Modelling the Development of a Regional Charging Infrastructure for Electric Vehicles in Time and Space

Johannes Wirges[a] and Susanne Linder[b]
European Institute for Energy Research (EIFER), Karlsruhe, Germany

Alois Kessler[c]
EnBW Energie Baden-Württemberg AG, Karlsruhe, Germany

This article presents a dynamic spatial model of the development of a charging infrastructure for electric vehicles in the German metropolitan region of Stuttgart. The model consists of several sub-models whose functioning and interactions are explained in detail. The first sub-model simulates the time-spatial development of electric vehicle ownership. The output of this module is used by the second component that determines the resulting demand for charging stations. To quantify this demand, the necessary utilisation of charging stations to allow for the profitability of the infrastructure is calculated. A final processing step simulates the mobility of EVs throughout the Region Stuttgart, and thus allows allocating the need for charging stations in space. We used our model to generate several scenarios of the development of a charging infrastructure in the Region Stuttgart until 2020.

The main finding of this work is that the number of public charging stations needed for the region in the long run is quite low. If too many charging stations are installed the infrastructure will be under-utilized and thus cannot be operated economically. The simulation runs show that the installation of public charging infrastructure should be focused on the few biggest urban centres of the region. The scenarios also show that publicly accessible charging stations form only a minor part of the overall number of charging stations. Additionally, it can be seen that the exponential growth of electric vehicle ownership, with very few vehicles at the beginning, but large gains after a few years, requires high flexibility from stakeholders involved in the implementation of charging infrastructure for electric vehicles.

Keywords: electric vehicle charging infrastructure, infrastructure planning, regional planning

1. Introduction

Concerns about global warming and the scarcity of fossil fuels have resulted in a rising interest in electric vehicle (EV) technology over the last years. EVs are seen as an opportunity to reduce carbon dioxide emissions, and lower the consumption of fossil fuels. They are also considered as

[a] Emmy-Noether Straße 11, 76131 Karlsruhe, Germany, T: +4972161051481, E: wirges@eifer.org
[b] Emmy-Noether Straße 11, 76131 Karlsruhe, Germany, T: +4972161051436, E: linder@eifer.org
[c] EnBW AG, Durlacher Allee 93, 76131 Karlsruhe, Germany, T: +497216317884, E: a.kessler@enbw.com

EJTIR 12(4), 2012, pp. 391-416   392
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

an important element for future smart grids development, and their manufacturing is seen as a chance to create green jobs. Therefore, developed nations all over the world have mapped out plans to introduce high numbers of EVs into their national car fleets. The German government has set up the goal of having 1 million EVs on German roads by 2020 (Bundesregierung der Bundesrepublik Deutschland, 2009). The governments of the U.S., France, U.K., Japan, China and further countries have set up similarly ambitious targets. As a first step to reaching these goals, numerous EV pilot projects are currently taking place in cities and regions worldwide. One main shortcoming of EVs today is their limited range, which can be below 100 km during everyday use (Priemer, 2010). In order to overcome this limitation, charging stations (CSs) are needed to extend the driving range and comfort the users. Within the pilot regions charging stations are currently installed at private and publicly accessible locations. The Region Stuttgart is one such electro mobility pilot region in Germany (Wirtschaftsförderung Region Stuttgart GmbH, 2010), which encompasses 3,654 million square km. 2.67 million people live in 179 municipalities.

The research question underlying the work presented in this paper is: *If the target of 1 million EVs in Germany by 2020 is met, how should a corresponding charging infrastructure for EVs be implemented in the Region Stuttgart in the years to 2020?* The results should be in form of time-spatial scenarios, showing the number of installed charging stations in municipalities of the region for each year.

Planning such a charging infrastructure for electric vehicles in cities and regions poses a new challenge for infrastructure developers and urban planners. Several publications already treat the planning of charging infrastructure as a static location planning problem. It is analysed where CSs should optimally be placed in geographic space. The used methods include analyses in a geographic information systems (Schirmer et al., 1996; Hanna, 2001), modelling the market areas of CSs by Voronoi diagrams (Koyanagi et al., 2001), modelling location choice as integer linear problems (Wang, 2007; Wang, 2008; Wang and Lin, 2009, Dashora et al., 2010), and treatment as a clustering problem (Ip et al., 2010). These methods do not consider a *temporal* development of the infrastructure however. They also seem more suitable to generate infrastructure plans on a fine geographic scale for individual cities or city quarters not for bigger regions, and thus were inappropriate for our case study.

Koyanagi and Yokohama (2010) present a method of prioritisation among a given set of candidate locations. Such an approach could be modified to introduce a temporal dimension into static location planning methods, such as those mentioned above.

Publications explicitly considering the temporal, dynamic aspect of EV charging infrastructure development stem mainly from research on the diffusion of new vehicle technologies. Struben (2006) and Struben and Sterman (2008) present a sophisticated system dynamics model of the diffusion of alternative drive train technologies and their corresponding refuelling infrastructure. The model is spatially disaggregated to calculate vehicle ownership and infrastructure availability in different parts of the state of California. These models were constructed to analyse the complex interactions of different policies and technology innovations on the diffusion of competing vehicle technologies, such as hybrid vehicles, hydrogen fuel cell vehicles and natural compressed gas vehicles. Thus these models did not seem suitable to us for efficiently simulating a development of charging infrastructure for EVs in a concrete case study.

The model presented by Struben (2006) has been applied and extended specifically to EVs and their infrastructure by Feller and Stephan (2009), and Kearney (2011). Kearney focuses on policies and economic questions around EV charging infrastructure, with no consideration of spatial distribution. Feller and Stephan also model the infrastructure in space. A weakness of these models is that concepts for the refuelling with conventional gasoline and alternative fuels (hydrogen, gas, etc.) are applied to the recharging of electric vehicles. Feller and Stephan assume charging stations with ultra-high charging speeds of 120 kWh/h and 480 kWh/h, which operate

EJTIR 12(4), 2012, pp. 391-416   393
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

like gasoline stations today. Kearney also uses the model introduced by Struben (2006), in which EVs wait in a queue for their turn to recharge.

But the charging of EVs takes place in a fundamentally different way to conventional gasoline refuelling. Electric vehicles are charged for longer durations during parking, at charging powers in the scale of 3.6, 22 or 44 kW (Nationale Plattform Elektromobilität, 2010) Furthermore electric vehicles recharge much more often, at intervals in the scale of 100-150 km (Priemer, 2010). Also, electric vehicles do not depend on publicly accessible charging infrastructure, as they can conveniently be recharged at home. These differences are also the reason why concepts cannot be easily transferred from publications dealing with the implementation of a refuelling infrastructure for hydrogen vehicles (Lin et al., 2008; Nicholas, 2004) to the planning of a charging infrastructure for EVs.

Further publications also present alternative system dynamics models of EV diffusion and associated development of charging infrastructure (Wansart and Schnieder, 2010; Yamashita et al., 2011). These two models do not contain any geographical aspect however.

Several documents from a political context already contain plans for the long-term development of charging infrastructure for areas of different sizes. For instance, London's Electric Vehicle Infrastructure Strategy is a plan for the long-term rollout of infrastructure in the city (Mayor of London, 2009; Mayor of London, 2009a). Another example of such a political infrastructure plan is the one being laid out for France. The National Working Group on Charging Infrastructure for Electric and Plug-In Hybrid Vehicles in France has developed a long-term vision of the national (PH-)EV stock and necessary charging infrastructure (Groupe de Travail sur les Infrastructures de Recharge, 2009). However, these reports do not state how the presented total number of charging stations, their distribution and the scheduling of their installation were determined. In April 2011, the French government has issued a handbook on public charging infrastructure for electric vehicles (Negre and Legrand, 2011). The document contains an example calculation for the demand for charging stations in the year 2015 in the city of Rouen. In this calculation, the evolution of the EV fleet is assumed to take place according to the French government's envisioned targets. The need for public charging infrastructure is then determined taking the number of EVs, overall demand at peak time, and the geographic distribution of demand into account.

Because the methods presented in the articles above did not seem suitable for our case study, we developed our own straight-forward model of infrastructure development for electric vehicles in a region. For our purposes, we wanted a model which put the main emphasis on the development of the infrastructure, and not on the simulation of policies. Our goal was to efficiently generate realistic time-spatial scenarios of EV infrastructure in the given Region of Stuttgart based on available spatial data on sociodemographics, land-use and mobility.

This article is structured as follows: First, we explain the basic assumptions and general structure of our model (Section 2). Then we present the main components of the model: the time-spatial model of EV ownership (Section 3), and the corresponding time-spatial model of EV infrastructure development (Section 4). The results of scenario calculations for the Region Stuttgart are then shown in Section 5. General conclusions from the scenario results are drawn in Section 6. Finally, possible extensions and refinements of the model are discussed in Section 7.

2. Basic assumptions and structure of the model

The conditions under which charging infrastructure is planned and developed varies from country to country and from region to region. In the following, we explain which frame conditions we assume to hold for such a development for our case. These frame conditions

EJTIR 12(4), 2012, pp. 391-416   394
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

determine the way in which we model the development of the infrastructure. We will also present an overview of the model and its main components in this section.

The following frame conditions are assumed to hold for the development of a charging infrastructure in the Region Stuttgart until 2020:

- We assume that the target stated by the Germany government of 1 million electric vehicles in Germany by 2020 (Bundesregierung der Bundesrepublik Deutschland, 2009) will be reached. This would mean that about 35,000 electric vehicles are owned in the Region Stuttgart in 2020.

- We assume that there will be no public funding, subsidies, or cross-financing for public charging infrastructure. The public charging infrastructure will be installed and operated by the private sector, and has to refinance itself by user fees alone. This corresponds to the current political practice in Germany (Bundesregierung der Bundesrepublik Deutschland, 2011).

- Concerning charging technology, we assume that conductive charging (via plug) will be used. We do not consider inductive charging or battery swapping here. This is in line with the outlook given by the German National Platform Electro-Mobility (Nationale Plattform Elektromobilität, 2010).

- At an organisational level, we assume that a coordinated planning and installation of public charging infrastructure will take place in the region. It is to be expected that the biggest electric utility in the Region Stuttgart, the EnBW AG is will play a key role in the development of public charging infrastructure.
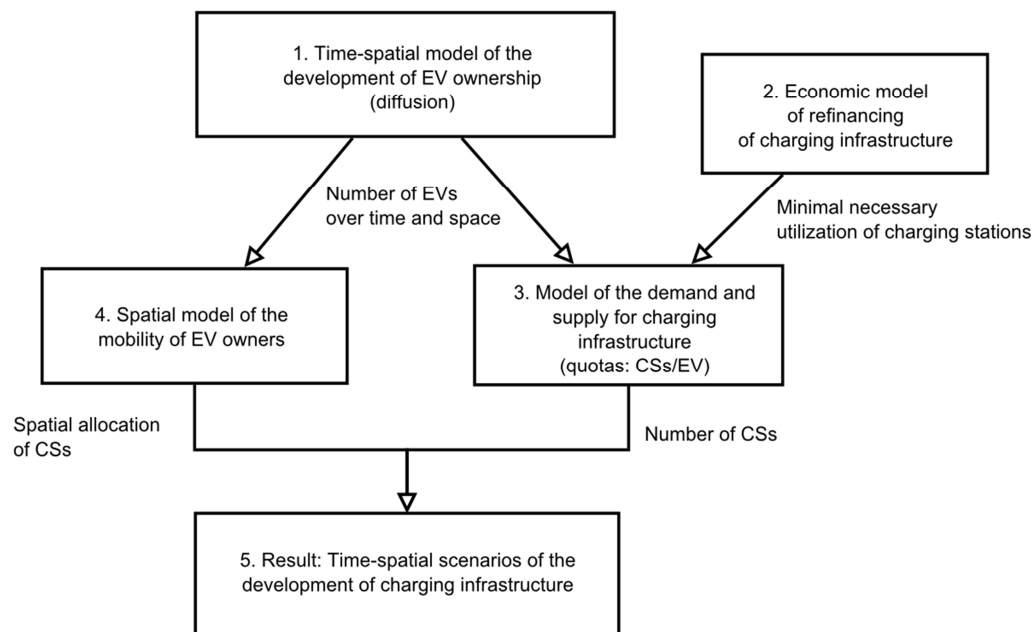

Figure 1. General structure of the model

We developed our model within this framework of basic assumptions. Figure 1 shows how the model is structured. Model component 1 simulates the time-spatial development of EV ownership. How this sub-model is constructed is explained in Section 3. In component 2, the minimum utilisation of public charging stations to assure the refinancing of the infrastructure is

EJTIR 12(4), 2012, pp. 391-416   395
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

calculated (see Section 4.2). Using the results of this calculation, as well as assumptions on the charging behaviour of EV drivers, quotas of charging stations per electric vehicle are calculated in model component 3 (see Sections 4.1 and 4.3). Model component 4 allocates the charging stations in space using a basic mobility model (see Section 4.4). The development of the numbers of CSs, as well as their spatial allocation is the result: the time-spatial development of charging infrastructure.

It should be noted that we only model the development of charging infrastructure as dependent on the development of EV ownership. We assume the diffusion of EVs as given by the German government's targets, and want to know how a corresponding charging infrastructure should be implemented. The inverse dependency of the diffusion of alternative drive train vehicles on infrastructure availability is modelled and analysed in more detail in other papers, for instance those by Struben (2006), and Struben and Sterman (2008).

3. Modelling the time-spatial development of EV ownership

In order to simulate the development of a charging infrastructure, it is first necessary to determine how the number of EVs might evolve over time. Several publications have already treated this diffusion of electric vehicle technology. Many of these studies originate from the USA, especially from California. EVs are usually considered as only one alternative for clean drive technologies, alongside hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). Household surveys and expert interviews have been conducted to estimate the future market development of these technologies (Brownstone et al., 1994; Leiby and Rubin, 2004). Other studies use a modelling approach to generate scenarios of the market penetration of EVs (Cao, 2004; Becker et al., 2009; Sullivan et al., 2009). These models build on the generic Bass Model of the diffusion of innovations (Bass, 1969). The presented results differ substantially, depending on the assumptions of each model and scenario. This is shown in a meta-study on such market forecasts done by Hacker et al. (2009). For the year 2020, the forecast market penetration for EVs lies in a range from 1 to 25 %, and for the year 2050 from 10 to 90 %. The situation in Germany is modelled by Feller and Stephan (2009). The scenarios show a market penetration of EVs of 7 to 9 % in 2020 and 45 % in the year 2030. This model was constructed on the scale of regions for the entirety of Germany. Another publication which treats the diffusion of vehicle technology as a spatial process is by Shinohara and Okuda (2010). In this publication, the diffusion of hybrid vehicles is modelled as a process which starts in the biggest cities of Japan, and then spreads across the country.

To build our own spatially detailed model of the diffusion of EVs in the German metropolitan region of Stuttgart, we proceeded in this way: First, we identified different socio-demographic categories of potential "Early Adopters" of EVs. The number of households falling into these categories was determined for each municipality of the region. The diffusion process was then simulated by using a Bass diffusion model for each adopter group in each municipality.

Our model of the time-spatial development of EV ownership in the Region Stuttgart, along with selected scenario results was already published (Linder and Wirges, 2011). Therefore we present this model in concise form here.

3.1. Categories of Early Adopters of EVs

Based on the results of the above mentioned articles, as well as on data on social mobility profiles (Follmer et al., 2008), and on the general theory of diffusion of innovations (Rogers, 2003), four types of potential Early Adopters of EVs were constructed:

EJTIR 12(4), 2012, pp. 391-416   396
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

The urban trend-setter

This category of Early Adopter consists of young persons between 18 and 35 years old, living in a single or couple household, with a high education level and high income. Such young, well-educated persons can be assumed to have a greater interest in new technologies than the average population, and are more capable of adapting to innovations.

The multiple-car family

This type of Early Adopter describes family households owning at least two cars and living in detached or semi-detached houses, with an own garage. The household has a high average income, and a high level of education. For this type, it can be assumed that the first car is used for long distance commuting and travels, while the second car is mainly used for everyday errands like shopping, or picking the children up from school. Thus, the second car could be replaced by an EV.

The dynamic senior citizen

This group of Early Adopters consists of people between the age of 60 and 75, living in detached or semi- detached housing, and owning high capital. The demographic development in the industrial nations will result in an increase in the number of elder people in the next years. However, the elderly of today and the future stay more mobile than those of previous generations (INFAS and Öko Institut e.v., 2009).

The innovative fleet manager

Especially those enterprises can be expected to adopt EVs in an early stage, which want to convey an innovative and environmentally friendly image. A comparison of current projects on the use of EVs in business fleets shows that Early Adopter enterprises can be expected to mainly be active in the domains of electric utilities, municipal services, social services, city-logistics, passenger transportation, telecommunication and other infrastructure services (Chavis et al. 2009; Groupe la Poste 2009; Mayor of London 2009a).

Table 1. Variables used to calculate the number of Early Adopters in the municipalities

Early Adopter category	Urban trend-setter	Multiple-car familiy	Dynamic senior citizens	Innovative fleet manager (fleet vehicles)
Variables used for calculation of # households, # fleet vehicles	Share of people 18-35 years old Share of single- and couple households Share of people with university degree	Share of family households Share of (semi-) detached houses Share of people with university degree	Share of people 60-75 years old Share of couple households Share of (semi-) detached houses	Share of business vehicles used by enterprises in an innovative domain (as described above)

The approximate number of these Early Adopter households and fleet vehicles in Early Adopter businesses in the municipalities of the Region Stuttgart were calculated by using data from the statistical office of Baden-Württemberg (Statistisches Landesamt Baden-Württemberg, 2011), geo-referenced household and building stock data from Infas (infas, 2011), and data on vehicle ownership from the Kraftfahrt-Bundesamt (Kraftfahrt-Bundesamt, 2009; Kraftfahrt-Bundesamt,

EJTIR 12(4), 2012, pp. 391-416   397
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

2010). This data consisted of the number of households and fleet vehicles, as well as different distributions (age, educational background, household type, house type, business type) for each municipality. The variables used for characterizing each category of Early Adopters are listed in Table 1. The total number of households and fleet vehicles of each type for each municipality was calculated by multiplying the total number of households or vehicles with the percentages used for characterizing the respective group. Because these percentages are not independent of each other (for instance, for young people it might be more probable to live in single households than for the entire population), and refer to different entities (persons, households, houses), the results are only approximate.

3.2. Using the Bass diffusion model to model the time- spatial diffusion of EVs

After having identified different categories of Early Adopters, and having located them in space, the next step was to build a model for the temporal development of EV ownership of each adopter type in each municipality. Next to the identified Early Adopter groups, the remaining households, and the remaining business fleet operators (fleet vehicles) were also included as groups. The Bass diffusion model (Bass, 1969) was used to model the adoption process for each group. This model of the diffusion of innovations is based on the basic idea that the adoption of a new product can be caused by two factors. These factors are the persuasion through advertisement and positive word-of-mouth from people who have already adopted the product. The System Dynamics version of the model according to Sterman (2000) was used for the implementation. In our implementation, the parameter of innovativeness (advertisement effectiveness) can be set for each adopter type separately. The diffusion of the innovation by word of mouth was modelled as to also take place between different adopter types and municipalities (see (Linder and Wirges, 2011) for details).
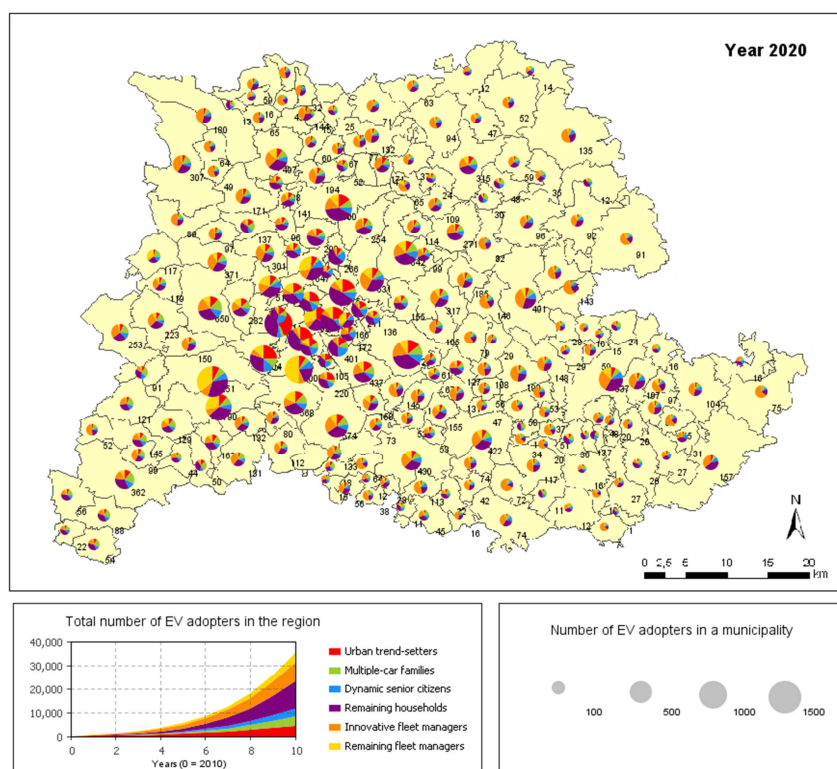

Figure 2. Basis scenario of the development of EV ownership in the municipalities of the Region Stuttgart

EJTIR 12(4), 2012, pp. 391-416
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

398

The resulting model was used to generate scenarios of the development of EV ownership in the Region Stuttgart. A discussion of different scenarios was already published in (Linder and Wirges, 2011). For the work presented in this paper, one baseline scenario of the EV diffusion was built on to generate different possibilities of long-term infrastructure development. The scenario that is used here is based on targets stated by the German national plan of EV development (Bundesregierung der Bundesrepublik Deutschland, 2009). In the scenario there are 35,001 EVs in the Region Stuttgart by 2020. Of those, 4,279 (12 %) are owned by urban trendsetters, 3,751 (11 %) by multiple-car families, 3,455 (10 %) by dynamic senior citizens, 11,575 (33 %) by other households, 7,748 (22 %) by innovative fleet businesses, and 4,193 (12 %) by other fleet businesses. The distribution of EV ownership in the different municipalities in the year 2020 is displayed in Figure 2. It can be seen that different adopter types live in different parts of the region. The urban trend-setters can mainly be found in the central districts of Stuttgart, while the multiple-car families live more in the periphery. Operators of fleet vehicles can mainly be found in municipalities with large industrial zones.

4. Modelling the time-spatial development of a charging infrastructure

The model presented above allows generating scenarios of the time-spatial diffusion of EVs. Vehicles are allocated in space according to the places of residence of private owners and locations of enterprise fleet managers on municipality level. In the following, we use this calculated time-spatial distribution of EVs to compute a time-spatial distribution of charging infrastructure. This is done in two steps: First, we develop a formula which allows calculating the demand for a number of CSs created by a given number of EVs. In a second step, this need for charging infrastructure is allocated in space according to inter-municipal mobility data.

4.1. Determining the number of charging stations for a number of EVs

The easiest way to put a number of EVs in relation to a number of CSs is using quotas, such as, for example, "1.5 public CS per EV". Such ratios can be estimated, or determined via calculations. In the following, we discuss quotas for three usage contexts of EV charging equipment: at home, at work, and in public locations.

Charging stations at homes of EV users are linked to private parking spaces. In small German municipalities with less than 500 residents, 71 % of car owners have their own garages. Even in big municipalities with more than 500,000 residents, 43 % of car owners can use a garage at home (Biere et al., 2009). Analyses of the potential Early Adopters of electric vehicles come to the result that in the next years, almost only those who can install charging equipment in their own garages will buy an electric vehicle (compare above and (Linder and Wirges, 2011)). Thus, for the next 10 years, quotas of 0.9-1.0 charging stations at home per privately owned electric vehicle seem realistic.

It is also expected, that many big companies will install CSs for their employees. In France, providing EV charging facilites for employees might even become obligatory (Ministère de l'Ecologie de l'Energie du Développement Durable et de la Mer, 2009). For London, it is planned to make the provision of charging infrastructure compulsory for 20 % of parking spaces of all new developments (Mayor of London, 2009). In Germany this is probably not going to be the case. In the next 10 years quotas in a broad range of 0.1-0.6 charging stations at working locations per private EV seem realistic. EVs which are used in company fleets must be provided with a charging possibility at the depot. For this usage, a quota close to 1.0 charging stations in depots per EV seems plausible.

EJTIR 12(4), 2012, pp. 391-416   399
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

Quotas for publicly accessible charging stations are difficult to estimate directly. In the following, we present a formula which allows calculating such a quota from given parameters. The general idea of this formula is to set up an energy balance. The amount of energy that is consumed by EVs has to correspond to the amount of energy that is drawn from CSs. Losses during recharging have to be included into the energy consumption of EV. Our formula is similar to the approach taken by Wiederer and Philip (2010). The following formula establishes the energy balance:

$$i = 1,2: \quad V \cdot e \cdot d \cdot R_i = C_i \cdot p_i \cdot 24[h] \cdot U_i$$

$i =1,2$: types of public CSs: normal, fast

V : number of EVs

e : energy consumption of an EV (including losses during recharging) [kWh/km]

d : daily driven distance of an EV [km]

R_i : percentage of consumed energy recharged at public CS of type i [%]

C_i : number of public CS of type i

p_i : power of public CS of type i [kW]

U_i : utilisation of public CS of type i [%]

The product $V \cdot e \cdot d$ on the left of the equation stands for the total energy consumed by all EVs on one day. Multiplying this by the percentage of public recharging R_i results in the total energy EVs recharge at public charging stations on one day. The product $C_i \cdot p_i \cdot 24[h]$ on the right of the equation stands for the energy that can be drawn from all public charging stations on one day. Multiplying this by the actual utilisation U_i results in the total energy that is actually drawn from public charging stations on one day.

Thus, this formula states the obvious: the energy that EVs charge at public charging stations is equal to the energy that is drawn from public charging stations. This formula can be converted to allow the direct calculation of the requested quotas, if the other parameters are given:

$$i = 1,2: \quad \frac{C_i}{V} = \frac{e \cdot d}{p_i \cdot 24[h]} \cdot \frac{R_i}{U_i} \quad (1.1)$$

The parameters e, d, and pi can be deduced from available data:

- **e : energy consumption of an EV [kWh/km]**: measured values of three current EVs on a realistic route, including losses during recharging, lie at 21.9, 22.4 and 24.0 kWh/100km (Priemer, 2010). For this parameter we calculate with an average value of 22.8 kWh/100km which corresponds to 0.228 kWh/km. For vehicles used in business fleets, the energy consumption of the electric transporter used in the mobility project in the Region Stuttgart of 0.46 kWh/km was used.

- **d : daily driven distance of an EV [km]:** According to the German mobility panel (Zumkeller et al., 2010), cars on average drive 1099 km per month, which corresponds to about 36.1 km per day. It can be argued that EVs' average daily driven distance should be *below* that of conventional vehicles, due to their limited range, the assumed use as a second car, and the assumed use by retired people, who tend to travel less kilometres per day (Follmer et al., 2008). On the other hand it can also be argued that the average driven distance of EV should be *above* the general average. People with higher incomes, who are assumed to be a major group among the Early Adopters of EVs, drive significantly longer distances per day (Follmer et al., 2004). Mobility surveys also show that diesel cars, which are similar to EVs from an economic perspective (higher purchase costs, but lower costs per driven km) are driven for longer average distances driven per day (Zumkeller et al., 2010). Because it is currently not

EJTIR 12(4), 2012, pp. 391-416   400
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

possible to assess which of these tendencies dominates, we maintain the average daily driven distance of 36.1 km per day, as stated above. Vehicles used in business fleets have higher daily kilometres travelled than privately owned cars. They drive average distances of 64.2 km/day (Wermuth, 2002).

- p_i : **charging power of public charging station of type i [kW]:** For Germany it can be assumed that 3.6 kW charging power will be mainly used at homes and working places. Public charging stations will mainly operate with 22 kW charging power, with some additional 44 kW fast charging stations (compare Nationale Plattform Elektromobilität, 2010).

The parameters R_i and U_i, which describe the charging behaviour of EV drivers are much more difficult to derive from data currently available.

- R_i : **percentage of consumed energy recharged at charging station of type i [%]:** Currently is not possible to say with certainty, how high this percentage will be for public charging stations, as there do not yet exist enough EVs and public charging facilities. Results from ongoing EV pilot projects are not entirely representative, nevertheless they indicate in what range this value will lie. In the EV Project, 2,704 residential and 438 publicly available charging units were installed by the last quarter of 2011 throughout pilot regions the USA. It is reported, that only 3% of recharged energy was drawn from publicly available charging facilities (ECOtality North America and Idaho National Laboratory, 2011). In the ChargePoint America project, 444 residential, 83 private commercial and 365 public charging were installed. Here, 9% of energy was found to be recharged at public charging facilities (ChargePoint Network and Idaho National Laboratory, 2011). Other available results back the finding, that public EV charging plays only a minor role. In the Cabled project in the U.K. is was found that over 85% of charging operations take place at home or at the working place (Cabled Project Consortium, 2011). Within the Electro Mobility Region in Munich, Germany it was also observed that public charging ranks only third, behind charging at home, and charging at the work place (E.ON AG, 2010). During the MINI-E trial in Germany it was observed, that only 9% of the charging operations took place during shorter parking durations of 2 hours or less, and that 56% of EV drivers had never used public charging during the entire trial (BMW Group, 2010). Four our analyses, *we assume that only **1-15 %** of driving energy is drawn from public charging stations.* For business fleet vehicles, we assume that usage of public charging infrastructure is even lower than for privately owned vehicles, due to their circuits being more predictable and better planned. But it can be expected that if such vehicles do need to be recharged at a public charging point, fast charging is preferred in order to make the vehicle available again much faster.

- U_i : **utilisation of charging stations of type i [%]:** This value also depends on the behaviour of the EV users, but additionally depends on economic factors. Simple 3.6 kW charging points installed at home and work places only cost a few hundred € (Kley et al., 2010), and they are usually installed for specific users. Here, the concept of utilisation does not play an important role. For charging stations at public locations, which costs several thousands of €, their utilisation is important for the cost effectiveness of such an infrastructure. If the available charging stations in a city quarter are not used often enough, additional public charging infrastructure should not be installed for the time being. In the following Section 4.2, we calculate the level of utilisation that is necessary for the amortisation of the costs of such public infrastructure.

It should be noted that the battery capacity or/and driving range of an electric vehicle are not needed as parameters in equation 1.1. These factors only play a role indirectly, as they have an influence on the recharging behaviour as it is described by parameter R_i. When battery capacity and driving range of EVs are bigger, the percentage of energy recharged at public charging stations can be expected to be lower.

EJTIR 12(4), 2012, pp. 391-416
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

401

4.2. Calculating minimum utilisation U_i of charging stations for the amortisation of public charging station costs

The formula for calculating quotas of charging stations per EV presented above contains the utilisation of charging stations U_i as a parameter. As explained, this parameter depends mainly on economic factors. Charging stations should be used often enough to allow the amortisation of the investment costs. In the following formula, we deduce the minimum utilisation of charging stations from an amortisation calculation. *This calculation is not meant to be a detailed investment and profitability analysis, but serves solely to determine plausible ranges for the minimum level of utilisation of public charging infrastructure.*

The level of utilisation of charging stations can be defined as:

$$U_i = \frac{t_d}{24[h/d]} \qquad (1.2)$$

With t_d [h/d] being the daily time in use of the facility.

The profits $p[€/a]$ that need to be generated yearly by the facility, in order to uniformly pay back the initial capital investment, as well as interest payments (which can be interpreted as opportunity costs of capital when own capital is used), can be calculated by (Götze and Bloech, 2004) :

$$p = c \cdot \frac{(1+i)^{t_a} \cdot i}{(1+i)^{t_a} - 1}$$

c [€] : initial capital investment

i [%] : interest rate of loan / interest rate to model opportunity costs

t_a[a] : time to repayment of loan / time period of amortisation

Also taking into account yearly tax deductions by depreciation allowances d [€/a], which is usual for amortisation calculations (Götze and Bloech, 2004, Kruschwitz, 2005) leads to:

$$p = c \cdot \frac{(1+i)^{t_a} \cdot i}{(1+i)^{t_a} - 1} - d \quad (1.3)$$

We assume that the profits from a charging station are generated by a price mark-up m [€/kWh] on the normal price of electricity per kWh. The profits p_a that a charging station actually generates per year depend on the (average) daily time in use t_d [h] and the power of the station p_i [kW]:

$$p_a = t_d \cdot m \cdot p_i \cdot 365[d/a] \qquad (1.4)$$

We demand that the profits actually generated must be at least as high as the profits necessary for the amortisation, so $p_a \geq p$, which using (1.3) and (1.4) leads to:

$$t_d \cdot m \cdot p_i \cdot 365 [d/a] \geq c \cdot \frac{(1+i)^{t_a} \cdot i}{(1+i)^{t_a} - 1} - d$$

The formula can be converted to calculate the minimum daily usage duration:

$$t_d \geq \frac{c \cdot \dfrac{(1+i)^{t_a} \cdot i}{(1+i)^{t_a} - 1} - d}{m \cdot p_i \cdot 365[d/a]}$$

Inserting this into (1.2) finally leads to a formula to calculate the minimum level of utilisation:

EJTIR 12(4), 2012, pp. 391-416
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

402

$$U_i \geq \frac{c \cdot \dfrac{(1+i)^{t_a} \cdot i}{(1+i)^{t_a} - 1} - d}{m \cdot p_i \cdot 365[d/a] \cdot 24[h/d]} \qquad (1.5)$$

The values of these parameters are set as follows:

- c : **initial capital investment [€]:** The values stated in (Kley et al., 2010) are taken. These values include the costs for the charging stations themselves, as well as installation and maintenance costs. According to this article, a public charging station costs 4,050-10,450 € for charging powers of 11 and 22 kW and 7,850 – 17,000 € for fast charging stations with 44 kW power. The case of 3.6 kW public charging stations is not considered here. This is because such charging stations cost only little less, but can distribute considerably less energy over a day for their amortisation.

- i: **interest rate of loan / interest rate to model opportunity costs of capital [€]:** For our calculation, we assume that the company's own capital is invested. We model opportunity costs of capital by taking the EnBW AG's annual Return on Capital Employed (ROCE) indicator of 11.7 % (EnBW Energie Baden-Württemberg AG, 2011) as the interest rate.

- t_a : **time period of amortisation [a]:** For the desired amortisation period we assume 6-8 years, based on a life span of about 8 years for CSs (Negre and Legrand, 2011).

- d : **depreciation allowance per year [€/a]:** In Germany, the fixed service life of electric supply equipment for depreciation allowances is 19 years (Bundesministerium der Finanzen, 2000). A linear depreciation is applied here, so $d = c/19[a]$.

- m : **mark-up on the normal price of electricity per kWh [€/kWh]:** According to Kley et al. (2010), mark-ups of 1.0 to 13.2 c€ per kWh are realistic. A simple calculation shows that, at a gasoline price of 1.50€/l and a consumption of 6l/100km, as well as a base price of 25 c€/kWh for electricity and a consumption of 25 kWh/100km for EVs, the mark-up of a kWh should not exceed 11.0 c€. Because then the operation of an EV (with only public recharging) would be more expensive than that of a conventional vehicle. Thus, we calculate with moderate mark-ups m of 2.5 to 7.5 c€

- p_i : **charging power of public charging station of type i [kW]:** For public charging stations we consider the cases of 11, 22 and 44 kW charging power (also see above, and compare Nationale Plattform Elektromobilität, 2010).

Figures 3-5 show the minimum level of utilisation necessary for amortisation, for charging powers p_i of 11, 22 and 44 kW and different combinations of initial capital investment c, mark-up m and time of amortisation t_a. The results show what has already been indicated in other publications (Kley et al., 2010; Ruschmeyer; 2010, Engel, 2011): the economic feasibility of a public charging infrastructure for EVs is uncertain. In unfavourable scenarios, charging stations would have to reach levels of utilisation of as high as 82 (for 11kW), 41 (for 22kW) or 33 (for 44kW) percent to reach an amortisation of the costs. This would mean being in use for 19 h 20 min, 9 h 36 min, and 7 h 55 min on an average day. Such high rates of utilisation are hardly achievable in practice. But the calculations also show that utilisation rates of 4-8% can be sufficient, if investment costs are kept low and a good pricing policy is applied. This would correspond to a daily usage duration of 58 min to 1 h 55 min.

Comparing the calculations for the different charging powers, it can also be seen that in the business model assumed here (making profits by adding a mark-up on the basic electricity costs), charging stations with high charging power are easier to operate economically: more EVs can be served daily, while the investment costs are not necessarily higher.
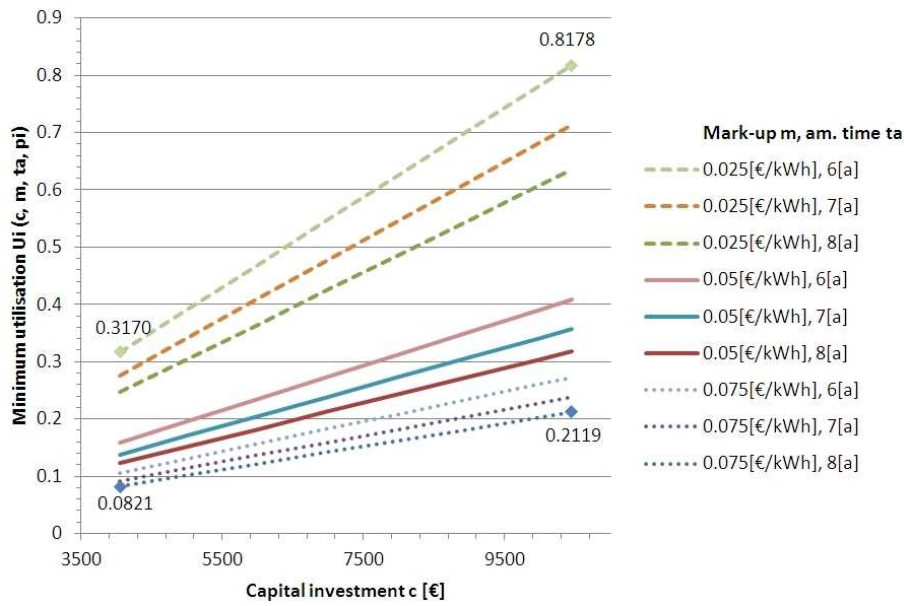
EJTIR 12(4), 2012, pp. 391-416   403
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

Figure 3. Minimum utilisation U_i of a charging station for charging power p_i=11kW and different combinations of parameters c, m, and t_a
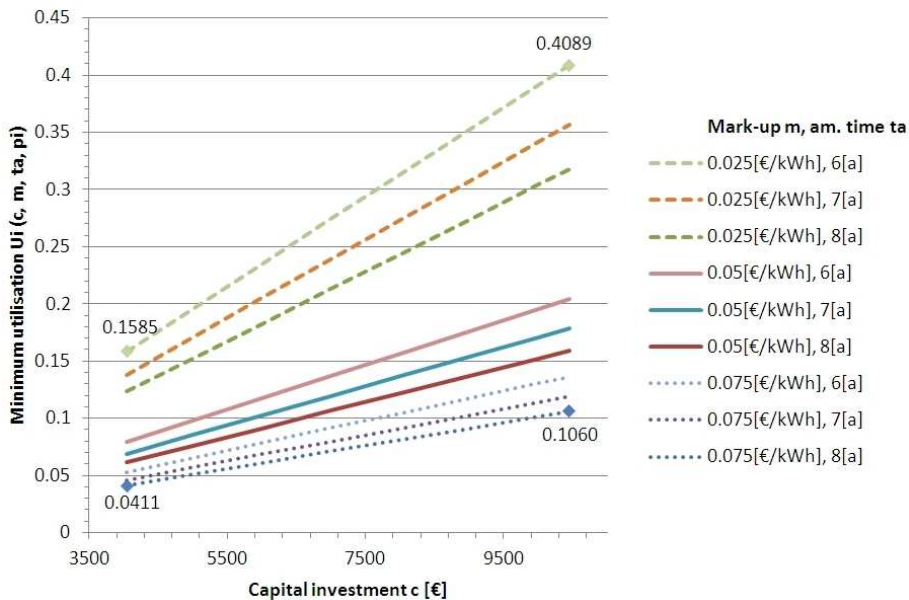

Figure 4. Minimum utilisation U_i of a charging station for charging power p_i=22kW and different combinations of parameters c, m and t_a
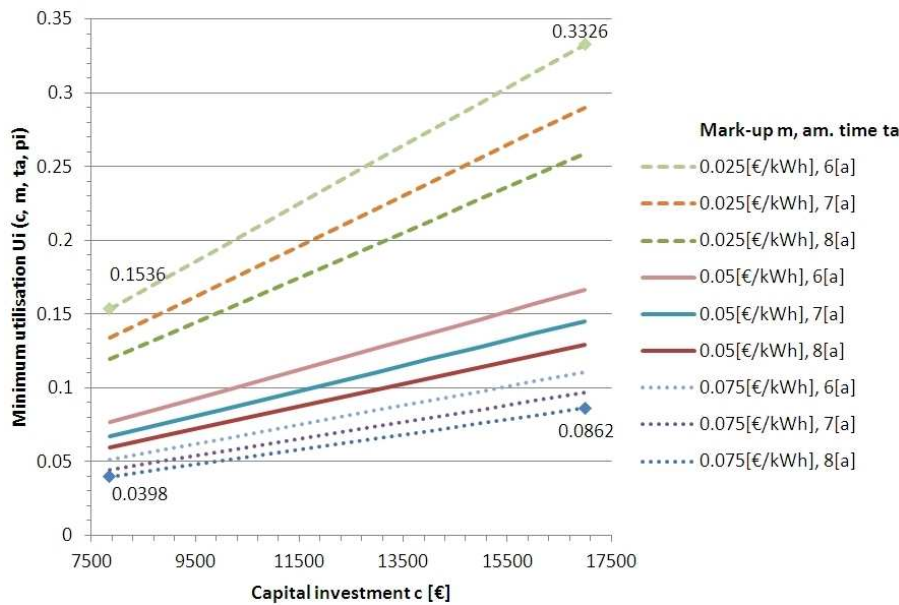
EJTIR 12(4), 2012, pp. 391-416   404
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

Figure 5. Minimum utilisation U_i of a charging station for charging power p_i=44kW and different combinations of parameters c, m and t_a

4.3. Determining quotas for public charging stations per EV

Based on the above analysis of the levels of utilisation necessary for the amortisation of the infrastructure cost, we now proceed to calculate quotas of charging stations per EV. For this we use the formula already stated in Section 4.1.:

$$i = 1,2: \quad \frac{C_i}{V} = \frac{e \cdot d}{p_i \cdot 24[h]} \cdot \frac{R_i}{U_i} \quad (1.1)$$

Figures 5 and 6 show the quota C_i/V as a function of the level of utilisation U_i and the percentage of energy recharged R_i. Four different cases are shown: private vehicles and business fleet vehicles combined with 22 and 44 kW stations (charging power p_i). For private vehicles, we assume an energy consumption e of 0.228 kWh/km, and a daily driven distance d of 36.1 km per day (also see discussion of parameters above). For business vehicles we calculate with an energy consumption of 0.46 kWh/km and a daily driven distance of 64.2 km per day. The interval for the value U_i is chosen according to the results obtained for different charging powers in the above analyses (see Figures 4 and 5). The percentage of energy recharged R_i is assumed to lie within the broad interval of 1-15% in all cases.
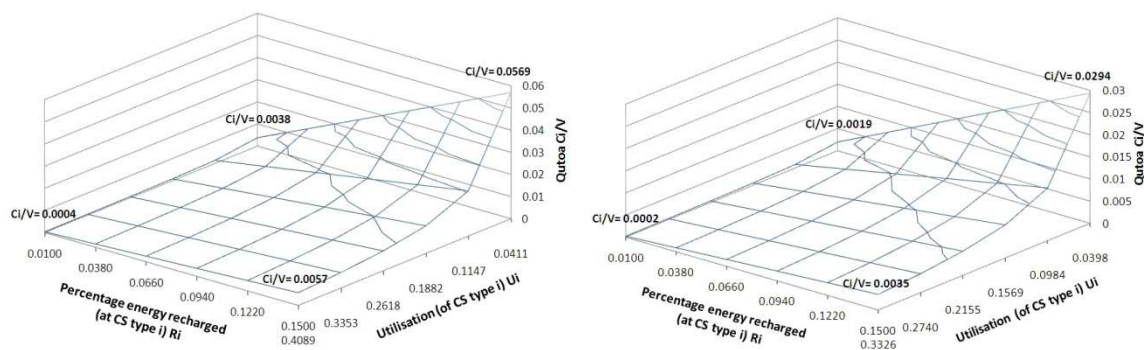

Figure 6. Quotas Ci/V for private vehicles and 22kW (left) and 44kW (right) charging stations

EJTIR 12(4), 2012, pp. 391-416   405
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
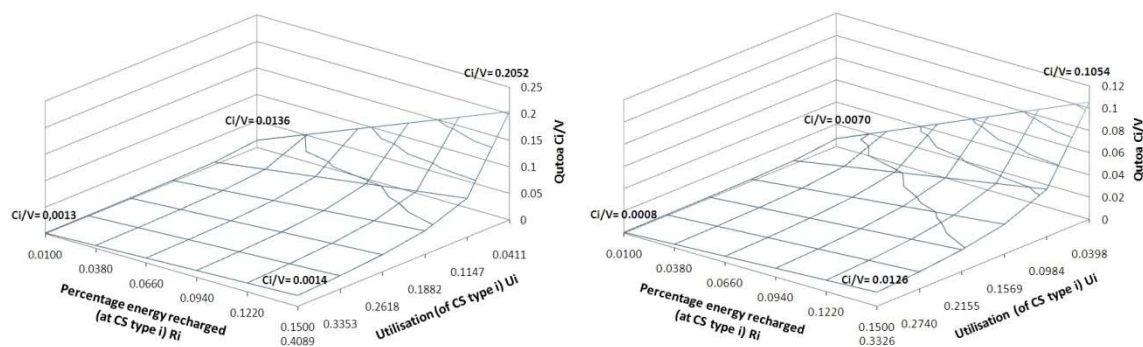for Electric Vehicles in Time and Space

Figure 7. Quotas Ci/V for business fleet vehicles and 22kW (left) and 44 kW (right) charging stations

As already discussed above, very high levels of utilisation U_i will probably be hard to achieve in practice. Therefore investments and pricing should be adjusted in such a way as to not require high levels of utilisation. The percentage of energy recharged at public charging stations Ri should not be overestimated either. This value might well lie below 5%. So in practice, both Ui and Ri can be assumed to lie within the lower ranges of the considered intervals. This would correspond to values lying in the father corner of the diagrams in Figures 6 and 7.

The quotas we calculated this way are significantly lower than the estimated quotas given in many political EV infrastructure plans (Groupe de Travail sur les Infrastructures de recharge 2009; Mayor of London 2009a; Nationale Plattform Elektromobilität 2011). This is probably due to the fact that we introduced a minimum tolerable utilisation of the infrastructure into our calculation.

4.4. Allocating charging infrastructure in space

The above derivations allow calculating the needed number of charging stations for a given number of EVs. In the final modelling step, these charging stations are allocated in space. This is done by distributing the demand for charging infrastructure that arises within a given municipality from the EVs of residents and fleets among the surrounding municipalities. This distribution is performed according to inter-municipal mobility behaviour. As data for the mobility on a regional scale, commuter data from the Statistisches Landesamt Baden-Württemberg was used (Baden-Württemberg Statistisches Landesamt, 2009). This data allowed simulating the cruising radius of EV drivers, and the mobility-related connectivity of municipalities. The data set contains the number of commuters that travel from one municipality to another for all pairs of municipalities in Baden-Württemberg. A possible alternative would have been to compute trips based on land-use data using a trip generation and distribution model (Ortúzar and Willumsen, 2010). For allocating the different kinds of charging stations at home, at working locations and in public space the following schemes were used.

- **Charging stations at home:** The charging stations are located at the places of residence (i.e. the municipality of residence). For our model we assume that no need for home charging is induced by EVs used in business fleets.

- **Charging stations at places of work:** For EVs used by enterprises, the charging stations are placed at the location of the enterprise. For private users of EVs the demand is distributed among the surrounding municipalities according to commuter data. The number of charging stations in a working place context allocated to a municipality by private EV drivers is computed by:

EJTIR 12(4), 2012, pp. 391-416
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

406

$$C_j^w = \sum_{municipalities\ i} \left(\left(\frac{x_{ij}}{\sum_{municipalities\ k}\ x_{ik}} \cdot M_i \right) \right)$$

C_j^w: number of CSs at working places allocated to municipality j

$x_i{}^j$: number of commuters travelling from municipality i to municipality j

M_i: number of CS at working locations needed by EVs of municipality i

This can be interpreted as a distribution according to probabilities. The probability that an EV owned in municipality i recharges at a working place at municipality j is assumed to corresponds to the number of commuters driving from i to j divided by the total number of commuter leaving municipality i.

- **Charging stations at public locations:** The public charging stations are distributed according to inter-municipal mobility data. Because no more refined mobility data was available on the regional scale of the model, commuter data was used (also see discussion below). For allocating the need for public charging stations in space, two modelling possibilities were implemented: The first possibility is to distribute the need for public recharging according to the commuters flows as was done above. The second possibility is to distribute the need for public charging that arises from the EVs of a given municipality only to other municipalities. This is based on the reasoning that EV drivers only make use of public charging infrastructure when they are on longer trips outside of their hometown municipalities. The formula for distributing public charging stations among the municipalities of the region in this case is:

$$C_j^p = \sum_{municipalities\ i} \left(\left(\frac{x_{ij}}{\sum_{municipalities\ k}\ x_{ik}} \cdot N_i \right) \right)$$

C_j^p: number of CSs at public places allocated to municipality j

$x_i{}^j$: number of commuters travelling from municipality i to municipality j

N_i: number of CSs at public locations needed by EVs of municipality i

For quantifying the number of CSs needed at work and public locations, the EVs which drive into the region from outside were also included. For this, the development of EV ownership in the municipalities lying outside of the region was modelled to progress as in the average of the region (concerning number of EVs per inhabitant).

5. Simulation results

In this section we present selected simulation results of our model. Three scenarios of charging infrastructure development in the Region Stuttgart until 2020 are shown. In the first scenario, we simulate the development for plausibly moderate levels of utilisation and public recharging. Because the resulting number of public charging stations is quite low, we simulate the development with higher charging station quotas in scenario 2. In scenario 3, we check, whether a change in the mobility model used results in significant changes in the simulation outcome.

EJTIR 12(4), 2012, pp. 391-416   407
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

5.1 Baseline scenario for the development of charging infrastructure

For our baseline scenario, the development of EV ownership is simulated as explained in Section 3.2 in accordance with the targets stated by the German national plan of EV development (Bundesregierung der Bundesrepublik Deutschland, 2009).

For calculating the quotas *Ci/V* for charging infrastructure, we assume the parameters and resulting quotas listed in Table 2. (also compare discussion of parameters above). Utilisations of 8.33 and 12.5 % correspond to 2 and 3 hours of minimum daily use. For charging stations at working places and homes, we use directly estimated quotas as explained in Section 4.1.). For this scenario, it was simulated that the need for *public* recharging arises only outside of the home municipality of EV drivers (see Section 4.4).

Table 2. Parameters and resulting quotas used for different EV users and CS types in the baseline scenario

EV users	e [kWh/km]	d [km]	R_i [%]	CS types (p_i [kW])	U_i [%]	Resulting quota: C_i/V
Private users	0.228	36.1	2.5	44 kW public fast charging	12.5	0.0016
	0.228	36.1	7.5	22 kW public charging	8.33	0.0140
	/	/	/	at working locations	/	0.2000
	/	/	/	at home	/	0.9500
Business fleet users	0.46	64.2	2.5	44 kW public fast charging	12.5	0.0056
	0.46	64.2	2.5	22 kW public charging	8.33	0.0168
	/	/	/	at working locations	/	1.0000
	/	/	/	at home	/	0.0000

The simulation results can be seen in Figure 8. For the 35 001 EVs of the region and those driving in from outside, there are a total of 38 691 CSs. Of those, 21 851 (56%) are located at homes of EV owners, 16 268 (42%) at businesses, 478 (1.2%) in public spaces for normal 22 kW recharging, and 94 (0.2%) in public locations for fast 44 kW charging. The entire proportion of public CSs of 1.4 % is so small that it is hardly visible in Figure 8. The simulation shows that CSs at homes and working places will mainly be located in the bigger municipalities of the region.

Figure 9 shows the spatial distribution of only those charging stations placed at public locations. It is clearly visible that the demand for public charging is only high enough to warrant the installation of such infrastructure in the biggest municipalities.

Looking at the development of the number of CSs over time (lower left in Figures 8 and 9), it can clearly be seen how the exponential character of the diffusion of EV technology is manifested in the growth of the charging infrastructure. Development begins quite slow in the first years, but begins to accelerate after a critical mass of EVs has been reached around 2015.

The total number of public charging stations this simulation run yields is rather low, even though we used plausible parameters in the middle range. In the following, we present further scenarios with higher quotas for public CSs.
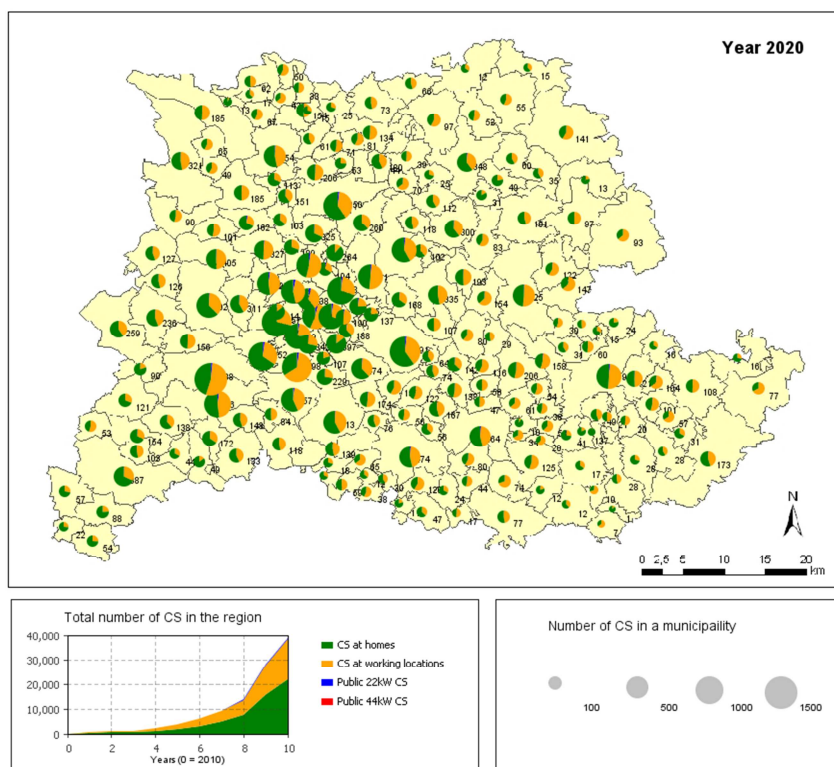
EJTIR 12(4), 2012, pp. 391-416
408
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

Figure 8. Development of charging infrastructure until 2020 in the baseline scenario
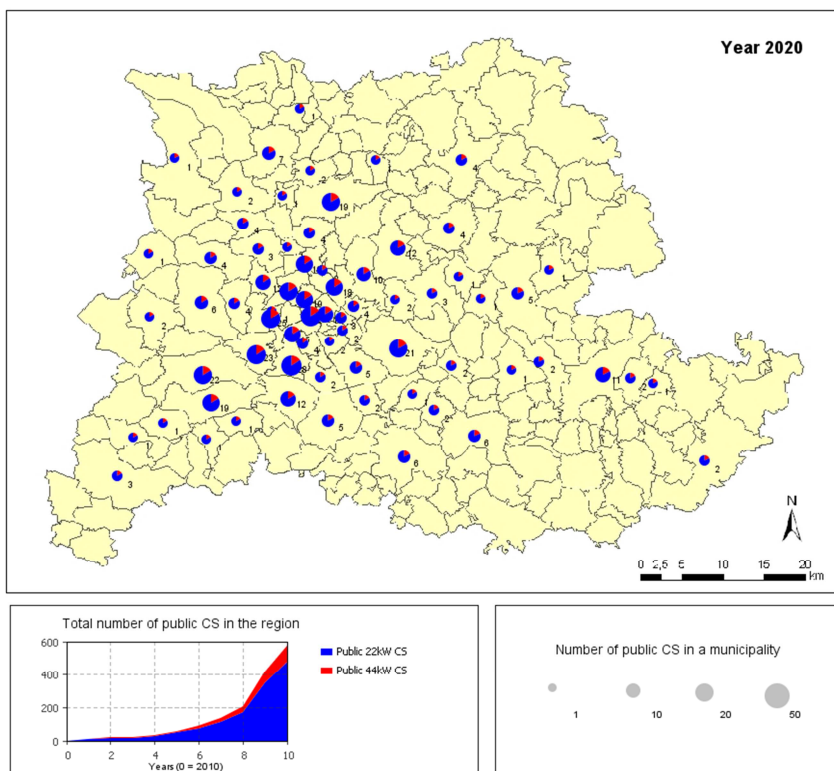
Figure 9. Development of public charging infrastructure until 2020 in the baseline scenario

EJTIR 12(4), 2012, pp. 391-416
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

409

5.2. Scenario with higher quotas for public charging infrastructure

In this and the following scenario, we focus solely on public charging infrastructure. In this scenario we use more optimistic (but still plausible) values for *Ui* and *Ri*, than in the first case. This leads to higher quotas and a thus an overall higher number of charging stations. The chosen parameters are listed in Table 3. We calculate with a higher percentage of energy publicly recharged, and lower necessary utilisation of public charging stations. Utilisation rates of 4.16 and 8.33 percent correspond to 1 and 2 hours of daily use.

Table 3. Parameters and resulting quotas used for different EV users and public CS types in the "higher quotas"-scenario

EV users	e [kWh/km]	d [km]	R_i [%]	CS types (p_i [kW])	U_i [%]	Resulting quota: C_i/V
Private users	0.228	36.1	3	44 kW public fast charging	8.33	0.0028
	0.228	36.1	12	22 kW public charging	4.16	0.0449
Business fleet users	0.46	64.2	5	44 kW public fast charging	8.33	0.0168
	0.46	64.2	5	22 kW public charging	4.16	0.0672

The results of the simulation for 2020 can be seen in Figure 6. With the higher quotas, there are 1,918 public CSs for 35,011 EVs within the Region Stuttgart, and those driving in from the outside. Of these CSs, 1,678 are stations with 22 kW charging power, and 240 are fast 44 kW charging points. Though the overall number of CSs is higher in this scenario, the spatial pattern of public EV infrastructure demand stays unchanged. The bigger part of the CSs is allocated to the biggest urban centres of the region. But since the overall demand is higher, it also becomes worthwhile to install public CS in smaller peripheral municipalities

5.3. Scenario with a different spatial usage of public charging infrastructure

As explained in Section 4.4., two model variants of the spatial use of charging infrastructure were implemented. In the first model, it is assumed that EV drivers recharge their vehicles at public CSs only when they are driving outside their hometown municipalities. This model was used in the above scenarios. Now, for the scenario presented here, the second model is used, in which EV drivers also recharge at public CS *within* their hometown municipalities. Such a usage pattern would for instance occur when people own an EV but do not dispose of a private charging station for themselves at home. Apart from this change, the parameters were left as they were set for the previous scenario 2.

The results for the year 2020 can be seen in Figure 11. The total number of charging stations of 1,971, with 1,724 of 22 kW and 274 of 44 kW charging power is slightly higher. This might be due to the EVs driving out of the region needing more public infrastructure in their hometown municipalities than before. The overall results indicate the same here: demand for public charging occurs mainly in the biggest urban centres. However, a slight change of emphasis take place in this scenario. When comparing the results of this scenario with those of the previous scenario, it can be noticed that the different CS usage profile results in more public charging stations being allocated to the big cities surrounding the central city of Stuttgart.
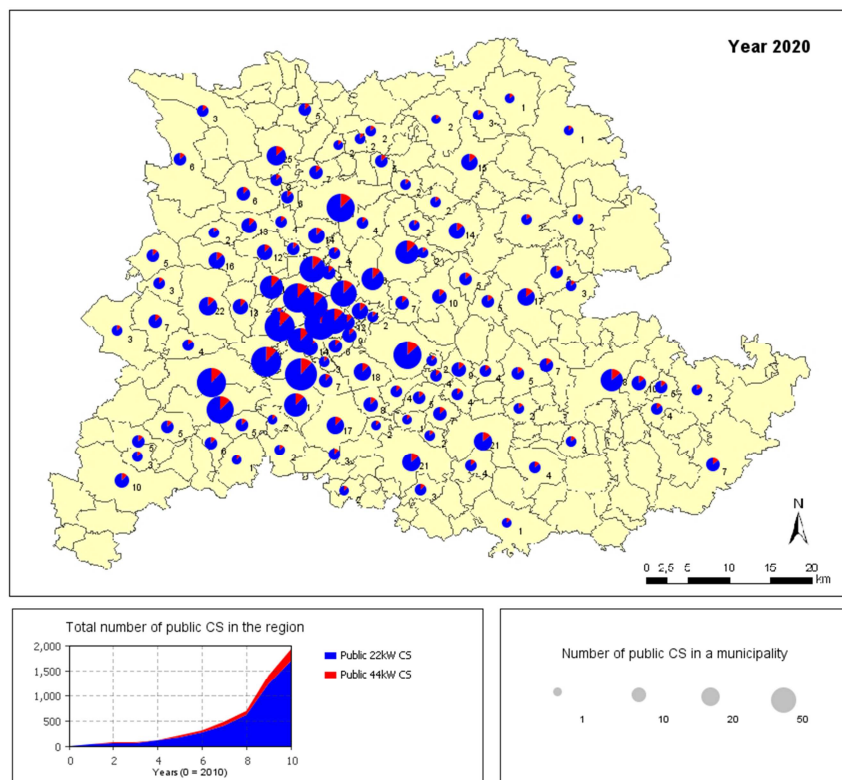
EJTIR 12(4), 2012, pp. 391-416   410
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

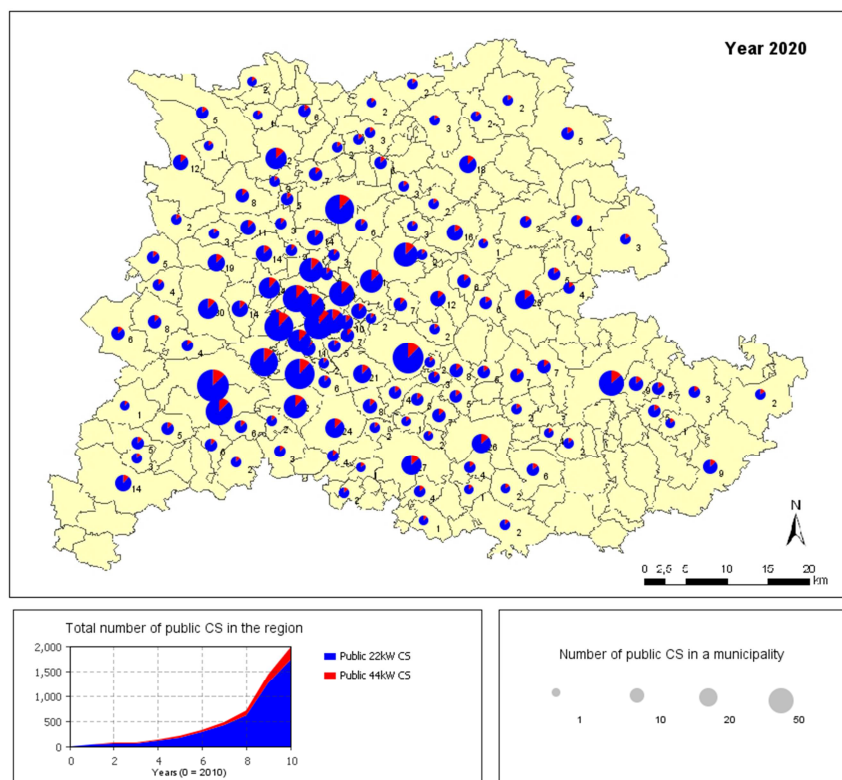*Figure 10. Development of public charging infrastructure until 2020 in the "higher quotas" scenario*

Figure 11. Development of public charging infrastructure until 2020 in the "different spatial usage" scenario

EJTIR 12(4), 2012, pp. 391-416   411
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

6. Conclusion: general implications for the long-term installation of public charging infrastructure

The main finding of our analysis is that the number of charging stations needed to provide a public charging service to a region is quite low. Our scenarios show that 600 to 2000 public charging stations placed in central city locations are sufficient for a large region such as the Region Stuttgart. If much more infrastructure is installed, it is bound to be under-utilised and thus cannot be operated economically.

A general trend can be observed in all three of the scenarios discussed above: demand for public EV charging arises mainly in the biggest urban centres of the region. Thus, the installation of public CSs should focus on central regional cities in the next few years. This approach combines two main advantages. Firstly, the number of potential adopters is high in these cities (see Figure 2). These might be convinced to buy an EV, when they see public EV charging infrastructure being deployed in their city. Secondly, such cities attract many drivers from the surrounding municipalities, who come to work, shop and for recreational activities.

The installation of charging infrastructure has to be planned several months or years in advance. But precisely forecasting the growth of EV ownership is difficult at the moment. The temporal development of EV ownership, as our model and many others project it, starts slowly but gains high momentum within a few years. This progression is typical for the diffusion of new products. Diffusion usually starts in an exponential growth, which only looses momentum after the product has reached the mass market. This results in the typical S-shaped diffusion curve. In order to keep track of EV market development, statistical data on new vehicle registrations should be evaluated regularly, and the announcements of EV manufacturers concerning the commercial launch of vehicles followed closely. Even though demand for public recharging can be expected to be low within the next few years to come, stakeholders wanting to take part in the future business of EV infrastructure should get involved in installing CSs as soon as possible. This will provide them an advantage regarding experience and know-how once the need for public recharging starts to rise dramatically.

Our model indicates that economic installation and operation of public charging infrastructure is only feasible in dense urban areas. However, if public charging stations are only available within the biggest cities in the long-term, EV drivers might severely be limited in their mobility. Alike to other kinds of infrastructure such as public transport, there seems to be a conflict between the provision of a public service to areas urban and rural alike, and the profitability of the service.

7. Outlook: improvements and extensions of the model

The model presented in this paper allows simulating the development of a charging infrastructure for EVs on a regional scale under different assumptions. It consists of several subcomponents which simulate the time-spatial development of EV ownership, the mobility of EVs between the municipalities of the region, and the number of charging stations required by a given number of EVs. This modular structure provides possibilities for several enhancements. Individual modules can easily be refined, without having to reimplement the entire program. In the following, we discuss several refinements we are planning to realize in the future.

The electric vehicles we modelled in this work are (pure) battery electric vehicles. However, plug-in hybrid vehicles will also use charging infrastructure in the future, even though they are not dependent on it. Plug-in hybrids could be integrated into the model as a separate product, concerning ownership and diffusion, with possibly different recharging behaviour, or

EJTIR 12(4), 2012, pp. 391-416   412
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

incorporated indirectly by determining the parameters of the model that would result by a mixed fleet of pure and plug-in hybrid EVs.

In our model, the time-spatial development of EV ownership was simulated using the established Bass model for the diffusion of innovations. Several assumptions had to be made to generate a projection of the development in the next ten years. When more data on the actual development of EV sales is available, our model can be recalibrated to better forecast this long-term development. Beyond this mere recalibration, it is also envisioned to extend the model to incorporate a positive reinforcement between the number of owned EVs and the number of available charging stations. As it is currently modelled, the necessary number of CSs is deduced from the number of EVs. However, an inverse influence is also to be expected. Potential adopters will be more willing to buy an EV, when they see charging stations being installed in their surroundings. Such kinds of effects were already modelled in system dynamics models (Struben and Sterman, 2008, Wansart and Schnieder, 2010, Yamashita et al., 2011).

We calculated the number of charging stations that is needed by a given number of EVs using a formula. The parameters of this formula can be readjusted as more viable information becomes available within the next years. It is especially interesting to integrate more reliable data on the utilisation and profitability of charging stations, which can be expected as a result of many pilot projects that are currently taking place all over the world. Our current model version keeps the quotas of CSs per EV constant over the simulation run. It is planned to adjust the model in such a way as to have quotas which change over the years.

The mobility of EVs between municipalities is modelled here using data on commuter flows. A more elaborate traffic model can be used instead. This allows simulating the differing traffic generated by diverse user groups (early adopter types, fleet users etc.) and different activities (driving to work, shopping, recreation etc.). Additionally, such a traffic model can incorporate more sophisticated models of recharging activities (charge when battery is 80 % depleted etc.). This can provide further insights concerning a prospective utilisation of charging infrastructure.

Acknowledgements

References

Baden-Württemberg Statistisches Landesamt (2009). Die Berufspendler in Baden-Württemberg, Reihe Statistische Daten. *Statistical data.*

Bass, F. M. (1969). A new product growth for model consumer durables. *Management Science*, no. 15, pp. 215-227.

Becker, T. A., Sidhu, I. and Tenderich, B. (2009). Electric Vehicles in the United States - A new Model with Forecasts to 2030. *Technical Brief,* Center for Entrepreneurship & Technology (CET), University of California, Berkeley.

Biere, D., Dallinger D. and Wietschel. M. (2009). Ökonomische Analyse der Erstnutzer von Elektrofahrzeugen. *ZfE Zeitschrift für Energiewirtschaft*, no. 2, pp. 173-181.

BMW Group (2010). E-Mobilität: Erkenntnisse aus dem MINI-E Feldversuch. *Project result report.*

EJTIR 12(4), 2012, pp. 391-416   413
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

Brownstone, D., Bunch, D.S. and Golob, T.F. (1994) . A Demand Forecasting System for Clean-Fuel Vehicles. *OECD Conference on Fuel Efficient and Clean Motor Vehicles*. May 1994, Mexico City.

Bundesministerium der Finanzen (2000). AfA-Tabelle für die allgemein verwendbaren Anlagengüter ("AV") - gilt für alle Anlagegüter, die nach dem 31.12.2000 angeschafft oder hergestellt worden sind. *Juristic text*.

Bundesregierung der Bundesrepublik Deutschland (2009). Nationaler Entwicklungsplan Elektromobilität der Bundesregierung. *Government report.*

Bundesregierung der Bundesrepublik Deutschland (2011). Regierungsprogramm Elektromobilität. *Governement report.*

Cabled Project Consortium (2011). Largest "Real World" Electric Vehicle Trial Reveals Full Year Findings. *Press Release.*

Cao, X. (2004). The future demand for alternative fuel passenger vehicles: a diffusion of innovation approach.. *Caltrans Air Quality Project - task order no. 31 final report*, Department of Civil and Environmental Engineering, University of California.

ChargePoint Network and Idaho National Laboratory (2011). ChargePoint America Vehicle Charging Infrastructure Summary Report : May 1, 2011 through August 31, 2011. *Project result report.*

Chavis, C., Kanairo, K., Samartino, A. L., SAathaye, N., Sidhu, I., Kaminisky, P. and Tendrich, B.(2009). Strategies for Electric Vehicle Deployment in the San Francisco Bay Area. *Technical Brief*, Center for Entrepreneurship & Technology (CET), University of California, Berkeley

Dashora, Y., Barnes, J.W., Pillai, R.S., Combs, T.E., Hilliars, M. and Chinthavali, M.S. (2010). The PHEV Charging Infrastructure Planning (PCIP) Problem. *International Journal of Emerging Electric Power Systems*, vol. 11, no.2, article 7.

E.ON AG (2010). E.ON präsentiert erste Zwischenergebnisse aus dem Pilotprojekt in München: Elektroautofahrer laden Fahrzeuge vor allem zu Hause und am Arbeitplatz. *Press Release*.

Ecotality North America and Idaho Nartional Laboratory (2011). EV Project Electric Vehicle Charging Infrastructure Summary Report. *Project result report.*

EnBW Energie Baden-Württemberg AG (2011). Geschäftsbericht 2011. *Annual business report*.

Engel, T. (2011). Die Netzintegration von Elektrofahrzeugen: Teil 8 der Serie: die Bedeutung öffentlicher Ladeinfrastruktur. *EMobile plus solar, no.82, pp. 27- 30*

Feller, A. and Stephan, M. (2009). Migrating from Oil- to Electricity-Powered Vehicles: Modelling Germany's Transition to the EV until 2040 in System Dynamics, *Bachelor Thesis*, Kühne Foundation Chair Logistics Management,WHU - Otto Beisheim School of Management.

Follmer, R., Gruschwitz, D., Jesske, B., Quandt, S., Lenz, B., Nobis, C., Köhler, K. and Mehlin, M. (2008). Mobilität in Deutschland 2008. *Technical report.*

Follmer, R. Kunert, U., Kloas, J. and Kuhfeld, H. (2004). Mobilität in Deutschland 2004. *Technical report*.

Götze, U. and Bloech, J. (2004*). Investitionsrechnung - Modelle und Analysen zur Beurteilung von Investitionsvorhaben*, Springer-Verlag, Berlin.

Groupe de Travail sur les Infrastructures de Recharge (2009). Presentation du résultats du Groupe de Travail sur les Infrastructures de recharge pour les véhicules électriques ou hybrides rechargeables.*Technical Report.*

Groupe La Paste (2009). La démarche de coordination de la demande de véhicules électriques. *Technical Report.*

EJTIR 12(4), 2012, pp. 391-416   414
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

Hacker, F., Harthan, R., Matthes, F. and Zimmer, W. (2009.) Environmental impacts and impact on the electricity market of a large scale introduction of electric cars in Europe - Critical Review of Literature. *ETC/ACC Technical Paper 2009/4*, European Topic Center on Air and Climate Research.

Hanna, M. (2001). GIS: Helping to Map the Future of Electro-Drive Cars. *Energy Currents, a publication of the AM/FM/GIS Marketing Group of ESRI,* Summer 2011

INFAS (2011). infas Institut für angewandte Sozialwissenschaft GmbH Website. Available at http://www.infas.de/, last accessed 08.10. 2011.

INFAS and Öko Institut e.V. (2009). Wie und warum sind wir mobil? Ergebnisse und Trends zur Mobilität in Deutschland. Paper presented at *Kongress ECOMOBIL Mobilität neu denken*, Nov. 2009, Offenburg.

Ip, A., Fong, S. & Liu, E. (2010). Optimization for allocating BEV recharging stations in urban areas by using hierarchical clustering. Peper presented at the *6th International Conference on Advanced Information Management and Service IMS2010, with 2nd International Conference on Data Mining and Intelligent Information Technology Applications ICMIA2010,* Nov. 2010, Seoul .

Kearney, M. J. (2011). Electric Vehicle Charging Infrastructure Deployment: Policy Analysis Using a Dynamic Behavioral Spatial Model. *Master Thesis*, Engineering System Division, Massachusetts Institute of Technology (MIT)

Kley, F., Dallinger, D. and Wietschel, M.(2010). Assessment of Future EV Charging Infrastructure. Paper presented at the *International Advanced Mobility Forum 2010.*, Mar. 2010, Geneve.

Koyanagi, F., Uriu, Y. and Yokoyama , R. (2011). Possibility of Fuel Cell Fast Charger and Its Arrangement Problem for the Infrastructure of Electric Vehicles. Paper presented at *2001 IEEE Porto Power Tech Conference*, Sept. 2011, Porto.

Koyanagi, F. and Yokoyama, R. (2010). A priority order solution of EV recharger installation by domain division approach.. Paper presented at the *45th International Universities Power Engineering Conference (UPEC)*, Aug. 2010, Cardiff.

Kraftfahrt-Bundesamt (2009). Fahrzeugzulassungen, Bestand, Halter - 1.Januar 2009. *Statistical data.*

Kraftfahrt-Bundesamt (2010). Bestand an Kraftfahrzeugen und Kraftfahrzeuganhängern nach Zulassungsbezirken - 1. Januar 2010. *Statistical data.*

Kruschwitz, L. (2005). *Investitionsrechnung,* R. Oldenburg Verlag, München und Wien.

Leiby, P. and Rubin, J. (2004). Understanding Transition to New Fuels and Vehicles: Lessons Learned from Analysis and Experience of Alternative Fuel and Hybrid Vehicles. In Sperling, D. and Cannon, J. S. (eds*.) The Hydrogen Energy Transition:Moving Toward the Post Petroleum Age in Transportation*, Elsevier Academic Press, Burlington.

Lin, Z., Ogden, J., Fan, Y. and Chen, C.-W. (2008). The fuel-travel-back approach to hydrogen station siting. *International Journal of Hydrogen Energy*, no. 33, pp. 3096-3101.

Linder, S. and Wirges, J. (2011). Spatial diffusion of electric vehicles in the German metropolitan region of Stuttgart. Paper presented at the *ERSA Congress 2011 - New Challenges for European Regions and Urban Areas in a Globalised World*, Aug. 2011, Barcelona.

Mayor of London (2009). An Electric Vehicle Delivery Plan for London. *Technical Report.*

Mayor of London (2009a). London's Electric Vehicle Infrastructure Strategy: Turning London Electric. *Technical Report.*

Ministère de l'Ecologie de l'Energie du Développement Durable et de la Mer (2009). Dossier de Presse: Lancement du Plan National pout le Développement des Véhicules Électriques et Hybrides Rechargeables. *Press release.*

EJTIR 12(4), 2012, pp. 391-416   415
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

Nationale Plattform Elektromobilität (2010). Zwischenbericht der Nationalen Plattform Elektromobilität: AG 3: Lade-Infrastrukutur und Netzintegration .*Technical Report*.

Negre, L. and Legrand, J.-L. (2011). Livre Vert sur les infrastructures de reacharge ouvertes au public pour les véhicules "décarbonés" Sénateur des Alpes-Maritimes, République Francaise. *Technical Report.*

Nicholas, M. A. (2004). Hydrogen Station Siting and Refueling Analysis Using Geographic Information Systems: A Case Study of Sacramento County. *Master Thesis*, University of California Davis.

Ortúzar, J. D. D. and Willumsen , L. G. (2010). *Modelling Transport*, John Wiley & Sons., Chichester.

Priemer, B. (2010). Munter Strom: Die E-Mobilität macht auch vor auto motor und sport nicht halt: Erstmals in der über 60-jährigen Tradition wurden 2010 E-Autos getestet. *auto motor und sport: ECO drive: Das Magazin für Umweltbewusste Mobilität*, no.1, pp.12-15.

Rogers, E. M. (2003). *Diffusion of Innovations*, Free Press, New York.

Ruschmeyer, T. (2010). Ladeinfrastruktur für Elektrofahrzeuge: Wald der Stromtankstellen und die Steckerdiskussion. Paper presented at *Zweiter Deutscher Elektro-Mobil-Kongress*, Jun. 2010, Bonn.

Schirmer, D., Morales, E. T. and Boruah, H. (1996). On The Integration of GIS within an Electric Vehicle Program for Predictive Analysis. Paper presented at the *ESRI Users Conference*, May 1996, Palm Springs.

Shinohara, K. and Okuda, H. (2010). Dynamic Innovation Diffusion Modelling. *Computational Economics*, no. 35, pp. 51-62.

Statistisches Landesamt Baden-Württemberg (2011). Statistisches Landesamt Baden-Württemberg Website. Available at http://www.statistik.baden-wuerttemberg.de/, last accessed 08.09.2011.

Sterman, J. D. (2000). S-Shaped Growth: epidemics, Innovation Diffusion, and the Growth of New Products. In Sterman, J.D. *Business Dynamics - Systems Thinking and Modeling for a Complex World*. McGraw-Hill Higher Education, New York.

Struben J. (2006). Essays on transition challenges for alternative propulsion vehicles and transportation systems, *PhD Thesis*, Alfred P. Sloan School of Management, Massachusetts Institute of Technology MIT.

Struben, J. & Sterman, J. D. (2008). Transition challenges for alternative fuel vehicle and transportation systems. *Environment and Planning B: Planning and Design*, no. 35, pp. 1070-1097.

Sullivan, J. L., Salmeen, I. T. and Simon, D. P. (2009). PHEV marketplace penetration: an agent based simulation, *Technical Challenges of Plug-In Hybrid Electric Vehicles and Impacts to the U.S. Power System: Final report*, Transport Research Institute, University of Michigan.

Wang, Y.-W. (2007). An Optimal Location Choice Model for Recreation-Oriented Scooter Recharge Stations. *Transportation Research Part D*, no. 12, pp. 231-237.

Wang, Y.-W. (2008). Locating Battery Exchange Stations to Serve Tourism Transport: A Note. *Transportation Research Part D*, no.13, pp. 193-197.

Wang, Y.-W. and Lin, C.-C. (2009). Locating Road-Vehicle Refueling Stations. *Transportation Research Part E*, no.45, pp. 821-829

Wansart, J. and Schnieder, E. (2010). Modeling market development of electric vehicles. Paper presented at the *4th Annual IEEE Systems Conference*, Apr. 2010, San Diego.

Wermuth, M. (2002). Kontinuierliche Befragung des Wirtschaftsverkehrs in unterschiedlichen Siedlungsräumen - Phase 2 Hauptstudie - (Kraftfahrzeugverkehr in Deutschland KiD 2002) - Schlussbericht Band 2. *Technical Report*.

EJTIR 12(4), 2012, pp. 391-416   416
Wirges, Linder, and Kessler
Modelling the Development of a Regional Charging Infrastructure
for Electric Vehicles in Time and Space

Wiederer, A. and Philip, R. (2010). Policy options for electric vehicle charging infrastructure in C40 cities - for Stephen Crolius, Director, Transportation, Clinton Climate Initiative *Technical Report*. Harvard Kennedy School.

Wirtschaftsförderung Region Stuttgart GmbH (2010). Modellregion Elektromobilität Region Stuttgart. *Technical report.*

Yamashita, D, Niimura, T., Takamori, H. and Yokoyama, R. (2011). A dynamic model of plug-in electric vehicle markets and charging infrastructure for the evaluation of effects of policy initiatives. Paper presented at the *Power Systems Conference and Exposition (PSCE)*, Mar. 2011, Phoenix

Zumkeller, D., Chlond, B., Kagerbauer, M., Kuhnimhof , T. and Wirtz, M. (2010). Deutsches Mobilitätspanel (MOP) - Wissenschaftliche Begleitung und erste Auswertungen. *Technical report*, Institut für Verkehrswesen, Karlsruher Institut für Technologie (KIT).