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Tien Linh Cao Van
Lukas Barthelmes
Till Gnann
Daniel Speth
Martin Kagerbauer

Addressing the gaps in market diffusion modeling of electrical vehicles – A case study from Germany for the integration of environmental policy measures

Abstract

Electric vehicles (EVs) can help to reduce greenhouse gas emissions of the transportation sector. Therefore, the German government has defined various measures and targets to promote the diffusion of EVs. However, factors influencing the market diffusion of EVs as well as interdependencies between policy measures and vehicle diffusion are often unclear and hence, diffusion simulations are probably inaccurate. At the same time, a precise simulation of EV diffusion is a relevant parameter in travel demand models building the base for transportation planning. This paper addresses the gaps in current market diffusion models for EVs with a particular focus on environmental effects as additional influencing factors of the market diffusion. Results will be drawn for the German car market with a market diffusion simulation until 2050. The market diffusion model ALADIN is applied and energy prices are extended by a CO_2 price to improve the consideration of environmental factors in the market diffusion modelling. The effectiveness of environmental policy measures is assessed in scenarios with three different CO_2 prices and their impact on the diffusion of EVs. The results show that the market diffusion is highly dependent on the evolution of external factors. A CO_2 price of at least 150 €/t of CO_2 by 2030 can have a significant impact on the market diffusion of EVs and may as well lead to changes in the drive mix for both, electric and conventional drives within the German passenger car fleet. The German government's target of seven to ten million EVs registered by 2030 seems in general achievable, if currently adopted purchase bonuses and expected cost degression for EVs also take effect. Until 2050, we find large effects with CO_2 prices up to 500 €/t, yet limited growth in market share above that threshold.

Table of Contents

Page

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 significant contribution to annual emissions in Germany (German Federal Environment Agency 2020). 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 (CO_2) and local (pollutants, noise) emissions, contribute to conserving resources and further develop a multimodal transport system (BMU 2019). 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 (BMU 2020). 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 (Federal Motor Transport Authority 2021).

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 ownership of EVs more precisely (Plötz et al. 2017). 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 (Heilig et al. 2020). 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-

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).

Choice models. 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.

In this paper, the impact of environmental costs on the market diffusion of EVs is assessed by integrating a CO_2 price 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 CO_2 prices are developed that illustrate possible pathways for political measures to incentivize a cost-based shift towards electrically-powered cars. According to the authors' knowledge, there is no literature available evaluating the impact of CO_2-pricing on the diffusion of EVs in Germany yet.

The paper is segmented into four sections. After the introduction in section 1, a brief literature review is given in section 2 that shortly introduces different kinds of market diffusion models in national and international research, followed by a discussion and evaluation of models, arguing that environmental aspects are poorly integrated in existing market models. Section 3 illustrates an adaption of the current Fraunhofer market diffusion model *ALADIN* through an integration of CO_2 prices as part of environmental costs into the TCO-logic with a subsequent simulation of the market diffusion of EVs in Germany until 2050. 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 Literature Review

There are numerous models and approaches in the literature that address the market diffusion of EVs. The models each 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. USA, China, Germany or other countries). Second, the existing models consider different sub-segments of the EV market (e.g. focus on plug-in hybrids or considering battery electrical 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).

Various authors have already collected and compared existing models under different focuses of analysis. For example, Al-Alawi et al. (2013) provide an overview of market diffusion models of different segments of EVs for the US market. Gnann et al. (2018), on the other hand, compare market diffusion models of EVs worldwide. Kickhöfer et al. (2017) 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 were identified. 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.

2.1 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. (2013) uses 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 7,000 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. (2013) predicts 50k to 1.4m EVs 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' (NPE 2018) takes the findings of Plötz et al. (2013) 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. (2013), but sets its simulation horizon to 2030. According to 'German National Platform for Electric Mobility' (2018) the cumulative new registrations of EVs will be between 1.7 and 3.1m in 2025, corresponding to a market share of 4 % and 6.5 %, respectively. By 2030, this figure may rise up to 7m EVs with a market share of 15 %.

Mock (2010) published a study with the aim of making projections regarding future market shares of alternative vehicle technologies and their effects on CO_2 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) emissions[2] in the final step of the purchasing decision. Depending on different scenario assumptions, a market evolution of up to 14m EVs in 2030 is projected.

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

Baum et al. (2010) 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 100k to 1.4m based on new registrations from 2010 to 2020.

b) Discrete-Choice based approaches

Models based on a Discrete-Choice Theory simulate decision processes of agents, with a finite set of choices (Train 2012). Regarding market diffusion modeling of EVs, 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 will be introduced in the following.

Holtermann et al. (2011) 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 predefined 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 (Bass 1969). 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. (2011) predict 6m 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. (2018) published different EV diffusion scenarios until 2035, using a car purchase and market simulation model of ETH Zurich (c.f. de Haan et al. (2007)) based on a Discrete-Choice approach as well as a diffusion model based on Moore (2014). Similar to the approach of Holtermann et al. (2011) 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. (2019), where the EV fleet is expected to grow up to 1.1m 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. (2014) 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 CO_2-emission standards. Depending on different scenario assumptions the model predicts between 1 to 3m BEVs and 3 to 5.5m PHEVs in the German vehicle fleet by 2040.

2.2 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 had to be 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 (1967) 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. (2015), Zanker et al. (2011) and Hanselka et al. (2010) 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 evaluation of the models. In particular, no quantitative scale will be 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 CO_2 prices or emission standards are based on legislative decisions.

2.3 Results of Model Evaluation

Figure 1 summarizes the results of the model evaluation using the mentioned criteria. For each model introduced in section 2, a degree of criteria fulfillment is determined by using Harvey Balls, where a completely filled Harvey Ball is indicating that the respective criteria is strongly integrated in the model's diffusion logic, whereas an empty Harvey Ball is indicating that the criteria is only poorly considered. To allow a more specific distinction of fulfillment levels between the models, quarter-stepped scaling of the Harvey Balls was applied.

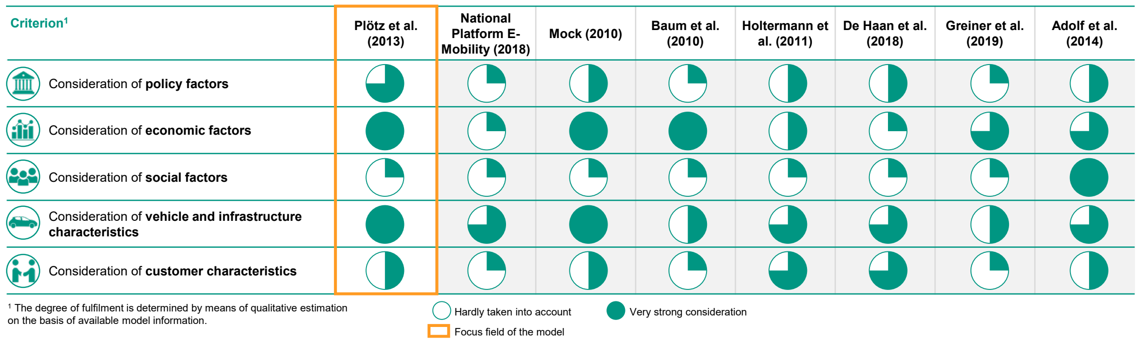


Figure 1: Overview of results of model evaluation

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 fulfillment, 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. (2013) or Mock (2010) 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. (2014) 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 CO_2 prices or restrictions for combustion engines in cities are not completely considered yet, which gives room for improvement.

Due to the relatively high degree of criteria fulfillment in Plötz et al. (2013), this model will be used for further extension regarding environmental policy measures. A transfer of environmental costs into the *ALADIN* model of Fraunhofer-ISI is aspired to improve the consideration of environmental aspects in the diffusion modelling process. The following case study integrates CO_2 prices as part of environmental costs into the *ALADIN* model that uses a TCO market diffusion logic based on Plötz et al. (2013).

3 Case Study

In this section, a case study is provided that integrates CO_2 prices 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. The model is based on a TCO approach with some integration of user behavior (c.f. Plötz et al. (2014)) and will be introduced shortly in the following. Subsequently, the model extension using CO_2 prices will be explained including an introduction of different policy scenarios for diffusion simulation from 2020 until 2050. Finally, the scenario results will be presented and compared followed by a discussion and derivation of conclusions regarding the impact of environmental costs and respective policy measures on the market diffusion of EVs in Germany.

3.1 ALADIN

Overview

The market diffusion of electric vehicles is simulated with the market diffusion model *ALADIN (**A**lternative **A**utomobiles **D**iffusion and **In**frastructure)* of Fraunhofer ISI that also has been used in several studies (c.f. Gnann et al. 2015c; Gnann et al. 2015b; Gnann et al. 2019). The evolution of the market is calculated successively based on a comparison of the economic efficiency of different drive systems and taking 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 (Zumkeller et al. 2011) and data collected within the 'region eco mobility 2030' project (Gnann et al. 2015a). 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 can be broken down by vehicle segment (small, medium, large) and by user group (private, fleet, company car). Figure 2 summarizes the procedure.[3]

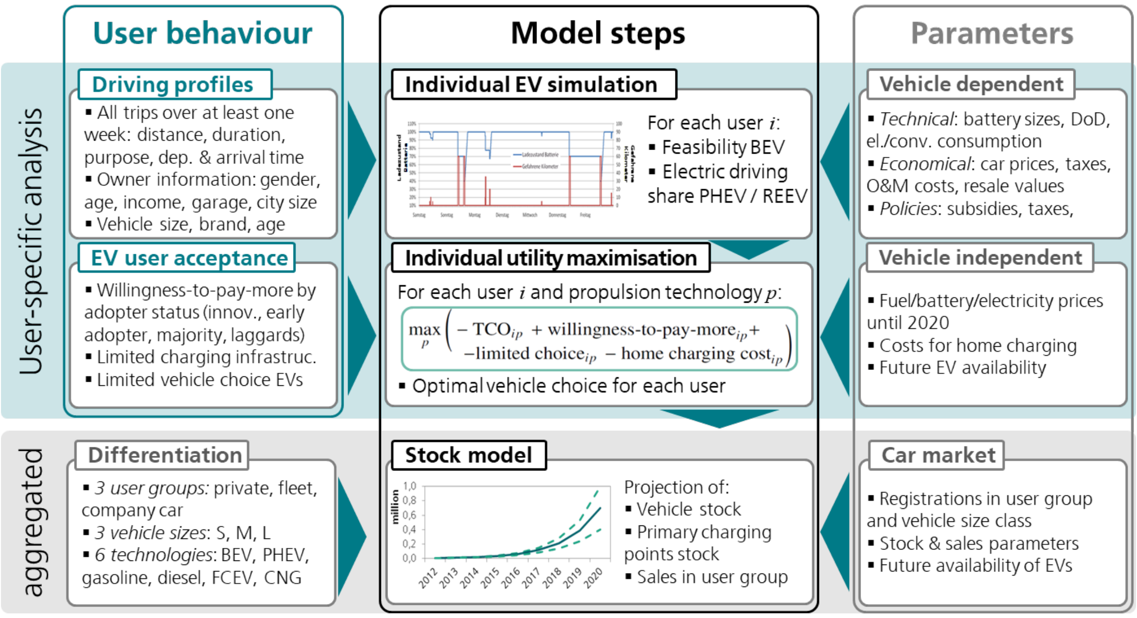


Figure 2: Overview of the approach taken in the ALADIN model

Mathematical approach

The annuitized utility $u_{i,s}^{a}(t)$ of user i for drivetrain s is calculated by the TCO of the vehicle $TCO_{i,s}^{a,veh}(t)$, the TCO of individual charging infrastructure $TCO_{i,s}^{a,CI}(t)$ and the WTPM for AFVs $WTPM_{i,s}^{a}(t)$:

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

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

3 More details can also be found at: www.aladin-model.eu

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

The individual and drivetrain specific capital expenditure is calculated as follows:

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

The vehicle investment $I_{r,s}(t)$ is annuitized with interest rate $z(t)$ and investment horizon $T^{veh}(t)$ while the resale price after use $SP_s(t)$ is subtracted.

The operating expenditure consists of kilometer dependent and independent cost. The individual annual vehicle kilometers travelled VKT_i multiplied by the energy consumption differentiated in electric driving (share of electric driving $s_i(t)$ times electric consumption $c_{r,s}^{e}$ times electricity price k^e) and non-electric driving (with conventional consumption $c_{r,s}^{c}$ times conventional fuel price k^c) and the operations and maintenance (OM) cost $k_{r,s}^{OM}(t)$ give the use-related costs. The annual vehicle tax $k_{r,s}^{tax}(t)$ is added independent of a user's driving behavior.

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

More details on the approach and its justification can be found in Plötz et al. (2014).

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 (Meszler et al. 2017). For BEVs, PHEVs and FCEVs investment costs are primarily driven by declining battery / fuel cell prices (Gnann 2015). Table A1 shows the vehicle investment costs, while Table 1 illustrates the development of battery prices assumed in the model.

Table 1: Battery and fuel cell price development. Own assumptions based on (Hülsmann et al. 2014; Lutsey 2017; Zapf et al. 2019)

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

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 will remain 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 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 smaller components that are wearing out slower due to operation in the optimum speed range.

3.2 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 CO_2 prices 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^c_{new} denotes the new fuel price for engines using fuels that emit CO_2 during combustion. k^c_{new} is calculated from the old fuel price k^c_{old} while taking the CO_2 price 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 CO_2 price, three scenarios will be defined to illustrate different policy paths. In the reference scenario, the CO_2 price is set according to the current policy path of the German Federal Government (2019) for the transport sector and is thus oriented towards current political targets and measures from the Climate Action Program (c.f. BMU (2019)). Moreover, a CO_2 price of 25 €/t CO_2 is defined for 2020, which will gradually increase to 65 €/t CO_2 in 2050. In the contra scenario, no CO_2 price is defined during the simulation period. Thus, no additional costs on operational costs of conventional vehicles are depicted. 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 CO_2 price of 25 €/t CO_2 in 2020 that will gradually increase to 500 €/t by 2050. By making these very different assumptions and varying the price of CO_2 within the scenarios, the impact of environmental costs on the market diffusion can be assessed quickly while respective steering effects on the market evolution are clearly observable. It should be noted that the present implementation only simplifies the logic of CO_2 prices from the Climate Action Program and an assessment of the policy measures is subject to various assumptions since the actual implementation of CO_2 prices is based on a national emission trading system, which is based on a cap-and-trade as well as auction mechanism. Depending on the defined CO_2 price, energy prices vary in the respective scenarios. Table 2 provides an overview of the scenario parameters.[4]

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

Table 2: Overview of scenario parameters

	scenario	2020	2030	2040	2050
oil price [€/MWh][1]	all scenarios	42	54	63	78
gas price [€/MWh][1]		24	25	28	30
electricity price private [€/kWh][2]		0.329	0.321	0.313	0.311
electricity price commercial [€/kWh][2]		0.226	0.217	0.210	0.208
hydrogen price [€/kWh][2]		0.469	0.390	0.282	0.235
CO_2 price [€/t CO_2]	contra	0	0	0	0
	reference	25	55	65	65
	pro	25	150	300	500
gasoline price [€/kWh][2]	contra	0.156	0.176	0.191	0.215
	reference	0.165	0.194	0.211	0.236
	pro	0.165	0.226	0.298	0.379
diesel price [€/kWh][2]	contra	0.120	0.138	0.152	0.174
	reference	0.128	0.156	0.172	0.195
	pro	0.128	0.187	0.257	0.335
gas price CNG [€/kWh][2]	contra	0.061	0.106	0.111	0.114
	reference	0.068	0.122	0.128	0.133
	pro	0.068	0.149	0.204	0.258

[1] primary energy source price without taxes taken from IEA (2020) (originally in US Dollar), exchange rate used: EUR/USD = 1.1

[2] incl. all taxes and duties described. VAT of 19% considered, temporary VAT reduction in 2020 not shown

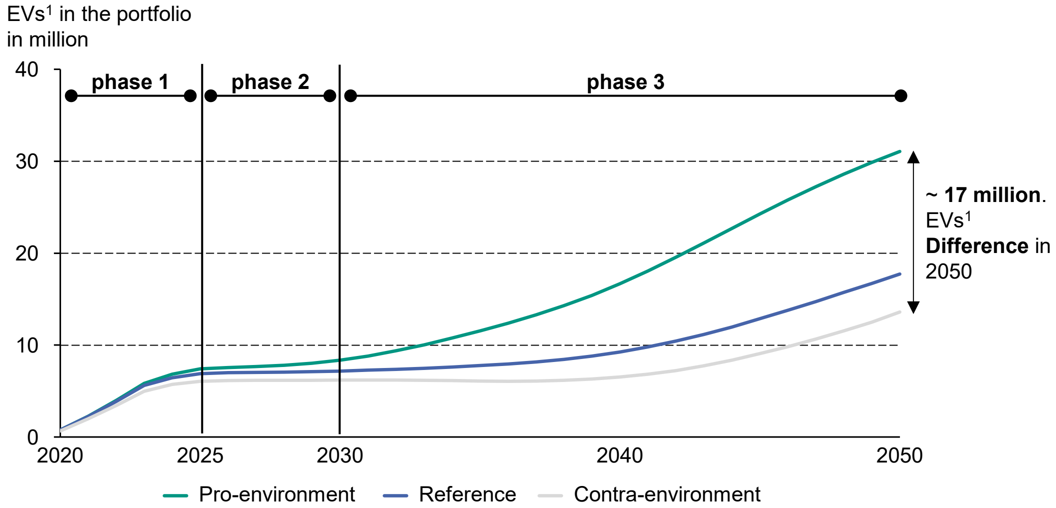
4 Results

The goal of this paper is to extend the market diffusion model *ALADIN* by environmental factors in the form of CO_2 prices as environmental factors. This section summarizes the results of the market diffusion simulation for EV including an evaluation of the CO_2 prices' impact on the EV fleet evolution and respective policy targets in Germany until 2050.

Overview of market diffusion

The calculated market evolution for the three scenarios is illustrated in Figure 3. Taking all effects into account, around 18m EVs are obtained in the reference scenario, while the contra scenario shows 14m and the pro scenario up to 31m vehicles in 2050, respectively. Looking at the development of the market diffusion, all three scenarios can be categorized in three phases. 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 due to the discontinuation of the purchase premiums 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 based on positive TCO evolutions of EVs compared to conventional drives until 2050. Thereby, the consideration of CO_2 prices as part of environmental costs can have significant impact on the market diffusion.

Results market ramp-up | Overview



Scenario		2020	2030	2040	2050
Pro-environment	CO_2-price [€/t CO_2]	25	150	300	500
Reference		25	55	65	65
Contra-environment		0	0	0	0

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

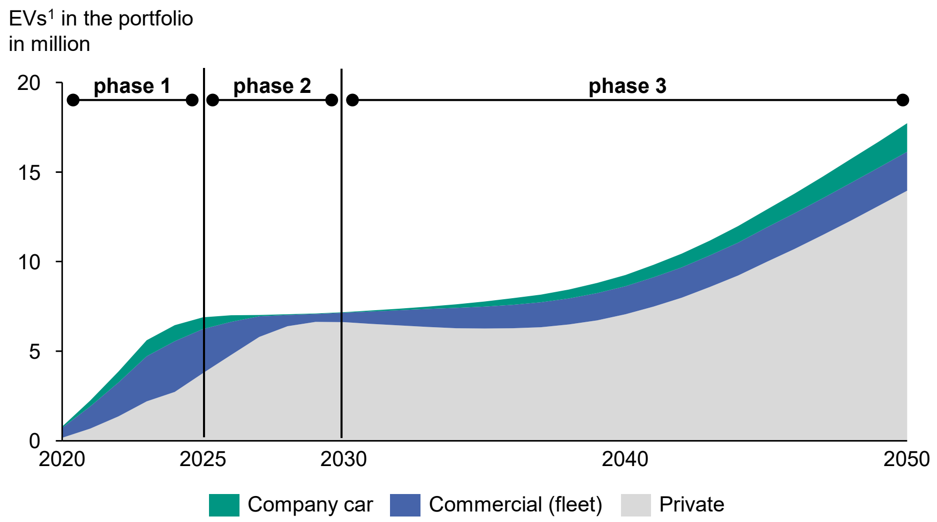
Figure 3: Overview scenario results market diffusion EVs

Based on the model results, an introduced CO_2 price of up to 65 €/t CO_2 over the next 30 years will lead to an additional amount of around 4m EVs compared to a scenario without CO_2 price. This effect increases the higher the CO_2 price is defined. Thus, comparing results between the pro and contra scenario leads to a difference of up to approx. 17m electric vehicles in 2050, illustrating the significant long-term impact of CO_2 prices on possible EV market diffusion evolutions if set sufficiently high. Based on the simulation results, a CO_2 price of at least 150 €/t CO_2 is found to be sufficient 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 to 10m EV stock in 2030 can be achieved even without the introduction of a CO_2 price, if current purchase bonuses on EVs continue being effective.

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 Figure 4).

Results market ramp-up by user group | Reference-scenario



User group		2020	2025	2030	2040	2050
Company car	Number of EVs[1] [million]	0.1	0.6	0.0	0.6	1.6
Commercial (fleet)		0.6	2.5	0.5	1.6	2.2
Private		0.2	3.8	6.6	7.1	14.0

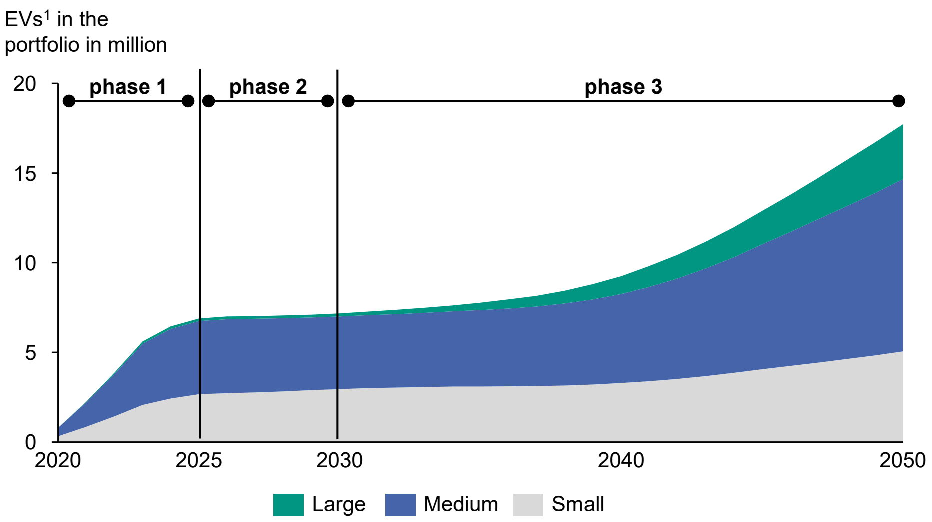
[1] Electric vehicles are defined here as BEVs. PHEVs and FCEVs. REEVs are implicitly included in PHEVs.

Figure 4: Market diffusion user groups in the Reference-scenario

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 company vehicles compared to privately owned vehicles (approx. 6 years, c.f. Plötz et al. (2013)) 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 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. Market evolutions in phase 3 are mainly driven by defined cost developments resulting in positive TCO effects of EVs as described above where higher CO_2 prices support the diffusion of alternative drives while inducing no significant mix effects within the user groups across the different scenarios.

As depicted in Figure 5, 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, predefined cost degression 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 CO_2 price 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.

Results market ramp-up by vehicle segment | Reference-scenario



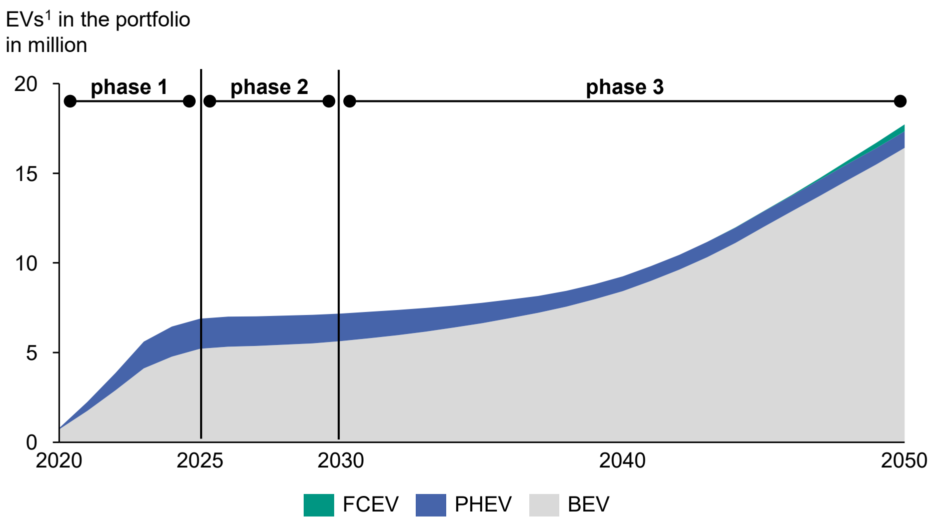
Vehicle segment		2020	2030	2040	2050
Large	Number of EVs[1] [million]	0.0	0.2	1.0	3.1
Medium		0.5	4.0	5.0	9.6
Small		0.3	3.0	3.3	5.1

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

Figure 5: Market diffusion vehicle segments in the Reference-scenario

Figure 6 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. 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.

Results market ramp-up by drive technology | Reference-scenario



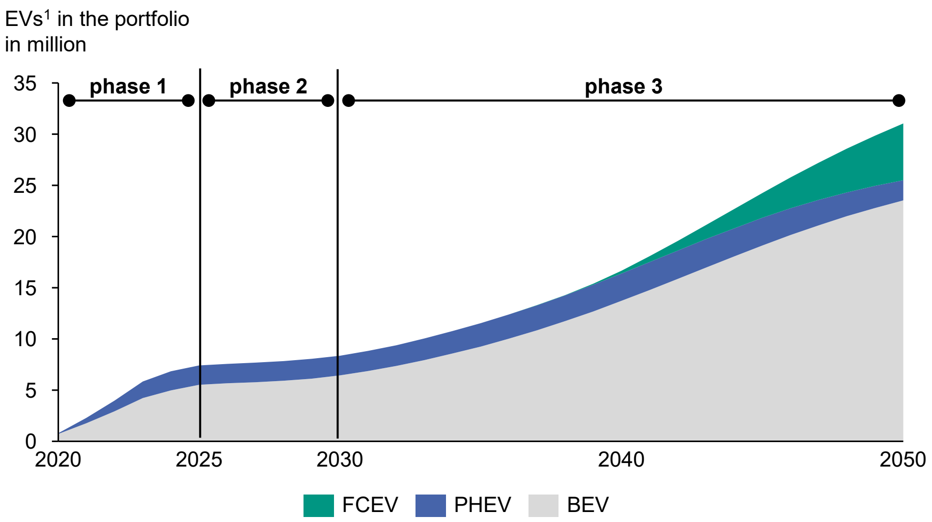
Drive technology		2020	2030	2040	2050
FCEV	No. of vehicles [million]	0.0	0.0	0.0	0.4
PHEV		0.1	1.5	0.8	0.9
BEV		0.7	5.6	8.4	16.4

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

Figure 6: Market diffusion drive technologies in the Reference-scenario

While there are no significant differences in the results between the contra and reference scenario, the pro scenario is illustrating possible effects of CO_2 prices on the diffusion of different alternative drive technologies, i.e. fuel cell technology, if set sufficiently high as depicted in Figure 7. This outcome is mainly driven by favorable price developments of hydrogen compared to conventional fuels, where the latter will rise sharply until 2050 as a result of CO_2 prices of up to 500 €/t CO_2. High investment costs for FCEV can be offset by lower hydrogen prices relative to conventional fuels leading to a faster amortization of FCEVs compared to lower CO_2 price scenarios.

Results market ramp-up by drive technology | Pro-environment scenario



Drive technology		2020	2030	2040	2050
FCEV	No. of vehicles [million]	0.0	0.0	0.3	5.5
PHEV		0.1	1.9	2.7	2.0
BEV		0.7	6.4	13.7	23.5

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

Figure 7: Market diffusion drive technologies in the Pro-scenario

5 Conclusion

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 CO_2 price 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 CO_2 prices can have significant impact on the German market diffusion of EVs if set sufficiently high (at around 150 €/t CO_2). 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 will begin 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 CO_2 price accelerates the diffusion of various electric drive systems, e.g. FCEV, even though no significant shifts within defined user and vehicle segments are observed.

The target of seven to ten million registered electric vehicles by 2030 seems achievable, if current purchase premiums and expected cost degressions for EVs take effect in combination with the introduction of a CO_2 price of around 150 €/t. To overachieve current EV targets, additional policy measures need to be introduced to induce a relative cost increase of conventional drives and support the diffusion of EVs. A further increase of the CO_2 price in 2030 and 2050 did not return a large effect as the stock turnover rate is not sufficient.

Further research on actual TCO developments across user segments is suggested in order to quantify possible bandwidths of CO_2 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. Moreover, the effects of different market evolutions based on varying CO_2 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. 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 may be refined in further research projects. In particular, the dynamic setting of CO_2 prices until 2050 needs to be assessed under the consideration of possible acceptance issues within the population regarding higher costs for mobility.

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6 Appendix

Table A1: Vehicle investment costs. All values in EUR without VAT. Own assumptions based on (Gnann 2015; Meszler et al. 2017; Pfahl 2013; Plötz et al. 2013; Wietschel et al. 2019; Zapf et al. 2019)

	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 (Helms et al. 2011; Meszler et al. 2017; Wietschel et al. 2019)

	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 (Helms et al. 2019)

		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 value in EUR/a. Own assumptions based on (Propfe et al. 2012)

	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

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Authors' affiliations

Till Gnann, Daniel Speth

Fraunhofer Institute for Systems and Innovation Research (Fraunhofer ISI)
Competence Center Energy Technology and Energy Systems

Tien Linh Cao Van, Lukas Barthelmes, Martin Kagerbauer

Karlsruher Institute of Technology (KIT), Institute for Transport Studies

Contact:

Dr. Till Gnann

Fraunhofer Institute for Systems
and Innovation Research
(Fraunhofer ISI)
Breslauer Strasse 48
76139 Karlsruhe
Germany
Phone: +49 721 6809-460
E-Mail : Till.Gnann@isi.fraunhofer.de
www.isi.fraunhofer.de

M.Sc. Lukas Barthelmes

Karlsruher Institute of
Technology (KIT)
Institute for Transport Studies
Otto-Ammann-Platz 9
76131 Karlsruhe
Germany
Phone: +49 721 608 44119
lukas.barthelmes@kit.edu
www.ifv.kit.edu

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