What is the future of public charging infrastructure for electric vehicles? – A techno-economic assessment of public charging points for Germany

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Abstract
Electric vehicles are able to reduce local and global emissions from the transport sector and thereby could help to slow down global warming if they achieved significant market shares. As all other vehicles, they need a charging or refuelling infrastructure to be built up simultaneously to vehicle market penetration. With the current disability to store energy for long distance trips in batteries, the need for a dense charging infrastructure appears to be even higher. On the other hand, many car users could charge at home in their private garages. The question therefore is whether domestic charging infrastructure is sufficient to trigger market penetration of electric vehicles. Or in other words: Do we need public charging infrastructure for a mass market diffusion of electric vehicles and if so, how much? Here we discuss technical and economic aspects of this question. Large data sets of German driving profiles are analysed to estimate the share of vehicles that could technically be operated as electric vehicles. In addition, the driving behaviour is combined with a simple market diffusion model for electric vehicles and their corresponding charging infrastructure where each user is assumed to choose the fuel option with the lowest total costs of ownership. We can thereby quantify the share of vehicles that can be replaced by electric vehicles and estimate the market diffusion of public charging points. We find that this technical and economic analysis does not justify a large development of public charging infrastructure which is confirmed by empirical user behaviour data in pilot projects where not more than 10 % of all electricity for driving is charged publicly.

Introduction
Motorised transport is responsible for a large share of global greenhouse gas (GHG) emissions. Where the specific CO_2 emissions of internal combustion engine vehicles are fundamentally limited, electric vehicles offer large emission reduction potentials when using low-carbon electricity from renewable energy sources. However, electric vehicles (EVs) are not fully comparable to conventional vehicles: battery electric vehicles with prices of the order of similar conventional vehicles have a range that is significantly smaller and plug-in hybrid or range extended EVs reach high electric driving shares only when used within a limited range. Public charging infrastructure appears to be a remedy for these limitations just as fuel stations allow refuelling for trips which are much longer than the normal range of internal combustion engine vehicles.

Charging infrastructure thus seems a supporting or even necessary instrument for a large scale introduction of EVs. However, public charging infrastructure is rather expensive to install and major public investments seem necessary as long as viable business models are absent. Taken together, we face a wish for public charging infrastructure for EVs in contrast to much uncertainty about financing and the future developments of the number of available charging options which are required as input for designing business models. Thus, the aim of the present paper is to answer the following question: Which future development of (mainly public) charging infrastructure seems likely, taking into account costs, technological options and actual user behaviour?

For the rest of the paper we will use the term "electric vehicle (EV)" throughout for plug-in electric vehicles (with four wheels). This includes battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), range extender electric vehicles (REEVs) but excludes hybrid vehicles (often abbreviated HEVs) since the latter are not able to run on electricity alone and are therefore not relevant for charging infrastructure. The article describes the current status of public charging infrastructure with examples form three major vehicle markets: the US, UK and Germany. Methods and data are introduced and the results are presented for technical and economic aspects of charging infrastructure separately. In the conclusions, the main findings are discussed.

The present status of public charging infrastructure

In order to discuss the future evolution of electric vehicles, we analyse the starting point of the evolution, i.e. the current status of EV registrations and public charging infrastructure.

CURRENT MARKET PENETRATION OF ELECTRIC VEHICLES AND CHARGING POINTS

Since we are in an early stage of market evolution for EVs, numbers of EVs in markets change quickly. We tried to retrieve the most up-to-date figures possible. However, in several cases official registration statistics are not available to date. In order to estimate the approximate number of EVs in the different markets, sales of several months and even recent years were added. This induces errors since an EV sold several years ago could have been scrapped by now. Accordingly, the number of EVs in the different markets below should only serve as estimates. We limit our discussion to three major car markets: The United States of America (U.S.), Germany and the United Kingdom (UK).

In the U.S., about 60,000–70,000 EVs are registered by the end of 2012 (EVIX 2012). As of 1.1.2012 4,541 EVs were officially registered in Germany (KBA2012) and 2012 saw additional 2,695 EVs being sold from January until November (Car Sales Statistics 2012) leading to approximately 7,200 registered EVs as of December 2012. Approximately 3,300 EVs are on the roads in the UK by the end of 2012. This is a sum of about 1,000 EVs registered up to 2010 (SMMT 2011) as well as 1,027 new registrations in 2011 and 1,614 new EV registrations by November 2012 (SMMT 2012).

In comparison to conventional gas stations the current number of charging points is difficult to estimate. Despite several searchable maps or databases for different countries (see below) accurate and comparable data is difficult to obtain for several reasons:

- There is ambiguity in counting either the number of charging points or charging stations where a single charging station can easily have two or four charging points.
- Since electricity is widely available for private and commercial consumers, either private or public or both charging options can be counted (see below for the US).
- Many different organisations offer public charging. This fragmented market structure makes statistics more difficult than it is in more oligopolistic markets such as, e.g., for conventional gas stations where a few companies are often organised in associations and jointly publish statistics on the station network, such as, e.g., EUROPIA (2012).

Thus the actual number of publicly available charging options is difficult to obtain for the different countries. In the U.S. about 5,200 public charging points should be available with about 1,000 public charging points in California alone (DOE2012a). However, according to a second DOE reference (DOE 2012b), the U.S. has approx. 14,000 public and private charging units, of which roughly 3,500 are located in California (DOE 2012b, Chargepoint.com 2013). However, the latter list explicitly mentions that "public and private alternative fuel station[s]" are included and "electric charging units are counted once for each outlet available" excluding residential charging infrastructure (DOE 2012b). Similar to the U.S., several organisations offer public charging points in Germany and approx. 3,000 are listed in a large database for public charging points in Germany (Lemnet 2012). Approx. 1,220 public charging points are available in the UK, including about 140 labelled as "coming soon" (Next Green Car 2012).

CURRENT USAGE OF CHARGING POINTS

Public charging points are expensive as investment, installation and maintenance costs are high. With low electricity prices and a limited profit margin that can possibly be added as a supplement to refinance the charging point, the degree of utilization has to be very high. While there are lots of research projects with field studies running at the moment, only very few report the usage of the charging infrastructure which is often set up in these projects (Gnann, Plötz and Wietschel 2012b).

The American EV-project is a field test with electric vehicles carried out from 2011 until 2013 in the United States. Within this project, 1,000 public charging points are available to 4,500 EV-users, which are used for 9 % of all charging events (Ecotality and Idaho National Lab 2012, p. 7). Only 8 % of the total energy consumed by the electric vehicles of the project is charged at these public charging points. The same holds for the British project CABLED where 110 EV-owners recharged their vehicles in 92 % of all charging events at home or at work and just 3–8 % at public facilities (Bruce, Butcher and Fell 2012).

In the German model regions of e-mobility there are no results published regarding usage and degree of utilization of charging infrastructure, but presentations and talks to project managers indicate similar percentages (Bieberbach 2010). Although users state their wish for more public charging points in surveys, this might simply be caused by range anxiety reasons while the actual usage could be the same (Dütschke et al. 2011; Tate, Harpster and Savagian 2008, 3).

CURRENT AND FUTURE FRAMEWORK OF ELECTRIC VEHICLES AND CHARGING POINTS

The range of an EV is determined by the vehicles' energy consumption and the battery's energy density (mass or volume related). It could be extended by future battery technologies with higher energy density but experts do not expect a significant increase within the next 15 years. The currently dominating Lithium-ion battery technology is expected to reach 125 Wh/kg and 200 Wh/l by 2030 from today's approximately 100 Wh/kg and 125 Wh/l (Thielmann et al. 2012 – all numbers for battery *systems* which are more relevant for our discussion of EV ranges than battery cell energy densities). This includes Lithium polymer batteries and Lithium ion batteries at different voltages. Lithium sulphur batteries might become commercially available around 2020 with energy densities by a factor of two (volume density) or three (mass density) higher than current Lithium based batteries. However, the inclusion of newly developed battery technologies in vehicles and the mass production at sufficiently low prices requires roughly another ten years such that we exclude a significant increase of EV range by increased battery technologies until 2030.

The range of EVs could of course also be extended by using larger batteries, i.e. more battery cells and accordingly more kWh such as the Tesla Model S uses (85 kWh in comparison to 24 kWh for the Nissan Leaf). However, this strongly increases the vehicle purchase price (as well as its weight and therefore consumption) and in order to address mass markets (which is not the case for the Tesla Model S) the vehicles price must be close to the price of a conventional vehicle of similar size (see Dimitropoulos et al. (2011) for a survey of willingness-to-pay studies). We therefore exclude a simple increase in EV range by adding battery cells from our discussion.

In addition to the limited speed of technological evolution, the rate of vehicle stock renewal poses a limit to the speed of increase in EV charging infrastructure demand. The current rate of change in vehicle stock in Europe is slow and very likely to remain slow. Currently, only 7–10 % of the vehicles in stock are renewed per year in major European countries. In other words, even if all future vehicles sold were EVs, it would take approximately 10–14 years for all registered vehicles to become electric vehicles. The actual sales share of EVs is likely to remain below 50 % for many years (similarly to slow adoption of diesel cars in Germany) and even more the share of EVs in stock. Thus, until 2030 only a certain share of vehicles clearly below 50 % will be EVs and accordingly infrastructure will not be needed to satisfy all drivers but only a certain fraction.

Methods and Data

Within this uncertainty about future demand for and evolution of public charging options, technology assessment can provide insights and hints concerning more likely or less likely developments of a technology and support both decision making and public discussions (Grunwald 2009). The approach we are following here can roughly be summarised as follows: (1) We combine today's user behaviour with the opportunities that upcoming technologies offer including the costs anticipated for these technologies. (2) With this input, we decide at which costs current user needs can be fulfilled. (3) Our conclusions for the probability of future technologies are based on the simple assumption: The more important the need and the lower the cost to fulfil it, the more likely is the development. This method of anticipating likely or unlikely future developments clearly has limitations and drawbacks. We do not include changing usage patterns or fundamental changes in attitudes or values. For example an expensive service that does not seem very rewarding for current consumers might become so (including an acceptance of higher prices) in the future but is excluded from our analysis.

METHODS

In our work we analyse driving profiles by simulating the battery profile to receive the technical EV-potential. This technical potential tells us if a BEV would be able to do one whole profile with a fixed battery size. In case of a PHEV, the technical potential describes what electric driving share would be possible in different infrastructure scenarios. We then continue with a macro- and microeconomic analysis.

Technical EV-potential – battery profile simulation

In the simulation of the battery profile, we use the following formula to calculate the battery state of charge (SOC):

$$\mathrm{SOC}(t+\Delta t) = \begin{cases} \mathrm{SOC}(t) - d_{\Delta t} \cdot c \\ \min\{\mathrm{SOC}(t) + \Delta t \cdot P_{loc_t}, C\} \end{cases} \quad (1)$$

$$\text{for} \quad \begin{matrix} d_{\Delta t} > 0 \\ d_{\Delta t} = 0 \end{matrix}$$

with a fully charged battery at the outset (SOC(0) = C). The battery is discharged (upper case) when distances d are driven ($d_{\Delta t} > 0$) in the time period Δt. In case the car is parked (lower case, $d_{\Delta t} > 0$), the battery is recharged with power P_{loc_t} at location where the car was parked at time t which depends on the available charging infrastructure. If the battery is fully charged (SOC(t) = C), we keep the state of charge at C We do this calculation individually for each user's driving profile and can thus determine the minimal battery capacity for a BEV for each driving profile, as well as the electric driving share of each user with a given battery capacity.

In the following analysis we use time periods of 15 minutes and an average consumption of 0.196 kWh/km which is the consumption for a medium-sized car, representing the largest vehicle segment in Germany (Helms et al. 2011; KBA 2011). The driving information derives from the driving profiles and infrastructure scenarios which will be explained below, the battery capacity remains variable. For further details on battery profile simulation see (Gnann, Plötz and Kley 2012).

Macroeconomic approach

With the technical potential described above, we can determine what share of driving profiles can be replaced by a battery electric vehicle with a given battery capacity κ in a charging infrastructure scenario IS (Kley 2011; Gnann, Plötz and Kley 2012, p. 5; Gnann, Plötz and Wietschel 2012a, p. 2). As described in (Gnann, Plötz and Wietschel 2012a) we may add additional users (Δs) by increasing the battery size ($\kappa+\Delta\kappa$) or by additional infrastructure ($IS+\Delta IS$). Within the macroeconomic approach we want to find out what option is cheaper, i.e. determine which investment is lower when both additional shares of users are equal:

$$\Delta s(IS + \Delta IS) = \Delta s(\kappa + \Delta\kappa) \quad (2)$$

Here we consider two cases which differentiate in who has to bear the investment:

- Case (1): only additional users bear the investment for charging infrastructure, e. g. as a supplement to the electricity price when charging at the charging point.
- Case (2): all EV-users share the investment, e. g. as an EV-tax payment.

Investments for a semi-public charging point are considered 2,500 Euro and 5,000 Euro for a public one (Kley 2011; NPE 2011). For more detail on this calculation see (Gnann, Plötz and Wietschel 2012a).

Microeconomic approach

In the microeconomic approach we determine the total cost of vehicle ownership for every user individually and include the cost for charging infrastructure. This can be regarded as a bottom-up approach similar to the top-down approach in case (1) in the macroeconomic analysis. We do this by finding every user's car option with the lowest total cost of ownership (*TCO*) discounted to one year:

$$TCO^a = a_{capex} + a_{opex} \quad (3)$$

With TCO being the sum of the capital expenditure a_{capex} and the operating expenditure a_{opex}, the capital expenditure in one year can be calculated using the discounted cash flow method by discounting the investment *I* with the annuity factor:

$$a_{capex} = I \cdot \frac{(1+i)^T \cdot i}{(1+i)^T - 1} \quad (4)$$

with interest rate *i* and time horizon *T* In the calculation investments are split into investments for the car without battery, the battery itself and the necessary charging infrastructure option, since all three may have different time horizons and interest rates given in ANNEX A.

As for the operating expenditure, we have costs that depend on driving and costs that do not:

$$a_{opex} = VKT \cdot (s_e(t) \cdot c_{el} \cdot k_{el} + (1 - s_e(t)) \cdot c_{conv} \cdot k_{conv} + k_{O\&M}) + k_{tax} + k_{IS} \quad (5)$$

The part depending on the vehicle kilometres travelled per year *VKT* is the share driven in electric mode $s_e(t)$ times the electric consumption c_{el} and the electricity price k_{el} plus the share driven in conventional mode $(1 – s_e(t))$ multiplied by the conventional consumption c_{conv} and the fuel price k_{conv}, plus the cost for operations and maintenance $k_{O\&M}$ The driving independent part is the sum of cost for vehicle tax k_{tax} and for charging infrastructure k_{IS} All parameters for this calculation are given in ANNEX A.

Summing up all drivers that could complete their profiles with an electric vehicle and dividing it by the total number of driving profiles we obtain the share of potential EV-users in the sample. With varying parameters in the TCO-calculation this share changes over time and we can calculate the number of EV-users (which is in this case equivalent to the number of charging points) in a simple stock model as:

$$N_t = N_{t_0} + \sum_{\tau=t_0}^{t} \sum_{u} (R_{u,\tau} \cdot s_{u,\tau}) - S_\tau \quad (6)$$

This means the number of electric vehicles N_t in year *t* is the initial number of electric vehicles N_{t_0} plus the share of electric vehicles $S_{u,\tau}$ in user group *u* times the registration of new vehicles in this user group $R_{u,\tau}$ in every year subtracted by the scrapping S_τ in each year.

In our calculations we distinguish between private and commercial users, as these two have significantly differing characteristics, while here especially the higher amount of VKT in the commercial sector is the relevant factor (Gnann et al. 2012, p. 10, 11). The different driving profiles for the calculation are described in the following section, the initial number of EVs as well as the scrapping in every is assumed to be zero as we just regard a total time horizon of eight years (until 2020). All other parameters can be found in Annex A.

GERMAN DRIVING BEHAVIOUR AND INFRASTRUCTURE SCENARIOS

As indicated in the previous section, we need driving profiles for the simulations as well as several infrastructure parameters for the different calculations.

Driving Profiles

For German driving behaviour there are five large collections of movement profiles: the German Mobility Panel (MoP), Mobility in Germany (MiD) for 2002 and 2008 and Motor traffic in Germany (KiD) for 2002 and 2010 (MOP 2010; infas and DLR 2002; infas and DLR 2008; IVS and TU Braunschweig 2002; WVI et al. 2010). As MoP and MiD are mainly for the private sector and KiD is the only one in commercial traffic, Fraunhofer ISI collected data itself in the project REM2030 (Fraunhofer ISI 2012). We compare the data bases used in the present paper in Table 1 to explain the main differences.

We can see that these data sets do not only differ in the type of collection, but also in time horizon and amount of data. (Given is the amount of data that is used in the analysis, which reduces the initial sample of MoP because of non-distinct driver-vehicle-allocation and of MiD because of missing information.) For our analysis it is better to have a data collection with longer time horizon as the upscale to VKT from a single day might cause a bias (Gnann, Plötz and Kley 2012; Gnann et al. 2012). So we prefer a longer observation time horizon over a better representation of the user group which would be given with a higher amount of data.

For all calculations regarding the technical and macroeconomic potential, we use the MoP as only data set. As this collection does not contain differentiated information about the usual parking spot during the night, we use MiD2002 and REM2030-profiles for the microeconomic analysis.

Table 1. Data sources on German driving behaviour.

Name	MoP	MiD	REM2030
Years of collection	1994–2011	2002, 2008	2011, 2012
User group	Private households	Private and some commercial users	Commercial vehicles
Type of collection	survey	survey	GPS-tracking
Time horizon	7 days	1 day	21 days
Amount of data	6,629 vehicles 118,029 trips	12,478 vehicles 75,279 trips	263 vehicles 48,899 trips

Infrastructure Scenarios

In the simulation we need charging infrastructure scenarios, which tell whether charging is possible (and at what power rate) at the stopping points of the driving profiles. For the technical and macroeconomic potentials we do use three scenarios (see Table 2) which are divided in private, semi-public and public charging locations. This differentiation is used in several other publications, specifying that private charging points can only be accessed by the car owner, semi-public by a certain group of people (e. g. a sports club) and public spots are open to everyone (Becker, T. A. 2009; Wietschel, Kley and Dallinger 2009). The information about the stops derives from the driving profiles which contain trip purposes that are converted into stopping locations (For MoP we set trips with trip purpose 7 or 77 to private locations, purposes 2 and 4 to semi-public ones and all others to public locations).

There is scenario A where charging infrastructure is only available at private locations with a power rate of 3.7 kW. In scenario B we add charging points at semi-public facilities with power rates of 11.1 kW, while in scenario C charging at 11.1 kW is also possible at all public stops.

In the microeconomic analysis, we use just one infrastructure scenario which defines that vehicles are able to charge overnight at a power rate of 3.7 kW. We do this to not overestimate the potential of private users in the MiD since they only drive one day. In addition, we do not know the trip purposes for commercial vehicles as the data is collected electronically with GPS-trackers.

Technical aspects of future charging points

This section analyses the technical aspects of future charging points for every day use and rare long-distance use of potential electric vehicles.

Table 2. Infrastructure scenarios for private users (charging powers in kW).

Scenario	Private	Semi-public	Public
A Home-only	3.7	–	–
B Home-and-semi-public	3.7	11.1	–
C Everywhere	3.7	11.1	11.1

EVERY DAY USE OF POTENTIAL ELECTRIC VEHICLES

Let us start by analysing the influence different charging options would have if all vehicles with their current usage patterns were to be replaced by electric vehicles. For BEVs this means to analyse the share of vehicles that could be operated as BEVs. For PHEVs, the likely effect of different charging options can be studied by analysing the changing electric driving share. To this end, we perform the battery simulation described above (see Battery Simulation in the Methods and Data section) and count the number of share of vehicles displaying only SOCs larger than zero. We use the data for Germany including the trips of one week (MoP, see Data section above). Please note that demanding the possible replacement of all day trips in one week per user is more restrictive than all day trips in single day per user, since the occurrence of longer trips is not covered in daily driving profiles and thus could lead to a misjudgement on the substitutability of conventional vehicles (see Gnann, Plötz and Kley (2012) for a discussion of the difference).

Figure 1 shows the share of vehicles from the sample that could be operated as BEVs as a function of battery size. Here we use the total battery size, of which the share of 80 % (depth-of-discharge) is used. Given a battery of 20 kWh in total and charging at home only, about 60 % of the users could drive all their trips of one week using a BEV. This share increases by about five per cent if all users were able to charge at work and by about 10 % more if all users were able to charge anywhere. The

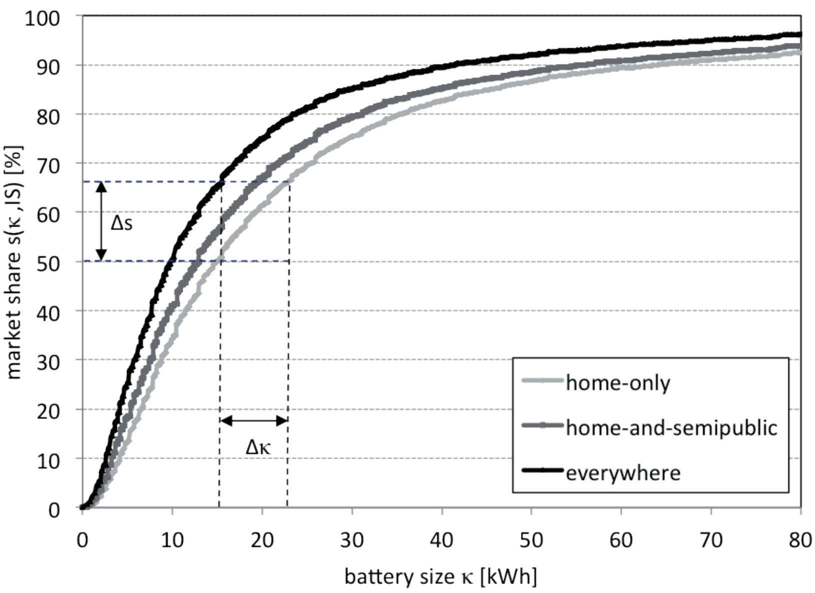

Figure 1. Share of possible BEVs. The share of vehicles that could be operated as BEVs is shown as a function of battery size. The shares are computed from the battery simulations described above including all trips of one week for each vehicle with different charging options present (see legend and Methods and Data section). Also indicated is the additional market share that could be reached through an increase of infrastructure or additional battery capacity (see section 'Economic Aspects of public charging points').

assumption that all users could charge anywhere at all stops is of course highly optimistic but indicates the importance of this limited increase in share of vehicles that could be operated as EVs when adding potential charging options. In other words, realising ubiquitous charging possibilities is a huge task but judging from current vehicle usage offers only a limited reward.

In a second step, we take into account that vehicles should have access to charging at home (mainly over night) for example within the garage. Figure 2 shows the usual parking option for German vehicles from the MiD survey (see Data section) as function of city size combined with the official car registration data (KBA 2011). We observe that more than half of all German vehicle users usually park their vehicle in a garage over night and either have charging possibilities already available there or could easily install them in their garage. Reducing the battery state simulation of Figure 1 to only those users that have access to a garage reduces the potential for replacement of a given vehicle by a BEV by about 10 % (Kley 2011).

Given the high share of vehicles that could be operated as BEVs with all their trips in one week and the measurable but limited increase of this share from additional ubiquitous public charging infrastructure we conclude that (1) a significant share of today's vehicles with their everyday use could easily be operated as BEVs despite their limited range and (2) that public charging infrastructure has a limited effect on this technical potential for replacement.

Let us now turn to the effect of additional public charging infrastructure on the PHEVs. Since PHEVS have an additional internal combustion engine for propulsion, there is now limited range. More technically speaking, the range limit is given by the size of the gasoline tank and thus (from a user's perspective) comparable to the range of today's conventional vehicles. We therefore assume that this range will not be experienced as limited. However, the limited battery size leads to a limited electric driving share. Additionally, the electric driving share strongly influences the usage cost of the PHEV (since electric driving is cheaper than gasoline driving) and a high electric driving share is desirable for users. Figure 3 shows the results from a battery simulation of the same vehicles as above (data from MoP (2010) with 6,629 vehicles with all their trips in one week) for two different PHEVs with 5 kWh usable battery capacity (left panel of Figure 3) and 10 kWh usable battery capacity (right panel of Figure 3) for two scenarios (only charging at home and charging everywhere).

The results for the PHEV battery simulation in Figure 3 indicate that a large share of users (30 % for an assumed 5 kWh PHEV and 55 % for a 10 kWh PHEV) could perform all their trips in one week all-electric, i.e., would have an electric driving share of more than 90 %. On average, the electric driving share would be 64 % if all users had a 5 kWh PHEV and 75 % for a 10 kWh PHEV. Assuming additional public charging everywhere and its use by all users, the average electric driving share increases to 80 % for 5 kWh PHEVs and to 88 % for 10 kWh PHEVs (see white bars in Figure 3). Large electric driving shares are desirable from a user's perspective since electric driving reduces costs and is experienced as low noise driving. We conclude from Figure 3 that both larger batteries and the installation of public charging infrastructure can significantly increase the average electric driving share and the share of users with high electric driving shares. As before, additional public charging infrastructure leads to a measurable but limited increase of the usage of electric vehicles (here: the electric driving share of PHEV).

RARE LONG-DISTANCE USE OF POTENTIAL ELECTRIC VEHICLES

Up to now we only discussed "every-day" use of vehicles, i.e. the usage patterns recorded over a limited period of time. The case we discussed above was one week, which is already more restrictive than single-day data. However, users perform rare but long-distance trips for a multitude of purposes such as vis-

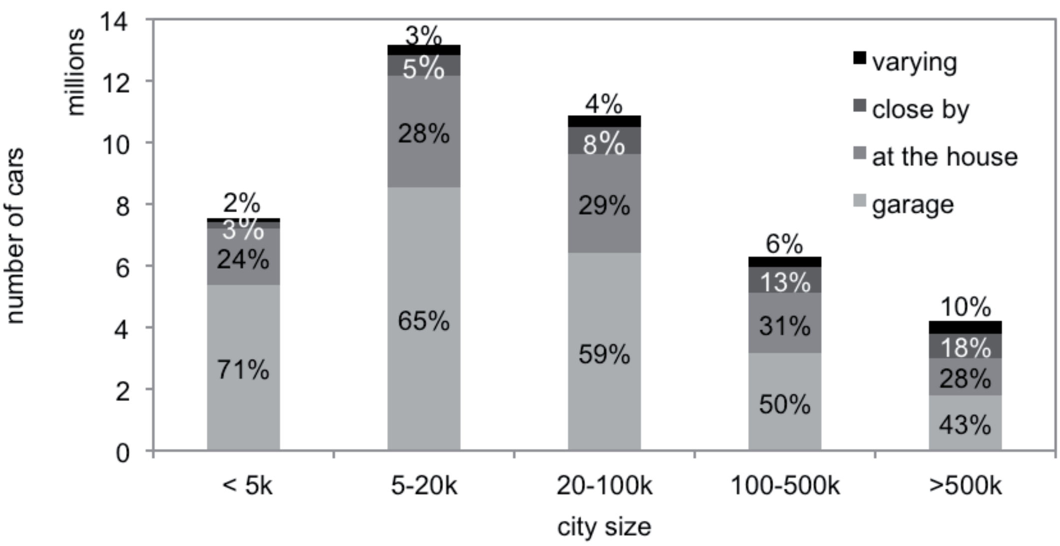

Figure 2. Distribution of overnight parking options for Germany. Shown are the numbers of cars from different city sizes and their usual overnight parking options. The shares were obtained from user answers to the question "Where do you usually park your vehicles overnight?" from a large scale survey of German vehicle users (infas and DLR 2002) and combined with the official 2011 car registration data (KBA 2011).

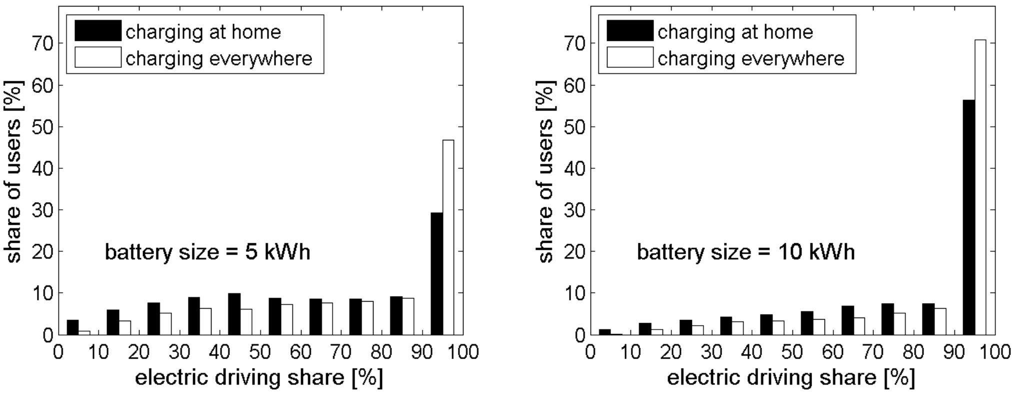

Figure 3. Distribution of electric driving share for potential PHEV users. Shown are the shares of potential PHEV users with different electric driving shares if their current vehicle was replaced by a PHEV of 5 kWh (left panel) or 10 kWh (right panel). Full black bars are for charging only at home and white bars for the additional effect of charging everywhere (with assumed ubiquitous public charging infrastructure).

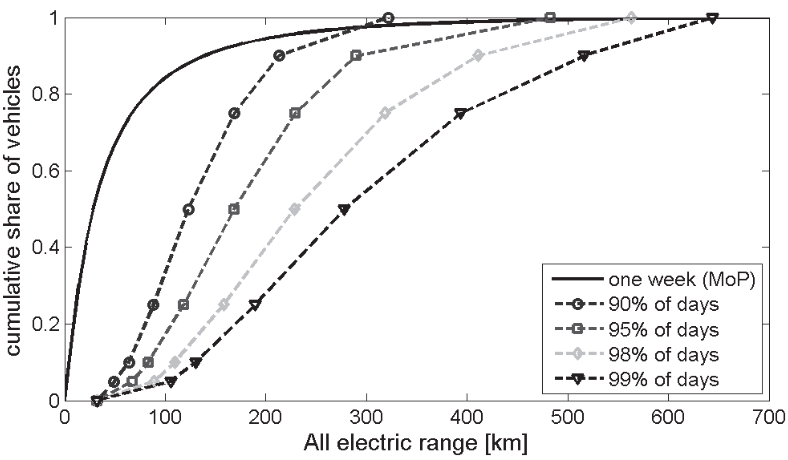

Figure 4. Required all electric range for rare long-distance trips. Shown is the cumulative share of users that can perform a certain share of trips as a function of all electric driving range (dashed lines) for different share of days. Also shown is the cumulative share of users that can perform all their trips of one week as a function of the assumed vehicle's all electric range.

iting relatives or going on vacation. Including such events in user-specific simulations is difficult since detailed driving data for individual users over longer observation periods is rarely available (the data used for Smith et al. (2011) provides a counter example).

Here we follow a different approach using likelihoods of trip lengths drawn from empirically estimated trip length probability distributions pioneered for electric vehicles by Greene (1985). For the present paper, we restate Greene's methodology and compare his results to the analysis performed in the previous sub section on every-day use of vehicles.

Greene (1985) studied U.S. gasoline fuelling log-books and finding that the trip length distribution of most individuals is right-skewed (similar to the trip length distribution of an ensemble of data, c.f. (Plötz, Gnann and Wietschel 2012)) assumed a Gamma distribution for each individual in his data base (Greene 1985). Finding the optimal parameters of the Gamma distribution for each individual of users, Greene obtains a family of Gamma distributions with a different parameter sets. From this family of distributions, Greene estimated the probability (at a given confidence interval of 95 %) of finding the share of users performing trips longer than a range L within a given time interval. The data for Greene's study is comparatively old, but we assume in the following that the basic distribution of trips has not changed but the parameters might have slightly changed. In this respect, the basic analysis of Greene (1985) is still valid today. The part of Greene's results relevant for comparison to the technical potential discussed above is reproduced in Figure 4. Also shown in Figure 4 (solid black line) is the cumulative share of users who can perform all their trips in one week as a function of the all electric range of the assumed vehicle.

We observe from Figure 4 that (according to Greene (1985)) approximately 100 kilometres of all electric range should suffice for all trips of 50 % of the users in 90 % of all days (i.e., all daily vehicle kilometres travelled). Please note that these statements are direct results from the work of Greene (1985) and are only reproduced here for comparison. As such, Greene's results in terms of share of users for which a given range suffices for a share of all days is not directly comparable to our share of users with all trips in one week. However, it is clear that very long trips are rather rare and that the probability of a long trip decreases with the length of the trip. This explains the shift of the dashed lines to the right for comprehending more days. Put differently, the more extreme the trip length, the longer is the required all electric range for such a trip. In comparison with the range required for all trips of one week, we observe that Greene estimates higher electric driving ranges to be required for completing a majority of their daily trips. Direct conclusions are difficult from Figure 4. For a real comparison and future analysis, a study of the representativeness of the individual user's daily vehicle kilometres travelled in one week is required. However, the results in Figure 4 indicate that the presence of rare long-distance trips can significantly reduce the technical replaceability of conventional vehicles by BEVs. This might either be an indicator that users who value a vehicle's ability to perform rare long-distance trips highly will prefer a conventional vehicle. But it may also indicate that users would favour PHEVs since an overall range limitation does not apply to them.

It is important to note that we only studied the technical consequences on the utility of electric vehicles from a user perspective but did not include any costs of the vehicles or charging infrastructure (neither for installation nor for usage). Costs can be considered from the perspective of individual users or larger user groups such as the society as a whole. Both will be discussed in the next section.

Economic Aspects of public charging points

In the present section the macroeconomic and microeconomic aspects of public charging points are analysed.

MACROECONOMIC ASPECTS

In the macroeconomic analysis we compare the additional market shares for battery electric vehicles by increasing infrastructure or battery capacity as indicated with deltas in Figure 1. Because of the slopes of the curves we can see, that with small initial battery capacities it is easier to increase the market share with an increase of battery size than with an increase of charging infrastructure, while with larger batteries in the beginning, we need a lot of additional battery capacity to increase the market share by the same amount as with an increase of charging infrastructure.

Thus the question is where the intersection for the two "curves of additional market shares" lies. (These curves are not shown this paper, but in (Gnann, Plötz and Wietschel 2012a, fig. 3)). By calculating the battery sizes necessary to receive the same additional market share and value both options with investments, it is important to define who has to bear the cost for the infrastructure. There is a case where only additional users through infrastructure bear the additional investment and we can find an intersection for the "curves of additional market shares" at an initial battery size of 50 kWh. When we increase infrastructure from infrastructure scenario A to B, every additional BEV-user we receive through the charging infrastructure increase would have to bear an investment of 2,500 Euro. These users would have to pay the same if they increased their battery capacity to 60 kWh. As this initial battery capacity is too high for a BEV, we can state that battery capacity would always be cheaper in this case. We find the second intersection for this case when we increase charging infrastructure from scenario A to C. This intersection is at 25 kWh initial battery size and the investment per user at 4,000 Euro. An initial battery size of 25 kWh seems more likely, but is still large for an average user.

There is also a second case where all BEV-users bear the investment for infrastructure. Here both intersections are at 10 kWh initial battery size. This would mean that if all users paid for the infrastructure it would be cheaper than additional battery capacity. Now this analysis is based on the assumption that every additional user needs one additional charging point. This may be possible if all potential users only use this charging point for all their charging, which is why we want to dig a little more into detail in the following microeconomic analysis. The first case seems to be more likely though.

For the macroeconomic part, we can sum up that it would be cheaper to invest in additional battery capacity than in charging infrastructure if only those users who needed the infrastructure paid for it. Based on the assumption that all users bear the investment for charging infrastructure (here one charging point per additional user), this investment would be lower per capita than an investment in additional battery capacity.

MICROECONOMIC ASPECTS

As mentioned in the previous section, we assume that users of public charging infrastructure have to pay for it (e.g. as a supplement), which is why in the microeconomic analysis we include the infrastructure cost in the total cost of ownership for every user. With a stock model and driving profiles for privately and commercially licensed vehicles, we can calculate the TCO-based diffusion of electric vehicles as shown in Figure 5 where eight years of use are considered as an average value.

In Figure 5 we see the number of charging points (here equivalent to vehicles as one charging point is assumed for every vehicle) for every year from 2012 to 2020. According to the common parking indicated in the driving profiles, we determine the cheapest charging option per user.

We see that charging infrastructure for electric vehicles in this analysis is dominated by simple sockets with which almost half of the users could cover their demand. The second largest group is private wallboxes which sum up to another 25 % of charging facilities in 2020, followed by commercial charging wallboxes with about 25 % as well. In 2020 only 1 % of all users could cover the cost of a public charging facility. Besides, privately owned vehicles start to diffuse into market from 2013 on, while commercial vehicles are cost competitive not until 2017. The same holds for private users with public charging points.

We can interpret these results for privately owned cars as follows: Private users may use simple charging infrastructure if they have a garage or parking lot close to their homes. This is the case for the majority of all users, as indicated in Figure 2. The low additional cost for simple sockets or wallboxes can be amortized without a problem, while public charging points are expensive and not many users can afford them. If we compare the results with all users in Figure 2, we can find that from the 10 % of car owners who do not have an own parking, only a few can afford an electric vehicle and the charging point. For further research we will have to determine if this is because of their driving behaviour or the high additional cost for charging infrastructure.

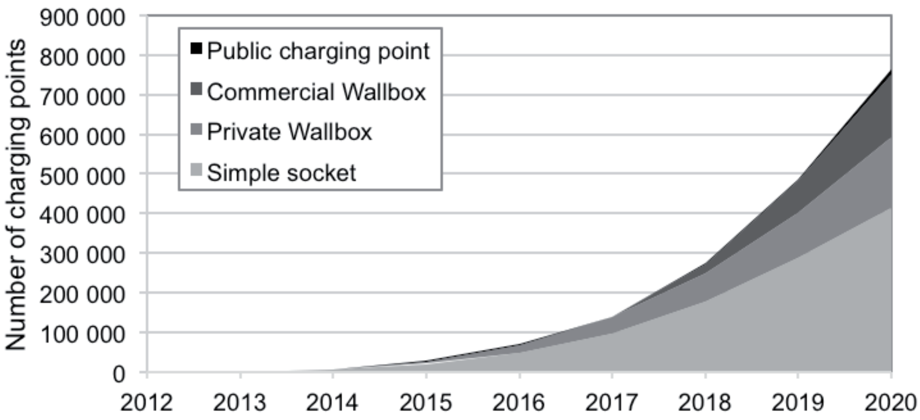

Figure 5. Number of charging points from 2012 to 2020. Based on TCO-calculations, results are subdivided into simple sockets, private wallboxes, commercial wallboxes and public charging points.

Concerning commercially licensed vehicles the late market entry could be caused by the longer driving profiles we use for the analysis. As discussed in (Gnann, Plötz and Kley 2012) there is evidence that shorter driving profiles lead to higher EV-potentials. Since we do have this detailed information for commercial vehicles and we don't for privately owned ones, further research is also necessary for private driving profiles containing infrastructure information and longer time horizons to not overestimate the private EV-potential. Having said that commercially owned vehicles have a share of 25 % on the overall charging points, which is large having in mind that the commercial car stock is at about 10 % in Germany.

Summary and Conclusion

In the present paper, we analysed technical aspects of future public charging infrastructure for electric vehicles. We found that high shares of vehicles could either be replaced by BEVs or reach high electric driving shares with PHEVs without additional public charging infrastructure by using the charging options at home only, such as present in many garages already today. The additional usage of public charging infrastructure increases the vehicles' utility by a measurable but limited extend. Rare long-distance trips, e.g. for holidays, which are hardly feasible with electric vehicles can reduce the utility of an EV. However, the magnitude of utility reduction as perceived by users is not clear and these trips can be performed with PHEVs instead of BEVs.

From an economic point of view, the future charging infrastructure should be largely dominated by simple charging infrastructure options. Almost half of the users could cover their demand by charging their EVs by simple sockets at home. Taking into account the costs for public charging infrastructure, only 10 % of the car owners without own parking could cover the costs of a public charging facility.

Our analysis is based on several assumptions and cannot be taken as a perfect forecast for the future. For the analysis we use driving profiles for users and determine the EV-potential technically and economically. First of all we do neither consider any behavioural change for driving, nor a change of car size classes, which might be possible for users. Longer observation times for driving profiles do return better information per user than shorter ones, but even the long observation times for the commercial driving profiles are insufficient to cover all possible driving information. Furthermore, we calculate the total cost of ownership in the economic analysis and regard them as only decision factor for car registration. From a psychological point of view this is surely not the only part of a buying decision, even if the main barriers to EV-adoption, range and charging infrastructure, are covered implicitly and explicitly in this analysis (Dütschke et al. 2011). There might still be users that want higher ranges, which can also not be covered economically by PHEVs.

Regarding charging infrastructure, it is necessary to repeat that we do not consider charging during the day in the micro-economic analysis. This largely decreases the number of public charging facilities compared to other calculations (NPE 2012). Including charging infrastructure into the TCO might also ban users from e-mobility which have suitable driving profiles but lack of a private parking. In general all parameters given in Annex A are well chosen and often reflected, but, especially for 2020, based on assumptions which can be discussed as well.

Based on the calculations and assumptions we conclude that public charging infrastructure is not necessary to start market diffusion of EVs, but may have psychological influence on users. However, this does not justify a large scale built-up of public charging points.

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Annex A – Input parameters

All parameters are based on (Fraunhofer ISI 2010; Helms et al. 2011; Bünger and Weindorf 2011, S. 87–100; Kley 2011).

Table A.1. Technical parameters 2012.

Parameter	Car size	Gasoline	Diesel	PHEV	BEV
Conventional energy consumption [l/100 km]	Small	6.1	4.8	6.5	-
	Medium	7.6	6.0	8.0	-
	Large	10.2	7.6	10.7	-
	LDV	15.1	11.3	16.1	-
Electric energy consumption [kWh/100 km]	Small	-	-	21.3	19.1
	medium	-	-	22.9	23.3
	Large	-	-	28.0	25.1
	LDV	-	-	42.0	37.6
Battery capacity [kWh]	Small	-	-	6	15
	medium	-	-	10	20
	Large	-	-	14	40
	LDV	-	-	14	40

Table A.2. Net investment 2012.

Parameter	Car size	Gasoline	Diesel	PHEV	BEV
Net investment for vehicle w/o battery [€]	Small	8,563	10,092	9,575	7,955
	Medium	19,560	21,560	21,529	18,391
	Large	27,475	29,060	30,877	28,362
	LDV	28,640	29,500	32,842	28,467

Table A.3. Net cost for operation and maintenance 2012.

Parameter	Car size	ICEV	Diesel	PHEV	BEV
Operation and maintenance [€/km]	Small	0.025	0.022	0.025	0.013
	Medium	0.025	0.023	0.025	0.014
	Large	0.025	0.023	0.025	0.015
	LDV	0.122	0.120	0.122	0.103
Vehicle tax [€/a]	Small	24	114	24	23
	Medium	114	242	114	30
	Large	248	428	248	36
	LDV	132	132	132	36

Table A.4. Technical parameters 2020.

Parameter	Car size	Gasoline	Diesel	PHEV	BEV
Conventional energy consumption [l/100 km]	Small	5.4	4.3	5.8	-
	Medium	6.5	5.3	7.0	-
	Large	8.5	6.6	9.3	-
	LDV	12.6	9.6	13.8	-
Electric energy consumption [kWh/100 km]	Small	-	-	18.8	17.2
	Medium	-	-	20.2	21.1
	Large	-	-	24.7	24.2
	LDV	-	-	37.0	34.3
Battery capacity [kWh]	Small	-	-	6	15
	Medium	-	-	10	20
	Large	-	-	14	40
	LDV	-	-	14	40

Table A.5. Net investment 2020.

Parameter	Car size	Gasoline	Diesel	PHEV	BEV
Net investment for vehicle w/o battery [€]	Small	8,563	10,092	9,575	7,955
	Medium	19,560	21,560	21,529	18,391
	Large	27,475	29,060	30,877	28,362
	LDV	28,640	29,500	32,842	28,467

Table A.6. Net cost for operation and maintenance 2020.

Parameter	Car size	ICEV	Diesel	PHEV	BEV
Operation and maintenance [€/km]	Small	0.025	0.022	0.025	0.013
	Medium	0.025	0.023	0.025	0.014
	Large	0.025	0.023	0.025	0.015
	LDV	0.122	0.120	0.122	0.103
Vehicle tax [€/a]	Small	24	114	24	7
	Medium	114	242	114	8
	Large	248	428	248	10
	LDV	132	132	132	10

Table A.7. Vehicle independent technical and economic parameters.

Parameter	2012	2020
Depth of Discharge (DoD)	75%	75%
Battery price BEV w/o VAT [€/kWh]	590	250
Battery price PHEV w/o VAT [€/kWh]	670	290
Electricity price w/o VAT [€/kWh]	0.20	0.20
Gasoline price w/o VAT [€/l]	1.34	1.71
Diesel price w/o VAT [€/l]	1.26	1.60
Pay back period battery [a]	4	4
Pay back period vehicle [a]	4	4
Pay back period charging infrastructure [a]	4	4
Interest rate for battery investment	3%	3%
Interest rate for vehicle investment	3%	3%
Interest rate for charging infrastructure investment	3%	3%

Table A.8. Charging Infrastructure Cost.

Type of Charging Infrastructure	Simple socket	Private Wallbox	Commercial Wallbox	Public Charging Point
Investment (I_{IS}) [€]	250	500	500	3775
Operating cost (k_{IS}) [€/a]	7.5	31.5	31.5	430