible with electricity from renewable energies and plug-in electric vehicles might cause peak loads if they started to charge at the same time. Both these issues could be solved with coordinated load shifting (demand response). Previous studies analyzed this research question by focusing on private vehicles with domestic and work charging infrastructure. This study additionally includes the important early adopter group of commercial fleet vehicles and reflects the impact of domestic, commercial, work and public charging. For this purpose, two models are combined. In a comparison of three scenarios, we find that charging of commercial vehicles does not inflict evening load peaks in the same magnitude as purely domestic charging of private cars does. Also for private cars, charging at work occurs during the day and may reduce the necessity of load shifting while public charging plays a less important role in total charging demand as well as load shifting potential. Nonetheless, demand response reduces the system load by about 2.2 GW or 2.8% when domestic and work charging are considered compared to a scenario with only domestic charging.

1. Motivation

To attain the climate targets, it is necessary to transform the energy system. Renewable energy sources (RES) can help to decrease greenhouse gas emissions in the electricity sector. In the transport sector, plug-in electric vehicles (PEVs) can be a means to reduce greenhouse gas emissions if powered by electricity from RES. However, in a significant number, they risk to cause additional load peaks that have to be balanced to ensure a stable electricity system [49]. In order to integrate RES into the electricity system and avoid grid congestions caused by electric vehicle charging, both can be coordinated, e.g. by demand response (DR). However, the DR potential can only be realized at times when electric vehicles are connected to the grid, i.e. are parked and connected to a charging point. Therefore, a sufficient charging infrastructure is needed. The influence of charging infrastructure on the DR potential of electric vehicles is complex, since it is threefold: (i) the availability of charging infrastructure influences the market diffusion of electric vehicles and thus the amount of vehicles that can be used for DR. (ii) Charging infrastructure influences the uncontrolled charging patterns, i.e. the times at which the vehicles are recharged, and (iii) it influences the amount of vehicles that are connected to a charging station and therefore available for DR measures.

The DR potential of electric vehicles has been studied extensively, among others by Refs. [2,32,52]; and [58]. There is also extensive literature on the market diffusion of PEVs, e.g. Refs. [22,31,46,47,51,53]. Recent studies stress the importance of charging infrastructure for the market diffusion of electric vehicles [10,28,29,60], and few market diffusion models include the expansion of public charging

---

* Corresponding author.
E-mail address: till.gnann@isi.fraunhofer.de (T. Gnann).

https://doi.org/10.1016/j.jpowsour.2018.04.029
Received 7 November 2017; Received in revised form 13 March 2018; Accepted 7 April 2018
0378-7753/

infrastructure endogenously [22,31]. Besides examining domestic charging facilities [8] or their profitability, e.g. by optimizing the usage of local (renewable) energy sources [12,61], most studies focus on methods of spatial planning to analyze charging infrastructure expansion [1,62] or include additional charging at work of private passenger cars [2]. Literature examining the effect of charging infrastructure on uncontrolled charging patterns, and thus on the future system load curve is however limited: Most load models scale historical system loads using annual demand projections without considering structural changes [17,55]. Others use an extrapolation of trends identifying periodicity in historical load curves [13] or aggregate demand from different sectors to obtain a system load profile [42]. Furthermore, all three effects of charging infrastructure on the load shifting potential of electric vehicles combined have so far not been addressed.

The aim of this paper is therefore to assess the extent to which additional charging facilities contribute to (i) PEV market penetration in Germany, (ii) the uncontrolled vehicle charging patterns and (iii) shaving of peaks in the residual load.[1] This paper further considers commercial plug-in electric vehicles and the influence of public charging stations on electric load and load shifting potential. Moreover, it is analyzed how these potentials relate to other flexibility options.

For this purpose, we combine two models that have been developed and described earlier: The model ALADIN (Alternative Automobiles Diffusion and Infrastructure) is used to determine the market diffusion of plug-in electric vehicles and their charging infrastructure. Also, the use of several types of charging infrastructure (domestic, work and public) as well as different vehicle user groups (private, commercial fleet vehicles and company cars) can be analyzed. Structure and results of the model have been described in several publications [18,19,43]. The results can be taken as an input into the eLOAD (energy LOad curve Adjustment) model which aims to analyze the load shift potential of several (new) technologies of which electric vehicles are one important technology [4]. This combination permits to provide a new contribution in this field since the potential of public charge shifting as well as the inclusion of commercial fleet vehicles has to the best of the authors' knowledge not been analyzed before. In a case study, we apply the integrated modelling system to Germany and make projections for 2030.

The paper is structured as follows: first, we introduce the methods and data in Section 2. Thereafter, the assumptions for our case study are presented in Section 3. The results are shown in Section 4 before we summarize and draw conclusions for electricity suppliers and policy makers in Section 5.

2. Methods and data

2.1. PEV market diffusion: the ALADIN model

The market diffusion model ALADIN (Alternative Automobiles Diffusion and Infrastructure, Fig. 1) is an agent-based simulation model that is based on a large number of vehicle driving profiles of conventional vehicles, which are also described in the following. The model was introduced in Ref. [43] and PEV market diffusion results were published in Ref. [19]. Based on the individual driving behavior, replaceability of a conventional car by a battery electric vehicle (BEV) and the share of electric driving (often called utility factor) that could be obtained by a plug-in hybrid electric vehicle (PHEV) are analyzed. Based on this technical feasibility, the utility of four drive trains (Gasoline, Diesel, BEV and PHEV) is calculated and compared. This utility consists of the total cost of ownership for the vehicle, but also contains the cost for individual charging points (at home or a designated charging point at work) as an obstructing factor and a willingness to pay more for a plug-in electric vehicle as a favouring factor. The share of driving profiles with PEVs as utility maximizing option is considered to be their market share for vehicle sales. The sold vehicles diffuse into the vehicle stock.

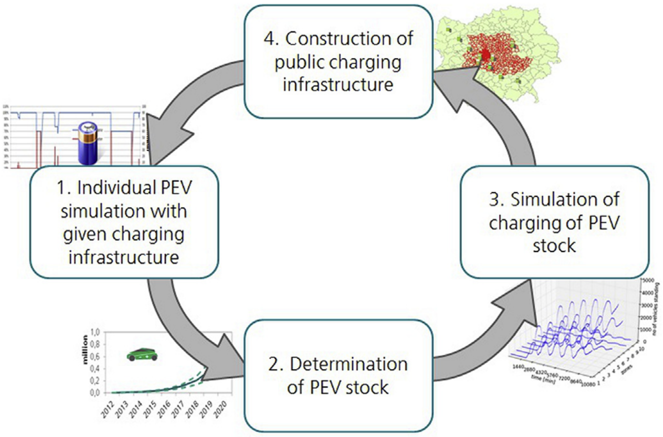

Fig. 1. Overview of the ALADIN model.

A model enhancement for the integration of public charging infrastructure was introduced in Ref. [18]. After the PEV diffusion, the charging behavior of the vehicle stock at public charging points is simulated and used to determine the energy charged in public. Based on this figure, the number of profitable public charging points is calculated and their construction simulated in the most frequented areas. This might also lead to a reduction of public charging points if the amount of public energy charged is not sufficient to cover their cost. The new public charging infrastructure is considered in the individual vehicle simulation and may lead to a higher utility of PEVs. For illustration of the model, refer to Fig. 1. For a detailed mathematical description of the model, refer to Annex A.

This model enhancement is necessary if public charging infrastructure is considered, since PEVs can only be charged in public if these charging points are free at the time a PEV arrives. Thus, they interact at public charging points, which makes a joint simulation necessary. This requires to understand geographic vehicle movements.

Hence, the main data source used in the model ALADIN are vehicle driving profiles, i.e. all trips of vehicles in a certain time period (here: at least one week). These profiles also contain socio-demographic information of the driver, the household and the vehicle in case of private vehicles as well as information about the vehicle and the company owning it for commercial fleet vehicles. Since geographical information is necessary, we use the mobility panel for Stuttgart (MOPS), and driving profiles of REM2030 from the same area for commercial driving profiles [15,23].[2] As the joint simulation of several thousand vehicles profiles is quite computation-intensive, only a part of the profiles is considered in the simulation. An overview of the full sample and the used share are presented in Table 1.

Since results for Stuttgart have to be extrapolated to Germany, the registrations are multiplied by 20.54, which is equal to the inverse of the share of the regions' registrations in Germany.

2.2. Optimal vehicle charging: the eLOAD model

The average driving, charging and different parking profiles (domestic, work, public) as well as the total number of PEVs and their

---

[1] The residual load equals the system load minus the generation of fluctuating renewable energies.

[2] Unlike in Ref. [43]; we do not use [36] which contains data representative for Germany, since we need the geographical information in MOPS. Results were tested for representativeness for the German car sales in Ref. [18] and were suitable for this purpose. Profiles for company cars were selected and information on garages and the willingness to pay more for PEVs was added and tested in Ref. [18] and will be used here.