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Modelling market diffusion of electric vehicles with real world driving data – German market and policy options

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ABSTRACT

Plug-in electric vehicles (PEVs) have the potential to reduce green house gas emissions from the transport sector. However, the limited electric range of PEVs could impede their market introduction. Still some potential users are willing to pay more for PEVs. The combined effect of these and other influencing factors as well as the resulting future market evolution are unclear. Here, we study the market evolution of PEVs in Germany until 2020. Our results reveal a great deal of uncertainty in the market evolution of PEVs due to external conditions and the users' willingness to pay. We find the future share of PEVs in German passenger car stock to range from 0.4% to almost 3% by 2020. Energy prices have a large impact on PEV market evolution as a 25% increase in fuel prices would double the number of PEVs in stock by 2020 compared to a reference scenario. We find a special depreciation allowance for commercial vehicles and a subsidy of 1000 Euro as the most effective and efficient monetary policy options. The high uncertainty of the market evolution implies that policies to foster market diffusion of PEVs should be dynamically adaptable to react to changing framework conditions.

1. Introduction

The reduction of green house gases and the scarcity of conventional energy resources are relevant challenges to the mobility sector in the 21st century (Kahn Ribeiro et al., 2007). Plug-in electric vehicles (PEVs) in combination with renewable energy carriers are one possible solution for these challenges. A standard approach to determine the market penetration of PEVs are so-called total cost of ownership (TCO) models (Thiel et al., 2010; McKinsey & Company, 2011; Pfahl et al., 2013). A common limitation of such models is the usage of average driving patterns (Mock et al., 2009). This could yield misleading results, since individual driving profiles show great variations both between different users as well as from day-to-day for an individual user (Neubauer et al., 2012; Gnann et al., 2012a; Plötz et al., 2013). Another shortcoming is the limited integration of other decision factors than cost in the vehicle buying decision (Mueller and de Haan, 2009; de Haan et al., 2009).

However, a successful market penetration of PEVs depends on several technical factors like the advancement of battery technology, economical factors like the development of oil or electricity prices, organizational factors like the availability of charging infrastructure and user behavioural factors like consumer acceptance of this new technology or individual driving behaviour. The difficulty is to include this large variety of input factors into a model and to be able to evaluate their contribution to results or suggest policy options consequently. To the best of our knowledge, there is no model up to now which

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copes with all these factors explicitly and uses individual driving behaviour (see Section 2 for a review of market diffusion models for electric vehicles).

In a previous paper we introduced and evaluated a model that incorporates the above mentioned factors (Plötz et al., 2014). In this part, we put more emphasis on results and their implications by answering the following research questions: *How will the market for PEVs in Germany evolve until 2020? Which factors are most important and how could policy makers influence PEV sales?* The focus of this paper is not an exact forecast of the future market diffusion until 2020 in Germany. Instead we perform a model-based assessment of the main influencing factors and policy options. In the following Section 2, we assort our model into the current literature on market diffusion models of alternative fuel vehicles. In the following Section 3 the model, the driving profiles and the main input data are presented. Section 4 comprises the results of the model application and an analysis of the main determining factors of the PEV market penetration as well as of monetary policy options and a discussion of the results. In the final Section 6, a summary and conclusions are given.

In this study, we consider three types of plug-in electric vehicles (PEVs): battery electric vehicles (BEVs) which can only drive electrically, plug-in hybrid electric vehicles (PHEVs) as well as range-extended electric vehicles (REEVs, often also extended-range electric vehicles (EREV)) which also have the possibility to refuel with conventional fuel. We do not distinguish the exact propulsion system (parallel or serial) since all vehicles' batteries are fully depleted before using the conventional engine in the simulation.

2. Existing models of electric vehicle market diffusion

The diffusion of new technologies and PEVs in particular has received considerable attention in the literature (see Al-Alawi and Bradley, 2013 for a recent review of PEV market diffusion models). A general classification of market diffusion models was given by Geroski (2000). He describes two groups of models for market diffusion of innovations: population and probit models. Since probit models are one classification of consumer choice models (see e.g. Train, 2009), we will refer to consumer choice models for the second group. The latter also includes the frequently used agent-based models. These two model classes are discussed briefly and some of the existing market diffusion models for PEVs are classified accordingly in order to categorise our model.

Population models describe users or adopters not as individuals, but as groups. Population models assume for example that the rate of adoption is proportional to the number of adopters and the remaining population that has not adopted a technology yet. This leads to the well-known logistic differential equation and can be interpreted via the spread of information about a technology (Geroski, 2000). Population models offer a simple structure and interpretation. They are usually applied by calibrating the market diffusion curve to existing market data or by assuming hypothetical growth rates. This procedure is rather sensitive in early market phases when little data is available. Furthermore, the heterogeneity of the individual buying decisions and preferences of users, for example reflected in the willingness to pay more for new technologies of some users as well as the individual economics of the driving behaviour, cannot be incorporated into these models. We find population models for PEV market diffusion or market diffusion of other alternative fuel vehicles in Duleep et al. (2011), Richter and Lindenberger (2010), Keles et al. (2008), Köhler et al. (2010), Lamberson (2008), Meyer and Winebrake (2009), Nemry and Brons (2010), Shepherd et al. (2012), Wansart and Schnieder (2010), and McManus and Senter (2009), which range from simple mathematical equations to complex system dynamics models.

The second group of market diffusion models, consumer choice and agent-based models, studies adopters individually. These models are often applied when the purchase decision is more complex or the technologies to be adopted are rather expensive. For example, a simple probit model for PEV adoption would calculate the average ownership cost difference between conventional and electric vehicles and estimate a PEV market share based on this difference. As fuel and battery prices change over time, these cost differences change and with them the estimated PEV market share. Thus, consumer choice models develop market diffusion bottom-up and acknowledge that individual users can be very different. This is particularly important to identify niche markets in early phases of market development. However, these models face the problem that consumer statements about their preferences for PEVs are often inaccurate. Given the current market shares of PEVs, the vast majority of users has never experienced a PEV and can hardly judge its utility. Accordingly, the majority of studies uses stated preference data to study AFV diffusion (see e.g. Bočkarjova et al., 2014; Brownstone et al., 2000; Batley et al., 2004; Potoglou and Kanaroglou, 2007; Glerum et al., 2013).

Consumer choice and agent-based models were used to model PEV market diffusion in Eppstein et al. (2011), Hacker et al. (2011), Mock et al. (2009), Propfe et al. (2012), Zhang et al. (2011), Shafiei et al. (2012), Yabe et al. (2012), Sullivan and Salmeen (2009), Elgowainy et al. (2012), Brown (2013), and Higgins et al. (2012) where the detailed modelling approaches range from determining user shares by stated preference experiments to agent-based models. Some of these models are based on driving behaviour of conventional vehicles (Hacker et al., 2011; Mock et al., 2009; Brown, 2013). This would in principle allow to analyse user behaviour in more detail. However, the latter models use driving profiles of only one day which can cause severe inaccuracies on the individual level as a single day might not show the individual's typical driving as is crucial for PEVs due to their limited range (see Neubauer et al., 2012; Gnann et al., 2012a; Plötz et al., 2013).

In summary, agent-based models offer the possibility to include several aspects of great relevance for the market diffusion of PEVs in the current market development phase: individual purchase preferences, individual driving behaviour (to account for the limited range of PEVs and the vehicle kilometres travelled (VKT) related usage costs), the need for frequent