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Modelling customer choice and market development for future automotive powertrain technologies

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Abstract

The paper introduces an innovative utility-based approach to model customer choice for alternative powertrain technologies within a dynamic scenario tool. The study covers a wide portfolio of different powertrain concepts from conventional combustion engines to advanced hybrid and electric cars. The assessment of their economic and technical attributes builds on a large set of vehicle simulation data and detailed cost models. In contrast to previous cost-based studies the applied methodology maps the observed diversity of user characteristics more realistically. Therefore, the driving behaviour and preferences of car buyers are analysed empirically based on major representative surveys and the resulting distribution functions are integrated in the model. After testing and validation with historic data the model is applied to the German vehicle market and a potential scenario for the prospective composition of the new passenger car fleet by 2030 is presented. The scenario simulation shows that a significant reduction of CO₂ emissions is feasible especially by the introduction of plug-in hybrids and range extended electric vehicles. However, the growing technical complexity and the additional effort for efficiency improvements also result in increasing total costs of ownership for the customer.

Keywords: Market potential, TCO, purchase and user behavior, hybrid and battery electric vehicles

1 Introduction

In the context of increasing climate protection efforts, limited fossil resources and rising environmental awareness from customer side the electrification of the powertrain is a preeminent development in the transport sector. The European Commission's transport strategy aims to cut greenhouse gas emissions by at least 60% until 2050 [1]. The German government plans to reduce the energy consumption of transport by 40% in 2050 (compared to 2005 level) according to the recently published mobility and fuel strategy [2]. Reaching these goals will not be

feasible with conventional combustion engines. Therefore a variety of propulsion concepts from mild hybrids to full electric cars are currently developed and will be introduced into the market by all major OEMs over the next years. However, the question which technology will be accepted by the user and hence will prevail in the long run has not been answered yet.

As a consequence of this development the decision process for car buyers is becoming more and more complex. While in the past a user could basically choose between spark ignition (SI) and compression ignition (CI) engines, which have only minor differences in purchase price and fuel consumption, the powertrain portfolio offered by

the automotive industry will grow in the future. At the same time the attributes of these advanced drivetrain architectures vary significantly. Investment and operating costs of the vehicle are definitely important for the user. However, minimizing cost is not sufficient to fully understand the future purchase behaviour of car buyers. Additional vehicle attributes, e.g. CO₂ emissions, driving range, and driving performance, as well as the individual willingness to pay have to be taken into account [3]. Therefore, this paper presents an innovative approach how to choose the optimal powertrain technology for different user characteristics and preferences within a dynamic market scenario model.

2 Methodology

Previous studies on the future penetration of alternative drivetrain concepts can be grouped into two major fields. The first one focuses on the technological potential and the projected cost development of the new propulsion systems. Here total cost of ownership (TCO) is widely used as key indicator to evaluate the competitiveness of electric vehicles. Important contributions in this research field have been made among others by Lipman [4], Delucci [5],

Kromer [6], Van Vliet [7] and Santini [8]. The second group applies advanced statistical methods, especially discrete choice models (e.g. Berry [9], Train [10], Golob [11] and Ziegler [12]) to assess the purchase behaviour of today's consumers. Based on their observations the researchers try to derive predictions on the future success of EVs.

While the cost centered approach is criticized for assuming an unrealistic *homo economicus* and neglecting other important vehicle attributes and the importance of consumer preferences [13], econometric studies traditionally put only a low emphasis on the technological side. Furthermore, discrete choice analyses are usually static, i.e. the vehicle properties and costs are provided externally which does not allow to model dynamic market scenarios over a long period of time.

The paper introduces a new interdisciplinary approach to model customer choice behaviour for conventional and advanced powertrain technologies by combining vehicle simulations, scenario technique and discrete choice analyses in a dynamic utility based market model. Figure 1 provides an overview on the model structure, which consists of the following modules:

- **Vehicles:** A wide set of different drivetrain architectures is covered by the model including vehicles with internal combustion engine

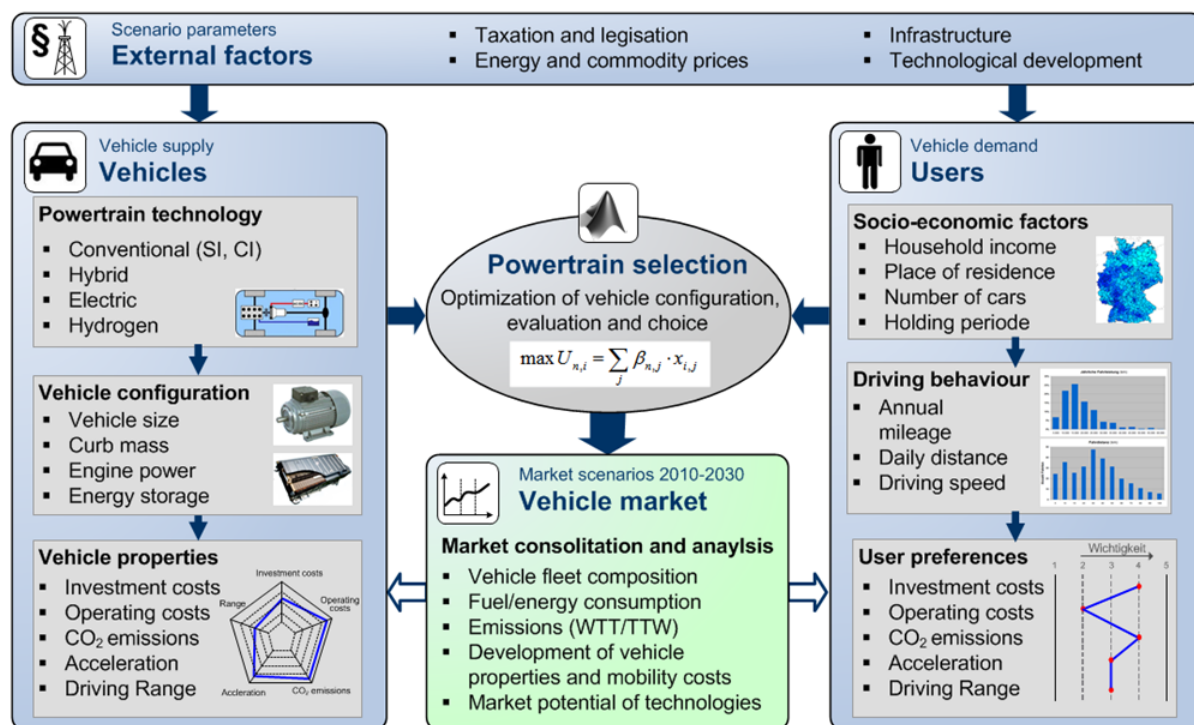


Figure 1: Structure of the market model

powered by gasoline, diesel or compressed natural gas (CNG), hybrids (HEV), plug-in hybrids (PHEVs), extended range electric vehicles (EREVs), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). The car configuration is flexible in several dimensions, e.g. curb mass, motor power or energy storage size. According to the selected setup key vehicle characteristics like costs, energy consumption and performance are calculated dynamically by the model [14].

- **User:** The model maps the diversity of car buyers in terms of socioeconomic factors, driving behaviour and individual preferences by applying a stochastic distribution functions. The underlying empirical data is based on the analysis of large representative surveys covering more than 30,000 respondents in Germany, e.g. the national travel survey *Mobility in Germany* (MiD) [15] and the consumer survey *Verbraucheranalyse* [16].
- **External factors:** A large set of scenario parameters which influence the purchase decision is included in the model (e.g. energy prices, CO₂ regulations, incentives and technology learning curves). These factors defined externally enable the model operator to simulate different market scenarios and to assess the impact of selected policy measures.
- **Vehicle market:** The results of the individual purchase decision are consolidated in market module which scales up the simulation results to be representative for the German car fleet. It also facilitates analysing the macroeconomic impact on CO₂ emissions, fuel consumption or mobility costs for the consumer. Moreover, the simulated market data can be used to identify early adaptor groups for electric vehicles by analysing which user types prefer which powertrain technology.

The center of this agent based model is the powertrain selection algorithm which is formulated as a utility maximization problem. While other vehicle market models such as presented by Mock [17], Kihm [18] or Plötz [19] apply TCO minimization as the objective of the customer, the introduction of utility as scoring variable allows multi-criteria decision making by the car buyer. The model provides the possibility to implement different decision functions. In this

study a linear utility function is applied where U represents the relative value a user n assigns to a powertrain option p :

$$\max U_{n,p} = \sum_i \beta_{n,i} \cdot x_{p,i} + \varepsilon \quad (1)$$

The utility score is determined by the vehicle attributes x (depending on the powertrain technology p) and the individual preferences β (depending on the characteristics of user n). In the current model version the following criteria i are evaluated: purchase price, operating cost (incl. fuel, electricity, maintenance and repair), CO₂ emissions, acceleration performance and driving range. In an iterative process each customer first adjusts the car configuration according to his preferences and then chooses the option with the highest score U . The iteration of this decision process for a large set of N users per year over a given time period allows analysing the future market prospects of alternative propulsion technologies.

3 Model data

In this study the model is applied to the German car market to assess the competitiveness and environmental impact of different powertrain concepts in the time horizon 2010-2030. Therefore an extensive data set is required as model input. The following paragraphs provide a brief overview on the data sources for vehicle, user and scenario data applied in the market simulation.

3.1 Vehicle data

To determine the energy consumption and driving performance of the selected powertrains the DLR proprietary Modelica library *AlternativeVehicles* [20] is applied and the simulation results are integrated into the model. The model covers eight different drivetrain architectures from conventional internal combustion engines (ICE SI/CI) to advanced technologies like battery electric vehicles in three car segments. In a first step the basic vehicle parameters (like curb weight, retail price, fuel consumption etc.) are calibrated to represent average passenger cars in small, medium and large segment sold in the Germany 2010 (according to ADAC [21] and KBA [22] data). The gasoline ICE, which dominated the car market in the past, serves as reference vehicle. All other powertrains are configured to show comparable performance characteristics (e.g. acceleration 0-100 km/h in 9-10 s in the medium segment). To

get realistic fuel economy data for the subsequent cost analysis, the assumed average power consumption of auxiliaries has been included in the simulation (0.7-2.0 kW). While HEV and PHEV use a parallel hybrid powertrain, the EREV is designed as series hybrid with larger battery. The size of the traction battery is dimensioned to reach an all-electric range of more than 50 km for the EREV and more than 100 km for the BEV. The PHEV is able to drive 35 km in all-electric mode in the urban part of the NEDC with a maximum velocity of 50 km/h. The HEV battery is sufficient to store the entire recuperation energy during the cycle. A summary of the most relevant underlying vehicle parameters for the midsize segment is presented in Table 1.

The cost development of the electric vehicle concepts over time is projected by a detailed TCO model. The calculation covers all types of expenses arising for a vehicle owner over lifetime including acquisition cost, operating cost, vehicle tax as well as maintenance and repair and the expected resale value. For the core components of the electric drivetrain (traction battery, electric machine and power electronics) specialized models, which have been developed at the DLR Institute of Vehicle Concepts, are applied to projects the future cost development. These models use a learning curve approach to forecast the cost degeneration dynamically with increasing economies of scale [23]. For example, the battery cost model estimates the cell, module, and pack production cost for the most important Li-ion chemistries as a function of the production volume [24]. In this assessment NMC has been selected for high-energy storage with a learning rate of 86% (i.e. with a doubling of output the average production cost decrease by 14% due to

economies of scales). For more details on the TCO calculation see [25], [26].

3.2 User data

For the modelling of the car user characteristics several empirical surveys and data sources have been analysed and integrated into the market model. Reflecting the diversity of consumers the population is segmented in three groups along the following three dimensions: annual mileage, household income and place of residence (see Figure 2).

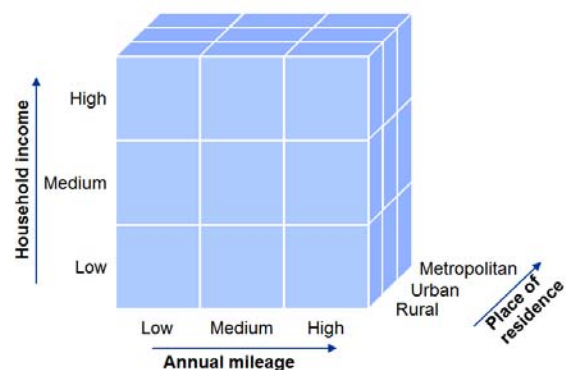


Figure 2: Dimensions of user segmentation

For each of the resulting 27 customer segments the distribution of preferences when buying a new car has been evaluated based on the data of a large representative consumer survey in Germany [16]. In this survey the respondents have been asked to rate the importance of multiple vehicle attributes when buying a new car. An excerpt of this analysis in Figure 3 contrasts the relative importance for purchase price, CO₂ emissions and acceleration performance of a single user segment (in this case frequent drivers with high income living in a rural area) against the average distribution.

Table 1: Vehicle parameter (midsize segment)

	Parameter	Unit	ICE-SI	ICE-CI	HEV	PHEV	EREV	BEV	FCEV	CNG
Energy converter	Combustion engine	kW	100	100	100	100	50	-	-	100
	Electric drive	kW	-	-	25	25	100	100	100	-
	Fuel cell stack	kW	-	-	-	-	-	-	100	-
Energy storage	Battery	kWh	-	-	2	7.5	15	30	2.5	-
	H ₂ / CNG tank	kg	-	-	-	-	-	-	4	25
	Fuel tank	l	50	50	50	40	30	-	-	-
Driving resistance	Curb mass	kg	1400	1470	1510	1570	1610	1610	1790	1540
	Frontal area	m ²	2.2							
	Aerodynamic drag		0.28							
	Rolling resistance		0.1							

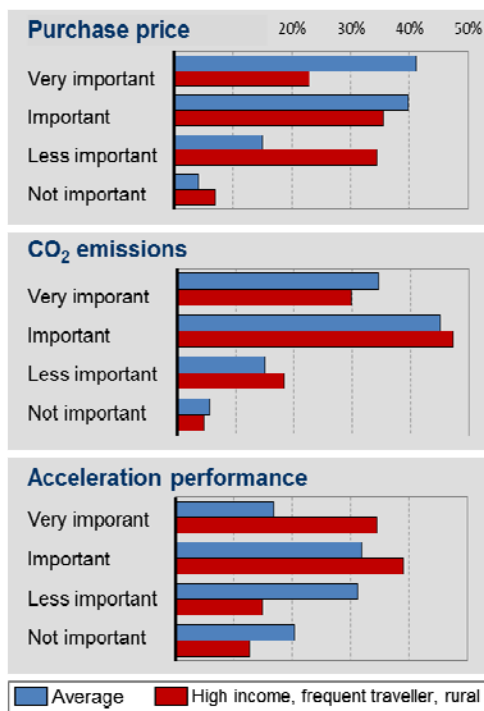


Figure 3: Distribution of customer preferences regarding selected vehicle criteria (own analysis based on [16])

The results indicate that the selected group with high purchase power values driving performance significantly higher than the population average, while the importance of the car price is relatively low. In line with this example the survey data has been used to model the preference distribution across all user segments. Furthermore, the average willingness to pay has been calibrated by performing a meta-analysis of available discrete choice analyses [27].

Besides individual attitudes and preferences the decision of a car buyer is also influenced by his driving behaviour. As electrified powertrains usually have higher initial investment costs, but lower running costs over life time, the economics of different technologies are strongly affected by the annual mileage and holding period [26]. Both quantities are analysed for German car drivers based on the national travel survey MiD and are integrated as a statistical distribution in the model. The resulting distribution functions for the annual mileage of small, medium and large cars are described mathematically by a log-normal fit. The plot in Figure 4 demonstrates that holders of small cars drive on average significantly less (11,600 km/year) than holders of larger vehicles (15,600 km/year).

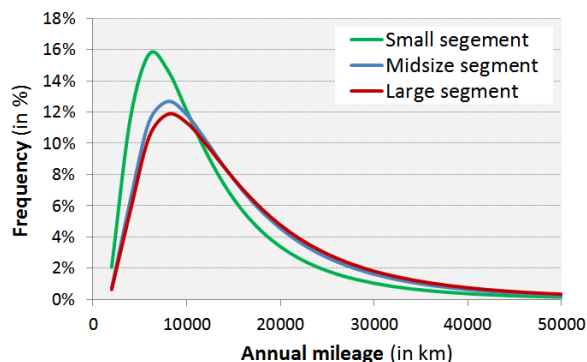


Figure 4: Distribution of annual mileage for different car segments in Germany (analysis based on [15])

Moreover, the MiD data is also applied to determine the average driving speed of different user types. The empirical data shows a functional relationship between mean speed and annual mileage. People who are used to travel longer distances spend more time on motorways with a higher average velocity than short distance drivers. Additionally, the driving speed is also influenced by the place of residence. City dwellers show a considerably lower average speed at short distances than inhabitants of rural areas due to frequent stop-and-go and traffic jams in metropolitan areas. With increasing driving distance the observed average speed converges between all groups (see Figure 5). To take these differences in driving style into account the mix of urban and extra-urban driving is adjusted in the model in a way so that the weighted average of the simulated driving cycle equals the statistically observed mean speed.

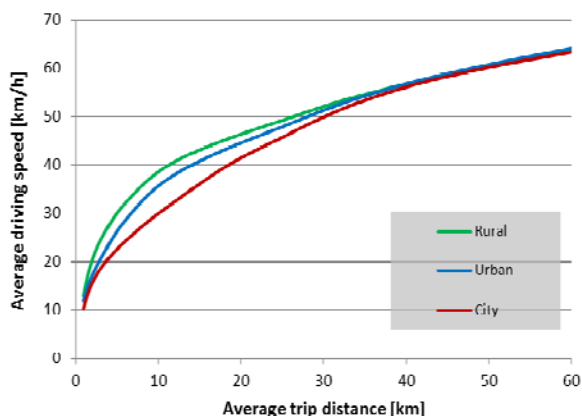


Figure 5: Average driving speed in Germany as a function of trip distance and place of residence [28]

Table 2: Summary of scenario parameters (in real prices year 2010)

	Parameter	Unit	2010	2015	2020	2025	2030	Source	
Energy prices	Oil price	USD/bbl	80	106	118	127	135	IEA [29]	
	Electricity price	EUR/kWh	0.25	0.26	0.27	0.26	0.26	BMU [30]	
	Hydrogen price	EUR/kg	16.6	9.9	6.6	5.5	5.0	EU Coalition Study	
CO ₂ regulation	CO ₂ fleet limit	g/km	-	130	95	82,5	70	EU regulation (interpolated)	
	CO ₂ penalties	EUR/(g/km)	0	95	95	95	95	EU regulation	
	Super credits		3,5	2,5	2	1	1	EU parliament [31]	
Economic parameter	Discount factor	%	5						
	Car holding period		Statistically distributed 1-10 years						Analysis based on [15]
	Willingness to pay		Distribution of preferences based on consumer analysis (no positive image effect for single powertrains assumed)						Meta-analysis discrete choice models, [16]
	Financial incentives		No direct financial bonus for buyers of low emission vehicle						Current German legislation

3.3 Scenario data

For the following simulation of the German car market a set of scenario assumptions have to be defined. The most relevant input parameters are summarized in Table 2. For exogenous factors such as energy prices a moderate business-as-usual scenario is assumed based on several renowned sources. For instance the oil price development reflects the current policy scenario published in IEA World Energy Outlook [29], which projects an average growth rate of 2.6% p.a. from 2010 to 2030. Electricity costs are based on expected end customer prices for Germany as specified in the 2012 study of the German Federal Environment Ministry [30]. The CO₂ emission regulation of the European Union which limits the new car fleet emission to 95 g/km in 2020 is extrapolated to 70 g/km by 2030. In this context low emission vehicles below 50 g CO₂/km benefit from super credits which are faded out gradually until 2025 according to the latest EU proposal [31]. In contrast to other countries in Germany as of today no direct financial incentives are granted to the buyers of electric cars from government side apart from the exemption of motor vehicle tax for BEVs (with savings of EUR 50-100 per year). The composition of the passenger car market in Germany for the base year 2010 reflects the segment split according to KBA data. For the future market development a limited growth in sales figure and a slow shift towards smaller cars are assumed in line with market forecast from IHS Global Insight [32].

4 Results and discussion

The newly developed market simulation tool enables a great variety of different analyses based on the model output. In the following the

scenario results for the future penetration of alternative powertrains are presented and the impact on CO₂ emissions and cost for the user are discussed. Prior to this the model is tested with a historical case study.

4.1 Model validation

To validate the model and evaluate the capabilities of the novel utility based approach the historical market development in Germany is simulated and compared with real world data. Therefore all relevant input parameters, e.g. fuel prices and the energy consumption of the available vehicles are adjusted to reflect the situation in Germany in the years from 1993 to 2010 [33].

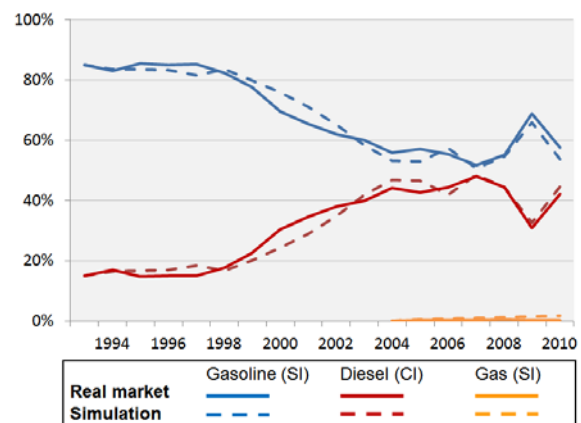


Figure 6: Market share of different powertrain technologies in Germany 1993-2010, historic development vs. market simulation [33]

The simulation results in Figure 6 demonstrate that the model predicts correctly the increasing market share of diesel cars from 15% to 44% during this time period. The average (absolute) deviation between the simulated and the real market share of the different powertrain technologies equals 3.5%. If the stochastic term ϵ in the linear utility function

(1) is calibrated to reflect the limited availability of gas vehicles on the supply side and the observed consumer reluctance for this technology on demand side the mean deviation is reduced to 1.7%. For comparison the simulation is repeated with a conventional *least-TCO* approach which results in a mean deviation of 5.8%. This comparison underlines the benefit of the new utility-based model approach which makes it possible to integrate multiple criteria and realistic user characteristics into the decision logic.

4.2 Vehicle market

The simulation results for the new vehicle market in Germany are presented in Figure 7 differentiated by powertrain technology. Based on the scenario assumptions described in the previous chapter conventional ICE powered by gasoline and diesel are expected to dominate the market over next decade. The political target of 1 million electric cars until 2020 set by the German government is not reached in this scenario. However, beyond 2020 the share of hybrid electric vehicles is expected to grow strongly. According to the market simulation more than 50% of the new passenger cars in 2030 will be grid connected (PHEV, EREV, BEV). On the other hand 90% of the cars still have a combustion engine on board, which is powered by oil-based fuels. The number of CNG cars increases, but does not surpass a market share of more than 4%. One reason for the limited growth expectations of CNG is the increasing energy price when the current tax advantage of natural gas as motor fuel ends in 2018, as assumed in this scenario. Another reason is the growing competition through hybrid electric cars which have even lower running cost and CO₂ emissions. The number of full electric vehicles grows steady within the next two decades, but they continue to stay a niche product with an overall market share of 6%. For most customers PHEV and EREV are more attractive options as they offer electric driving without the strict range limitation of BEVs. (The main disadvantage of BEVs in the utility rating according to formula (1) is caused by the low driving range. In most cases only users with more than one car who have lower range requirements in the model buy a BEV). Fuel cell vehicle do not enter the mass market due to the absence of a comprehensive hydrogen infrastructure in this scenario.

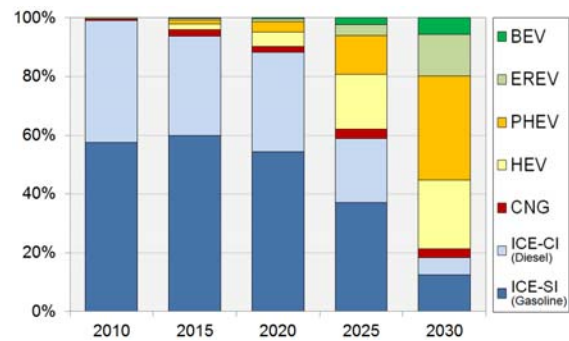


Figure 7: Market share of powertrain technologies in the German new vehicle fleet 2010-2030

4.3 Impact on CO₂ emissions

According to the scenario simulation the CO₂ emissions of the new vehicle fleet decrease by 47% until 2030 (see Figure 8). This decline is caused on the one hand by efficiency improvements of conventional cars through the introduction of new fuel save technologies (e.g. downsizing, start-stop generator, light weight design), on the other hand by the growing market penetration of electrified powertrain. The EU emission target of 70 g CO₂/km which is assumed for this scenario is exactly met in 2030 by the chosen technology mix. Also well-to-tank emissions of the new vehicle fleet can be reduced from 1.2 to 0.7 million tons CO₂ per year in the time span 2010-2030 if the use of renewable energies in the electricity generation is expanded as planned by the German government [30].

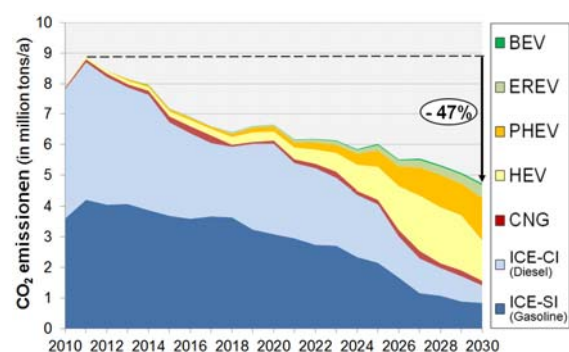


Figure 8: Development of annual well-to-wheel CO₂ emissions of the new vehicle fleets by powertrain technology in Germany 2010-2030

4.4 Impact on mobility costs

However, the observed reduction of CO₂ emissions and energy consumption does not come for free. The average investment costs for a buyer of a midsize passenger car will increase by EUR 3,900

in the presented scenario.¹ But at the same time the operating cost drop by about 20% despite rising energy prices. A detailed cost analysis of the scenario results shows that the improved energy efficiency of the advanced drivetrain technologies overcompensates the assumed energy prices increase, but does not fully offset the additional technology cost. So, over a period of 5 years the TCO for holders of medium size cars will be on average 5% or EUR 1,700 higher in 2030 compared to 2010 (see Figure 9).

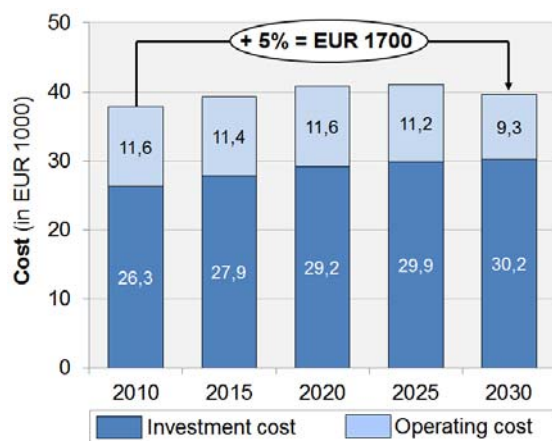


Figure 9: Development of average TCO for the holder of a midsize car over 5 years (in EUR 2010, excluding resale value)

5 Conclusions

In this paper an innovative utility based approach to model customer choice for alternative powertrains has been introduced which integrates the multi-criteria assessment of vehicle attributes and the diversity of user characteristics into a dynamic market scenario tool. The newly developed model could be successfully implemented and validated in a historic case study. Furthermore, the scenario model has been applied to analyse the prospective development of the new car market in Germany by 2030.

The simulation results show that under the assumed business-as-usual scenario the political target of 1 million electric cars by 2020 is likely to fail, if no additional effort is made. But in the time frame from 2020 to 2030 the number of alternative powertrains, especially advanced hybrid electric vehicles with grid connection

¹ In EUR 2010, excluding inflation and resale value

(PHEV, EREV), will grow significantly reaching a market share of 50%. Nevertheless, none of the new propulsion concepts is expected to dominate the market within the next two decades. Therefore, OEMs have to adapt their R&D strategies offering a broad portfolio of different powertrain technologies to meet customer demand while managing the increased complexity. Moreover, the market simulation demonstrates that a massive reduction of CO₂ emissions in the new vehicle fleet by almost 50% in 2030 is possible through the improvement of existing technologies as well as the introduction of new efficient electric drivetrains. For the end customer this development will be associated with higher mobility cost compared to today's level.

In future studies the presented model should be applied to analyse the buying behaviour of different customer groups in more detail under varying scenario assumptions. The realistic modelling of user behaviour and preferences offers a great potential to gain additional insights such as the identification of potential early adopters and critical factors for the success of low emission vehicles.

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