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What drives the market for plug-in electric vehicles?

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Abstract

Market diffusion of plug-in electric vehicles (PEVs) is an often-addressed research topic, yet PEV market diffusion models differ in approaches, factors included and results. Here, we compare 40 market diffusion models for PEVs in scope, approach and findings to point out similarities or differences and make recommendations vor futue research in this area. We find that important input factors for the US are purchase price and operating cost, while for Germany energy prices and charging infrastructure are mentioned more often. Furthermore, larger sales shares of plug-in hybrid electric vehicles than battery electric vehicles are often found in the short term results while the picture is not so clear for the medium- to long-term. Future models should include specific PEV features like limited range of battery electric vehicles or access to charging infrastructure which are currently not covered by many models. Also, the integration of current policy regulations and, if possible, indirect policy incentives would enhance research in this field.

Keywords: Plug-in electric vehicle market diffusion, literature review, diffusion model

1 Introduction

The need to reduce CO_2 emissions and petroleum use from the transport sector forces the automobile industry, researchers and policy makers to think about the diffusion of plug-in electric vehicles (PEVs). For this purpose, a variety of models has been set up to analyze factors that influence market diffusion and ways to accelerate it, e.g., by subsidies or restrictions (USEPA/NHTSA 2010, EU 2014).These models differ greatly in structure, internal logics and input factors, resulting in different diffusion results. A comparison of these models can have at least two benefits – explaining the modeling reasons for the result differences so that the probability of these different results misleading and obstructing policy discussion can be mitigated; and exposing the underlying wisdom in designing the model structure, formulating the internal logics and choosing the input factors so as to advance the state of art in diffusion modeling.

Al-Alawi and Bradley (2013) reviewed market diffusion models for PEVs in the US and compared the various model approaches used (agent-based, discrete choice, diffusion models, etc.) to make recommendations for improved approaches. Daziano and Chiew (2012) also compared PEV market diffusion models for the US. They discussed relevant factors influencing PEV adoption in the US and identified additional data needed for developing improved models. There remains a need for a broader review of recent models comparing approaches, input factors and findings from markets worldwide. Comparing models developed for different markets as well as models for specific markets provides new understanding of what factors are (or thought as) important and how they have been represented in models.

For this reason, the authors of this paper compare recent research papers on PEV market diffusion to determine general conclusions and to address the following research questions:

- *What factors do current models include and what data do they use?*
- *What factors influence market diffusion the most according to the papers?*
- *Are there important factors that are not well modeled or not included in models at all?*

We focus on papers on at least a national or state level (no local models) and compare only those where a PEV market diffusion model is explicitly described. Expert estimates or very simple calculations are not considered here. For those models that are used in multiple publications, we focus on the main publications and discuss results of the most recent one. In the following, we use the terms “paper” or “model” equivalently.

The present work differs from previous studies in several respects. First, we compare models for different geographical regions: Europe, U.S., and other countries. Second, we compare input factors and projected market shares from a wide range of models at a high level without a detailed evaluation of model algorithms or mathematical formulations. This provides a broad perspective of PEV market diffusion.

2 Methods and Data

In this analysis, we compare 40 models from 16 different countries. Since PEV market diffusion has been an active field of research for several years in the US and in Germany, we found more papers for these countries (16 for US, 14 for Germany). We focused on most recent publications; the majority (39/40) of papers reviewed were published after 2010. Papers describing models giving estimates or projections of future PEV sales or stock fractions were selected from those found using Google Scholar with the search terms "market diffusion electric vehicles", "market penetration electric vehicles", "market electric vehicles", "electric vehicles market forecast", "electric vehicles forecast" and "projection PEV", as well as articles that cited or were cited by these. Only models for PEV markets at a national level were included, not at the state or subnational level.

For each model reviewed, we noted the research questions addressed in the paper, methodological approaches, main findings and results. We created clusters based on the research questions posed and main findings as stated in the selected articles. We categorized the methodological approaches following Al-Alawi and Bradley (2013) and Gnann and Plötz (2015) into three categories: 1) aggregate stock models, 2) models that compute sales by one or more consumer segments, and 3) detailed agent-based models. We also noted whether battery electric vehicles and plug-in hybrid electric vehicles were represented separately or combined as PEVs, and we compared projected sales shares for the baseline scenario for those papers that gave sales shares. Furthermore, we identified factors (vehicle attributes, market conditions, etc.) that authors indicated were influential on PEV market diffusion and then analyzed which of these factors were included in the models.

We looked for patterns in the model approaches, findings, and influential factors across the models and how the relative importance of factors, frequency of research findings or modeling approaches varied between for different regions (U.S., Germany, and other countries) and over time of publication.Table 1 shows a summary of the papers reviewed with the country of observation.

Table 1: Models analyzed with area of observation

Citation	Area
Argonne 2014	US
Barter et al. 2015	US
Becker and Sidhu 2009	US
Brooker 2015	US
Brown 2013	US
Bühne et.al. 2015	DE
de Santa-Eulalia et al. 2011	DE
Driscoll et a. 2013	IE
Duan et al. 2014	US
Eggers and Eggers 2011	DE
EIA - Annual Energy Outlook	US
Fu et al. 2011	CN
Gnann 2015	DE
Harrison et.al. 2016	EU
Hess et al. 2012	US
IEA 2016	World
Kieckhäfer et al. 2014	DE
Kihm and Trommer 2014	DE
Lebeau et al. 2012	BE
Lee et al. 2012	KR
Lee et al. 2013	KR
Liu and Greene 2015	US
Liu and Lin 2016	US
Liu, Klampfl, & Tamor 2013	US
Nemry and Brons 2010	EU
Noori and Tatari 2016	US
Orbach, Fruchter 2011	US
Pasaoglu et al. 2015	EU
Pfahl et al. 2013	DE
Propfe et al. 2013	DE
Qian, Soopramanien 2015	CN
Redelbach et.al. 2013	DE
Shafiei et al. 2012	IS
Shepherd et al. 2011	UK
Tran 2012	UK
Wansart and Schnieder 2010	US
Wu et al. 2015	DE
Yabe et al. 2012	JP
Zeng et al. 2013	CN
Zhang et al. 2011	US

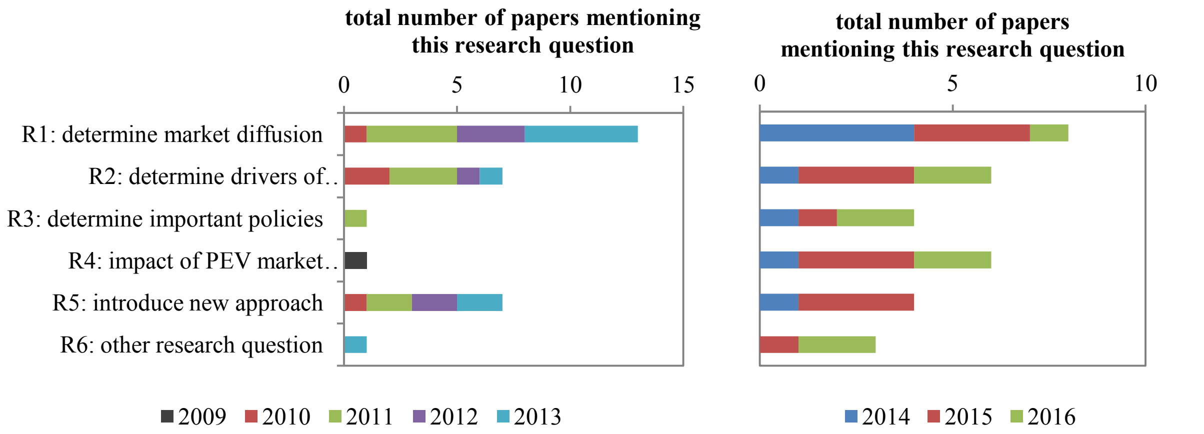

Figure 1: Timely evolution of research questions in papers analyzed. *Left panel:* Papers published before 2014, *right panel:* papers published after 2013.

3 Results

The results consist of a comparison of the 40 papers mentioned before. It is divided into four parts: Firstly, we take a look at the modeling approaches and research questions which derive from the "Introduction" and "Method" sections of the papers (Section 3.1). Secondly, we analyze the individual attributes that are covered in the models and described in the sections "Methods", "Data" or "Assumptions" of the research papers (Section 3.2). Thirdly, we focus on the "Results" of the 40 papers and compare them in an adequate way (Section 3.3). And lastly, we take a look at the factors mentioned to be important for PEV market diffusion according to the "Discussion" and "Conclusions" of the papers (Section 3.4).

3.1 Model approaches

In the papers reviewed, we find five main research questions that are considered and correspond to the findings: (1) projected market shares of PEVs for a specific region, (2) determination of most important input factors, (3) which policies would be most promising, (4) projected impacts of extensive PEV market diffusion (e.g. for the energy system) or (5) introduction of a new modeling approach. In Figure 1, these research questions (R1…R5) are shown according to their date of publication. Other research questions were combined and are listed as R6 (Other research questions). We find that the intention of most papers is to determine the market diffusion of PEVs for a certain area or the drivers of PEV market diffusion. The third most mentioned research question is to introduce a new approach (R5) with a focus rather on the method than the content. Lastly, the determination of important policies as well as the impact of the PEV market diffusion (e.g. on the electricity grid) has gained more attention in the last years. This shift to consider the impacts and policies more in the last years may be explained with the maturity of modeling approaches in the last years or a necessity to introduce policy measures to speed up the markets.

When comparing model approaches, there are many possible classifications (see e.g. (Al-Alawi and Bradley 2013, Jochem et al. 2017, Daziano and Chiew 2012) as well as [Gnann and Plötz, 2015, Section 3.1] for a discussion). In this model comparison, we choose a simple classification, since many models cannot be categorized well according to the above mentioned categorizations. We classify them with respect to their level of aggregation to highlight the general detail of the models: (1) Very aggregated models that consider only the vehicle stock for their analysis; (2) more disaggregated models that model the vehicle sales and differentiates multiple market or customer segments; (3) the most disaggregated approaches model on the level of individuals and combine them for vehicle sales afterwards. The numbers of each type of published models per year of publication are shown in Figure 2. We show some numbers in the bubbles to indicate their size.
First of all, the majority of publications uses the second approach and models the vehicle sales by year (20 models in total), most of them with multinominal logit (MNL; four models) or nested multinominal logit (NMNL; eight models) while some use simpler utility functions (eight models). The twelve very disaggregated models also use utility functions for each consumer (five with simple utility functions, five with MNL and two with NMNL). Lastly the very aggregated approaches either use simple utility functions (four) or do not explain it in

detail. We also observe a tendency toward more complex models, which is especially the case for German models (not shown in the graph). This might stem from the very heterogeneous car market where vehicle sales are distributed between private vehicles (40%), commercial fleet vehicles (30%) and company cars (30%) that have different characteristics in the purchase decision (see (Plötz et al. 2014, Kihm and Trommer 2014, Hacker et al. 2015) for a discussion). However, fewer simple models appear to have been published in recent years and are being replaced by models that are more realistic and complex. This is also evident from the number of factors included in the models which are presented in the following section.

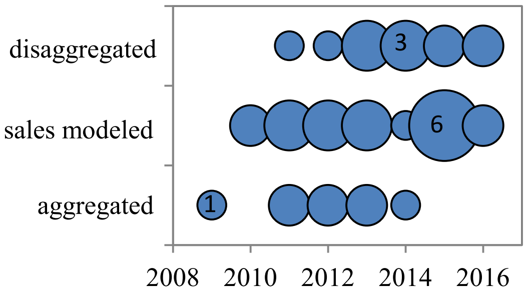

Figure 2: Model type and year of last publication

3.2 Attributes included

We analyze four groups of attributes that are considered in the models: (1) factors directly related to the purchase decision, (2) attributes of vehicles that are considered in the models, (3) attributes to describe consumer characteristics and (4) factors especially important for PEVs.

To model the consumer choice, ownership costs are often used which contain vehicle cost and energy prices. Furthermore, a common differentiation in the consumer choice is the number of decision alternatives that is presented to the consumer.[1] Almost all models cover the purchase price (37/40) as a simple factor for vehicle cost. Also fuel costs are taken into account by 33 models. However, operating costs apart from fuel cost (e.g. operations & maintenance, insurance or vehicle registration tax) are not so often covered (20/40) and the inclusion of resale prices is very rare (5/40). While these other costs are hard to determine, the difference in O&M can play an important role in the operating cost and should not be neglected (see e. g. (Propfe et al. 2012) for a good approach).

Most models include the energy prices in the purchase decision since they differ for conventional and alternative fuel vehicles and are one main difference. We find a few models that include energy prices endogenously (3/40), thus the energy prices change due to the market diffusion of PEVs (and sometimes other factors). The majority uses exogenously defined energy prices (30/40) while seven models neglect energy prices completely. Since energy price differences a typically represent a large part of the disparity in ownership cost of vehicles, they should be included in future modeling exercises.

Lastly, the number of decision alternatives varies widely. Most models use conventional cars as benchmarks and more than one type in some markets (gasoline and diesel in Germany, only gasoline in the US). Almost all models (90%) model BEVs and PHEVs separately while the inclusion of other alternative drive trains (fuel cell vehicles, natural gas vehicles, etc.) is somewhat rare in the set of studies reviewed (which was selected to include only studies that model PEV market diffusion). Including other alternatives seems to be useful depending on the country modeled (e.g. natural gas vehicles in the Netherlands or Italy).

Apart from the drive trains, the vehicle attributes considered in this review included vehicle registration attributes, which are: vehicle size class, diversity of makes and models within a powertrain type, and car holder (private, company or commercial fleet ownership). We also reviewed technological improvements in battery technology or energy consumption, vehicle availability and other vehicle attributes such as comfort, power or emissions.

We find three main differentiations in vehicle registration attributes in the models which are also evident in Figure 3.

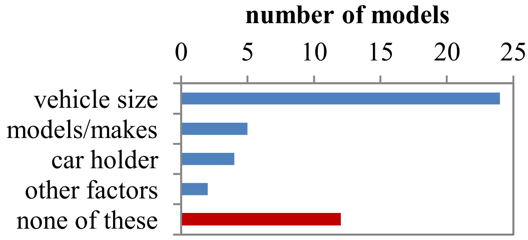

Figure 3: Vehicle registration attributes covered in models

The most common differentiation of vehicle registration groups is according to their vehicle size (24/40). This is useful as currently especially large vehicles sell well while smaller PEVs should be an option for the future. The differentiation between models or makes is rare (5/40) as are car holder groups (privately or commercially registered vehicles) which seems to be a specialty of the German car market. Twelve out of forty models use no differentiation at all.

[1] More aspects that might be interesting for an inclusion are covered in the vehicle attributes, consumer characteristics and other factors.

As the two main technological improvements in the vehicles, we investigate the development of the battery technology and energy consumption of the vehicles in the models. Improved battery technology was represented in models has contributing to lower cost and mass of batteries (and therefore of PEVs). Energy consumption is covered more often (17/40 models) while the majority uses exogenous assumptions (12) and a few model the improvement endogenously (5) with rising market shares. The progress in battery technology is considered in 16 of 40 models with predominantly exogenous assumptions (11). The five models with endogenously improving batteries are also triggered by higher sales shares and investments in battery advancement.

The currently low availability of plug-in electric vehicles for every registration group or every brand is considered in some of the models. Eleven models use simple rules to constrain the market (e.g., with sigmoid functions) while four models try to capture the model or make availability in the early years. In our point of view, these constraints could be helpful in a young car market, yet not useful to integrate with more maturity when the constraints are not justifiable anymore. Other vehicle attributes were included in the models, yet they seemed to be considered less important by the authors of the papers.[2]

Several consumer characteristics are considered in the models: differentiation or segmentation of consumers by different characteristics, and the interaction between consumers. The most important attributes for the characterization of certain consumer groups are shown in Figure 4.

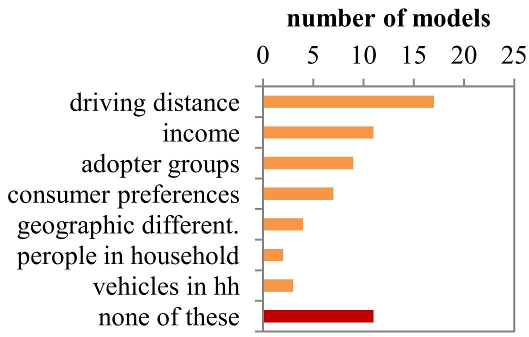

Figure 4: Consumer attributes used in models

The most common distinction of consumers is according to their driving distances (17/40). The income (11), adopter groups (9) and consumer preferences from surveys (7) are the consecutive factors while some models use no differentiation of consumers at all (10). In our point of view, a segmentation of consumer or vehicle groups is useful to cover the diversity of the car markets and should be chosen according to data available.

About two thirds of the models do not model any interaction effects between the consumers, while 14 models model the interaction explicitly or through feedback loops.

The factors especially important for the PEV market diffusion comprise factors related to vehicle range, charging infrastructure and which type of policy measures are included.

The majority of models considers the limited range of BEVs (24), yet there are still quite a few models that do not. When projecting short- to medium-term PEV market diffusion, this is an obligatory factor to consider and together with cost, the main factor preventing many consumers from buying BEVs (NRC 2015). A few authors try to include the range anxiety (5) or the charging times (5) explicitly in their models. Since this will remain an issue for some years, a consideration in future models could be useful.

Charging infrastructure is also decisive for the market diffusion of PEVs. Yet, 15 models do not contain charging infrastructure at all. In 18 papers, the authors model charging infrastructure without a differentiation between private, semipublic and public charging infrastructure (LIT) while seven models do. An endogenous infrastructure evolution with a rising number of PEVs is considered in eleven models. Although, we believe that the differentiation in different types of charging infrastructure is helpful to also consider the benefits of plug-in electric vehicles, the inclusion of any kind of charging infrastructure should be a prerequisite for PEV market diffusion modeling.

Lastly, we take a look at the policy inclusion. We find 22/40 models being able to consider direct incentive such as purchase price reductions, four that may capture indirect incentives, like HOV lane access or free parking, and nine models that explicitly model regulations like CAFE or the CO_2 emissions standards for Europe. Given the fact that an inclusion of a direct incentive is easy if the purchase price is considered in most models, the number of capable models is actually low. Also, regulations that are in place at present should be considered by models trying to project the future car market evolvement. Lastly, indirect incentives are said to have high impact on PEV market diffusion (Lutsey et al, 2015, Tietge et al., 2016). Although these are difficult to address because they are often granted locally and the considered models are analyzed on the state or national level, it seems to be worth trying.

All these factors influence the PEV market diffusion results that are analyzed in the following.

[2] Vehicle power was mentioned in six models, emissions in seven models.

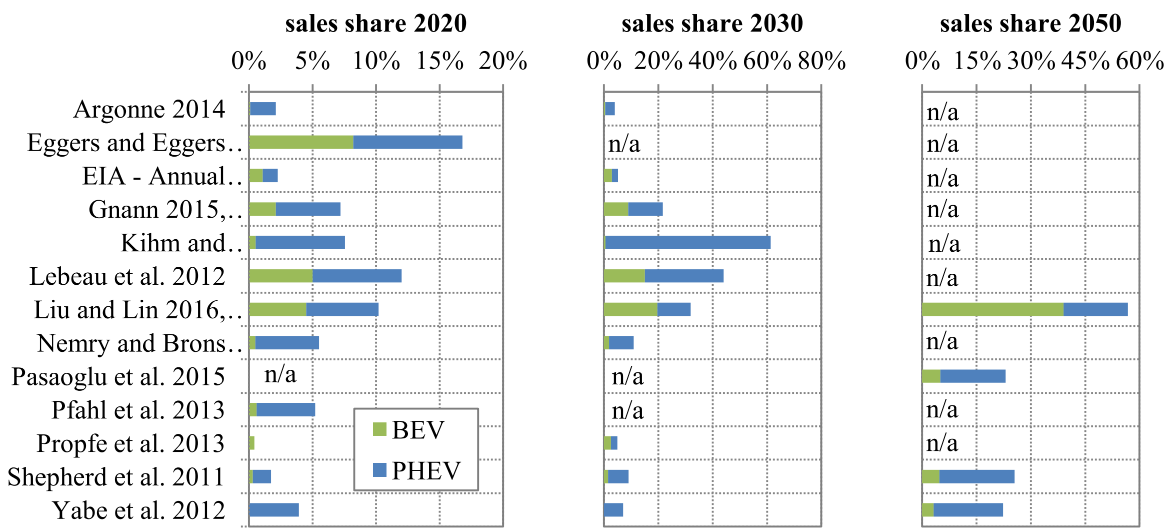

Figure 5: Sales shares in base scenarios of models for 2020, 2030 and 2050 distinguished by PEV type

3.3 Comparing model projections

Results are at the heart of each scientific publication. However, a comparison of results from the papers is very difficult since their assumptions are often different and the influence of different input factors is investigated while a comparison with the same input factors may be a valuable comparison (e.g. Stephens 2014)..The absolute number of PEVs is not the only and most of the time not the most important outcome. Nevertheless, there are some outputs that may be compared, e.g. the sales shares of PEVs in different years distinguished by battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) in Figure 5. Here, we only show the results from the base scenarios of the papers and only those where a distinction of these PEV types is clearly shown for the vehicles sales. We show these results for the years 2020, 2030 and 2050.

The first observation in these graphs is that market diffusion results are extremely uncertain and the market shares in 2020 vary between 0.4% in (Propfe at al. 2013) and 16.8% in (Eggers and Eggers 2011) for the German market. This range is even higher when looking to 2050 where Liu and Lin (2016) derive a 60% market share for the US market while Pasouglu et al. (2015) determines 23% for the EU in 2050. Yet again, the absolute market shares should not be in focus of market diffusion model results, this just shows the great deal of uncertainty.

One result that can be compared is the ratio of market shares of BEVs and PHEVs. Here, we observe that PHEVs have higher market shares in all studies in 2020. This reflects the current situation in the major car markets where PHEV sell better because of the longer ranges that can be performed. However, if battery prices decrease further (Nykvist and Nilsson 2015), larger batteries could become affordable. Some studies reflect this change (Liu and Lin 2016, Gnann 2015) and find equal or higher market shares for BEVs compared to PHEVs in 2030 and 2050. Yet, this change of best sellers has to go in line with the ability to recharge on long-distance trips or a decreasing range anxiety of the consumers. As mentioned earlier, only a few models consider these factors in much detail and so do two of the models with results until 2050: Pasaoglu et al. (2015) do not consider any “limited range factors” in their model and Shepherd et al. (2011) do not include charging infrastructure. Not to say that both papers do not contain good models, but both these factors are decisive for the future BEV market diffusion. One critique to the fourth study until 2050 (Yabe et al. 2012) is the focus on the most cost efficient solution for the future. As almost all studies on PEV market diffusion mention global warming and the reduction of GHG emissions as a main driver to PEV market diffusion, the single focus on cost until 2050 might be misleading. Thus, we can retain that there might be higher market shares for BEVs in the long-term, yet scenarios for this time horizon are rarely modeled and depend on a variety of unsure assumptions. The last subsection in the results deals with the most important drivers to PEV market diffusion according to the authors.

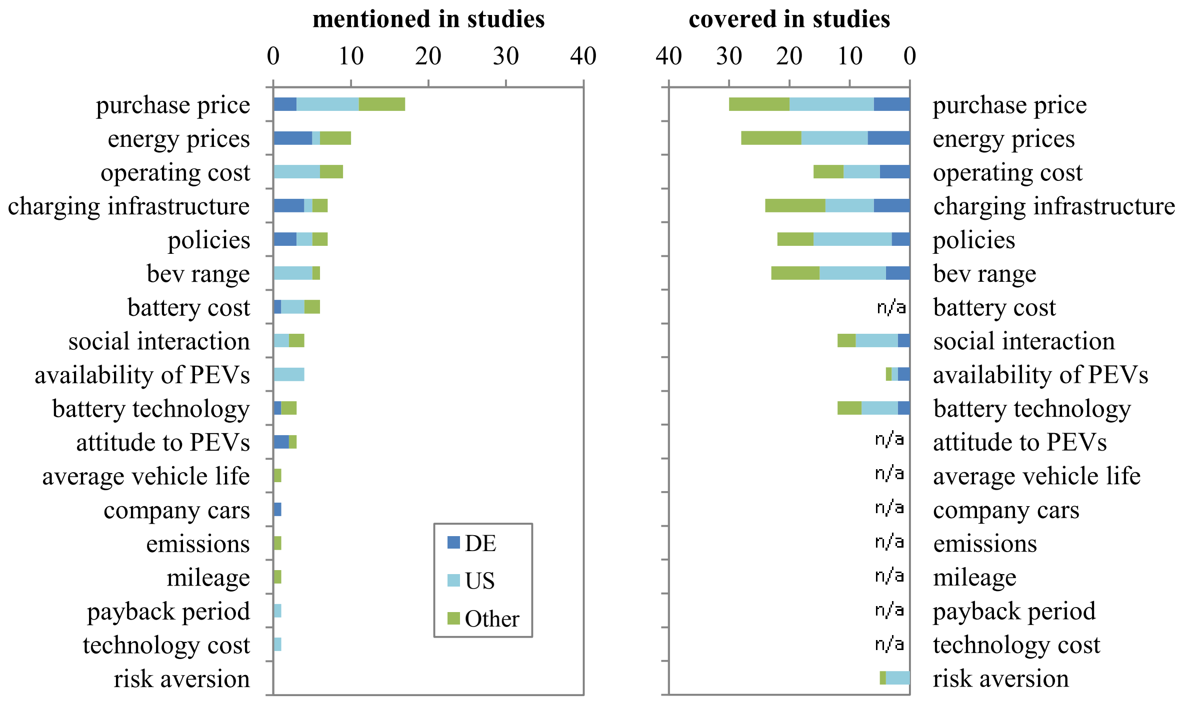

Figure 6: *Left panel:* Most important factors for PEV market diffusion stated by the authors of the models; *Right Panel:* Factors covered in the studies (factors with "n/a" were not investigated)

3.4 Important factors for PEV market diffusion models

This variation in results stems from different input factors in the models, but also from differing country specifics. We analyzed the discussion and conclusion sections to find out which factors are mentioned most often to influence the PEV market diffusion the most. These factors are shown on the left panel of Figure 6. In the papers, purchase price (17), energy prices (10), operating cost (9), charging infrastructure (7), policy measures (7) and BEV range (6) are mentioned most often to be the main influencing factors.[3]

Here, we also find country-specific differences: Purchase price and operating cost are covered by far more US models than energy prices and charging infrastructure which are mentioned most often by German models. This could stem from higher energy prices in Germany compared to the US. Also, the policy measures are mentioned more often in Germany, probably because there weren't any worth mentioning in place until last year.

Now, an interesting question is, whether the models cover these factors appropriately. On the right panel of Figure 6, we show the factors covered in the models if we had a look at them. If we didn't investigate on the specific factor, we indicate it with "n/a" in the graph. On the first look, we find that factors mentioned to be important correspond well to the factors included in the models. However, there are some discrepancies when taking a closer look: The operating cost is mentioned to be important by more US models than covered in the US studies. Also, policy measures in Germany are mentioned to be important by three models and three models mention it to be important. Thus, one interpretation might be that only factors are mentioned that are also covered in the model, probably also to pass the publication process. Yet, when analyzing the factors mentioned to be important and covered in the models individually for each publication, the availability of PEVs is mentioned to be important by four models that do not cover it. Hence, the other interpretation may be that apart from some exceptions (especially the PEV availability), most factors are mentioned to be important based on evidence.

Thus, we can summarize that a variety of factors is included in PEV market diffusion models and most factors project the PEV market diffusion reasonably well. Some factors which are mentioned to be most important should be covered in future PEV market diffusion modeling attempts.

[3] We are aware that some of the factors mentioned are correlated. Yet, we only mention what was stated in the papers.

4 Conclusions and recommendations for further research

Based on our findings, we conclude the following:

Important factors vary between countries but could indicate future evolutions. Currently, there is a focus on purchase prices and vehicle attributes in the US and more weight is put on energy prices in Germany. Yet, this could change for the US if energy prices rise.

Models should not be interpreted beyond the focus of their research questions. Only some results can be compared between models, e.g. PHEV vs. BEV shares.

Models cannot predict exact market shares, but they help to understand what influences market diffusion (drivers and barriers). A large variety of results and heterogeneity of research questions is found. Different changeable factors (e.g. vehicle attributes) and external input factors (which can't be influenced directly, e.g. energy prices) influence them and a large variety of these factors are observed (16 in total).

For future research and PEV market diffusion models, several key points stand out:

Future models for PEV market diffusion should cover more attributes than purchase price and operating cost. Several models lack the important PEV-specific features (limited range of BEVs: 16/40, Charging infrastructure: 15/40, technological and cost improvement of batteries over time 15/40). Some segmentation is helpful since not all vehicle buyers are equal (e.g. both product and consumer segmentation) and is especially important when early markets are modeled.

Current (and future) policies should be integrated in model development. Future models should be capable of incorporating policy regulations (CAFE standard or CO_2 limits on vehicle sales). Also, the incorporation of indirect (non-monetary) incentives should be considered, although it is difficult (since they often apply on a local level or apply to suppliers rather than to consumers), but could largely influence PEV market diffusion.

Authors of future papers should mention important factors for PEV market diffusion especially if they have some quantitative evidence. One may interpret some of the papers that they overestimate importance the factors they integrate instead of mentioning and discussing other important factors. An objective evaluation and quantitative assessment of the modeled and missing factors would contribute even more to this field of research.

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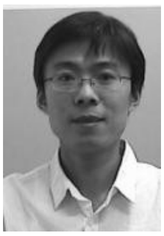

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