

Enhancing electric vehicle market diffusion modeling: A German case study on environmental policy integration

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ABSTRACT

In order to reduce national and global greenhouse gas (GHG) emissions, many countries worldwide have committed themselves to a more sustainable development of their transport sector. Promoting the use of electrical vehicles (EVs) rather than combustion engine cars is one political strategy to achieve a reduction in GHG emissions. To implement targeted and effective promotion measures governments can refer to market diffusion models for EVs. However, in our study we identify that in existing models the consideration of environmental measures is underrepresented. Hence, this paper addresses this gap in current market diffusion models for EVs by particular focusing on environmental effects as additional influencing factors of the market diffusion. Results are drawn for the German car market with a market diffusion simulation until 2050 applying the market diffusion model *ALADIN* considering the introduction of distinct CO₂ tax trajectories. The results are analyzed based on scenarios, where (i) no CO₂ tax, (ii) the current governmental plan for a CO₂ tax, and (iii) a considerable high CO₂ tax is applied. Additional insights when incrementally increasing the CO₂ tax are provided. The scenario analysis shows that the market diffusion is highly dependent on the evolution of external factors. A CO₂ tax considerably higher than the current governmental plan by 2030 (such as 150€/t, based on its monetary value by 2020) is required to have a meaningful impact on the market diffusion of EVs. Moreover, applying a considerable high CO₂ tax leads to a slower growth of BEV and PHEV from 2040 onwards that is compensated by a growth in FCEV vehicles.

1. Introduction

In November 2016, the German government adopted the Climate Action Plan 2050 by setting the long-term goal to achieve a drastic reduction in greenhouse gas (GHG) emissions by at least 80–95 % compared to 1990 and become GHG-neutral by 2050 in order to offset effects resulting from climate change. In 2019, the transport sector was responsible for around 20 % of annual GHG emissions, thus making a strong contribution to annual emissions in Germany [1]. Therefore, several goals and measures have been defined in the Climate Action Plan to lower the impact of the transport sector on GHG emissions. An increasing shift towards electrically-powered cars offers the chance to reduce the dependency of Germany on oil imports, minimize both global (CO₂) and local (pollutants, noise) emissions, contribute to conserving

resources and further develop a multimodal transport system [2]. Defining the promotion of electric vehicles as a key element in establishing climate-friendly mobility, the government is targeting 7 to 10 million registered electric vehicles (EVs)¹ in Germany by 2030 [3]. In order to accelerate the market diffusion, several policy measures such as purchase bonuses and tax incentives for EVs have been defined to support the substitution of conventional combustion engine cars. However, as of January 2021, only around 640,000 EVs (≈1 %) were registered in the German passenger car fleet [4].

The government can only implement targeted and effective support measures if they understand the underlying factors that drive the market diffusion for EVs in Germany. Moreover, the diffusion of EVs is a relevant parameter in travel demand models, where a well-founded understanding of possible market evolutions is necessary to model car

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¹ EV is used as a generic term for vehicles with an electric drive. In particular, EV are capturing pure battery electric vehicles (BEV), plug-in hybrids (PHEV), range extenders (REEV) and fuel cell electric vehicles (FCEV).

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ownership of EVs more precisely [5]. The ownership in turn affects the simulation of travel demand induced by EVs, which again is a relevant information for governments e.g., to correctly determine charging infrastructure capacity spatially and temporally [6]. Therefore, it is important to develop reliable models of possible market evolutions. In recent years, various studies have dealt with the topic of modelling the market diffusion of EVs using different simulation techniques and methodologies such as Total-Cost-of-Ownership (TCO) calculations or Discrete-Choice models.

The models in the literature differ in their underlying focal points of investigation and can be distinguished on the basis of mainly three characteristics. First, the models focus on the market diffusion of electric vehicles in different geographical regions (e.g. United States, China, Germany or other countries). For example, Barter et al. [7] model the adoption rate of electric vehicles in the United States through 2050, whereas Qian and Soopramanien [8] present an forecast approach for electric vehicle shares in China. However, model approaches are not limited to national borders, e.g. Harrison et al. [9] model the development of EV market shares for the whole European Union. The International Energy Agency (IEA) even gives an outlook for the development of worldwide EV market shares [10]. Second, the existing models consider different sub-segments of the EV market (e.g. focus on plug-in hybrids or considering battery electric vehicles). Eppstein et al. [11] model the market penetration of plug-in hybrids, whereas Fojcik and Proff [12] reveal dependencies on the market share of battery electric vehicles. Moreover, studies such as Shafiei et al. [13] provide a more generalized investigation of the market evolution of electric vehicles. Third, the existing models apply different methodological approaches to determine the market diffusion of EVs (e.g. Discrete Choice Modeling or Market Diffusion Modeling). There is a wide variety of methods used [14]. However, to name just a few examples, Diamond [15] uses a discrete choice based model to analyze the effect of governmental incentives on the evolution of EVs. Won et al. [16] instead apply a diffusion model approach. Other studies such as Higgins et al. [17] also combine different approaches to determine the market diffusion of EVs.

While these models have certain strengths in specific areas of market diffusion modelling, research gaps still exist since circumstances are constantly changing as part of the dynamic setting of the EV market, resulting in new diffusion parameters that have not been integrated in existing literature yet due to lack of availability of empirical data or high complexity. To identify gaps, some authors have already collected and compared existing models under different focuses of analysis. For example, Al-Alawi and Bradley [18] provide an overview of market diffusion models of different segments of EVs for the US market. Gnann et al. [19], on the other hand, compare market diffusion models of EVs worldwide. Kickhöfer and Brokate [20] limit their analysis to the German market, but compare market diffusion models for passenger cars in general. For the objective of this study, a comparison of models that focus on the market diffusion of all segments of EVs for the German market is relevant. Based on already carried out comparisons of market diffusion models as well as an additional in-depth literature review of further models for the German market, eight relevant approaches have been identified and analyzed, which builds the base for the study at hand. For the interested reader, the results of the analysis are presented in appendix B.

One of the main findings of the literature analysis is that existing TCO or Discrete Choice based EV market diffusion models are lacking in the consideration of environmental policy measures, such as a CO₂ tax or restrictions for combustion engines in cities. However, these measures are a highly relevant aspect, and are broadly discussed in politics worldwide. Policymakers in many countries think about the introduction and also future development of a CO₂ tax or even have already installed it. However, based on the analyzed model types, it is not clear yet, which effects a certain CO₂ tax has for example on the market diffusion of EVs. Existing studies such as Hu et al. [21] only consider CO₂ prices implicitly by taking e.g. oil prices into account. Therefore, in this

paper, the impact of environmental costs on the market diffusion of EVs is assessed explicitly by integrating a CO₂ tax on conventional fuels into an existing model (i.e. *ALADIN* model) of Fraunhofer-ISI. This model applies a utility analysis that integrates a TCO-approach to model the market evolution of EVs in Germany. Based on this, different scenarios of CO₂ prices are developed that illustrate possible pathways for political measures to incentivize a cost-based shift towards electrically-powered cars.

The paper is segmented into four sections. After the introduction in section 1, section 2 illustrates an adaption of the current Fraunhofer market diffusion model *ALADIN* through an integration of a CO₂ tax as part of environmental costs into the TCO-logic with a subsequent simulation of the market diffusion of EVs in Germany until 2050. Section 3 presents the results of the simulation. Finally, section 4 concludes the paper by summarizing the results and deriving the relevance of policy measures regarding the introduction of environmental costs for the market diffusion of EVs in Germany.

2. Case study

In this section, a case study is provided that integrates a CO₂ tax as environmental costs into the market diffusion modelling of EVs in Germany. The market diffusion model *ALADIN* of Fraunhofer-ISI is used for EV market ramp-up as it showed in the model comparison presented in appendix B a relatively high degree of criteria fulfillment. In addition, a recent model comparison between discrete choice models and the agent-based simulation model *ALADIN* shows that agent-based simulation is particularly suitable for analyzing the impact of individual measures (c.f. [19,22]). The model is based on a TCO approach with some integration of user behavior (c.f. Plötz et al. [23]) and is introduced shortly in the following. Subsequently, the model extension using a CO₂ tax is explained including an introduction of different policy scenarios for diffusion simulation from 2020 until 2050. Finally, the scenario results are presented and compared.

2.1. *Aladin*

2.1.1. Overview

The market diffusion of electric vehicles is simulated with the market diffusion model *ALADIN* (*Alternative Automobiles Diffusion and Infrastructure*) of Fraunhofer-ISI. It has been used in several studies (c.f. [24–26]) before. *ALADIN* covers the period from 2011 to 2050, with the period up to 2020 for calibration. The evolution of the market is calculated successively based on a comparison of the economic efficiency of different drive systems and takes obstructive and supportive factors into account. *ALADIN* distinguishes between six drive alternatives for passenger cars: (1) gasoline vehicles, (2) diesel vehicles, (3) natural gas vehicles, (4) plug-in hybrid electric vehicles, (5) battery electric vehicles and (6) fuel cell electric vehicles. In addition, a distinction is made between three vehicle segments: small, medium and large. The purchase decision is performed in a multi-stage decision-making process. First, the battery state of charge is simulated individually for each vehicle based on almost 7,000 driving profiles to assess whether the individual driving profile can be realized with a BEV and how high the electric driving share of a PHEV would be. The driving profiles are based on data of the German Mobility Panel [27] and data collected within the ‘region eco mobility 2030’ project [28]. In a second step, an individual utility maximization is performed for each driving profile. This is based on a cost analysis, i.e. TCO analysis, which is supplemented by obstructing and favoring factors such as a limited selection of vehicle models and political measures, e.g. purchase bonuses, subsidies and taxes. Based on this annual and user-specific analysis, the market share and resulting diffusion for EVs is calculated. The results

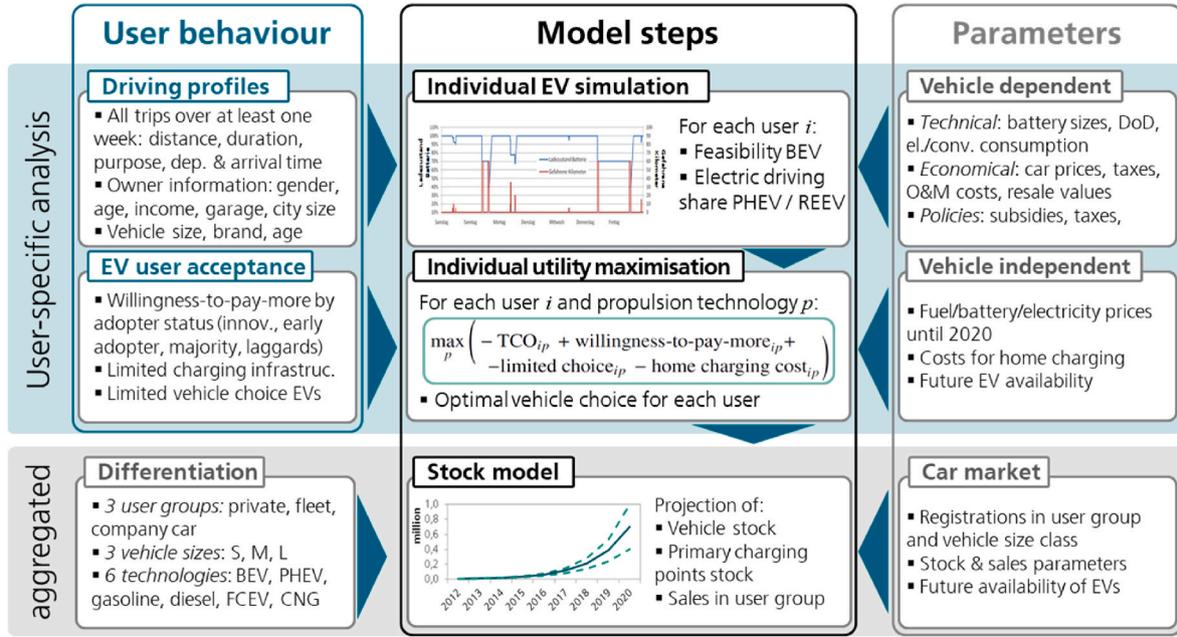


Fig. 1. Overview of the approach taken in the ALADIN model.

can be broken down by vehicle segment (small, medium, large) and by user group (private, fleet, company car). Fig. 1 summarizes the procedure.²³

2.1.2. Mathematical approach

The annuitized utility $u_{i,s}^a(t)$ of user i for drivetrain s is calculated by the following formula

$$u_{i,s}^a(t) = -TCO_{i,s}^{a,veh}(t) - TCO_{i,s}^{a,CI}(t) + WTPM_{i,s}^a(t)$$

where $TCO_{i,s}^{a,veh}(t)$ are the TCO of the vehicle, $TCO_{i,s}^{a,CI}(t)$ represents the TCO of individual charging infrastructure and $WTPM_{i,s}^a(t)$ considers the WTPM (willingness-to-pay-more) for AFVs (alternative fuel vehicles).

Further, the vehicle TCO consists of an annuitized capital expenditure $a_{i,s}^{veh,capex}(t)$ and operational expenditure $a_{i,s}^{veh,opex}(t)$:

$$TCO_{i,s}^{a,veh}(t) = a_{i,s}^{veh,capex}(t) + a_{i,s}^{veh,opex}(t)$$

The individual and drivetrain specific capital expenditure is calculated as follows

$$a_{i,s}^{veh,capex}(t) = \left(I_{r,s}(t) \cdot (1 + z(t))^{T^{veh}(t)} - SP_s(t) \right) \cdot \frac{z(t)}{(1 + z(t))^{T^{veh}(t)} - 1}$$

where $I_{r,s}(t)$ are the vehicle investments, $z(t)$ the interest rate for annuitization, $T^{veh}(t)$ the investment horizon while $SP_s(t)$ as the resale price after use is subtracted.

The operating expenditure consists of fixed and variable costs and are determined according to the following formula

$$a_{i,s}^{veh,opex}(t) = VKT_i \cdot \left(s_i(t) \cdot c_{r,s}^e \cdot k^e + (1 - s_i(t)) \cdot c_{r,s}^c \cdot k^c + k_{r,s}^{OM}(t) \right) + k_{r,s}^{tax}(t)$$

where VKT_i are the individual annual vehicle kilometers travelled multiplied by the energy consumption differentiated in electric driving, comprising $s_i(t)$ as the share of electric driving, $c_{r,s}^e$ as electric consumption and k^e as electricity price, and non-electric driving,

comprising $c_{r,s}^c$ as conventional consumption and k^c as conventional fuel price. $k_{r,s}^{OM}(t)$ give the use-related costs as operations and maintenance (OM) costs. The annual vehicle tax $k_{r,s}^{tax}(t)$ is added independently of a user's driving behavior.

More details on the approach and its justification can be found in Plötz et al. [23].

2.1.3. General input parameters

Several parameters are relevant for the purchase decision during market diffusion. A key aspect is the development of the vehicle investment costs. Due to necessary improvements in drive efficiencies, an increase in investment costs of conventional vehicles with combustion engines is assumed [29]. For BEVs, PHEVs and FCEVs investment costs are primarily driven by declining battery/fuel cell prices [30]. Table A1 shows the vehicle investment costs, while Table 1 illustrates the development of battery prices assumed in the model.

Furthermore, the battery capacity plays an essential role in the diffusion of electric drive trains, as they influence the total investment costs on the one hand, while on the other hand large battery capacities enable the use of electric drives also for long distance travelers. It is assumed that battery capacity will grow until 2030, which corresponds to today's announcements. For large BEVs a real range of approx. 440 km, for medium BEVs a range of approx. 330 km and for small BEVs a range of approx. 220 km is assumed. The range of the PHEV is about 1/3 of the range of the BEVs. From 2030 onwards it is assumed, that the desire for more range is saturated. Thus, the battery capacity remains constant from 2030 onwards and range improvements can only be achieved via efficiency improvements of the vehicle. Table A2 and Table A3 summarize the respective parameter assumptions.

Regarding maintenance costs it is assumed that they remain constant over the simulation period and are proportional to mileage and vehicle

Table 1

Battery and fuel cell price development. All monetary figures refer to its value in 2020. Own assumptions based on [31–33].

	Unit	2030	2040	2050
Battery - BEV	EUR/kWh	120	110	100
Battery - PHEV	EUR/kWh	132	120	110
Fuel Cell	EUR/kWh	80	66	55

² More details can also be found at: <http://www.aladin-model.eu>.

³ All formulas within this subsection were taken from Ref. [23].

size. Table A4 shows that maintenance costs for BEVs and PHEVs are lower than for conventional vehicles which is explained by the fact that BEVs and PHEVs often contain fewer components that are wearing out slower due to operation in the optimum speed range.

The existing policy measures of a purchase premium at the beginning of the simulation period is seen as given and hence, considered in all scenarios. The maximum purchase premium for BEVs is €4,000⁴ and for PHEVs €3,000 and is based on the purchase premium set by the German government until the end of 2019. As half of the purchase premium has to be covered by the manufacturer, it is assumed that manufacturers will cancel additional rebate campaigns on EVs and that there will be a substitution of the subsidies. Based on this, the purchase premium gradually increases from 2020 onwards and reaches only 2/3 of the maximum defined premium in 2025.

2.2. Extension of environmental module

Currently, environmental factors are not considered in the model yet, which is why the introduced ALADIN model shall be extended by an environmental module that consists of the integration of a CO₂ tax affecting fuel prices for vehicles with combustion engines. Formally, this is represented by:

$$k_{new}^c = k_{old}^c + p_{CO_2} \cdot em^c$$

where k_{new}^c denotes the new fuel price for engines using fuels that emit CO₂ during combustion. k_{new}^c is calculated from the old fuel price k_{old}^c while taking the price of the CO₂ tax p_{CO_2} multiplied with the specific fuel emission em^c into account. This also can be considered as a tax and therefore affects the operational costs (OPEX) of conventional vehicles, which in the end leads to an increase in TCO over time affecting the market diffusion for alternative drives.

Regarding the CO₂ tax, three scenarios are defined to illustrate different policy paths. In the *Reference scenario*, the CO₂ tax is set according to the current policy path of the German Federal Government [34] for the transport sector and is thus oriented towards current political targets and measures from the Climate Action Program (c.f. Federal Ministry for the Environment [2]). Moreover, a CO₂ tax of 25 €/t CO₂ is defined for 2020, which gradually increases to 65 €/t CO₂ in 2050. In the *Contra scenario*, no CO₂ tax is defined during the simulation period. Thus, no CO₂ surplus is added to the operational costs of conventional vehicles. This scenario illustrates pessimistic assumptions regarding the environment efforts by the federal government, while the third scenario, the *Pro scenario*, assumes optimistic environmental policy assumptions with a defined CO₂ tax of 25 €/t CO₂ in 2020 that gradually increases to 500 €/t by 2050. Here, we do not consider an admixture of green synthetic fuels to conventional fuels to understand the full effect of CO₂ prices. By making these very different assumptions and varying the price of CO₂ within the scenarios, the impact of environmental costs on the market diffusion can be assessed while respective steering effects on the market evolution are observable. It should be noted that the present implementation only simplifies the logic of a CO₂ tax from the Climate Action Program and an assessment of the policy measures is subject to various assumptions since the actual implementation of a CO₂ tax is based on a national emission trading system, which is based on a cap-and-trade as well as auction mechanism. However, the chosen CO₂ tax prices aim to most accurately approximate the discussed values in the Climate Action Program, also considering the estimated price development of relevant energy sources as well as other related literature such as Krail et al. [35]. Depending on the defined CO₂ price, energy prices vary in the respective scenarios. It should be noted that the variation of the CO₂ price has no effect on the price of electricity and hydrogen, since underlying mechanisms are independent of each other.

CO₂ pricing for gasoline, diesel, and CNG in Germany is currently based on a fixed CO₂ price, which can be modeled as a tax. In the future, the CO₂ for those fuels will be integrated into the EU Emissions Trading System for building and road transport (EU-ETS2), which is currently under development. In contrast, the generation of electricity and synthetic hydrogen are covered by the already existing EU-ETS1, which concern large industrial facilities and power plants. Table 2 provides an overview of the scenario parameters.⁵

3. Results

This section presents the results of the previously described CO₂ tax scenarios gained from the ALADIN model. It summarizes the results of the market diffusion simulation for EVs including an evaluation of the CO₂ prices' impact on the EV fleet evolution and respective policy targets in Germany until 2050.

3.1. Overview of market diffusion

The calculated market evolution for the three scenarios is illustrated in Fig. 2. Taking all effects into account, around 18 m EVs are obtained in the *Reference scenario*, while the *Contra scenario* shows 14 m and the *Pro scenario* up to 31 m vehicles in 2050, respectively. Looking at the development of the market diffusion, three phases are observable across all three scenarios. In phase 1, the increase of EVs is mainly driven by purchase subsidies offered by the government that do not vary across the scenarios thus leading to a parallel market evolution until 2025. Phase 2 is characterized by a stagnation of the market diffusion. ALADIN considers, as described in the methodology section, purchase premiums of €4,000 for BEV and €3,000 for PHEV, which is based on the premiums set by the German government. In relation to the applied vehicle investment costs as presented in Table A1, these premiums make up 8–30 % of the total investment costs depending on vehicle type and size. However, according to the government's commitment those premiums

Table 2

Overview of scenario parameters used in the ALADIN model. All monetary figures refer to its value in 2020.

	Scenario	2020	2030	2040	2050
oil price [€/MWh] ^a	all	42	54	63	78
gas price [€/MWh] ^a	scenarios	24	25	28	30
electricity price private [€/kWh] ^b		0.329	0.321	0.313	0.311
electricity price commercial [€/kWh] ^b		0.226	0.217	0.210	0.208
hydrogen price [€/kWh] ^b		0.469	0.390	0.282	0.235
CO ₂ tax [€/t CO ₂]	<i>Contra</i>	0	0	0	0
	<i>Reference</i>	25	55	65	65
	<i>Pro</i>	25	150	300	500
gasoline price [€/kWh] ^b	<i>Contra</i>	0.156	0.176	0.191	0.215
	<i>Reference</i>	0.165	0.194	0.211	0.236
	<i>Pro</i>	0.165	0.226	0.298	0.379
diesel price [€/kWh] ^b	<i>Contra</i>	0.120	0.138	0.152	0.174
	<i>Reference</i>	0.128	0.156	0.172	0.195
	<i>Pro</i>	0.128	0.187	0.257	0.335
gas price CNG [€/kWh] ^b	<i>Contra</i>	0.061	0.106	0.111	0.114
	<i>Reference</i>	0.068	0.122	0.128	0.133
	<i>Pro</i>	0.068	0.149	0.204	0.258

^a primary energy source price without taxes taken from IEA [10] (originally in US Dollar), exchange rate used: EUR/USD = 1.1.

^b incl. all taxes and duties described incorporating also a CO₂ surplus depending on the estimated share of renewable energy in the electricity mix. VAT of 19 % considered, temporary VAT reduction in 2020 not shown.

⁴ All monetary figures in this study refer to its value in 2020.

⁵ Additional information on the different parameter developments can be found in the appendix.

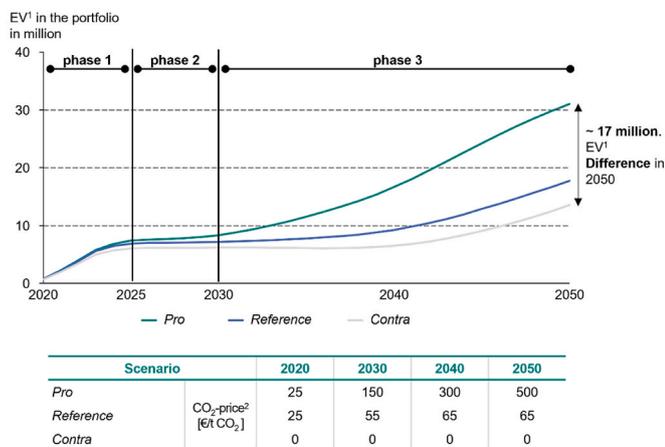


Fig. 2. Overview scenario results market diffusion EVs.

only apply until 2025 inducing overall higher TCO for EVs compared to conventional drives until 2030. In phase 3, differences in scenario results can be observed. Since investment and operational costs for conventional vehicles are increasing according to the defined parameter assumptions above, EVs penetration is rising. This is based on the relative reduction in TCO of EVs compared to conventional drives until 2050. Thereby, the consideration of CO₂ prices as part of environmental costs can have a meaningful impact on the market diffusion.

Based on the model results, an introduced CO₂ tax trajectory of up to 65 €/t CO₂ over the next 30 years leads to an additional amount of around 4 m EVs compared to a scenario without a CO₂ tax. This effect increases the higher the CO₂ tax is defined. Thus, comparing results between the *Pro* and *Contra* scenario leads to a difference of up to approx. 17 m electric vehicles in 2050, illustrating the strong long-term impact of CO₂ prices on possible EV market diffusion evolutions if set sufficiently high. Based on the simulation results, a CO₂ tax trajectory such as set in the *Pro* scenario is found to be suitable to induce relevant controlling effects on the increase of EVs in the German car population. Nonetheless, the results also show that the German government's target of 7–10 m EV stock in 2030 can be achieved even without the introduction of a CO₂ tax, if current purchase bonuses on EVs continue being effective.

3.2. Segmentation of market diffusion results

When splitting the market evolution up into the different user groups of private car owners, fleet and company cars, private owners dominate in the *Reference* scenario followed by the fleet and company cars (see Fig. 3).

Interestingly, the market ramp-up for fleet and company EVs is faster in phase 1 compared to private cars due to the effect of purchase bonuses that has a stronger effect on fleet and company car owners. This effect is mainly due to the shorter first holding period (approx. 4 years) of fleet and (approx. 1 year) of company vehicles compared to privately owned vehicles (approx. 6 years, c.f. Plötz et al. [36]) that result in stronger purchase price premium effects lowering the annuitized investment costs compared to the operational costs over the ownership time for fleet and company car owners. In particular, it is assumed that after approx. four years commercial vehicles and after approx. one year company cars will be transferred to the private car stock resulting in a market upswing of privately-owned cars despite the discontinuation of the purchase bonus after 2025 and thus delaying the diffusion stagnation in terms of EVs for private car owners in phase 2. The effect of market ramp-up of fleet and company EVs on the overall EV stock appears even stronger considering that these contribute only 15 % to all newly registered

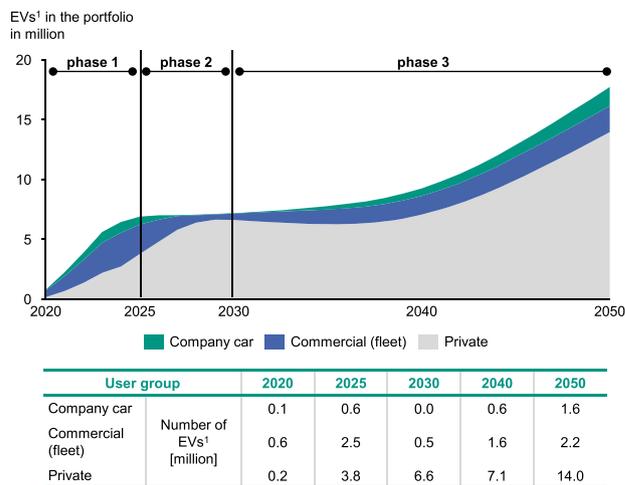


Fig. 3. Market diffusion user groups in the *Reference* scenario.

vehicles. Market evolutions in phase 3 are mainly driven by defined cost developments resulting in positive TCO effects of EVs as described above where a higher CO₂ tax supports the diffusion of alternative drives while inducing no meaningful mix effects within the user groups across the different scenarios.

As depicted in Fig. 4, the market ramp-up segmented by vehicle size is mainly driven by small and medium sized vehicles in the *Reference* scenario that can be found mainly in the private and commercial fleet sector. Large vehicles tend to travel longer distances, implying that these driving profiles may not be electrically realizable or not economically efficient in phase 1 and 2. However, pre-defined cost depression of EVs, rising conventional fuel prices and increasing battery ranges can push large vehicles into the market in phase 3. Comparing the results across the scenarios, a higher CO₂ tax leads to higher EV shares in all three segments with a slight shift towards medium sized vehicles due to the fact that medium sized vehicles have the highest share in all three customer groups within the driving profiles.

Fig. 5 illustrates the diffusion results segmented by drive technology in the *Reference* scenario indicating that the market diffusion is mainly driven by BEVs with a share within the EV stock of over 90 % in 2050. Due to the relatively high investment costs for PHEVs and FCEVs compared to conventional vehicles, they do not play a major role in the EV market diffusion based on the *Reference* scenario in the long-term.

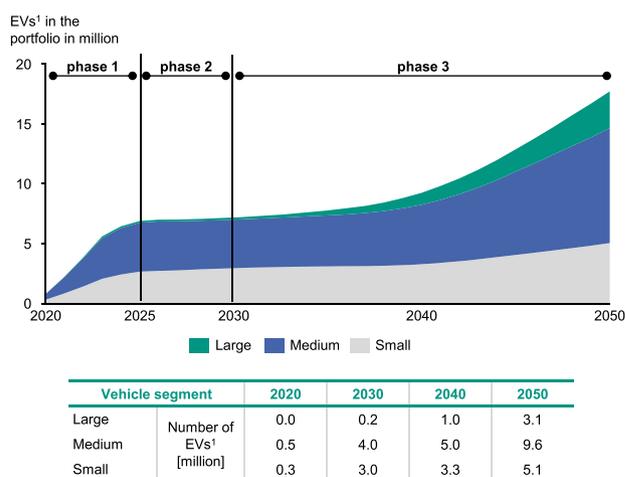
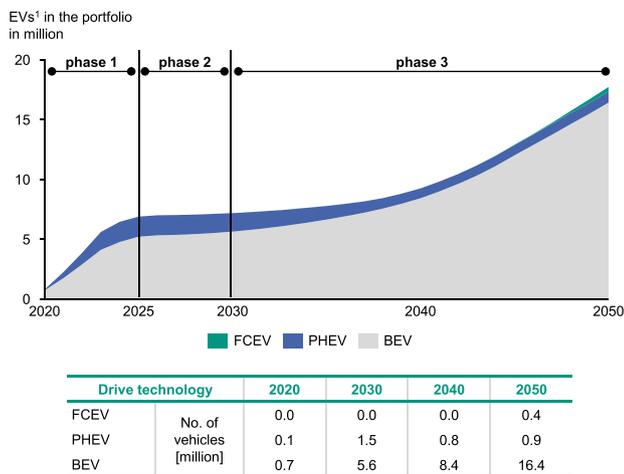


Fig. 4. Market diffusion vehicle segments in the *Reference* scenario.



¹ Electric vehicles are defined here as BEVs, PHEVs and FCEVs. REEVs are implicitly included in PHEVs.

Fig. 5. Market diffusion drive technologies in the *Reference scenario*.

The initial diffusion of PHEVs in phase 1 and 2 weakens in phase 3 as a result of investment cost degression especially of small and medium BEVs compared to PHEVs, followed by possible substitutions as a result of higher BEV battery ranges. Possible second-best solutions in favor of PHEVs as a result of limited EV brand availability regarding BEVs are no longer implemented from 2030 onwards, thus slowing the market diffusion for PHEVs especially in phase 3.

Moreover, Table 3 shows the sale percentages of the three drive technologies in the *Reference scenario* in the respective years. It becomes clear, that in phase 1 and 2 conventional drive technologies still dominate the market of newly registered vehicles although the absolute number of EVs increases tremendously, especially in phase 1. Only in the middle of phase 3 do new EV registrations exceed a share of one-third of all newly registered vehicles, rising to about two-thirds by 2050.

While there are no meaningful differences in the results between the *Contra* and *Reference scenario*, the *Pro scenario* is illustrating possible effects of a CO₂ tax on the diffusion of different alternative drive technologies, i.e. fuel cell technology, if set high enough as depicted in Fig. 6. This outcome is mainly driven by favorable price developments of hydrogen compared to conventional fuels, where the latter rises sharply until 2050 as a result of CO₂ prices of up to 500 €/t CO₂. High investment costs for FCEV can be offset by lower hydrogen prices in comparison to conventional fuels.

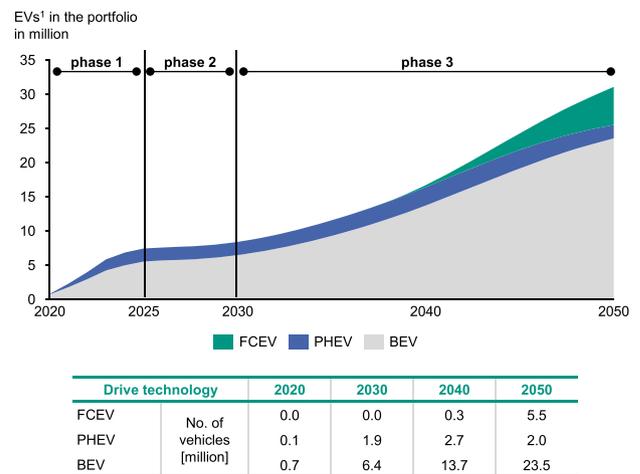
3.3. Sensitivity analysis for CO₂ prices

Lastly, we vary the CO₂ price in a sensitivity analysis for a deeper understanding of this impact factor. Fig. 7 contains the market diffusion results of the three scenarios discussed before (in grey, blue, and green solid lines) plus an additional four scenarios with a CO₂ price of 100, 200, 300 and 400 €/t CO₂ (S100 to S400 in dashed, dotted and dash-dotted lines). First, one may observe that scenario results increase with increasing CO₂ price, especially in the long-term. However, the distance between scenarios decreases with increasing CO₂ prices. In other words, the marginal benefit (additional electric vehicles in stock per additional 100 €/t CO₂ price) declines. In 2050, this effect is easily visible due to the higher variation of CO₂ prices and a large number of

Table 3

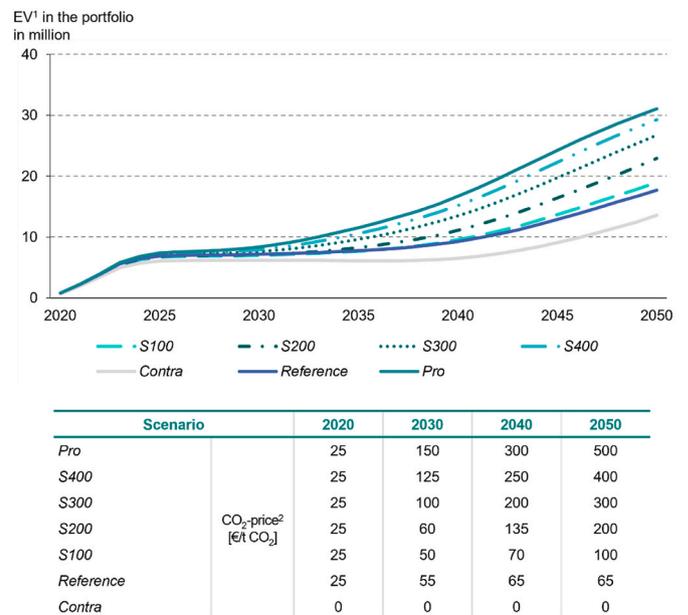
Sales percentages of BEV, PHEV and FCEV in the *Reference scenario* per year.

	2025	2030	2040	2050
Battery - BEV	15.27 %	10.80 %	31.91 %	58.40 %
Battery - PHEV	0.21 %	0.45 %	2.96 %	2.10 %
Fuel Cell - FCEV	0.00 %	0.00 %	0.00 %	3.59 %



¹ Electric vehicles are defined here as BEVs, PHEVs and FCEVs. REEVs are implicitly included in PHEVs.

Fig. 6. Market diffusion drive technologies in the *Pro scenario*.



¹ Electric vehicles are defined here as BEVs, PHEVs and FCEVs. REEVs are implicitly included in PHEVs.

² All monetary figures refer to its value in 2020

Fig. 7. Sensitivity analysis on market diffusion with changing CO₂ prices.

vehicles affected by the CO₂ price. In 2030, the effect of a CO₂ price increase of 100 €/t CO₂ between the *Reference* and *Pro scenario* is around 1 m additional EVs. EVs in stock and all CO₂ price variations can be overcompensated by other policies until then. Hence, a considerably higher CO₂ price in 2030 of around 150 €/t CO₂ can really bring meaningful changes compared to a *Reference scenario* with 55 €/t CO₂ until then.

4. Conclusions

This paper addresses the gaps in current market diffusion models for EVs with a particular focus on environmental effects as additional influencing factors by incorporating the CO₂ tax into an existing market diffusion model for alternative fuel vehicles. Results are drawn based on the development of the German car market by applying an EV diffusion simulation until 2050.

It is shown that a CO₂ tax can have a strong impact on the German

market diffusion of EVs if set sufficiently high (at around 150 €/t CO₂ in 2030). Above this threshold relevant effects on the EV stock become evident with up to 17 million additional EVs until 2050. The diffusion is mainly driven by fleet and company cars until 2025 as an effect of already defined purchase subsidies for these segments. Forecasts show that EVs are expected to gain popularity after 2030 for private customers especially in the small and mid-size vehicle segment mainly as a result of a relative cost increase for conventional drives. A higher CO₂ tax accelerates the diffusion of various electric drive systems, e.g. FCEV, even though no meaningful shifts within defined user and vehicle segments can be observed.

Nonetheless, the results also show that the German government's target of 7–10 m EV stock in 2030 can be achieved even without the introduction of a CO₂ tax, if current purchase premiums are continued as well as expected cost depressions for EVs take effect. However, a further increase to around 150 €/t CO₂ in 2030 should be required to further accelerate the market diffusion. Due to the stable stock turnover rate by 2040 and ongoing, we do not assume a large effect when the CO₂ price is further increased in 2040 and 2050.

Certainly, these results are subject to uncertain developments. For example, it is yet unclear, if the German government will really stop purchase premiums in 2025, which may affect the stagnation in phase 2. It is even unclear, how manufacturers will react to changes in purchase premiums, e.g. they could reduce the investment costs by higher discounts to keep the investment costs for customers stable. However, policy makers should consider a well analyzed and flexible CO₂ tax trajectory for future legislation that also reflects energy generation cost changes, user behavior or vehicle availability. To this point, we can retain, however, that a CO₂ tax will have a meaningful impact up to a certain threshold where policy makers should focus on purchase price premiums or regulations for vehicle sales (c.f. [37]).

The method used to gain the previously results is not a cost-benefit analysis. It is rather cost-driven based on an adapted TCO approach. In contrast to a cost-benefit analysis, more emphasis was placed on the precise reflection of the utility-based user behavior. Besides a cost-benefit analysis also a discrete choice-based approach could have been chosen. However, the suitability of the chosen approach with its advantages and disadvantages has been assessed for example in Gnnann et al. [22].

Further research on actual TCO developments across user segments is suggested in order to quantify possible bandwidths of CO₂ prices that have relevant steering effects. Furthermore, the transferability of the underlying results to other EV markets can be analyzed by comparing cost structures and automotive or rather EV affinity within the population. According to the transferability to other regions outside the European Union, we plan to integrate carbon pricing on electricity and H₂ in future work. Moreover, the effects of different market evolutions based on varying CO₂ prices have to be analyzed in travel demand

models to evaluate the impacts on e.g., public charging infrastructure and further measures the government has to take care of. The influence of the CO₂ tax on the choice of the transport mode is not considered in our model and should be investigated in the future. Furthermore, in several years a comparison with real world sales data is necessary to validate the model's results. Finally, the underlying simulation model is subject to various assumptions concerning the purchasing behavior of potential EV customers (e.g. complete information on cost structures, brand loyalty etc.) that have a direct effect on the results obtained from the model. Although these assumptions have already been discussed to a great extent, e.g. in Plötz et al. [23], they may be refined in further research projects.

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CRedit authorship contribution statement

Tien Linh Cao Van: Conceptualization, Methodology, Validation, Writing – original draft, Visualization. **Lukas Barthelmes:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Till Gnnann:** Methodology, Validation, Software, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Daniel Speth:** Methodology, Validation, Software, Data curation, Writing – review & editing, Visualization. **Martin Kagerbauer:** Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Table A1

Vehicle investment costs. All values in EUR without VAT. All monetary figures refer to its value in 2020. Own assumptions based on [36,29,30,32,38,39].

	2020			2030			2050		
	small	medium	large	small	medium	large	small	medium	large
Gasoline	10,700	17,700	31,400	11,300	18,800	33,200	12,500	20,600	36,600
Diesel	12,900	19,900	33,600	13,700	21,100	35,600	15,000	23,200	39,200
PHEV	16,712	24,004	39,824	16,184	24,004	39,692	15,920	23,620	39,010
BEV	16,500	27,800	47,720	14,760	24,880	41,500	14,000	23,500	39,500
CNG	12,400	19,400	33,100	13,200	20,600	35,100	14,500	22,700	38,600
FCEV	34,300	51,000	72,100	17,600	27,100	42,800	15,800	24,300	39,000

Table A2

Assumed energy consumption [kWh/km]. Own assumptions based on [29,39,40].

	2020			2030			2050		
	small	medium	large	small	medium	large	small	medium	large
Gasoline	0.547	0.669	0.886	0.490	0.590	0.769	0.441	0.531	0.692
Diesel	0.430	0.514	0.634	0.378	0.440	0.530	0.340	0.396	0.477
PHEV el.	0.159	0.198	0.214	0.141	0.177	0.190	0.127	0.159	0.171
PHEV con.	0.501	0.614	0.777	0.449	0.539	0.668	0.404	0.485	0.601
BEV	0.172	0.211	0.227	0.153	0.188	0.203	0.138	0.169	0.183
CNG	0.574	0.702	0.930	0.502	0.605	0.788	0.441	0.531	0.692
FCEV	0.300	0.320	0.336	0.290	0.310	0.329	0.280	0.295	0.320

Table A3

Development of battery capacity. Usable battery capacity for BEV 90 %, for PHEV 80 %. Own assumptions based on [41].

		2020	2030	2050
BEV	small	25	38	38
	medium	45	69	69
	large	73	100	100
PHEV	small	8	12	12
	medium	11	22	22
	large	16	31	31

Table A4

Assumed maintenance costs. All values in EUR/a. All monetary figures refer to its value in 2020. Own assumptions based on [42].

	small	medium	large
Gasoline	0.026	0.048	0.074
Diesel	0.027	0.049	0.076
CNG	0.028	0.050	0.078
BEV	0.018	0.033	0.051
PHEV	0.023	0.043	0.066
FCEV	0.028	0.050	0.078

Appendix B

In the following, identified models are classified and introduced based on their underlying methodology. Such methods pertain to three different approaches: (1) Total-Cost-of-Ownership (TCO), (2) Discrete-Choice or (3) other.

Existing models

a). TCO based approaches

A TCO-approach is based on the comparison of capital and operating costs of different technologies. In most cases it assigns individual demand to a technology with respective minimal costs. The market diffusion is determined by the aggregation of different customer groups with individual driving characteristics and respective demands based on underlying TCO calculations. There are several examples for models using a TCO approach to model the market diffusion for EVs in Germany.

Plötz et al. [36] use the diffusion model *ALADIN* to forecast the diffusion of EVs in Germany until 2020 based on a TCO-analysis of real driving profiles. The market evolution is calculated successively based on a comparison of economic efficiency for different drive systems while taking obstructive and supportive factors into account as well as the electrical feasibility for almost 7000 driving profiles. The drive technologies analyzed include BEVs, PHEVs and REEVs as EVs as well as conventional gasoline and diesel cars, with the cheapest respective drive technology being selected for modelling individual demand. Depending on different scenario and infrastructure assumptions Plötz et al. [36] predict 50 k to 1.4 m EV in 2020, while this high level of uncertainty in the market diffusion phase is mainly driven by external factors such as the development of crude oil, electricity and battery prices.

The approach by the ‘German National Platform for Electric Mobility’ [43] takes the findings of Plötz et al. [36] into account when forecasting the market evolution for EVs in Germany. Moreover, it uses a similar approach and model as provided in Plötz et al. [36], but sets its simulation horizon to 2030. According to ‘German National Platform for Electric Mobility’ [43] the cumulative new registrations of EVs are predicted to be between 1.7 and 3.1 m in 2025, corresponding to a market share of 4 % and 6.5 %, respectively. By 2030, this figure may rise up to 7 m EVs with a market share of 15 %.

Mock [44] published a study with the aim of making projections regarding future market shares of alternative vehicle technologies and their effects on CO₂ emissions of the transport sector until 2030. The model captures the decision-making process of customers when buying a new vehicle and thus the diffusion of alternative vehicle technologies including BEVs, REEVs and FCEVs. The underlying basis for the decision-making process is the

integration of TCO considerations while additional aspects such as increased environmental awareness of customers are added by assuming the selection of a vehicle with minimal Well-to-Wheel (WTW) emissions⁶ in the final step of the purchasing decision. Depending on different scenario assumptions, a market evolution of up to 14 m EV in 2030 is projected.

Baum et al. [45] provide a market diffusion model for EVs in Germany until 2020 based on a break-even analysis between EVs and gasoline cars, calculating the necessary annual mileage for EVs to be economically efficient based on fixed and operational cost parameters. Based on the parameter assumptions regarding gasoline and battery price developments the model predicts an aggregated EV fleet between 100 k to 1.4 m based on new registrations from 2010 to 2020.

b). *Discrete-Choice based approaches*

Models based on the Discrete-Choice Theory simulate decision processes of agents, with a finite set of choices [46]. Regarding market diffusion modeling of EVs, these approaches model the decision process for a car purchase. Hereby, different user groups are confronted with a portfolio of vehicles with different characteristics (e.g. price, drive, etc.) from which a choice must be made. A consumer chooses an alternative with the highest probability that imposes the highest utility. In particular, a vehicle's utility does not only base on its pure consumption, but rather on the characteristics of the vehicle that the consumer implicitly evaluates. Depending on the utility value the purchase probability is calculated for each possible vehicle alternative with its respective vehicle characteristics, while each characteristic is endowed with a specific parameter for calculation depending on the preferences of the consumer group. This specific parameter is identified beforehand for each consumer group through surveys and conjoint experiments. According to the research objective two relevant approaches have been identified and are introduced in the following.

Holtermann et al. [47] model the market diffusion based on a Discrete-Choice approach (i.e. a Nested Logit model) in order to project the market evolution for EVs, specifically BEVs, PHEVs and REEVs, in Germany until 2050. Based on a synthetically created fleet of possible EVs with different characteristics offered by OEMs, the willingness to pay (WTP) of customers is derived through pre-defined utility functions using specific vehicle characteristics and charging infrastructure data as input parameters. Subsequently, the model calculates purchase probabilities for different vehicle technologies according to the calculated WTP and forecasts adjusted market shares based on a Bass diffusion model [48]. By using a Nested Logit approach the model allows to picture correlations regarding the decision of consumers between several alternatives from the same *nest*, whereas a nest can represent a vehicle segment or drive technology. Holtermann et al. [47] predict 6 m EVs by 2030 in its reference scenario, while different EV-favorable policy measures such as purchase bonuses or free parking can increase this figure by up to half a million vehicles.

De Haan et al. [49] published different EV diffusion scenarios until 2035, using a car purchase and market simulation model of ETH Zurich (c.f. de Haan et al. [50]) based on a Discrete-Choice approach as well as a diffusion model based on Moore [51]. Similar to the approach of Holtermann et al. [47] different vehicle attributes are depicted and assessed by a WTP- and utility function for different customer segments. The characteristics include the purchase price, the fuel costs, the vehicle length, the size of the luggage compartment, the acceleration time, the vehicle brand and an additional valuation of the vehicle purchase price depending on the median purchase price of the entire available fleet. Depending on the underlying scenario assumptions, the model forecasts an EV share from 15 % up to 60 % in new car registrations in 2035.

c). *Other approaches*

In addition to TCO and Discrete-Choice models, there are other diffusion methodologies that cannot be classified into one of the two categories. This includes for example approaches that use historical growth rates to determine future market penetration such as in the approach of Greiner et al. [52], where the EV fleet is expected to grow up to 1.1 m vehicles in 2022 based on a compounded annual growth rate of 65 % for EV between 2016 and 2018 in Germany. Another example is provided by Adolf et al. [53] that uses projections regarding socio-economic developments and possible degrees of motorization in the population to calculate overall vehicle stock developments in Germany until 2040. Based on the overall vehicle stock, the overall EV share is analyzed by calculating the optimal drive mix in OEM vehicle fleets depending on European CO₂-emission standards. Depending on different scenario assumptions the model predicts between 1 and 3 m BEVs and 3–5.5 m PHEVs in the German vehicle fleet by 2040.

Model Evaluation

In order to identify strengths of existing models for the market diffusion of EVs on the one hand and to reveal possible research gaps on the other hand, the introduced models are evaluated. For this purpose, an evaluation scheme was derived that fully reflects the factors that have an influence on the market diffusion of EVs. As a basis the PESTEL analysis framework of Aguilar [54] was considered, which is often used in strategic management to analyze the external market environments. Additionally, the generic dimensions provided by the PESTEL-framework were refined to different aspects of e-mobility in order to ensure an overarching analysis of the e-mobility ecosystem. Hereby, three different perspectives of e-mobility, namely (1) the technological perspective, (2) the market-oriented perspective as well as (3) the social perspective as stated in literature such as Scheurenbrand et al. [55], Zanker et al. [56] and Hanselka and Jöckel [57] were integrated. Consequently, the following main criteria were identified and used to evaluate the existing market diffusion models for EVs.

- (1) **Consideration of policy factors**, e.g. through the modelling of policy measures such as taxes, emission standards or other environmental policy measures etc.
- (2) **Consideration of economic factors**, e.g. through the modelling of oil, gas and energy prices as well as overall depiction of the development of new car registrations and vehicle stocks.
- (3) **Consideration of social factors**, e.g. through the modelling of population development, overall mobility behavior and evolution in new types of mobility such as car or ride sharing.
- (4) **Consideration of vehicle and infrastructure characteristics**, e.g. through the modelling of drive systems, vehicle costs and charging infrastructure etc.
- (5) **Consideration of customer characteristics**, e.g. through the modelling of purchasing behaviors, innovation-readiness or brand loyalty etc.

It should be noted that the description of the criteria with their respective sub-items is only intended to provide guidance for the analysis and

⁶ Well-to-Wheel emissions examine the emission generated from primary energy production to local emissions from fuel combustion in the vehicle.

evaluation of the models. In particular, no quantitative scale is provided to assess the degree to which the described sub-items are achieved. The determination of the degree of fulfilment of the criteria within the individual models is exclusively based on a qualitative discussion of the criterion in relation to the diffusion methodology considered. The aspect of environmental measures is considered in (1) since measures such as CO₂ taxes or emission standards are based on legislative decisions.

Results of Model Evaluation

Fig. 8 summarizes the results of the model evaluation using the mentioned criteria. For each model introduced in section 2, a degree of criteria fulfilment is determined by using Harvey Balls, where a completely filled Harvey Ball is indicating that the respective criteria is strongly integrated in all its relevant dimensions in the model's diffusion logic, whereas an empty Harvey Ball is indicating that the criteria is only poorly considered. The evaluation is performed relatively between the considered models. To allow a more specific distinction of fulfilment levels between the models, quarter-stepped scaling of the Harvey Balls is applied.

Criterion ¹	Plötz et al. (2013)	National Platform E-Mobility (2018)	Mock (2010)	Baum et al. (2010)	Holtermann et al. (2011)	De Haan et al. (2018)	Greiner et al. (2019)	Adolf et al. (2014)
 Consideration of policy factors								
 Consideration of economic factors								
 Consideration of social factors								
 Consideration of vehicle and infrastructure characteristics								
 Consideration of customer characteristics								

¹ The degree of fulfilment is determined by means of qualitative estimation on the basis of available model information.

 Hardly taken into account  Very strong consideration

 Focus field of the model

Fig. 8. Overview of results of model evaluation.

Several conclusions can be drawn based on the evaluation results. First, no model covers all relevant criteria for the market diffusion of EVs to a very high degree. While a model may cover certain aspects with very high degree of fulfilment, different aspects are only considered roughly on a sufficient basis. Second, strengths of the models examined can be distinguished in particular with regard to the methodology used as different diffusion methodologies show different fields of focus. While TCO models like Plötz et al. [36] or Mock [44] often consider overall economic factors for the diffusion simulation, Discrete-Choice models focus more on customer characteristics, which in turn is due to the nature of both diffusion methodologies. For the other models, focus fields may vary depending on the methodology and the goal of the study. Adolf et al. [53] for example, provide a strong focus on sociodemographic developments and its impact on the diffusion of alternative drives. Third, policy measures are considered in all models, however not all relevant aspects are covered. Especially environmental policy measures, such as a CO₂ tax or restrictions for combustion engines in cities are not completely considered yet, which gives room for improvement.

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