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What drives the market for plug-in electric vehicles? - A review of international PEV market diffusion models

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ABSTRACT

The market diffusion of plug-in electric vehicles (PEVs) is a research topic which is often addressed, yet PEV market diffusion models differ in their approaches, the factors they include and results. Here, 40 market diffusion models for PEVs are compared in their scope, approach and findings to point out similarities or differences and make recommendations for future improvements in modeling in this field. Important input factors for the US are the purchase price and operating costs, while for Germany energy prices and the 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 (until 2030) while the picture is not so clear for the medium- to long-term. Future market penetration models should include specific PEV features like the 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.

1. Introduction

The transport sector requires a reduction in CO_2 emissions and petroleum use which 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 the market diffusion and ways to accelerate it, e.g., by subsidies or restrictions [1,2]. These models differ greatly in structure, internal logics and input factors, producing different diffusion results. A comparison of these models can have at least two benefits – explaining the modeling reasons for the differences in results so that the probability of these different results misleading and obstructing policy discussion can be mitigated; and identifying best practices 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 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 [3]. Daziano and Chiew also compared PEV market diffusion models for the US. They discussed relevant factors that influence the adoption of PEVs in the US and identified additional data needed to develop improved models [4]. Jochem et al. extended the work of Al-Alawi and Bradley and added a detailed mathematical description of models for the market diffusion without focusing only on PEVs [3,5].

A need remains for a broader review of recent models comparing approaches, input factors and findings from markets worldwide. Comparing models developed for different countries as well as models for specific markets provides a new understanding of what factors are (or are thought to be) important and how they have been represented in models. This will help future modelers to learn from earlier modeling attempts when creating or improving their 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 models are used for the market diffusion of PEVs?*

Abbreviations: BEV, Battery electric vehicle; CAFÉ, Corporate Average Fuel Economy; HOV lane, High-occupancy vehicle lane; MNL, Multinominal Logit; NMNL, Nested Multinominal Logit; O&M, Operations and Maintenance; PEV, Plug-in electric vehicle; PHEV, Plug-in hybrid electric vehicle

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- *What factors do current models include and what data do they use?*
- *According to the papers, which are the most influential factors for market diffusion?*
- *Are there important factors that are not well modeled or not included in models at all?*
- *Are there general results that can be obtained from comparing results?*

The focus here is on papers on at least a national or state level (not local models) and on only those which explicitly describe a PEV market diffusion model. Expert estimates or very simple calculations are not considered here. For those models that are used in multiple publications, the main publications are reviewed here and results of the most recent one are discussed. In the following, the terms “paper” or “model” are used equivalently.

The present work differs from previous studies in several respects. First, models for different geographical regions are compared: Germany, U.S., and other countries. Second, input factors and projected market shares from a wide range of models are compared at a high level without a detailed evaluation of model algorithms or mathematical formulations. This provides a broad perspective of PEV market diffusion and helps to guide the development of future, improved models for PEV market diffusion.

2. Methods and data

This analysis compares 40 models from 16 different countries (cf. Table 1 for details). Since PEV market diffusion has been an active field of research for several years in the US and in Germany, more papers were found for these countries (16 for US, 14 for Germany). The focus here is 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 or state level were included, not at the local or subnational level.

For each model reviewed, the research questions addressed in the paper were noted, as were methodological approaches, main findings and results. Papers were clustered based on the research questions posed and main findings as stated in the selected articles. The methodological approaches were grouped into three categories, following Al-Alawi and Bradley and Gnann and Plötz: (1) aggregate stock models, (2) models that compute sales by one or more consumer segments, and (3) detailed agent-based models [3,6]. Also noted was whether battery electric vehicles and plug-in hybrid electric vehicles were represented separately or combined as PEVs, and the projected sales shares for the baseline scenario were compared for those papers that gave sales shares. Furthermore, the factors (vehicle attributes, market conditions, etc.) that authors indicated as being influential on PEV market diffusion were identified and papers were reviewed to determine which of these factors were included in the models. These factors were retrieved from the papers under review as well as other literature [3,7–9]. They are

Table 1
Models analyzed including the area of observation.

Citation	Area of observation	Observation period	Model type	Refs.
Argonne, 2014	United States	present-2050	sales modeled	[10]
Barter et al., 2013	United States	present-2050	sales modeled	[11]
Becker and Sidhu, 2009	United States	2010–2030	aggregated	[12]
Brooker, 2015	United States	present -2050	sales modeled	[13]
Brown, 2013	United States	2009–2030	disaggregated	[14]
Bühne et al., 2015	Germany	2010–2030	disaggregated	[15]
de Santa-Eulalia et al., 2011	Germany	2011–2020	sales modeled	[16]
Driscoll et al., 2013	Ireland	today	aggregated	[17]
Duan et al., 2014	United States	2011–2020	aggregated	[18]
Eggers and Eggers, 2011	Germany	2009–2018	sales modeled	[19]
EIA - Annual Energy Outlook 2016	United States	2015–2040	sales modeled	[20]
Fu et al., 2012	China	2011–2050	aggregated	[21]
Gnann, 2015, Gnann et al., 2015, Plötz et al., 2014	Germany	2013–2030	disaggregated	[22–24]
Harrison et al., 2016	European Union	1995–2050	disaggregated	[25]
Hess et al., 2012	United States	not stated	sales modeled	[26]
IEA 2016 -WEO, 2016	World	2010–2050	sales modeled	[27]
Kieckhäfer et al., 2014	Germany	2010–2030	disaggregated	[28]
Kihm and Trommer, 2014	Germany	2015–2030	disaggregated	[29]
Lebeau et al., 2012	Flanders, Belgium	2012,2020,2030	aggregated	[30]
Lee et al., 2012	South Korea	2005–2050	sales modeled	[31]
Lee et al., 2013	South Korea	2010–2050	sales modeled	[32]
Liu et al., 2015	United States	present-2050	sales modeled	[33]
Liu and Lin, 2017, Lin and Liu, 2015, Lin and Greene, 2011, Lin and Greene, 2010	United States	2010–2050	sales modeled	[34–37]
Liu et al., 2013	United States	2010 – 2025	sales modeled	[38]
Nemry and Brons, 2010	European Union	2010–2030	sales modeled	[39]
Noori and Tatari, 2016	United States	2015–2030	disaggregated	[40]
Orbach and Fruchter, 2011	United States	2009–2018	aggregated	[41]
Pasaoglu et al., 2016	European Union	1995–2050	disaggregated	[42]
Pfahl et al., 2013	Germany	2011–2020	sales modeled	[43]
Propfe et al., 2013	Germany	2010–2030	disaggregated	[44]
Qian and Soopramanien, 2015	China	2010–2030	sales modeled	[45]
Redelbach et al., 2013	Germany	2010–2030	disaggregated	[46]
Shafiei et al., 2012	Iceland	2011–2030	disaggregated	[47]
Shepherd et al., 2012	United Kingdom	2010–2050	sales modeled	[48]
Tran, 2012	United Kingdom	2000–2035	aggregated	[49]
Wansart and Schnieder, 2010	United States	2010–2020	sales modeled	[50]
Wu et al., 2015	Germany	2014,2020,2025	sales modeled	[51]
Yabe et al., 2012	Japan	2010–2050	sales modeled	[52]
Zeng et al., 2013	China	2013–2020	aggregated	[53]
Zhang et al., 2011	United States	not stated	disaggregated	[54]