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# Can public slow charging accelerate plug-in electric vehicle sales? A simulation of charging infrastructure usage and its impact on plug-in electric vehicle sales for Germany

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**ABSTRACT**
Alternative fuel vehicles face the lack of refueling infrastructure as one obstacle to market diffusion and potential operators of refueling stations await significant market shares before constructing a dense refueling network. The resulting lock-in effect or chicken-egg-problem has scarcely been analyzed for plug-in electric vehicles (PEVs) up to now. The research question of this article is How much public charging infrastructure for PEVs is needed and is there mutual interaction in the diffusion of public charging infrastructure and electric vehicles?
Here, we present an agent-based market diffusion model for PEVs and their charging infrastructure that is based on a large number of individual driving profiles for private and commercial car holders in Germany. Our results demonstrate the possibility of a market diffusion in Germany without any slow public charging infrastructure until 2030. Although a charging point at home is obligatory for early adopters, the second-best option for an infrastructure set-up is at work where the majority of vehicles is parked for a long time during the day, the installation is not costly and users profit more than from public facilities. Public slow charging facilities do not increase PEV market shares and they need to be subsidized for a long time.

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## 1. Introduction

The introduction of alternative fuel vehicles (AFV) may help to reduce greenhouse gas emissions from the transport sector. As AFVs are an infrastructure dependent technology, they face the problem of lacking refueling infrastructure for their introduction. Potential AFV users do not buy vehicles they cannot refuel and commercial infrastructure suppliers await a meaningful market share of vehicles so that refueling stations can pay-off. This lock-in effect is often named a chicken-egg-dilemma where none of the two parties acts, waiting for the other (Flynn, 2002; Mahler & Rogers, 1999). Some authors have suggested a simultaneous AFV and infrastructure market diffusion to circumvent this potential dilemma (BCG, 2009; Kalhammer, Kopf, Swan, Roan, & Walsh, 2007), whereas others demand an initial refueling infrastructure construction to trigger vehicle market penetration (Melaina, 2003; Schwoon, 2007) to reach a critical mass or tipping point (Flynn, 2002; Mahler & Rogers, 1999; Sterman, 2002) whereupon the system becomes self-sustaining. All of these studies support a relevant interaction in the codiffusion of AFVs and their infrastructure (see Gnann & Plötz, 2015 for a review).

The market diffusion of PEVs is a research goal of many studies. A broad review of market diffusion models for plug-in electric vehicles (PEVs) in the US is Al-Alawi and Bradley (2013) and they compared the various model approaches used (agent-based, discrete choice, diffusion models, etc.) to make recommendations for improved approaches (Al-Alawi & Bradley, 2013). Daziano and Chiew (2012) also compared PEV market diffusion models for the US. They discussed relevant factors that influence the adoption of PEVs in the US and identified additional data needed to develop improved models (Daziano & Chiew, 2012). Jochem, Gómez Vilchez, Ensslen, Schäuble, & Fichtner (2018) extended the work of Al-Alawi and Bradley (2013) and added a detailed mathematical description of models for the market diffusion without focusing only on PEVs (Jochem et al. 2018). A more recent review of market diffusion models for PEV and the factors that were included is Gnann, Stephens, et al. (2018). They find that many studies mention PEV-specific features such as limited range of battery electric vehicles (BEVs) and access to charging infrastructure as important but only very few models include them explicitly. Thus, only a few PEV market diffusion models presently cover PEV charging infrastructure.

A second line of research studies the codiffusion or even an endogenous development of charging infrastructure. Yet, the number of studies on this topic is still rare. Pasaoglu et al. (2016) and Liu and Lin (2017) analyze an endogenous modeling of charging infrastructure (Liu & Lin, 2017; Pasaoglu et al., 2016). Onat et al. (2017) integrate local charging infrastructure availability in an agent-based model (ABM) for a comparison

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/ujst.

of PEV suitability in all US federal states (Onat et al., 2017). Only a few PEV market diffusion models take the distinction of different charging options into account (Harrison, Thiel, & Jones, 2016; Lee, Park, Kim, & Lee, 2013; Liu & Lin, 2017). Public charging infrastructure exists in several countries, yet its usage is low if users have to wait for a long time or they have to pay for it (Ecotality & INL, 2012; Gnann, Funke, et al., 2018). However, potential and early users often state the lack of public charging infrastructure as one of the main obstacles in buying a PEV (Dütschke et al., 2011). Charging infrastructure has received less attention with respect to PEVs, yet probably because charging facilities are already available to many potential users: in several developed countries, the electricity grid and various outlets are usable for PEVs. Although most vehicles are parked in garages overnight (Gnann, Plötz, & Haag, 2013) and parking at work offers a second low-cost option to recharge easily, the construction of a public charging infrastructure often seems not that important. This is in contrast to other countries were the housing situation is different, e.g., in China (Zhang & Bai, 2017). In summary, despite its acknowledged importance, public charging infrastructure has been covered in a limited number of PEV market diffusion models and its impact on PEV market diffusion is not fully understood. Hence, the aim of this article is to answer the following research questions: How much charging infrastructure for PEVs is needed at domestic, commercial, work and public places to overcome the potential lock-in effect and is there mutual interaction in the diffusion of public charging infrastructure and PEVs?

In this study, we propose an ABM that treats the interaction of PEVs [here, BEVs and plug-in hybrid electric vehicles (PHEVs)] and recharging facilities at domestic, commercial, work, and public places. Slow charging points are defined according to BMWi (2015) as charging points with a power ≤22 kW, whereas charging points above 22 kW are considered fast chargers and not considered in this study. Over one million multiday vehicle-driving profiles of German car holders are simulated individually to determine the most useful drive train based on the current charging infrastructure network. The energy consumption of the PEV stock at public charging stations determines the number of profitable charging points until 2030. This article differs from other studies in the following aspects: first, we model users individually based on broad data sets with individual driving behavior over at least 1 week. This observation period longer than 1 day is crucial (Plötz, Gnann, & Wietschel, 2014). Second, we distinguish different types of charging infrastructure available to users. Third, we propose a new approach to combine PEV and charging infrastructure market diffusion. With the individual simulation of each user combined with the joint simulation for the charging infrastructure supplier. The latter two aspects are complex extensions to previous model versions (Gnann, Plötz, Kühn, & Wietschel, 2015; Plötz et al., 2014) where we modeled charging infrastructure exogenously. The explicit modeling of a combined market diffusion helps to understand the impact of public slow charging to the diffusion of PEVs. The outline of this article is as follows: the model, methods, and data are described in the next section. Thereafter, results are presented in Section 4, followed by a discussion and conclusion.

## 2. Proposal of a new model for PEVs and charging infrastructure

### 2.1. Model overview

For the codiffusion of PEVs and their charging infrastructure, an agent-based simulation (ABS) model is developed since simulation models best fulfill the requirements extracted from Gnann and Plötz (2015). (For a classification of models refer to Gnann & Plötz, 2015, Section 3.1.) In ABMs, a number of agents interact based on a set of rules over a certain time (Bonabeau, 2002) while the complexity rises with the number of agents, rules, and the complexity of rules that are integrated. According to Bonabeau (2002), an ABM is useful "when the interactions between the agents are complex, nonlinear, discontinuous, or discrete. [...] When the population is heterogeneous, when each individual is (potentially) different". It is common practice to distinguish between ABS and multiagent simulations (Hare & Deadman, 2004). The first type of ABMs is used for the simulation of individuals with different characteristics and those individuals interacting with each other (also called individual-based simulation, Huston, DeAngelis, & Post, 1988). The latter group of models additionally assumes that agents learn from each other and from their surroundings while interacting (Wooldridge & Jennings, 1995). Yet, we use the first model type where individual vehicles differ from each other in their driving behavior and their sociodemographic characteristics (see Gnann & Plötz, 2015) as well as their willingness to pay more (WTPM) for PEVs (Peters, Agosti, Popp, & Ryf, 2011). An interaction at public charging stations is not predictable without the diffusion of PEVs and their individual driving behavior. They interact when several users arrive at a public charging points the same time and only one vehicle is able to recharge. The effect of interactive learning is not modeled as no data are available to calibrate these network effects.

For the codiffusion of PEVs and their charging infrastructure, the agent-based simulation model Alternative Automobiles Diffusion and Infrastructure (ALADIN) was developed which has already been used to determine the market diffusion of PEVs (Gnann, Plötz, Kühn, et al., 2015; Plötz et al., 2014). While the earlier versions focused on the impact of energy prices, driving behavior, and non-monetary factors on PEV market diffusion, the model was largely extended to simulate the impact of charging infrastructure with an endogenous development. The explicit introduction of a charging point operator as cost-optimizing agent helps to make the modeling more realistic and better understand the impact of charging at different charging options. The model is structured as depicted in Figure 1. There are four main model steps: (1) the individual PEV simulation, (2) the individual utility calculation, (3) the aggregation in the stock model and joint PEV simulation, and (4) the optimal charging infrastructure setup by the charging point operator.

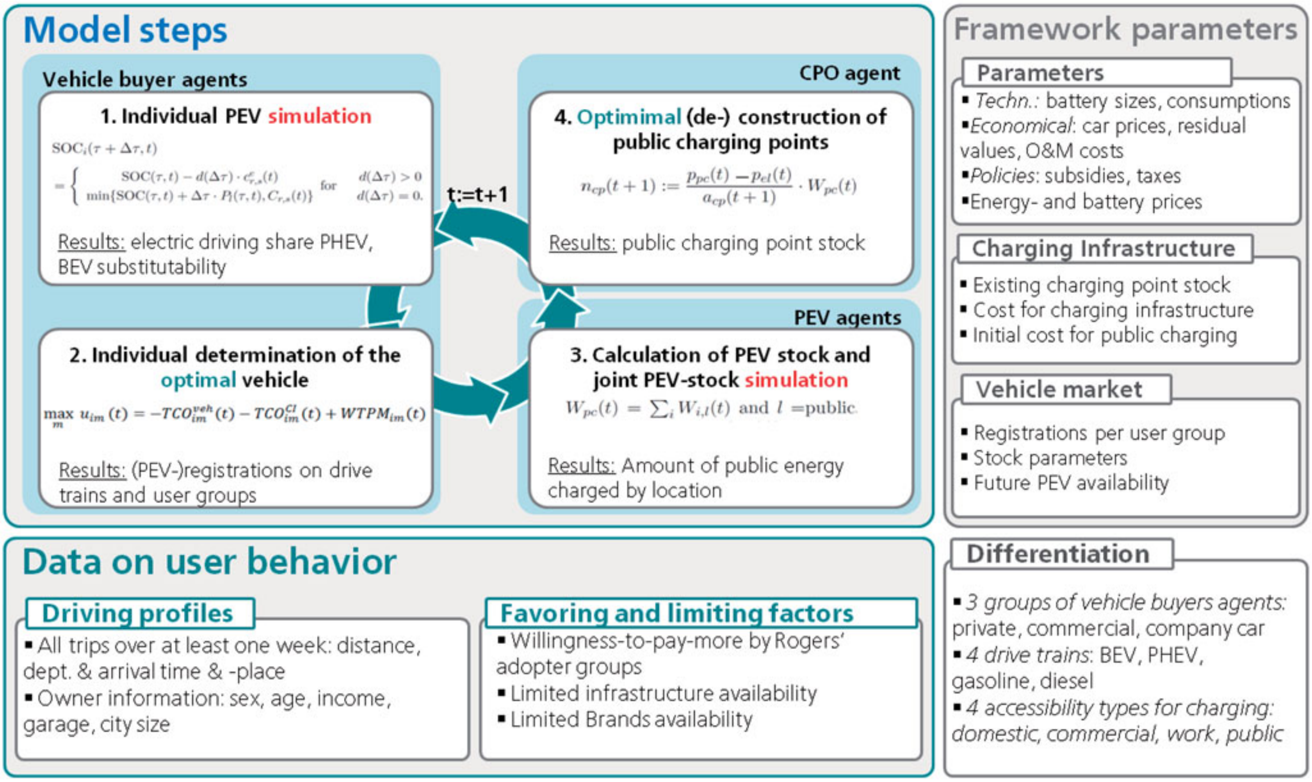


**Figure 1.** Overview of the model Alternative Automobiles Diffusion and Infrastructure (ALADIN). Based on individual driving data from private, commercial and company cars (left panel) and using technoeconomical parameters (bottom), the market shares of different propulsion technologies are determined in four steps (central panel): (1) each driving profile is simulated as PEV and conventional vehicle; (2) based on the vehicle's cost, the cost for individual charging, the limited choice of PEV makes and models and the individual willingness to pay more, the utility maximizing vehicle option is chosen; (3) the vehicle choices are aggregated to a PEV stock and jointly simulated at public charging points; and (4) the charging point operator decides about the public charging price and construction based on the amount of public charging from the previous model step.

While the first two model steps are performed individually for every vehicle driving profile, the stock model aggregates the preceding results to a market diffusion. A joint simulation of the vehicle stock allows the charging point operator to determine the public charging price and the infrastructure setup for the subsequent individual simulation.

One of the most important aspects of ALADIN is the usage of about one million real-world driving profiles. These are synthetic driving profiles from vehicles as explained in Section 3.1. As explained in Gnann, Plötz, Funke, and Wietschel (2015), the distribution and regularity of trip lengths varies strongly between different users and influences the utility of PEVs significantly. Consequently, driving profiles of at least 1 week are analyzed. Each vehicle profile is simulated as BEV and PHEV based on the existing charging infrastructure. The resulting electric driving share and annual vehicle kilometers traveled (VKT) are used to calculate the individual utility of each driving profile and vehicle option. Based on the individual utility and the additional favoring and limiting factors integrated in the model as user specific utility, the utility maximizing propulsion technology for each driving profile is chosen. The favoring factors are expressed in a WTPM[1] for PEVs that was collected in a survey and assigned to the driving profiles. The limiting factors are the limited range of an electric vehicle and its necessity of a charging option which is integrated into the model as the cost for the primary charging point and the limited availability of PEV makes reflected in the vehicle registrations. These factors are described in more details in Plötz et al. (2014) and Gnann, Plötz, Kühn, et al. (2015). The first model outputs are the individual utility of each vehicle technology and the individual purchase decision in a given year. Thus, in each user group, a share of driving profiles will correspond to PEVs. This share is then extrapolated to the annual registrations of vehicles in this user group. The technological and economical parameters vary over time and the decision process is repeated for each year. The annual registrations are built up to a stock of PEVs via a stock model.

To determine the need for public charging spots, the PEVs in stock are simulated to calculate the amount of energy charged at public charging points and act as individual agents there. This is different to the individual PEV simulation where vehicle buyer agents are simulated independently for PEV registrations. The PEV stock has to be simulated simultaneously to determine the usage of charging points. Based on the public charging cost, their batteries' state of charge (SOC) and the availability of a free charging spot, PEV agents decide to charge in a joint simulation. Thereafter, the charging point operator agent determines a new public charging price that covers the price for electricity

[1]The term WTPM is used as amount a user is willing to pay more for a PEV compared to a conventional car (cf. Plötz et al., 2014).

and charging points. Further, he decides on the optimal (de-) construction of public charging points. The market diffusion of charging points is based on economical assumptions and the return on invest since charging stations have to become profitable soon after they are built (see argument C in Gnann & Plötz, 2015, Section 2.5). In the following simulation run, these charging points can be used in the individual simulation of vehicle-driving profiles to obtain higher electric driving shares and thus a higher PEV utility. The mathematical details of the model will be described in the following subsection.

### 2.2. Mathematical description of the model

The four model steps of ALADIN are explained in the following subsections: the individual PEV simulation (Section 2.2.1), the determination of the individual utility (Section 2.2.2), the stock model and joint simulation of PEVs (Section 2.2.3), and setup of charging points by the charging point operator (Section 2.2.4).

In the following, let $i$ be a vehicle driving profile of user group $u$ (private, fleet, company vehicle), $s$ the propulsion technology (Gasoline, Diesel, PHEV, BEV), and $t$ the year of simulation. All costs are VAT exempted for commercially licensed vehicles and include VAT for privately owned cars. A vehicle-driving profile contains all trips of a vehicle within at least 1 week including all starts and stops in a certain geographic zone. These driving profiles will be further described in Section 3.1.

#### 2.1.1. Individual PEV simulation

In the PEV simulation, the battery's SOC for each driving profile to determine whether it could be performed by a BEV or which electric driving share would result for a PHEV of the same vehicle size. More specifically, the SOC is calculated for each point in time $\tau$ of the observation period of the driving profile as

$$\mathrm{SOC}_i(\tau+\Delta\tau,t)=\begin{cases}\mathrm{SOC}(\tau,t)-d(\Delta\tau)\cdot c_s^{el}(t) & \text{for} \quad d(\Delta\tau)>0\\ \min\{\mathrm{SOC}(\tau,t)+\Delta\tau\cdot P_l(\tau,t),C_s(t)\} & \quad\quad\; d(\Delta\tau)=0.\end{cases} \tag{1}$$

where the initial value for each year $t$ is given by $\mathrm{SOC}_i(\tau_i^0,t)=C_s(t)$. $C_s(t)$ is the net capacity of the battery analyzed, calculated as the gross capacity multiplied by its maximum depth of discharge (DoD), and $\tau_i^0$ is the starting time of the driving profile. $\mathrm{SOC}_i(\tau,t)$ denotes the SOC at time $\tau$ in year $t$. The distance driven between $\tau$ and $\tau+\Delta\tau$ is given by $d(\Delta\tau)$. $c_s^{el}(t)$ is the consumption of electric power in kWh/km, depending on propulsion technology $s$. $P_l(\tau,t)$ in kW describes the power for charging at the location where car $i$ was parked at $\tau$ and year $t$. If no charging infrastructure is available, $P_l(\tau,t)=0$. The locations $l$ of $P_l(\tau,t)$ are domestic, commercial, work, or public grounds ($l\in\{domestic,commercial,work,public\}$) for charging facilities, while for public charging $P_{public}(\tau,t)=(P_{public,z_{min}}(t),\ \ldots,P_{public,z_{max}}(t))^T$ and $P_{p,z}(t)$ signifies the power for public charging in zone $z$ at time $t$.

For public charging, there are additional conditions integrated: since public charging is always considered less convenient and more expensive than charging at home or work, a BEV is only recharged when (1) its battery capacity is below 50% (to return home) and (2) there is a predefined minimum number of public charging points available within the area where the vehicle is parked. The minimum number of public charging points will be determined in Section 3.2. Furthermore, (3) for PHEV also the cost for electric driving has to be lower than for conventional driving since the vehicle could drive with conventional fuel otherwise.

With this simulation, it is possible to determine the VKT with positive SOC divided by the distance of all VKT for each profile, i.e., the electric driving share that should be high because of the PEV's economics (Plötz et al., 2014). Furthermore, with increasing public charging infrastructure, the vehicle buyer considers more public charging points in his buying decision if they are above a certain threshold.

#### 2.1.2. Determination of utility

Based on this first model step, the most beneficial vehicle type from the four propulsion technologies $s$ (Gasoline, Diesel, PHEV, and BEV) for every user $i$ is determined by

$$u_{i,s}^{ann}(t)=-\mathrm{TCO}_{i,s}^{ann,\mathrm{veh}}(t)-\mathrm{TCO}_{i,s}^{ann,\mathrm{CI}}(t)+\mathrm{WTPM}_{i,s}^{ann}(t) \tag{2}$$

That is, the utility function consists of the total cost of ownership (TCO) of the vehicle $\mathrm{TCO}_{i,s}^{ann,\mathrm{veh}}(t)$, the TCO of the individual charging infrastructure $\mathrm{TCO}_{i,s}^{ann,\mathrm{CI}}(t)$, and the WTPM $\mathrm{WTPM}_{i,s}^{ann}(t)$; the latter being added to the first two terms that are subtracted and all terms are discounted to an annual value. In this function, monetary and non-monetary factors are combined in a utility function measured in EUR/yr. The inclusion of the vehicle's TCO assumes that users weigh the purchasing costs as important as the operating costs, which is a common approach for PEV market diffusion models (see Harrison et al., 2016; Liu & Lin, 2017; Noori & Tatari, 2016; Pasaoglu et al., 2016; Qian & Soopramanienen, 2015). Utility is calculated for each vehicle type. Note that, some terms can also be zero, e.g., the charging infrastructure cost or the WTPM if conventional vehicles are considered. Costs for commercial vehicles contain some specialties concerning taxes and they are VAT exempted in all calculations. Results for individual analyses of driving profiles are shown for the commercial passenger car sector in Gnann (2015). The individual best vehicle choices are aggregated in a stock model (Gnann, 2015; Gnann, Plötz, Kühn, et al., 2015; Plötz et al., 2014). We restrict vehicle sales in the first years due to the limited PEV availability derived from announcements from car manufacturers. Due to the limited PEV availability, only a share of vehicles are considered for vehicle sales (e.g., 58% of the calculated BEV market share in 2016 or 87% in 2020) and these are randomly chosen for the vehicle stock simulation (see Gnann, 2015; Gnann, Plötz, Kühn, et al. (2015); Plötz et al., 2014 for more details).

### 2.1.3. Joint EV stock simulation

For an economic operation of public charging infrastructure, a sufficient occupancy rate by PEVs in the vehicle stock is decisive. For this reason, in the simulation of the vehicle stock, not only the number but also the driving profiles of PEVs within stock are needed. The occupancy of public charging spots is analyzed in a joint simulation of PEVs that interact when arriving at a charging point. Thus, the arrival of two or more vehicles at a charging point is to be simulated with an analysis of spatial driving behavior as well. For this analysis, geographical information within the driving profiles will be used (cf. Section 3).

The charging behavior of the PEV stock determines the total electricity consumed at public charging points. Here, the same charging rules as in the individual simulation (Equation 1) apply and all PEVs battery capacities are simulated individually with the same charging rules except for the charging point density at public charging points, which is replaced by a real availability of charging points: a user may charge his PEV only if a charging point is not in use at his arrival. While in the individual simulation, every user performs a simple forecast of his driving behavior and estimates his charging shares based on his usual routes and his impression of charging stations available to him (see Section 3.2 for details), in the simulation of the PEV stock the usage of individual charging points is simulated. Whenever a BEV arrives at a charging point which is not in use and the SOC of BEV is below 50%, the vehicle is recharged. The same holds for PHEVs, where in addition electric driving with the current public charging price has to be cheaper than conventional driving. The outputs of this model step are the amount of vehicles and their energy consumption distinguished by accessibility types for each year. The total amount of electricity publicly charged $W_{pc}(t)$ is the main input for the consecutive model step.

### 2.1.4. Charging point operator

Based on the energy consumption at all public charging spots $W_{pc}(t)$ in year $t$, the number of public charging points and the price for public charging in the next period $t+1$ is determined in the fourth model step. Equation 3 shows the relationship between prices, charging points, and public energy consumed:

$$p_{pc}(t) := p_{el}(t) + p_{cp}(t) = p_{el}(t) + \frac{n_{cp}(t) \cdot a_{cp}(t)}{W_{pc}(t-1)}. \tag{3}$$

The public charging price $p_{pc}(t)$ consists of a price for electricity $p_{el}(t)$ and a price for charging points $p_{cp}(t)$ which is the number of charging points $n_{cp}(t)$ multiplied by their annual cost $a_{cp}(t)$ and divided by the total energy consumed at public charging points $W_{cp}(t)$. A charging point operator would try to get his charging points paid off, so he would try to get as much income from charging as possible, yet only so much that users still intend to charge. The annual cost for a public charging point is defined by $a_{cp} = I^{CP}(t) \cdot \{(1+q)^{T_u^{CI}(t)} \cdot q\}/\{(1+q)^{T_u^{CI}(t)} - 1\} + a_{i,s}^{\mathrm{CP,opex}}(t)$ with the discounted investment $I^{CP}(t)$, interest rate $q$, usage time $T_u^{CI}(t)$, and operating expenditure $a_{i,s}^{\mathrm{CP,opex}}(t)$. While the energy consumed is derived within the PEV stock simulation, the price for electricity and the annual cost for charging infrastructure are exogenously defined.

Since the consumption of energy charged at public charging points changes with an increasing number of PEVs, the charging point operator is assumed to build new charging points based on the current public charging price $p_{pc}(t)$ and electricity price $p_{el}(t)$, but considering the new cost for public charging points $a_{cp}(t+1)$:

$$n_{cp}(t+1) := \frac{p_{pc}(t) - p_{el}(t)}{a_{cp}(t+1)} \cdot W_{pc}(t). \tag{4}$$

Note that increasing prices for electricity $p_{el}$ or charging points $p_{cp}$ may also lead to a decreasing number of public charging points, i.e., a shut down of several public charging points.

With the number of charging points, the electricity price, and the charging point costs in the next period as well as the energy consumed at public charging stations, the public charging price for the next period $p_{pc}(t)$ is calculated with Equation 3 and the simulation can start at the first step again. Note again, that in Equations 3 and 4, the price for electricity $p_{el}(t)$ and the cost for public charging points $a_{cp}(t)$ are externally defined, while the amount of public charging $W_{pc}(t)$ is a simulation result. Both the price for electricity and the annuity of public charging points may include a contribution margin.

The mechanism to determine the zones in which charging points are built, is divided in two parts: at first, the number of charging points to be built are constructed in the zones with the highest occupancy of all vehicles. This zone occupancy is determined by the total time of all vehicles parked per km$^2$ in the observation period (cf. Section 3.2). After constructing a minimum number of public charging points, the occupancy of electric vehicles determines their setup. The minimum number of public charging points will be determined in Section 3.2. However, if the number of charging points in $t+1$ is smaller than in $t$, the lowest charging point occupancy per zone determines the deconstruction. For more details on the exact algorithm refer to Gnann (2015).

Thus, in the last part of the model the charging point operator decides on the public charging price as well as the (de-)construction of public charging points. Based on this simulation, potential PEV users may buy a PEV based on the increased utility through new charging points. Thus, the new vehicle registrations are dependent on the charging

**Table 1.** Vehicle registrations in region of Stuttgart and corresponding driving profiles.

| Attribute | Private cars | Company cars | Fleet cars |
|---|---|---|---|
| Registrations in observation area[a] | 63,772 | 39,391 | 39,391 |
| Vehicle driving profiles in data sets | 1,273,426 | 39,391 | 164 |
| Driving profiles used for simulation | 15,943 | 9,848 | 164 |

[a]KBA (2014a, 2014b) and Pfahl (2013).

**Table 2.** Considered battery sizes and resulting ranges.

| Parameter | Unit | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| BEV gross battery capacity[a] | kWh | 27 | 40 | 40 | 40 |
| BEV range | km | 121 | 189 | 200 | 212 |
| PHEV gross battery capacity[a] | kWh | 10 | 10 | 10 | 10 |
| PHEV electric range | km | 42 | 45 | 48 | 50 |

[a]Hacker et al. (2011), Gnann et al., (2012), Linssen, Bickert, Hennings, et al., (2012), and Pfahl (2013).

point stock which completes the joint simulation of PEV and charging infrastructure simulation.

## 3. Data and parameters

### *3.1. Vehicle usage data*

We use two data sets of driving profiles which all contain geographical information about the starting and stopping points of their trips.

For private vehicles and company cars, we use a synthetic data set based on a mobility survey in the region of Stuttgart Mobility Panel Stuttgart (MOPS). The data were collected in a 7-day mobility survey with about 5,000 households in the region of Stuttgart in Germany. Based on this survey, sociodemographic data of the region and trip matrices, the data set was extrapolated to the whole region of Stuttgart. Thus, this sample contains trips for 2.7 million persons, including all trips by foot, public transport, or bike with their starting and stopping zones. Those zones are different in size and smaller the closer they are to the city center (central station of Stuttgart). They range from 100 $m^2$ for the area around the central station and 10 $km^2$ at the very outside of the observation area. These sizes are defined in the data set and not possible to change by the authors of this article. As we are only interested in vehicle trips, an allocation of personal trips to vehicles is performed where unambiguously possible (Gnann, 2015) and a focus on 15-min intervals reduces the sample and complexity.

For commercial fleet vehicles, we use part of a data set REM2030 we collected ourselves for commercial vehicles that drive in the region of Stuttgart (Fraunhofer ISI, 2014; Hautzinger, Kagerbauer, Mallig, Pfeiffer, & Zumkeller, 2013). The REM2030 data were collected for 21 days on average with GPS trackers for fleet vehicles of companies all over Germany and could thus be transferred to the above described zones too. The focus on the region of Stuttgart reduces the sample size significantly, but a neglect of this user group or a modeling with private profiles would have resulted in greater uncertainty than including the small sample. Table 2 gives an overview of data sets and vehicle statistics in the observation area.

**Table 3.** Framework parameters used in ALADIN. All prices with VAT in $EUR_{2014}$.

| Parameter | Unit | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| Diesel price[a] | EUR/l | 1.45 | 1.50 | 1.58 | 1.65 |
| Gasoline price[a] | EUR/l | 1.52 | 1.61 | 1.68 | 1.75 |
| Oil price[a] | EUR/bbl | 118 | 126 | 136 | 149 |
| Electricity price private[b] | EUR/kWh | 0.29 | 0.32 | 0.33 | 0.32 |
| Electricity price commercial[b] | EUR/kWh | 0.21 | 0.22 | 0.22 | 0.22 |
| Battery price[c] | EUR/kWh | 500 | | | 266 |

[a]IEA (2013) and own assumptions.
[b]Own assumptions based on McKinsey (2012) and BCG (2013).
[c]Pfahl (2013).

**Table 4.** Cost for charging infrastructure options. All prices without VAT in $EUR_{2014}$.

| Parameter | Unit | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| Invest wallbox[a] | EUR | 404 | 370 | 343 | 323 |
| Operating cost wallbox[a] | EUR/yr | 0 | 0 | 0 | 0 |
| Invest domestic on-street charging point[b] | EUR | 657 | 537 | 444 | 372 |
| Operating cost domestic on-street charging point[b] | EUR/yr | 287 | 246 | 211 | 182 |
| Invest public charging point (3.7 kW)[c] | EUR | 1,314 | 1,074 | 888 | 744 |
| Operating cost public charging point (3.7 kW)[c] | EUR/yr | 574 | 492 | 422 | 364 |
| Invest public charging point (22 kW)[c] | EUR | 5,281 | 4,694 | 4,107 | 3,521 |
| Operating cost public charging point (22 kW)[c] | EUR/yr | 795 | 712 | 628 | 544 |

[a]3.7 kW, domestic users with garage, commercial, and work charging facilities.
[b]3.7 kW, domestic users without garage.
[c]In public places. All cost assumptions based on Plötz et al. (2013).

Since the MOPS data were designed to be representative for the vehicle stock, we randomly choose subsamples of one-quarter of registrations every year for private and company cars, while the commercial vehicle data set is used completely every year. The initial charging infrastructure stock is taken from the open access database www.lemnet.org, where 688 publicly available charging points (374 at 3.7 kW, 22 at 11.1 kW, 289 at 22.2 kW, and 3 at 43.6 kW) were found in the observation area in summer 2014 (Lemnet, 2014).

As our simulations are performed for the particular observation area, we transfer them to Germany by multiplying results by the inverse value of the share of registrations in the observation area of German registrations (20.54). This is a valid approach since the registrations of vehicles consider other factors like income, vehicle ownership, or settlement structure.

### *3.2. Static analysis of vehicle usage data*

Before starting the simulation, we need to define the minimum of public charging points per zone (cf. Section 2.2.4). In Funke, Gnann, and Plötz, (2015), differences in a geographical coverage and a user-oriented charging infrastructure set-up were discussed, finding that a user-oriented approach would need less charging infrastructure than an approach based on a predefined geographical coverage (defined number of charging points per square meter for three types of population densities). Still, if public

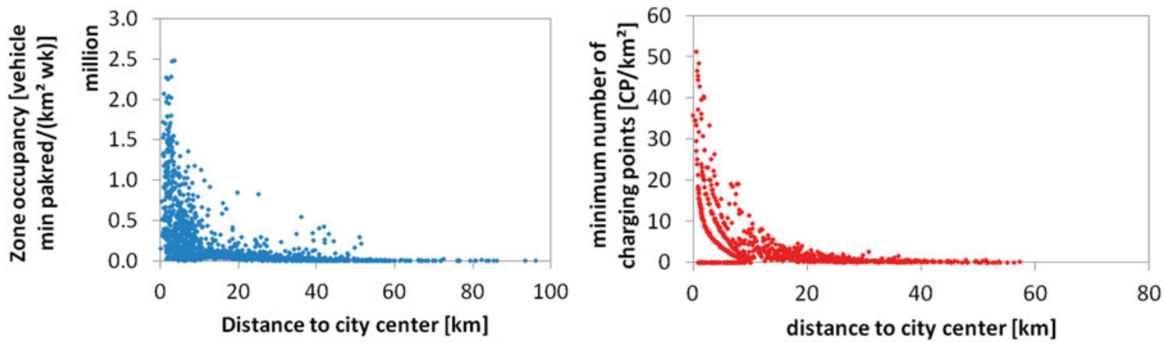


**Figure 2.** Specific zone occupancy and minimum number of public charging points in different zones in the region of Stuttgart. *Left panel*: specific zone occupancy in different zones in relation to distance to city center. Every point corresponds to one zone. *Right panel*: minimum number of public charging points in different zones in relation to distance to city center. Every point corresponds to one zone.

authorities set up charging infrastructure because of their public supply mandate, a geographical coverage is of interest. Since there is information about driving behavior and geography in the data sets, it is possible to combine both approaches. As the option to recharge publicly is given when a vehicle is parked in public places, the total vehicle minutes parked publicly per zone in the driving profiles divided by the area are summed up and defined as the specific zone occupancy. Thus, this indicator describes how many vehicles are parked how long over the full observation period while discrepancies in surface area are reflected. The indicator is shown on the left panel of Figure 2 with respect to the zone's distance to the city center (central station). It is visible that zones which are closer to the city center are more likely to have a higher zone occupancy. That implies the further one approaches the city center the more vehicles are parked publicly.

To transform this variation of specific zone occupancies to charging points, it is assumed that users wish for a charging point within every 300 m. This assumption is based on the average distance people are willing to accept to walk to the next public transport stop, which is also 300 m according to KVV (2006). With three circles that intersect in one point, the highest coverage with lowest overlap is possible, which results in 4.28 charging points per km$^2$ (see, e.g., Rune, 2001). When this average charging point necessity $\overline{CPN}$ is multiplied by the total area, the result would be the minimum number of public charging points for the geographical coverage approach (Funke et al., 2015). Instead the zone occupancy and area are used to weigh the minimum number of public charging points:

$$CPN_z = A_z \cdot \overline{CPN} \cdot \frac{occ_z}{\overline{occ}} \tag{5}$$

With $CPN_z$ being the minimum number of public charging points in zone $z$, $A_z$ the area of zone $z$ and $\overline{CPN}$ the above mentioned average minimum number of charging point, the vehicle occupancy $occ_z$ of zone $z$ and the average $\overline{occ}$ include the user-oriented approach to the analysis. The result of this equation for each zone can be found on the right panel of Figure 2 with respect to its distance to the city center.

One can clearly observe that zones that are further away from the city center (>40 km) need less charging points than those which are 10–40 km away while small zones in the city center also need less charging points because of their small size. When considering that zones are larger the further they are away from the city center, the low occupancy in the zones further away from the city center weighs larger than their area. Also the total sum of charging points necessary for the observation area (3,168 charging points) is significantly lower than with the geographical coverage (15,632 charging points). This zone-specific minimum number of public charging points will be used in the individual battery simulation where users are expected to only recharge their vehicle when the number of charging points in the zone they are stopping is equal or higher than the minimum number of public charging points ($n_{CP_z} \geq CPN_z$). Furthermore, charging infrastructure will be constructed in areas with a high zone occupancy $occ_z$ until the minimum number of charging points $CPN_z$ is reached (cf. Section 2.2.4). Note that this constraint is not considered in the PEV stock simulation where vehicles stop at a charging point and charge their vehicle if it is not in use (and the battery's SOC is below 50%).

### 3.3. Parameters

The market diffusion of PEVs is influenced by framework conditions and parameters concerning the vehicles themselves. The framework conditions include the number of new car purchases divided into segments and user groups forming the general potential for electric cars. Other parameters like the oil price and the electricity price are almost independent from an early PEV diffusion which has not reached a mass market level. Vehicle dependent parameters such as purchase price or fuel consumption form the basis for the utility calculation for each segment and user group. All parameters in the following section have been described and discussed in detail in Gnann (2015), Gnann, Plötz, Kühn, et al. (2015), and (Plötz et al., (2014) and only the most important ones will briefly be introduced here. For all other parameters, refer to Gnann (2015). All costs are given in $EUR_{2014}$ and real values for the future.

One important factor to be able to interpret results properly are the battery sizes and resulting ranges of PEVs. These are summed up in Table 6. For all BEVs, a maximum

**Table 5.** Cost and subsidies for public charging points with a charging power of 3.7 kW in three scenarios.

| Scenario | Option | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| S1—no subsidy | Real charging point annuity | 700 | 596 | 508 | 434 |
| | Annual subsidy | – | – | – | – |
| S2—subsidy until 2020 | Assumed charging point annuity | 100 | 100 | 508 | 434 |
| | Annual subsidy | 600 | 496 | – | – |
| S3—subsidy until 2030 | Assumed charging point annuity | 100 | 100 | 267 | 434 |
| | Annual subsidy | 600 | 496 | 241 | – |

All costs in $EUR_{2014}$ without VAT.

**Table 6.** Results for scenarios S1–S3.

| Result | Scenario | 2020 | 2025 | 2030 | Total subsidy |
|---|---|---|---|---|---|
| PEV stock | S1 | 0.5 m | 1.8 m | 4.1 m | – |
| | S2 | 0.5 m | 1.8m | 4.0 m | – |
| | S3 | 0.5 m | 1.8m | 3.9 m | – |
| Public charging points | S1 | 0 | 0 | 0 | – |
| | S2 | 125 | 0 | 0 | 10 m EUR |
| | S3 | 125 | 7,000 | 78,000 | 26 m EUR |

All costs in $EUR_{2014}$ without VAT.

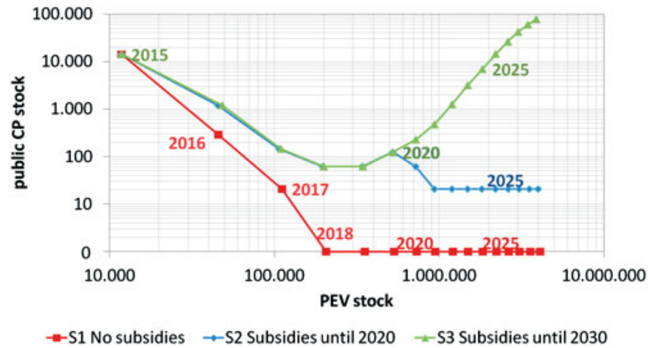


**Figure 3.** Simulation results for Germany for PEV and public charging point stock with different subsidies. Axes with logarithmic scales. Results without subsidies with red squares, for subsidies until 2020 with blue circles and for subsidies until 2030 with green triangles.

depth of discharge of 90% is used, while PHEVs may use 80% of their battery capacity (Plötz, Gnann, Wietschel, & Kühn, 2013). We consider an increase in battery size for BEVs to meet the range needs of users based on discussions with experts from the automotive industry. Combined with the electric consumption which is decreasing due to technological improvement over time, the resulting electric ranges are displayed as well.

For battery prices, electricity, and fuel prices, we use a scenario defined in Gnann (2015) which is an average scenario with not too optimistic and not too pessimistic assumptions. The battery price decreases exponentially from 500 EUR/kWh in 2015 to about half in 2030 (all values without VAT; Plötz et al., 2013). The prices for batteries used for the simulations were discussed with several experts of the German automotive industry (Plötz et al., 2013). Long-term prices are at the upper end of other existing estimates (see, e.g., Nykvist & Nilsson, 2015; Rousseau, Badin, Redelbach, et al., 2012), yet they present prices to the consumer, not at cell or pack-level. Prices for diesel and gasoline in 2015 are based on IEA (2013). Their development until 2030 is based on the New Policy Scenario in IEA (2013) reaching 1.75 EUR/l for gasoline in 2030. This corresponds to an oil price of 149 $/bbl for a constant mineral oil tax.

For Germany, several studies predict a further increase of electricity prices in the future (BCG, 2013; McKinsey, 2012; Schlesinger, Lindenberger, & Lutz, 2011). We assume the average wholesale price for electricity to rise only slightly until 2020 and to remain stable until 2030 due to the increase of renewable energies (in line with BDEW, 2014; Capros, Vita, Tasios, et al., 2013). Further, the investments for grid expansion slightly raise the electricity price (0.005 EUR/kWh in 2030). The revision of the renewable energy law of 2014 performs well and leads to price decrease of 0.02 EUR/kWh. This results in electricity prices as shown in Table 2. As vehicle sizes are not available in MOPS, all vehicles are considered medium sized.

Concerning charging infrastructure, we assume that private and company cars can charge with 3.7 kW whenever they are at home. The trip purpose "home trip" is used to decide about the parking spot of the vehicle (MOP, 2010). For fleet vehicles, the GPS-location is used to determine the distance from the company location (Fraunhofer ISI, 2014). Thus, fleet vehicles charge with 3.7 kW during the day when they are not further than 500 m away from their main company location. In addition, they are assumed to charge overnight irrespective of their charging location. Private and company car users with and without garage are differentiated concerning the cost of their primary charging point: users of vehicles that are parked in a garage are assumed to buy a wallbox for charging, while non-garage-owners have to pay for a simple on-street charging facility. Note, that we do not consider this charging point as public, since a user needs to be assured that he can charge his car overnight. This issue could also be solved with a contract from an infrastructure supplier of public charging points, yet this would limit the use of the public charging point for other vehicles. Hence, a one-to-one allocation charging points to PEVs is assumed for domestic, commercial and work charging. The assumption is discussed in more detail in Gnann, Plötz, Kühn, et al. (2015) and Plötz et al., (2014). Investment and operating cost for both solutions are given in Table 4.

The one-to-one allocation of charging points is also assumed for private and company car users at work: in scenarios where charging at work is allowed, every vehicle owner pays for his individual work charging point. As the installation is assumed to be simple, the cost for wallboxes in Table 4 is used. For public charging points, two slow-charging solutions are considered by the charging point operator: a 3.7-kW lantern charging option with one charging point and a 22-kW charging station with two charging points. While the first solution is a low-cost option, the second is an average charging point that is currently most common in Germany (Lemnet, 2014). For all charging options an investment horizon of 15 years is assumed (Plötz et al., 2013).

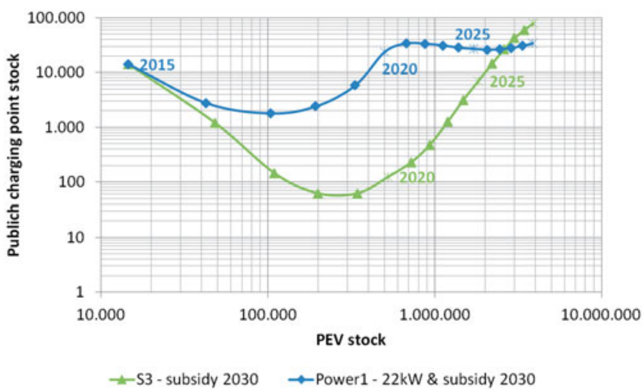


Figure 4. Simulation results for Germany for PEV and public charging point stock with variation of charging power. Axes with logarithmic scales. Results for scenario S3 with 3.7 kW (subsidies until 2030) with green triangles, charging power of 22 kW (with subsidies until 2030) with blue diamonds.

## 4. Results

### 4.1. Vehicle and charging infrastructure diffusion

Initial simulations show that public slow charging infrastructure cannot pay off without subsidies as the number of users is too small in the beginning. This is consistent with findings for other alternative fuels (Yeh, 2007). Accordingly, three scenarios with home and public charging points with 3.7 kW are analyzed in detail in this section: In scenario S1, public charging points are not subsidized while in scenario S2 the charging points are subsidized until 2020 and in S3 until 2030. The annuities of charging point costs and their subsidies are summarized in Table 5. A large subsidy for each charging point is considered for the first 5 years in scenario S2 while in scenario S3 it is phased out linearly until 2030.

Simulation results for the PEV and charging point stocks in three scenarios for Germany can be found in Table 6 and Figure 3 (S1 in red, S2 in blue, and S3 in green). This figure uses a double-logarithmic scale to compare small and large values more easily. Several years are shown to indicate the evolution over time—every marker is equal to 1 year in the simulation.

First of all, we may observe that public charging points are not able to economize when they are not subsidized (scenario S1). Already in 2018, all charging stations are taken out of order since they are not profitable. This reveals from the number of PEVs in stock at this time (about 200,000 PEVs), as the charging points have to be subsidized until a sufficient number of PEVs is in place.

Taking a look at scenario S2, the public charging point stock is not falling as much as in scenario S1; however, it is much lower (about 800 public charging points in 2020) than in the beginning (about 14,000 public charging points). After 2020, the slope is declining too, since the amount of charging by the PEV stock at these charging stations is not sufficient for a take up thereafter. Only some public charging points can be maintained for scenario S2 until 2030. From 2015 until 2030, about 10 million EUR would have to be paid for subsidies in S2. In the last scenario (S3) results differ in terms of public charging points. The number of public charging points is rising when subsidies are still in place until 2030. Although the slope of the curve is declining, it remains positive until 2030 and supposedly thereafter. Thus, a tipping point is reached in this scenario and the system becomes self-sustaining when the subsidy is faded out slowly. The investment doubles (26 million EUR) when compared to scenario S2 as the subsidy per charging point decreases after 2020. When comparing the three scenarios the difference in public charging point stock is obvious, yet the number of PEVs in the vehicle stock does not differ at all. For all three scenarios, about 4 million PEVs diffuse into the PEV stock until 2030 independent of the public charging options. That implies an impact of the PEV stock on public charging points (a sufficient number of PEVs has to be reached to pay off public charging points), yet an influence of public charging points on the evolution of the PEV stock is not noteworthy and even negative. Also, the share of PHEVs in stock is similar for all three scenarios at about 70%.

Thus, the subsidies for scenarios S2 and S3 allow to keep a certain number of charging points in the charging point stock, so charging in public remains possible after 2017. However, the sudden suspension of subsidies in S2 in 2020 decreases the number of charging points (and the amount of energy charged). Since the prices for public charging points decrease over the years the decrease of S2 to a small number of charging points is not as sudden as in scenario S1. Thus, it is possible to keep this small number of charging points until 2030 with a slightly increasing amount of energy charged at this charging point. In scenario S3 instead it is possible to maintain the slightly increasing cost for charging points after 2020 lower than the additional earnings from energy sold at public charging points. Remembering Equation 4 for the abovementioned case, let the public charging price $p_{pc}(t)$ and the price for electricity $p_{el}(t)$ be constant. Then, the number of charging points $n_{cp}$ stays stable if $\Delta n_{cp} = n_{cp}(t+1) - n_{cp}(t) = 0$ or $\Delta a_{cp} = \Delta W_{pc}$, the change in additional cost for charging points is compensated by the additional energy charged. It increases if the change in public energy charged is larger than the change in cost and subsidies, respectively. However, this is no trivial connection as the amount of energy charged depends on the number of charging points and PEVs and it is not possible to draw a simplified form of this connection.

In summary, (1) public charging points have to be subsidized to be kept in the market and (2) PEV diffusion is unaffected by the number of public charging points. (3) Subsidies to public charging points are necessary until 2030 since the amount of energy charged publicly is not sufficient to pay off earlier.

### 4.2. Variation and test of assumptions

The results presented in the previous section are subject to a number of assumptions. Several of these assumptions are varied in the following to test their influence: charging power, charging availability with additional charging at work, and the individual limit to recharge. For more tests of assumptions refer to Gnann (2015).

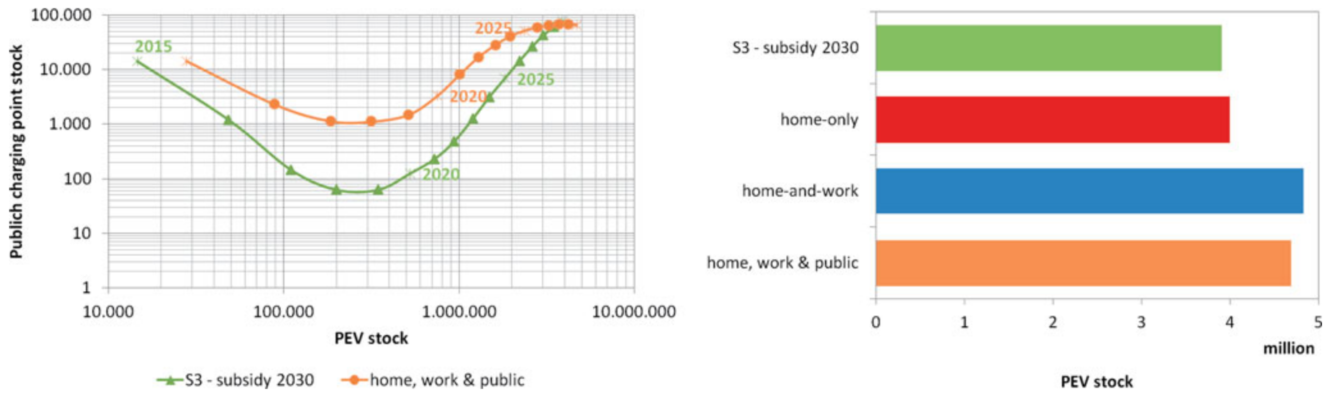


**Figure 5.** *Left panel*: simulation results for Germany for PEV and public charging point stock with variation of infrastructure availability. Axes with logarithmic scales. Results for scenario S3 (subsidies until 2030) with green triangles, additional charging at work (home, work, and public) with orange diamonds. *Right panel*: PEV stock in scenario S3 (home and public, green), and variations home-only (red), home-and-work (blue), and home, work, and public (orange).

#### 4.1.1. Increasing charging power

The first variation is to increase charging power. A scenario with 22 kW chargers that are also subsidized until 2030 is compared to scenario S3 from the previous section. In this scenario, the assumed annual costs for the charging point are cut down to 100 EUR/yr by subsidies. Results for this scenario (Power 1) and scenario S3 are displayed in Figure 4 with the PEV and charging point stock using the same display as Figure 3.

With the 22 kW variation, a slight decrease in charging points can be observed until 2017, then an increase until 2021 and from then the number stays almost equal until 2030. Remembering the calculations for the differences of additional energy charged and change in subsidies, the amount of additional energy charged after 2021 is enough to compensate the higher cost of charging points. When comparing this variation to S3, a lower number of charging points is found in 2030 (34,000 vs. 78,000) and the fluctuation is not as high as in S3. However, the number of PEVs in stock and the share of PHEVs is unaffected of this change in power.

Hence, the power at public slow charging points does not influence the market diffusion of PEVs within the technoeconomical perspective in the model.

#### 4.1.2. Additional charging at work

The second variation is to change the availability of charging options. Here, three different charging options are compared to scenario S3: (1) charging at home-only (and at commercial charging spots for fleet vehicles, respectively), (2) charging at home and at work for private vehicles, and (3) charging at home, work, and in public. Since public charging infrastructure is only contained in scenario S3 and the variation with home, work, and public charging, these are shown on the left panel of Figure 5 with the same display as in Figures 3 and 4. On the right panel, the total number of PEVs in stock in 2030 for all four options is visualized instead.

On the left panel of Figure 5, the green graph is used for scenario S3 and the orange one for the home, work, and public charging variation, i.e., in the orange variation all private users are able to recharge at work additionally. All assumptions for subsidies to public charging points are equal in both variations. One observes a slightly higher starting point in terms of PEVs in 2015 for the orange graph due to the higher registrations of private PEVs. Also the number of public charging points in the home, work, and public charging variation does not decrease as much as for home and public charging since the number of PEVs and their amount of public charging is higher. Most interesting, the number of PEVs in 2030 is higher when additional charging at work is possible for private users (4.7 million vs. 3.9 million PEVs in S3) and also the number of public charging points differs slightly with a higher number of public charging points in scenario S3. While the latter can be explained with the less frequent use of public charging points when additional work charging is available, the change in PEV stock has to be further analyzed. The question is, whether the additional charging spot at work or the combination of home, work, and public charging is responsible for the change in the number of PEVs?

On the right panel of Figure 5, the amount of PEVs in 2030 for all four charging availability options is shown. Here, it is possible to compare whether public charging may help to increase the number of PEVs in stock. By comparing the green (scenario S3) and red bars (home-only charging), it can be confirmed that additional charging in public has no positive influence on the PEV stock when added to home-only charging. It even decreases the number of PEVs slightly due to some users that may incorporate public charging in their buying decision although charging at home would have been more economical for them. Then, the utility values for PEVs for these users may be higher than for conventional fuels and the number of registrations decreases. Although this effect should not be overstated as variations are small, an influence of public charging points is not found. Comparing the blue (home and work charging) and orange bar (home, work, and public charging) in Figure 5, the same effect is visible as for the other two variations—additional public charging slightly decreases the number of PEVs. For all PEV options the share of PHEVs does not change noteworthy. In summary, (1) no influence of public charging points on PEV diffusion can be found and (2) charging at work increases the number of PEVs.

#### *4.1.3. Varying individual recharging limits*

As explained in Section 2.2.1, BEVs are always assumed to recharge in public when their battery's SOC is below 50%. The same holds for PHEVs for which driving with publicly charged electricity has to be cheaper than driving with conventional fuels additionally. This limit is changed to 70% and to 30% for two more calculations, which can also be understood as the range anxiety level of PEV users. Subsidies to public charging points are equal to scenario S3.

Surprisingly, results are almost equal for both variations and all public charging points are taken out of service until 2018. But, how can these very different assumptions return the same results? Let us turn to the variation with a limit of 30% at first. In this variation, it is assumed that vehicles are only recharged publicly when their battery's SOC is below 30%. Considering a case where a BEV arrives at a charging point with the battery SOC at 45% and it would not recharge although this would not be sufficient to return home. This may exempt several users from buying a BEV, if the individual simulation a BEV could not fulfill all his trips. Thus, only users that could fulfill their trips without public recharging would buy a BEV in this variation in the beginning, leading to a low amount of energy charged publicly and a deconstruction of charging points. Also the PEVs in vehicle stock would recharge only at a SOC of less than 30%, hence the amount of energy charged publicly would decrease even further. The variation with a 70% recharging limit suffers from a different problem: Vehicles that could return home to recharge now charge at public charging points. This increases their TCO for BEVs and they buy a PHEV or conventional car instead. In fact, results for BEVs decrease in the early years of market diffusion which decreases the amount of public charging. A higher subsidy to charging points would have been needed to keep them in stock.

These analyses show that the level to recharge for public charging points have a major impact on the number of public charging points, yet the number of PEVs diffusing into the vehicle stock remains unaffected.

Our results show that from a techno-economical point of view, public slow charging options do not increase PEV market diffusion. Public charging points only remain in the market if they are heavily subsidized. These results are robust through several tests of assumptions.

## 5. Discussion

### *5.1. Discussion of approach and model assumptions*

For the codiffusion of PEVs and their charging infrastructure, a simulation model is proposed. This is the most common approach for the interaction of AFVs and their refueling infrastructure (Gnann & Plötz, 2015). The variations in driving behavior between users and days within individual profiles favors an agent-based simulation approach with individual agents and their vehicle purchase decisions that depend on their vehicle usage (Gnann & Plötz, 2015). Hence, driving profiles for a large number of private and commercial vehicles were analyzed, both with an observation period of at least 1 week. The observation period is limited though and does not cover occasional long trips. However, the electric driving shares of PHEVs can be determined reasonably well and as the focus is on slow charging at public charging facilities and not for interim charging and range extension, the data are appropriate. A change in driving behavior is not considered though. As the vehicle purchase behavior does not only depends on cost but also depends on several non-monetary factors (see, e.g., Plötz et al., 2014) which were partly monetized in an individual utility function (Equation 2). These are the favoring WTPM for a new technology that was explicitly collected for PEVs (Plötz et al., 2014) and integrated into the model as well as the obstructing factor charging infrastructure which is integrated as cost for individual charging points. Similar approaches for the integration of non-monetary factors into the buying decision can be found in Liu and Lin (2017) and Wolinetz and Axsen (2017). The interaction between individual agents is needed when the PEV stock and their public charging point usage is simulated and a charging point operator decides about the public charging price and infrastructure stock of the following period.

The individual PEV simulation is probably more abstract or mathematical than the actual purchase decision of private users. Yet, it covers the important aspect of the regularity of an individual users' driving behavior. Users are aware of PEVs' limited electric range and understand the general economics of low operating costs for electric driving (Dütschke et al., 2011). Similarly, the TCO calculation behind Equation 2 is rather complex but the purchase and operation costs of a vehicle are an important aspect in the purchase decision both for private (Peters & Haanan, 2006) and commercial buyers (Dataforce, 2011). This is indicated by the average annual VKT for diesel vehicles (22,300 km) and gasoline vehicles (11,800 km) in Germany (Follmer, Gruschwitz, & Jesske, 2010)—reflecting the average fuel economy under the German conditions of both propulsion technologies. Accordingly, TCO calculations are a part of many PEV market diffusion models (Harrison et al., 2016; Liu & Lin, 2017; Noori & Tatari, 2016; Pasaoglu et al., 2016; Qian & Soopramanien, 2015). Along the same direction, recent studies pointed out that the costs of PEVs are a major influence factor in the purchase decision (Götz, Sunderer, Birzle-Harder, & Deffner, 2011; Gnann, Plötz, Kühn, et al. 2015; Peters & Dütschke, 2014).[2]

The charging point operator is designed to behave like a company that is cost-oriented and wants profits from its investments. The total energy charged at public charging stations retrieved from the PEV stock simulations is a key performance indicator that will be technically available for every company working with charging points. Basing the construction and public charging price on this figure would be a common approach for an economical decision making process (Section 2.2.4). An annual change might be

[2]See Plötz et al. (2014) and Peters and Haan (2006) for a detailed discussion of aspects in the vehicle buying decision.

discussible, yet the variations in the public charging price mainly depend on the change in charging point cost (see Equation 3) which changes only slightly and the availability of charging stations is the main focus of this research. An inclusion of potential subsidies through a charging point operator or state were discussed in Section 4.1. Finally, the deconstruction of public charging points could be scrutinized, yet the operating cost of public charging points is considerably high. The operating cost of the charging infrastructure (see Table 4) is larger than the annuitized investment in every year of investigation: e.g., in 2015 the annuitized investment is 127 EUR/a while the operating cost is 574 EUR/a. When the subsidies are taken into account, 83% of the sum is subsidized in scenarios S2 and S3. Still, the charging infrastructure cannot pay off in the early years, which is the reason for a subsidy that might as well be internal (from the charging point operator).[3] For this reason, charging points are taken out of service until they are needed to reduce sunk costs.

### 5.2. Discussion of results

Several assumptions for charging points were discussed in Section 4.2 in which the influence of charging power, charging infrastructure availability, SOC-limits for users to recharge, or another initial charging price were discussed. Also different strategies for the CPO for charging point deconstruction and setup as well as different battery sizes were investigated. The minimum number of public charging points also influences results as the first charging points to be built are created based on the (driving and) parking behavior of conventional vehicles. It could be better to focus on the parking of PEVs, however, in the beginning the limited number of PEVs is not expressive for the zone occupancy and a CPO would focus on the congestion and zone occupancy of conventional vehicles. With a certain number of PEVs his focus would change to PEVs. Another option would be to combine the two setup strategies, however, no good mechanism was found to combine the occupancy of a small number of PEVs (e.g., 0.5 million in 2020) and a large number of conventional vehicles (45 million conventional vehicles), since their occupancy rates differ largely. A different initial charging infrastructure could also be used, e.g., a randomly distributed. Yet, the current public charging points in the observation area are already in place and should be integrated. Moreover, in all variations most of this initial charging infrastructure is deconstructed.

The results of this article are based on the model proposed in Section 2 in which public charging infrastructure is modeled from a mostly technoeconomical point of view. In Section 3.2, a zone-specific minimum number of public charging points was defined which has to be in place for a vehicle buyer to consider it in his buying decision (see Section 2.2.1). Although minimum number of charging points symbolizes a potential barrier to the adoption of PEVs, the option to potentially recharge could have a greater influence on model results. This could be a field of further research, since data are lacking in this field.

Furthermore, there might be a psychological need and a willingness-to-pay for public charging points even when they are not used by these PEV users. This also relates to the "EV range paradox" mentioned in Franke and Krems (2013). A possible approach to include this aspect into the vehicle buying decision might be stated preference experiments as in Hidrue, Parsons, Kempton, and Gardner, (2011), IIto, Takeuchi, and Managi, (2013), and Jensen, Cherchi, and Mabit, (2013). We consider this an interesting field of further research to make public slow charging points more profitable.

Apart from the psychological value that could be quantified and added to the earnings side, the users that do not own garages could add additional earnings for public slow charging stations. Here, we assume these potential customers need their own dedicated charging option at which they recharge their car overnight. This could also occur at a publicly available parking spot and make the latter more profitable. The assumption in this article takes the long waiting times and unavailable public fast charging stations for a quick recharge into account, yet fast charging during the day might occur more often in the future and might make a slow charging option at home unnecessary.

Also, we analyzed the influence of public slow charging infrastructure where PEVs are charged if they are stopped in public. This does not consider the possibility of an interruption of trips to recharge—so-called interim charging. Yet, a higher power than 22 kW would be needed for this purpose—fast charging—which was not part of this study. Higher power rates (22 kW) at home and at work were also tested and described in Gnann (2015). Both power increases had no impact on the results for PEV sales and public charging infrastructure since vehicles are parked sufficiently long at home or work to cope with slower charging options. If the higher cost was considered for the user market shares even decreased.

We also ran simulations with different battery sizes (keeping the battery size for BEV at 24 kWh or at 40 kWh until 2030) (Gnann, 2015). This increases the market shares for PEVs (because of the lower vehicle cost) if the small battery is also used in 2030 and decreases if users already have to pay for the large battery (40 kWh) in 2015. However, we find only an incremental change to the usage of public charging points and no difference in PEV stock when scenarios with and without subsidies were run. This confirms the findings in the results section.

To the best of the authors' knowledge, there are no studies treating the interaction of PEVs and their charging infrastructure that could serve for comparison. The studies analyzed by Gnann and Plötz (2015) treated different AFV types, yet several results could be generalized to all AFVs. Köhler, Wietschel, Whitmarsh, Keles, and Schade (2010) found that only a small subsidy is needed for the initial refueling infrastructure and infrastructure was not a major

[3]Already today, we see some charging point operators switching off the charging points because of the high operating cost. The same holds for hydrogen refueling stations as well.

barrier for the diffusion of FCEVs. While the small subsidy to public charging can be confirmed with this analysis, the present study shows that public charging infrastructure is not necessary for a PEV market diffusion when PEV users buy a private or commercial home-charging point. This primary charging point is necessary for a market diffusion of PEVs.

## 6. Conclusion

In this article, the codiffusion of PEVs and charging infrastructure was analyzed with an agent-based simulation model. While the model bases on a technoeconomical evaluation of public charging infrastructure in Germany and we focus on the influence of public slow charging options ($\leq$22 kW), the following can be concluded: a market diffusion of passenger PEVs is possible without public slow charging options. This result can be transferred to other countries with a comparable availability of private slow charging options if driving does not vary much from Germany as is the case in the rest of Europe and North America (Gnann, Plötz, & Kley, 2012; Pasaoglu et al., 2014). Further, we found that large numbers of public slow charging options for opportunity charging cannot accelerate PEV sales from a technoeconomical point of view. However, a base network of public fast chargers for long-distance travel or a network of public slow chargers for users without home charging could lift some barriers to PEV diffusion. In terms of mutual interaction in the diffusion, our results show that subsidies for charging options need to be in place for a long time, since the amount of energy charged publicly is not sufficient to economize for the majority of charging points in the coming years. Apart from public slow charging, charging at work may increase the number of PEVs as may complimentary public fast charging. These different charging options and the determination of the psychological value for public charging are beyond the scope of the present work and are interesting fields for further research.

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