How to address the chicken-egg-problem of electric vehicles? Introducing an interaction market diffusion model for EVs and charging infrastructure

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Abstract

Alternative fuel vehicles (AFVs) face the lack of refuelling infrastructure as one obstacle to initial market diffusion. Also potential operators of refuelling stations await significant market shares before constructing a dense refuelling network. The resulting lock-in effect or chicken-egg-problem has been a field of research for many AFVs, but the co-diffusion of PEVs has rarely been analysed for plug-in electric vehicles (PEVs) up to now.[1] This might derive from the large availability of private charging options (simple sockets at home) or semi-public charging options (at work). The question is whether these charging options are sufficient to overcome the potential lock-in or how much additional public charging infrastructure is needed.

Here, we develop 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. Within the model, we determine the utility-maximising fuel type for each user based on cost, willingness-to-pay and the available charging infrastructure which derives from its driving behaviour and socio-demographic information. Infrastructure agents build public charging points when economically sensible.

Our results show that there can be a market evolution in Germany without any public charging infrastructure facilities, since many vehicles are parked in garages or close to a house where power outlets are already available or easy to install. The second-best option for an infrastructure set-up is at work where the majority of vehicles is parked over a long time during the day, the installation is not costly and users profit more than from public facilities. Public charging facilities can increase PEV market shares, but they need to be subsidised for a long time.

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. Some authors have suggested a simultaneous AFV and infrastructure market diffusion to circumvent this potential dilemma (NPE 2012, Kalhammer et al. 2007, BCG 2009) while others demand an initial refueling infrastructure construction to trigger vehicle market penetration (Melaina 2003, Schwoon 2006, Yeh 2007) to reach a critical mass or tipping point (Flynn 2002, Mahler and Rogers 1999, Sterman 2002) whereupon the system becomes self-sustaining. All of these studies support a relevant interaction in the co-diffusion of AFVs and their infrastructure.

1. For an overview on market diffusion models for PEVs, refer to (Al-Alawi and Bradley, 2013), for different set-up algorithms of charging infrastructure see e. g. (Chen et al. 2013, Ge et al. 2011, Lam et al. 2013, Li et al. 2011, Siefen 2012, Stroband et al. 2013, Worley et al. 2012).

This research topic has not received much attention with respect to plug-in electric vehicles yet, probably because of charging facilities already available to potential users: in most countries the electricity grid and a variety of outlets are usable for plug-in electric vehicles (PEVs). While most vehicles are parked in garages overnight (Lin and Greene 2011, Gnann et al. 2013) and parking at work offers a second low-cost option to recharge easily, the construction of a public charging infrastructure often seems unnecessary. However, potential and early users often state the lack of charging infrastructure as one of the main obstacles in buying a PEV (Dütschke et al. 2012). Hence, the aim of this paper is to answer the following research question: *How much charging infrastructure for plug-in electric vehicles is needed at domestic, work and public places to overcome the potential lock-in effect?*

The interaction of AFV and AFV infrastructure has been a field of research for some years and different drive trains were analyzed. Some studies modeled the interaction of natural gas vehicles (NGV) or liquefied petrol gas (LPG) vehicles and their refueling infrastructure. Janssen et al. (2006) studied NGVs in Switzerland with a system dynamics simulation and defined the vehicles to refueling station index (VRI = vehicles / (1,000 × refueling stations)) which tends to be one for mature NGV markets. Van der Vooren and Alkemade (2010) used an accounting model for LPG vehicles and find that lock-in occurs only when vehicles and their refueling stations reach the tipping point. Many vehicle and infrastructure interaction models treat fuel cell electric vehicles (FCEV) where the investment for an initial infrastructure is also much higher than for gas vehicles or electric vehicles as there is no supply network (like the gas or electricity grid) and transport via truck is only sensible for short distances because of hydrogen's low energy density (compared to conventional fuels) (Ball et al. 2009, Offer et al. 2010). Hu and Green (2011) study LPG vehicles and FCEVs in several countries in a macro-econometric model and conclude that the system cannot become self-sustaining without subsidies. Several studies use simple (Meilaina 2003), agent-based (Huétink et al. 2010, Schwoon 2008, Stephan and Sullivan 2004) or system dynamics models (Köhler et al. 2010, Meyer and Whinebrake 2009) to either determine the existence and height of a tipping point or to test policy options and roll-out strategies (Gnann and Plötz, i.p.).

Unfortunately there is no model that treats PEVs and none of the existing models can be used to analyze the interaction of PEVs and their charging infrastructure without major adaptations. None of the models analyzed accounts for different refueling infrastructure owners as is the case for PEVs. Neglecting this variety of recharging options does not account for the fact that charging infrastructure is already available to users. Also the duration of charging, which is significantly higher than refueling with conventional fuels when vehicles are charged at simple sockets, and the higher frequency of recharging, due to smaller energy storage capacities, cannot be covered by the current models. For a detailed response to the proposed research question, a simulation model is the appropriate choice according to the literature review. A bottom-up approach also allows us to identify market niches.

In this study, we propose an agent-based model that treats the interaction of PEVs (here, battery electric vehicles [BEVs] and plug-in hybrid electric vehicles [PHEVs]) and recharging facilities at private, work and public places. Over one million multi-day vehicle driving profiles (all trips during one week of observation) 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 recharging points until 2030. This paper 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 one week. This long observation period is crucial to reduce errors due to data sources (Plötz et al. 2014). Second, we distinguish different types of charging infrastructure available to users. To the best of our knowledge this has not been done in market diffusion models before. 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, this is unique to date.

The outline of this paper is as follows: the methods and data are described in the next section. Thereafter results are presented, followed by a discussion and conclusions.

Methods and Data

METHODS

For the market diffusion of PEVs and their charging infrastructure, a simulation model coined ALADIN (Alternative Automobiles Diffusion and Infrastructure) is used. Earlier versions of this model were used to determine the market diffusion of PEVs including the influence of charging infrastructure (Plötz et al. 2014, Gnann et al. 2014), while the model developed in the present paper includes the diffusion of public charging stations and the feedback on PEV diffusion. The integration of this feedback loop in the model is shown in Figure 1.

The model consists of four steps: (1) Every vehicle is simulated individually as PHEV and BEV based on the existing charging infrastructure. (2) Based on the battery simulation, the best vehicle option is determined for each driving profile and in case of PEV they are added to the PEV stock. (3) The usage of charging stations is determined in a charging simulation of the PEV stock followed by (4) the construction of new charging points based on the usage of the charging infrastructure stock. The new construction of charging points changes the options to recharge for users, thus a new PEV simulation is performed in a new time step. These four steps are described in more detail.

The battery simulation for every driving profile is as follows: The battery is discharged when the vehicle is driven according to the driving profile. After each trip we determine whether to charge or not and if yes, the vehicle is recharged until the next trip. The decision to charge depends on the location where the vehicle is parked which derives from the driving profiles and on the availability of infrastructure at this location: Vehicles that are privately used can always be recharged at domestic stops if charging infrastructure is available there. The same holds for stops at work if work charging is permitted in the charging scenario. Commercial fleet vehicles can charge at their company or organisation as a pendant to domestic charging facilities. If vehicles stop at a public charging spot (stop is not a domestic, commercial or work location), the PEV-type and the charging

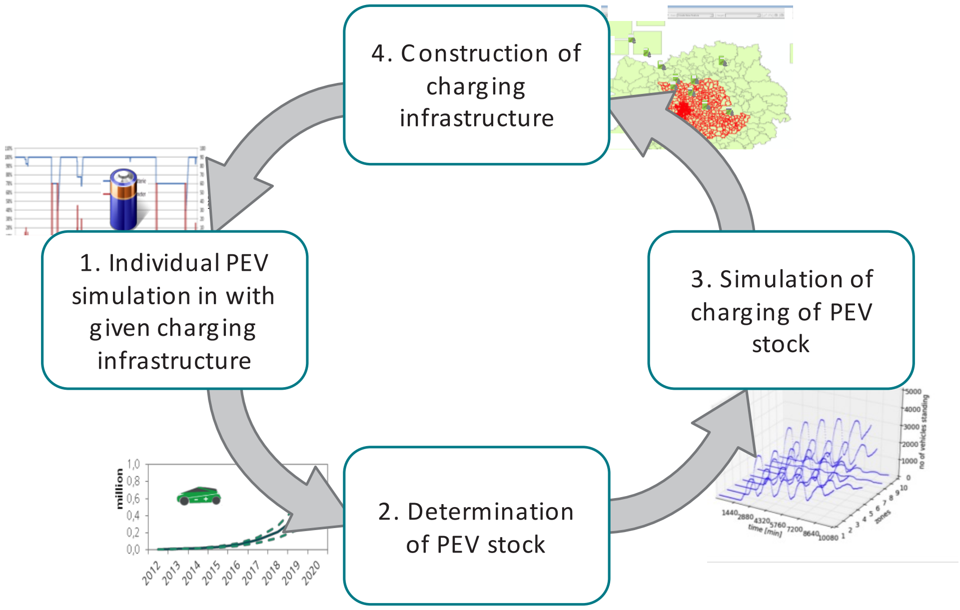

Figure 1. Feedback loop in model ALADIN.

spot necessity determine the possibility to recharge: If the battery state of charge (SOC) is below 50 %, i.e. in case the vehicle was charged completely before the last trip, the way back to the last charging facility would not be possible, and the charging spot density at the stopping point is high enough, a BEV will be charged. For a PHEV the SOC has to be lower than 50 %, the charging spot density must be high enough and the cost for driving in charge depleting mode must be lower than for driving in charge sustaining mode. Otherwise a PHEV could also use its internal combustion engine. The charging point density will be introduced and discussed in the first part of the results. With these decision rules, we can determine what shares of electricity every PEV would need at which location and include this in the buying decision. Also the ability of BEVs to perform the whole profile as well as the share of electric driving for PHEV are outputs of this step. Apart from the driving profiles as main input, we also need several vehicle parameters, such as electricity or fuel consumptions, scenarios where charging is permitted as well as the initial charging infrastructure stock.

The second model step is the determination of the PEV stock. Since the buying decision of a vehicle is based on a variety of factors, we determine the best vehicle option by utility maximisation:

$$u_{im} = -TCO_{im}^{veh} - TCO_{im}^{CI} + wtpm_{im} \quad (1)$$

The utility function includes the vehicle's total cost of ownership (TCO_{im}^{veh}), the cost for individual charging points (TCO_{im}^{CI}) as a hampering factor and the willingness to pay more (WTPM, $wtpm_{im}$) for an electric vehicle as a favouring factor symbolizing the enthusiasm for a new technology (Plötz et al. 2014, Gnann et al. 2014). Based on this equation the utility maximizing drive train is chosen. The limited number of makes and models of electric vehicles is another obstructing factor integrated in the PEV registration: Profiles with the highest use as electric vehicles are registered to the PEV stock up to this limited amount of vehicles deriving from diffusion curves of PEVs (see section 2.3.2 in Plötz et al. 2014 for details). Commercial electric vehicles in the PEV stock that are older than their average holding time (of 3.8 years) are replaced by private electric vehicles (second hand car market). The electric driving share deriving from the previous model step as well as the location-specific energy consumption serve as input to the vehicle's TCO. Vehicle-specific assumptions like the cost for operations and maintenance or vehicle tax are shown in Table 6, the cost for individual charging points as well as the WTPM will be discussed in the next subsection.

In the third step we simulate charging of the PEV stock to determine the total electricity consumed at public charging points. Here we use the same charging rules as in the individual simulation except for the charging station density which is replaced by a real availability of charging points. While in the individual simulation, every user performs a simple forecast of his driving behaviour and estimates his charging shares based on his usual routes and his impression of charging stations available to him, 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 BEV's SOC is below 50 %, the vehicle is recharged. The same holds for PHEVs where electric driving at the current public charging price has to be cheaper than conventional driving. Here, the PEV and charging point stock serve as main inputs.

Based on the energy consumption at all public charging spots the number of public charging points and the price for public charging in the next period is determined in the fourth model step. These quantities are connected via:

$$p_{pc} = p_{el} + p_{CP} = p_{el} + \frac{n_{cp} \cdot a_{cp}}{W_{pc}} \quad (2)$$

The public charging price (p_{pc} [€/kWh]) consists of a price for electricity (p_{el}) and a price for charging infrastructure (p_{CP}). The second term comprises the number of charging points (n_{cp}) multiplied by their annual cost (a_{cp}) divided by the public energy consumed at public charging points (W_{cp}). While the energy consumed derives from the PEV stock simulation, the price for electricity and the annual cost for charging infrastructure are externally defined and scenario dependent. Based on the current public charging price, infrastructure cost and electricity price, the number of charging stations for the next period is defined. With this number of charging stations, the electricity price and the charging point cost of the next period as well as the energy consumed at public charging stations, the public charging price for the next period is defined and the simulation can start at the first step again. The number of charging points of the next and the current period determine the construction of charging points. If this delta is negative (there are fewer charging points in the following period), the charging stations with the lowest usage are put out of service. The construction in case of a positive delta is performed in two phases: At first charging infrastructure is built in places with a high vehicle occupancy until the necessary charging station density is reached (see first part of the results section). Therafter the charging infrastructure is built in places with a high PEV occupancy. This two-step approach assures a minimal coverage at the beginning moving to a user-oriented approach after the coverage is given (Funke et al. 2015).

In this paper we distinguish three user groups that are important in the German car market: private users that own and use their vehicles privately, commercial fleet vehicles which are owned by companies and only used for commercial purposes as well as company cars which are company-owned but can be used privately and commercially. Also we analyze four different drive trains: Gasoline and diesel powered conventional drive trains which each account for about 50 % of the German vehicle stock while gasoline vehicles are used as short-distance and diesel as long-distance vehicles as well as plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEV). While BEVs can only run powered by an electric machine, PHEVs may also use an additional conventional motor. In this paper, we assume the vehicle to always run in charge depleting mode, i.e. the battery is discharged completely before conventional fuels are used, without differentiating different motor compositions.

DATA SETS

We use two data sets: For private vehicles and company cars we use a synthetic data set based on a mobility survey in the region of Stuttgart similar to the German Mobility Panel (MOP) which we call MOPS (Mobility Panel Stuttgart); for commercial fleet vehicles, we use part of a data set REM2030 we collected ourselves for commercial vehicles that drive in the same region (MOP 2010, Hautzinger et al. 2013, Fraunhofer ISI 2014). All these driving profiles contain geographical information about the starting and stopping points of their trips. We briefly describe their preparation in the following.

For the MOPS-data a seven-day mobility survey was performed with about 5,000 households in the region of Stuttgart (the six districts: Stuttgart, Ludwigsburg, Göppingen, Rems-Murr-Kreis, Esslingen and Böblingen – see Figure 2). Based on this survey, socio-demographic 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 including their starting and stopping zones. Those zones are different in size and smaller the closer they are to the city centre (central station). There are also zones outside the observation area in which are starting and stopping points of trips, although the home of all users is within the observation area (see right panel of Figure 2). For more details on these zones refer to Table 1. As we are only interested in vehicle trips, an allocation of personal trips to vehicles is performed where unambiguously possible (Kley 2011, Gnann et al. 2012) and a focus on 15 min-intervals reduces the sample and complexity.

The REM2030-data was collected for 21 days on average with GPS-trackers for fleet vehicles of companies and could thus be transferred to the described zones too. This reduces the sample size significantly, but a neglect of this user group or a modelling 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.

The MOPS data contains not only information about the trips, but also some socio-demographic information. This additional information about the age, sex and occupation of the driver does unfortunately not contain information about the availability of garages, company car usage or the household income and city size which were used in earlier simulations to assign the WTPM to individual profiles via cluster analysis (Plötz et al. 2014). For this reason we used the MOP to describe a subsample of company cars with the attributes: sex, occupancy, household size, number of vehicles in the household as well as the shape and scale parameters of a log-normal fit of their average daily driving which are significantly different from those of private vehi-

Figure 2. Observation area on German map (left), in detail (center) and divided into zones including surrounding outer area (right).

Table 1. Description of observation area and corresponding statistics.

Attribute	Value
Surface of inner area	3,652 km² (1 % of Germany)
Zones in inner area	1,014
Average surface of inner area zones	3.8 km² (SD=6.1 km²)
Surface of outer area	13,186 km²
Zones in outer area	140 (+20 distant zones)
Average surface of outer area zones	97.0 km² (SD=92.9 km²)

Table 2. Prepared data sets and vehicle statistics in observation area.

User group	Private cars	Company cars	Fleet vehicles
Data set	MOPS [1]		REM2030S [2]
Total no of vehicles [3]	1,273,426	39,391	164
Total no of trips [3]	18,909,380	191,049	13,374
Total vehicle registrations in observation area (2014) [4]	63,772	39,391*	39,391*
Total vehicle stock in observation area (01/01/2014) [4]	1,343,016	39,391	128,297
Subsample sizes	15,943	9847	164

[1] (Hautzinger et al. 2013); [2] (Fraunhofer ISI 2014); [3] reduced sample after assignment of personal trips to vehicles and clustering to 15 min-intervals; [4] registrations from (KBA 2014).
** Distribution between fleet and company cars is an assumption based on (Pfahl 2013).*

Table 3. Size of adopter groups and corresponding WTPM.

Adopter group	WTPM [1]	Sample size [2]
Innovators	30 %	0.5 %
Early adopter	15 %	1.5 %
(Early and late) majority	10 %	48.5 %
Laggards	1 %	50.5 %

[1] (Peters et al. 2011); [2] (Dütschke et al. 2013, Wesche 2013).

cles (see Plötz 2014 for details). Then we compare all profiles of MOPS to this subsample and define those vehicles as company cars that have the largest similarity to the company cars from MOP (all factors weighted equally). This approach is similar to the assignment of the WTPM in (Plötz et al. 2014). However, it is not possible to proceed similarly for the WTPM since we lack information about the household income and education of the drivers, thus we randomly assign a WTPM to a certain amount of private vehicles according to Table 3. The third missing attribute for our analysis is garage ownership. For this assignment we use data from (infas and DLR 2002) to determine the garage availability according to settlement structure types and assign garages randomly to a share of users in zones with the highest settlement structure type (45.1 % for Stuttgart) and to the second highest for all other users (56.8 % for other rural districts).

Since the MOPS data was 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 amount of charging infrastructure 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). For the model, all charging points are assumed to offer charging power of 3.7 kW.

With these preparations we are able to analyse the driving profiles in the above mentioned model.

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 (20.69). This is a valid approach since the registrations of vehicles contain discrepancies in other factors like income, vehicle ownership or settlement structure.

TECHNO-ECONOMICAL ASSUMPTIONS

For the simulations we need a variety of technical and economical assumptions. We only simulate medium-sized vehicles and neglect the information in REM2030-data, since there is no vehicle size information available in the MOPS-data. For BEVs we consider battery sizes of 40 kWh and a depth of discharge of 90 % which results in an average electric driving range of 180 km (2015) to 210 km (2030). The PHEV contains a battery with 10 kWh capacity allowing 42 km (2015) to 50 km (2030) electric driving distance at 80 % depth of discharge. All other vehicle parameters can be found in Annex A while battery and energy prices are shown in Table 4. Here we consider an average scenario with a conservative exponential decrease of battery prices and a slight increase of fuel prices based on the New Policies scenario of the World Energy Outlook (Pfahl 2013, IEA 2012). Electricity prices increase until 2025 due to the EEG-supplement, but profit from economies of scale for renewables in 2030 (Schlesinger et al. 2011, BCG 2013, Leipziger Institut für Energie GmbH 2012, McKinsey 2012). The investment horizon as well as holding time for first vehicles is 3.8 years for commercial vehicles and 6.2 years for private vehicles (DAT, 2011, VCD 2008). An interest rate of 5 % is assumed (Pfahl 2013).

Furthermore we assume infrastructure costs to be very low from the beginning – decreasing 5 % per year until 2030 (see Table 5). We distinguish charging infrastructure according to the four types of accessibility (at home, at work, commercial and public) and consider also for private users if they own a garage. The investment horizon is assumed to be 15 years (Kley 2011, Plötz et al. 2013). First simulations show that charging points always need to be subsidized.

Results

ZONE OCCUPANCY AND DERIVATION OF ZONE SPECIFIC CHARGING POINT DENSITY DEMAND

Before we begin the simulation we take a look at the zone specific need for charging infrastructure necessary for the individual charging point simulation. In Funke et al. (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 m² for three types of population densities). Still, if public authorities set up charging infrastructure because of their public supply mandate, a geographical coverage is of interest. Since there is information about user behaviour and geographic information in our data sets, we are able to combine both approaches. As the option to recharge publicly is given when a vehicle is parked in public places, we sum up the total vehicle minutes parked publicly per zone in the driving profiles divided by the area and define this as the specific zone occupancy. (The trip information allows us to distinguish between trips with private, work or public destinations and parking times are from vehicle-individual driving behaviour.) Thus, this indicator tells us how many vehicles are parked how long over the full observation period while discrepancies in surface area are reflected. It is shown on the left panel of Figure 3 with respect to the zone's distance to the city centre. We find that zones which are closer to the city center are more likely to have a higher zone occupancy which means that the further we approach the city center the more vehicles are parked publicly. A further analysis shows that most zones have a zone occupancy lower than 500,000 vehicle minutes parked/km².

To transform this variation of zone occupancies to charging points, we assume that users want a charging point within 300 meters. 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 meters 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 km². If we multiplied this average charging point necessity by the total area, we would receive the number of charging points necessary for the geographical coverage approach. Instead we use the zone occupancy and area to weigh the charging point necessity:

$$nCP_z = A_z \cdot \overline{nCP} \cdot \frac{occ_z}{\overline{occ}} \tag{3}$$

With nCP_z being the necessity for charging points in zone z, A_z the area of zone z and $\overline{nCP}$ the above mentioned average charging point necessity, the vehicle occupancy occ_z of zone z

Table 4. Battery and energy prices (all prices without VAT in €$_{2015}$).

Battery and energy prices	unit	2015	2020	2025	2030	Reference
Battery price	€/kWh	359	282	246	224	[1]
Gasoline price	€/l	1.274	1.339	1.408	1.471	[2]
Diesel price	€/l	1.201	1.262	1.327	1.403	[2]
Electricity price private	€/kWh	0.249	0.269	0.273	0.269	[3]
Electricity price commercial	€/kWh	0.179	0.185	0.189	0.185	[3]

[1] (Pfahl 2013); [2] (IEA 2012, MWV 2013); [3] (Schlesinger et al. 2011, BCG 2013, Leipziger Institut für Energie GmbH 2012, McKinsey 2012).

Table 5. Cost assumptions for charging infrastructure (all prices without VAT in $€_{2015}$)[1].

Vehicle group	Charging infrastructure	unit	value 2015	value 2030
Private and company cars	investment at home for user with garage	€	398	314
	variable cost at home for user with garage	€/yr	0	0
	investment at home for user w/o garage	€	635	340
	variable cost at home for user w/o garage	€/yr	279	181
	investment at work	€	398	314
	variable cost at work	€/yr	0	0
Fleet vehicles	investment for commercial car holder	€	398	314
	variable cost for commercial car holder	€/yr	0	0
All	Annual cost for public charging point	€/yr	800	450
	Annual subsidized price	€/yr	100	450

[1] (Plötz et al. 2013).

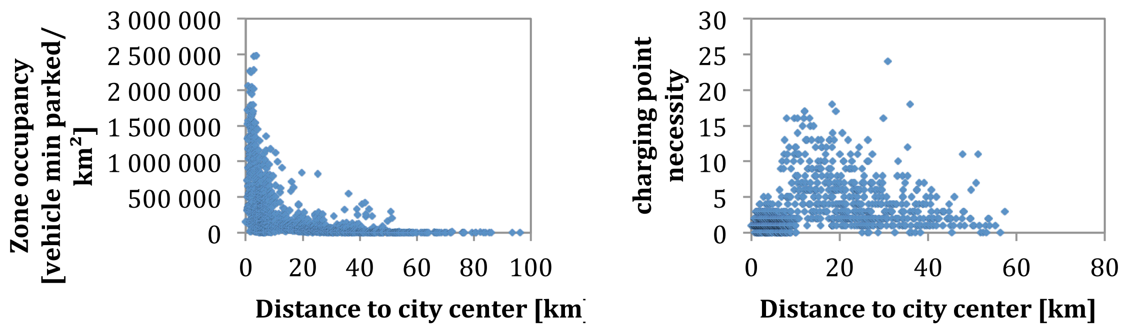

Figure 3. Zone occupancy [veh. min parked/km^2] and corresponding charging points necessary with respect to distance to city center [km].

and the average $\overline{occ}$ include the user-oriented approach to the analysis. The result of this formula for each zone can be found on the right panel of Figure 3 with respect to its distance to the city center. We can clearly see that zones that are farther 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 size.[2] Combining this information with Table 1 which showed that zones are larger in the outside area (and increase with distance from the city center which is not shown here), we find that even though these zones are larger their lower occupancy results in a lower public charging infrastructure need. 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).

We will use this specific charging point necessity in the individual battery simulation and expect that users only recharge their vehicle when the number of charging points in the zone they are standing in is equal or higher than the charging point necessity. Note that this constraint is not considered in the EV stock simulation where vehicles stop at a charging point and charge their vehicle if it is not in use (and the battery is half empty).[3]

2. Remember that the zone size increases with distance from the city center.

3. In the stock simulation, vehicles can charge if the charging station is free. In the individual simulation, the user has to assume whether his charging station might be free when he would need it. His assumption is based on the zone occupancy (the more vehicles are parked in this zone, the more charging points are needed).

SIMULATION RESULTS

We will now turn to the results of our simulations. Since the research question is to determine the number of public charging points necessary for PEV market diffusion, we define three charging infrastructure scenarios:

1. Charging is possible when vehicles are parked at home at 3.7 kW and private vehicle users pay for their private charging point. Commercial fleet vehicles charge only commercially at 3.7 kW and pay for this charging possibility.
2. Charging is possible at home and at work at 3.7 kW while users have to pay for the private charging point and the one at work. Commercial fleet vehicles are charged like in the first scenario.
3. Charging is possible at home, at work and in public at 3.7 kW. Users pay for their private charging points, the one at work while fleet users pay for the commercial charging possibility. All users pay for public charging through the public charging price which contains the costs for public charging infrastructure, but may also include a subsidy from public authorities.

First simulations show that a subsidy for public charging points is a requirement until 2030 and charging stations will be decommissioned in the first years. Thus, in the following results public charging points are always subsidized (see also Table 5).

Figure 4 illustrates the results of the simulations for PEVs (left panel) and charging points (right panel) in the three scenarios from 2015 to 2030. We can observe the following: The PEV stock rises to 4 million in the home charging scenario (1), 4.7 million in the home and work charging scenario (2) and to 4.7 million PEVs in the home, work and public charging scenario. Thus, with the availability of additional work charging infrastructure the PEV stock increases by about 700,000 vehicles. However, additional public charging infrastructure has no effect on the PEV stock.

Also for charging points we find two different curves: in the home-charging scenario, the number of charging points is equal to the number of vehicles and thus at about 4 million in 2030. In both the home and work charging scenario as well as the home, work and public charging scenario, we find about 8.2 million charging points in 2030. Thereof a about half are home charging points and almost all of the rest are charging points at work (for all private vehicles). Some slight differences are caused by the public charging points which sum up to 65,000 in 2030. The calculation of charging points is simple for the first two scenarios: in the first scenario there is one charging point per user while there is a second (at work) for every private user in the home and work charging scenario. In the third scenario there is a private or commercial charging point for every user plus one at work for every private user plus a number of public charging points available to multiple users. We show the interaction of the PEV and the public charging point stock in Figure 5.

Figure 5 shows the public charging point stock on the ordinate and the PEV stock on the abscissa. Both axes are displayed with logarithmic scales to be able to compare small to large values. We find a decrease of charging points in the beginning when the amount of public charging is not sufficient due to limited numbers of PEVs. With a rising PEV stock the number of charging points increases as well until it reaches a maximum of about 65,000 public charging points that is not growing with PEV sales any more.

When we compare the three scenarios with respect to PEVs and charging points, we find that home charging is sufficient to reach significant market shares for PEVs without charging facilities at work or in public. The number of PEVs can be increased by about 20 % if charging facilities at work were available to private users. The cost for the second individual charging point does not play a significant role here: additional calculations show 4.8 million PEVs when the cost for the charging point at work is not considered. Additional public charging points do not change EV market penetration, yet, public charging points have to be subsidized until 2030 to overcome the lock-in. With the assumed cost decrease of simple public charging facilities of 9 % per year, the necessary subsidies would total circa 86 million Euros.

Discussion

In reviewing the literature on the co-diffusion of alternative fuel vehicles and their refuelling infrastructure, no model was found that covers the interaction of plug-in electric vehicles and their charging infrastructure. The present study was designed to model this interaction explicitly.

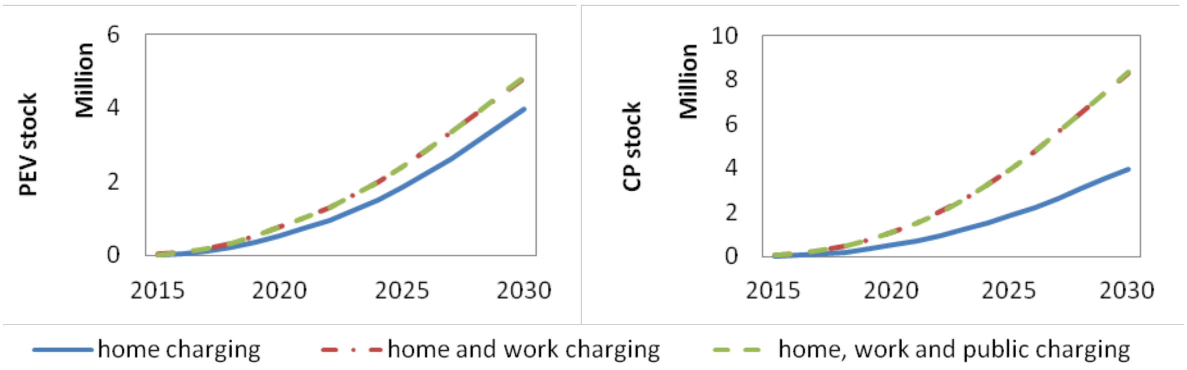

Figure 4. Stock of plug-in electric vehicles and charging points in three scenarios.

In our study we propose a model that analyses driving profiles and determines the registrations for a PEV stock model based on the individual best vehicle choices. This is an acknowledged approach for market diffusion models, but has not been used for the interaction of PEVs and charging infrastructure to this point (see e.g. Santini and Vyas 2005, Lamberson 2008, Nemry and Brons 2010). Within this individual simulation we assume that BEVs and PHEVs are only recharged publicly when their battery state of charge is below 50 % and support this assumption with the necessity to return to their previous charging facility. However, this is a simplification of driving behaviour since the consecutive trip might be longer or more following trips might afford charging even if the battery state of charge is more than 50 %. Yet, since we cannot assume that users do a perfect trip forecast when buying a vehicle, we assume this to be a useful simplification.

Based on the PEV stock, the charging infrastructure usage is re-evaluated every year and a charging point operator decides whether to build or shut down charging points. This annual evaluation is a simplification of the behaviour of a real charging point operator who would probably build some charging points during the years and evaluate less frequently. However, this simplification seems in order since the same holds for vehicles and other approaches also simulate their stock on an annual basis (see literature above).

For the model simulations we used a variety of techno-economical assumptions that are important for market diffusion. While most of them were discussed in previous works (Plötz et al. 2014, Gnann et al. 2014), e. g. the inclusion of the cost for individual charging points or the WTPM into the use function, we have to mention two more simplifications. In this paper we only consider medium-sized vehicles although the market diffusion of electric vehicles suggests that different size classes should be considered as they diffuse differently into the market. However, the private driving profiles do not permit such a distinction and our focus on charging infrastructure and its interaction with PEV diffusion justifies this simplification. In addition, we do only consider one type of hybrid solutions of PEVs, PHEVs, which can be based on the same reasoning.

Furthermore, this work does not consider fast charging infrastructure or a behavioural change in driving. In our simulations, we find that public charging points have to be financially supported to be able to economise. While fast charging stations are even more expensive (and thus need a higher charging occupancy to economise), the assumption that charging points are not available to other users for the time the vehicle is parked is not sensible for fast charging stations. They could be simulated with changing driving behaviour and recharging during trips or based on rare long-distance trips like conventional refuelling stations (Plötz 2014).

Conclusions

This study treated the co-diffusion of plug-in electric vehicles and their charging infrastructure and aimed at determining the number of charging points necessary to overcome the lock-in of PEVs and their charging infrastructure. We proposed a model that is based on more than one million driving profiles of conventional car owners. We simulate these profiles individually and determine whether they would buy a PEV based on the existing charging infrastructure. Further, the total PEV stock is simulated to determine the necessity for a construction of additional charging points in the subsequent simulation run. Three scenarios were simulated until 2030 with different amounts of infrastructure availability: home charging, home and work charging as well as home, work and public charging.

With respect to the research question, we draw the following conclusions: (1) A PEV market diffusion can occur only with domestic and commercial charging facilities. One charging point per user at the most common parking spot is sufficient for a large number of users. (2) The second best option is charging at work which is affordable for a large number of users as well. Thus, a second charging point at work increases the number of private PEV owners also when its payment is considered. (3) Public charging points can only economize if they are subsidized. A charging infrastructure supplier will not be able to earn money with low-budget charging facilities until 2030.

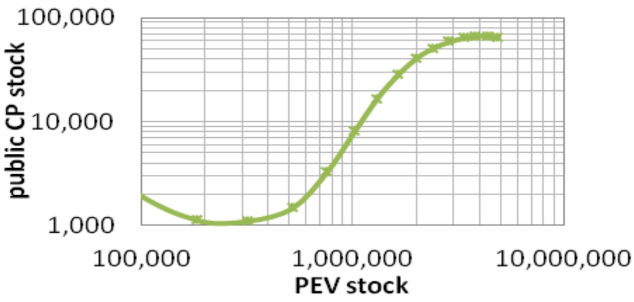

Figure 5. PEV and public charging point in third scenario (home, work and public charging).

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Annex A – Assumptions for vehicle attributes

Table 6. Technical and economical assumptions for vehicle attributes (all prices without VAT in €$_{2015}$).

Vehicle attributes	unit	value 2015	value 2030	Reference
Depth of discharge BEV	–	90 %	90 %	[1]
Depth of discharge PHEV	–	80 %	80 %	[1]
Battery capacity BEV	kWh	40	40	[1]
Battery capacity PHEV	kWh	10	10	[1]
Conventional consumption Gasoline	l/km	0.072	0.057	[2]
Conventional consumption Diesel	l/km	0.057	0.046	[2]
Conventional consumption PHEV	l/km	0.066	0.055	[2]
Electric consumption PHEV	kWh/km	0.189	0.159	[2]
Electric consumption BEV	kWh/km	0.201	0.170	[2]
Operations&maintenance Gasoline	€/km	0.048	0.048	[3]
Operations&maintenance Diesel	€/km	0.048	0.048	[3]
Operations&maintenance PHEV	€/km	0.043	0.043	[3]
Operations&maintenance BEV	€/km	0.033	0.033	[3]
Net list price Gasoline	€	17,298	18,969	[4]
Net list price Diesel	€	19,485	21,152	[4]
Net list price PHEV	€	21,677	21,116	[4]
Net list price BEV	€	17,613	17,042	[4]
Vehicle tax Gasoline	€/yr	125	101	[5]
Vehicle tax Diesel	€/yr	226	209	[5]
Vehicle tax PHEV	€/yr	34	34	[5]
Vehicle tax BEV	€/yr	0	0	[5]

[1] (Hacker et al. 2011, Gnann et al. 2012, Linssen et al. 2012, Pfahl 2013); [2] (Helms et al. 2011); [3] (Propfe et al. 2012); [4] (Pfahl 2013); [5] (BMF 2014).