Attractiveness of electric vehicles under current tax and incentive schemes in Germany: a total cost of ownership calculation from the customer's perspective

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Abstract

Electric vehicles (EVs) have the potential to significantly reduce greenhouse gas emissions from private motorized transport. While the registered number of EVs is increasing in Germany, their share of registrations still lags far behind that of conventional vehicles with internal combustion engines (ICEVs). In the literature, many studies compare the total costs of ownership (TCO) of EVs and ICEVs, as these have significant influence on customers' purchasing decisions and thus on vehicle market shares. However, these studies rely mostly on parameters derived under laboratory conditions instead of considering realistic data on technical (e.g. fuel consumption), behavioural (e.g. share of electric driving of plug-in hybrid electric vehicles (PHEVs)), economic parameters (e.g. insurance costs, prices for public (fast) charging) as well as financial incentives and taxes. Our research creates greater transparency for customers and policy makers alike with a detailed and customer-centric TCO calculation with the base years 2020 and 2030. We compare vehicles from different segments with conventional, hybrid and electric powertrains. Our analysis uses large parameter data sets sourced from the General German Automobile Association and retail price comparison portals, and we supplement these by meta-analyses of academic literature and market studies. We found that battery electric vehicles (BEVs) and PHEVs in the small and lower-medium segments are the cheapest options under current purchase price premiums for EVs in Germany. Long-range electrified SUVs are more expensive than conventional SUVs. Contrary to the widespread view in current literature, EVs are not necessarily the most economical option in a 2030 scenario in our analysis. If taxes and incentives are neglected, BEVs and PHEVs become even less attractive. This highlights the importance of carefully designed energy and vehicle taxes and purchase incentives for a successful market diffusion of EVs.

Introduction

More than 10 percent of global greenhouse gas (GHG) emissions from fuel combustion are attributable to private motorized road transport (IEA 2020). Thus, in order to meet the targets for GHG emission reduction set in the Paris agreement, strong efforts are required in this sector. Electric vehicles (EVs) are a promising option to substantially lower GHG emissions from transport. EVs as discussed within this paper include, amongst others, battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Governments all around the world, including Germany, are offering monetary and non-monetary incentives to increase the market share of EVs even though the potential of these vehicles to reduce GHG emissions depends strongly on energy system-specific factors as well as user-specific factors and is thus subject to large variation. The incentives for EVs in Germany, such as direct purchase price subsidies and exemption from motor vehicle tax, have shown some success. The registered number of EVs increased steadily from 23,000 vehicles in 2015 up to 395,000 vehicles in 2020 (KBA 2021a). EVs amounted to around 13 % of the more than 2,917,000 passenger vehicle registrations in 2020 (KBA 2021a), which is a remarkable increase in their market share. Overall, however, the market share of EVs still lags far behind that of ICEVs.

Since the total costs of ownership (TCO) are still one of the most significant factors influencing customers' vehicle purchasing decisions (Kumar and Alok 2020), many studies in the literature analyse the TCO to determine the attractiveness of EVs in comparison to ICEVs from the customer's perspective (Wu et al. 2015; Letmathe and Suares 2017; Palmer et al. 2018; Cox et al. 2020). Only a few of these studies, however, include monetary incentives (Letmathe and Suares 2017; Palmer et al. 2018). Furthermore, these studies predominantly use parameters derived under laboratory conditions or assumptions for their calculations instead of real-life technical or behavioural data, such as fuel consumption or the share of electric driving of PHEVs. Moreover, not all the economic parameters relevant for customers are considered in these studies, e.g. insurance costs, and prices for public (fast) charging. Consequently, the TCO calculated in these studies do not reflect real-life TCO from the customer's perspective.

In this paper, we determine the attractiveness of EVs in comparison to ICEVs based on a TCO calculation from a private customer's perspective with the focus on Germany. In contrast to the existing literature, we consider taxes and incentive schemes for vehicles as well as for fuels and electricity in Germany, and base our analyses on large real-life parameter data sets derived from the General German Automobile Association and retail price comparison portals. We supplement these with meta-analyses of academic literature and market studies. Diesel, gasoline and methane vehicles are compared to BEVs and PHEVs in the small, compact and SUV segments for the base year 2020 as well as in an outlook for 2030.

We address the following questions:

- How do different powertrains and segments compare in a user-centric TCO calculation?
- What impacts do taxes and incentive schemes have on the TCO?

First, we outline the data and methodology used. Second we describe the results, followed by a discussion and conclusions.

Methods and data

METHODS

This paper presents a detailed cost comparison for different powertrains and segments. We used a TCO analysis as the framework to consider all the costs incurred during the period of owning a vehicle. Rather than using literature values, we conducted detailed meta-analyses and collected empirical near-market data for TCO relevant costs.

Total cost of ownership calculation

For the economic evaluation over the vehicle's service life, we performed a total cost of ownership analysis from vehicle purchase until resale. Relevant costs can be characterized as capital expenditures (CAPEX) and operational expenditures (OPEX). In our customer-centric calculation, all prices are given as gross values including relevant taxes such as VAT. To calculate the net present value of all future costs, an interest rate i was used to discount these payments to the base year. Eq. 1, adopted from Wietschel et al. (2019), summarizes our TCO formula:

$$TCO = RP_0 - S_0 - \frac{RV_T}{(1+i)^T} + \sum_{t=1}^{T} \frac{\left(fc * fc_{corr,t} * p_{e,t} + c_{M\&R}\right) * VKT_t + c_{Ins,t} + c_{Tax} + c_{Infr}}{(1+i)^t} \quad (1)$$

Here, the vehicle purchase price was determined using its original retail price RP_0 [EUR] and respective purchase subsidies S_0 [EUR]. RV_T represents the vehicle residual value [EUR] and T stands for service life or ownership period [a]. Operational and thus, mileage-dependent costs include costs for maintenance and repair $c_{M\&R}$ [EUR/km] and energy. The latter was calculated based on vehicle energy consumption fc [kWh/km] from WLTP (worldwide harmonized light vehicle emissions test procedure), a real-world correction based on empirical data $fc_{corr,t}$ [%] and the respective energy prices $p_{e,t}$ [EUR/kWh]. The average annual mileage is given in VKT_t [km]. Additional annual costs [EUR/a] include insurance premiums $c_{Ins,t}$, vehicle tax c_{Tax} and charges for additional electric home infrastructure c_{Infr}. Overall, and in line with a stated policy approach, existing regulations on subsidy volume, time period and tax without extrapolation were used.

DATA

This section focuses on vehicle prices based on component costs, techno-economic vehicle specifications and data, as well as other vehicle-related TCO elements. We provide a detailed insight into our energy cost modelling. If not specified, all costs are expressed in real prices EUR2020.

Techno-economic vehicle parameters in 2020 vs. 2030

Two different methods were applied to determine technical specifications and purchase prices. For 2020, values were taken from real-world models. These then constituted a baseline for the technical specifications in 2030 and for bottom-up price determination. Table 1 summarizes our calculated vehicle purchase prices whereas Table 2 lists the most important technical vehicle data.

For 2020, we used the Top 5 models per segment and powertrain as reference. Technical information comprises engine power, displacement, vehicle weight and WLTP energy consumption as well as electric range and battery capacity for PHEVs and BEVs. These data were taken from the General German Automobile Association ADAC 2020. To condense all the technical specifications, a registration-weighted average was calculated. For PHEVs and BEVs, YTD September 2020 registration figures. 2019 data were used for conventional vehicles, both figures according to the Federal Motor Transport Authority (KBA 2020b). As studies such as Dornoff et al. (2020) or Plötz et al. (2020) indicate, there are powertrain-specific deviations between test cycles such as WLTP or NEDC (New European Drive Cycle) and real-world consumption. Thus, a real-world correction based on empirical data from (spritmonitor.de 2021; ADAC 2021) was calculated for each powertrain. For electric powertrains, this correction was additionally used to account for charging losses. Market prices were determined using the same methodology. Here, we derived retail prices using the ADAC Vehicle Cost Calculator (ADAC 2020a) and a list of eligible vehicles specifically for alternative powertrains (KBA 2020a), both averaged over different configurations per model. An increase of €9,000 to €17,000 for a PHEV and €12,000 to €23,100 for a BEV were derived for these synthetic but near-market vehicles in 2020.

For 2030, purchase prices were calculated using a bottom-up cost model based on the vehicle component costs (see next section for details). Based on 2020 market prices, we calculated a powertrain-specific vehicle body price top-down, mainly consisting of chassis, suspension, on-board electronics and equipment. Future purchase prices were calculated bottom-up using individual powertrain component costs and their cost evolution.

Technically, we assumed real-world ranges of 400, 500, and 600 km for BEVs, for which insufficient range is still cited as the most common reason for their slow market penetration (Mobile.de 2021). For PHEVs, we anticipated an increase in electric range to between 80 and 100 km, which is consistent with findings from (Plötz et al. 2020). Both, BEVs and PHEVs are associated with a larger battery capacity, which affects retail prices. As already mentioned, mild hybridization was assumed for gasoline and diesel vehicles from 2030. Further efficiency improvements were considered for all powertrains. Among ICEs, this was especially applicable to gasoline and gas-powered vehicles. Assumed efficiency improvements ranged from about 4 % for diesel, 19 % for gasoline, to 21 % for gas. These efficiency increases were modelled using the correction factor, so that the WLTP value remained constant.

Component data

In total, we performed meta-analyses for 4 components to model reliable and comprehensive cost trends for major vehicle components. These comprise (1) engine and transmission, (2) lithium-ion battery system, (3) power electronics (PE) including high-voltage system, and (4) electric motors. Statistical evaluations include confidence intervals, medians, quartiles, and standard deviations for each year and each component. Final cost assumptions are derived from the temporal evolution of the calculated medians. A regression was used to harmonize these and to derive a consistent trend. This was modelled using the power law function to approximate learning and experience curves, although no cumulated volume was specified.

We modelled the BEV powertrain using components (2) to (4). Figure 1 illustrates our cost assumptions for the example of a HV battery system (2). Here, 20 studies from 2019 to 2020 were considered to avoid outdated cost assumptions and account for the rapid advances in battery development (see details and further analyses for other components in Jander et al. (in press)). We used boxplots over time to disclose embedded data. In addition, our calculated regression curve is plotted with a corresponding R^2-value of 0.94 to indicate the quality of the curve fit. In total, we derived HV battery system costs of around €150/kW in 2020 and €80/kWh in 2030. We derived a decrease from €20 to €16/kW for power electronics and HV system and a decrease from €16 to €13/kW for electric motors for the same period. For PHEVs, we assumed the same component costs,

Table 1. Vehicle purchase prices for 2020 and 2030.

[EUR2020]	*Year*	Diesel	Gasoline	Methane	PHEV	BEV
Small	*2020*	18,700	17,100	18,800	26,100	29,100
	2030	19,800	18,600	19,700	25,000	27,100
Compact	*2020*	29,400	27,500	29,200	36,200	39,100
	2030	30,600	29,100	29,700	35,400	37,200
SUV	*2020*	33,200	31,800	33,600	48,800	54,900
	2030	34,500	33,600	34,900	48,500	53,600

Table 2. Techno-economic vehicle parameters 2020/2030. Diesel and gasoline WLTP consumption in l/100 km. Methane in kg/100 km. Electricity consumption in kWh/100 km. G = Gasoline; E = Electric.

Parameter	Segment	Diesel	Gasoline	Methane	PHEV	BEV
Rated power [kW]	Small	75	79	66	G: 94 E: 63	103
	Compact	99	99	96	G: 150 E: 106	128
	SUV	120	109	105	G: 201 E: 182	182
HV battery [kWh]	Small	– / –	– / –	– / –	14 / 19	49 / 76
	Compact	– / –	– / –	– / –	14 / 22	55 / 91
	SUV	– / –	– / –	– / –	14 / 28	66 / 124
WLTP [–]	Small	4.00	5.60	4.26	G: 0.88 El: 14.28	15.86
	Compact	4.74	5.69	4.70	G: 1.12 El: 14.61	16.06
	SUV	5.78	6.64	5.65	G: 1.83 El: 16.92	18.25
Real-world correct. [%]	All	1.25 / 1.20	1.25 / 1.01	1.15 / 0.93	G: 3.00 / 1.65 E: 0.75 / 0.90	1.15 / 1.04

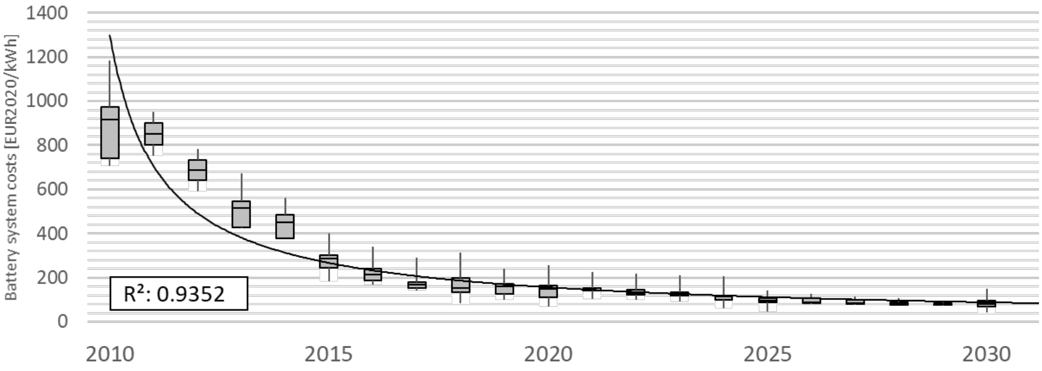

Figure 1. Meta-analysis for battery system costs [EUR2020/kWh].

but scaled up battery costs by 1.5 as PHEVs require high-power cells rather than high-energy cells (Zapf et al. 2020).

Four components were priced for an ICE powertrain. Apart from the actual engine and transmission, efficiency improvements were included due to internal engine optimization, exhaust gas after-treatment and mild hybridization. The latter was assumed to be the new normal in 2030 for gasoline and diesel vehicles. Our meta-analysis for (1) revealed differences between €26/kW (Fries et al. 2017) and €74/kW (Bubeck et al. 2016). Here, we adopted the component costs and embedded cost decreases based on learning curves from (Ricardo 2015), specifically for gasoline, diesel and methane. In addition, we priced efficiency improvements for gasoline, diesel, and methane engines based on our assumptions. For efficiency improvements and exhaust gas after-treatment, costs were derived from Ricardo (2015) as well. Combining these three engine-related aspects resulted in an increase of specific costs of up to 10 %. Thus, the additional costs outweigh any cost decrease. This coincides with the general cost increase identified in our meta-analysis (1), exemplified by i.e. Bubeck et al. (2016). The costs for mild hybridization were derived from literature values and real mark-ups of commercially available models. Costs in the literature were between about €700 and €1,600 (i.e. Ricardo 2015), whereas market price differences ranged between €200 and €3,250 (ADAC 2020a). In total, we assumed additional costs of €910 for a small car and €1,200 for an SUV according to (Tschiesner et al. 2020).

Residual value and vehicle service life

The residual value per segment and powertrain was calculated using a regression formula based on annual mileage and ownership period. According to (Plötz et al. 2014b), the typical vehicle ownership period in Germany is about 7 years. Our regression formula and its coefficients were originally determined for conventional vehicles, slightly generalized, and adjusted by (Plötz et al. 2014a). This resulted in a residual value relative to the original vehicle price. For 2030, we used the averaged value from 2020 per segment. Overall, this rather conservative approach as it resulted in a higher absolute depreciation for PHEVs and BEVs. Other approaches exist (Hacker et al. 2015) and some market reviews indicate that the relative residual value is even higher for current PHEVs and BEVs (i.e. Brzeski and Fechner 2019). Table 3 summarizes the results for 2020.

We modelled the annual mileage per segment by matching the mean value per segment according to (BaSt 2017; KBA 2021b) over total vehicle lifetime (15 years) and without commercially used vehicles. This yields to about 10,400 km for small cars, 12,500 km for compact cars, and 14,000 km for SUVs. In-between, we assumed a continuous decrease in mileage over time, as typical in Germany. With empirical data on the dependency between vehicle age and annual mileage adopted from (BaSt 2017; BMVI 2019; KBA 2021b), we calculated a ratio compared to our average mileage. Thus, mileage decreased from 140 % in the first year to 102 % in the seventh year and, theoretically, 70 % in the last year.

Vehicle insurance

Insurance premiums were determined using an empirical evaluation based on the consumer comparison website Check24 in December 2020 (Check24 2020). According to GDV (2021), premiums are highly individual and depend on a variety of owner- and driver-specific, regional, and usage- and vehicle-specific factors. Data were collected for the Top 5 vehicles per segment and powertrain using a standard and synthetic customer profile. Finally, raw data were averaged with vehicle registrations. Table 5 shows our results relative to vehicle retail prices. A relative cost advantage for alternative drives was evident in 2020 regardless of segment. In similar studies like Hacker et al. (2015), relative premiums are typically assumed to be identical. We assumed that this advantage will decrease with further diffusion of alternative powertrains. According to the stock scenario in Prognos AG et al. (2021), we assumed constant relative factors until 2025 and equalized the absolute insurance premium of all powertrains per segment to the 2020 average until 2035.

Subsidies and taxes

Subsidies were calculated based on stated-policies. Since the end of 2019 and until 2021, the previously introduced purchase subsidy was doubled. This subsidy depends on the degree of electrification and the net retail price, and amounts to a maximum of €9,000 for BEVs and €6,750 for PHEVs (BMWi 2020). These limits were applied to small and compact cars in our TCO analysis for 2020. For an SUV, the subsidy was reduced to €7,500 and €5,625, respectively, caused by the higher retail prices above €40,000. We assumed that no subsidies will be available in 2030.

Vehicle tax was calculated according to the current CO_2 regulation schema in Germany with a fuel consumption and an engine displacement part and specific coefficients for diesel or gasoline vehicles (BMF 2020). Taxes were calculated for 2020 and 2030 based on the technical vehicle specification. BEVs remain excluded from taxation after 2030, as no future calculation methodology is known to date. We did account for the €30 discount for low-emission vehicles, which expires in 2024. For our specifications, this discount only occurs for PHEVs.

Energy prices and blends

The prices for liquid and gaseous fuels were calculated bottom-up from production costs, import costs if there is non-domestic production, to service costs at the refuelling station and finally the corresponding end consumer prices. The latter include all the relevant taxes and charges. For diesel, gasoline and gas, first- and second-generation biofuels as well as synthetic fuels from Pt-L and Pt-G were included in addition to conventional crude oil or natural gas. Crude oil and natural gas prices were taken from (IEA 2020). For biofuels and synthetic fuels, a meta-analysis of the production costs was executed. Here, we assumed domestic production of biofuels and import of synthetic fuels from the MENA region. For detailed results, please refer to Jander et al. (in press).

Costs other than production costs were assumed to be identical for all alternatives independent of feedstock. These include transport and distribution costs, profit margins, marketing and sales, energy taxes, and grid charges and duties. For conventional fuels and biofuels, a CO_2 charge from Prognos AG et al. (2021) was imposed, depending on the respective CO_2 equivalent. Blends for first- and second-generation biofuels as well as final blends for biofuel, synthetic and conventional fuels were taken from (Prognos AG et al. 2021). In 2030, ethanol or biodiesel blends were assumed to be 10 % (E10 or B10) plus about 5 % synthetic fuel. Changes in the fuel heating value were considered accordingly. For methane, 80 % biogas was assumed. Ultimately by 2050, all blends will be climate neutral. Table 7 summarizes the total end consumer prices.

Electricity prices reflect private charging at home, commercial charging at the workplace, and public charging with differ-

Table 3. Relative residual value [%] per segment and powertrain in 2020.

Residual value [%]	Diesel	Gasoline	Methane	PHEV	BEV
Small	31.4	32.3	31.8	29.5	28.8
Compact	29.5	30.0	29.7	28.4	27.8
SUV	28.6	29.0	28.7	27.5	27.0

Table 4. Annual vehicle mileage per segment [km].

Annual mileage [km]	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Small	14,517	13,767	13,055	12,379	11,741	11,141	10,577
Compact	17,449	16,547	15,691	14,879	14,112	13,390	12,713
SUV	19,543	18,533	17,574	16,665	15,806	14,997	14,239

Table 5. Relative insurance premiums (vs. retail price) [%] per segment and powertrain in 2020.

Insurance [% RP]	Diesel	Gasoline	Methane	PHEV	BEV
Small	2.38	2.29	1.94	1.32	1.19
Compact	1.75	1.87	1.58	1.47	1.32
SUV	1.96	1.84	1.56	1.54	1.41

Table 6. Vehicle taxes per segment and powertrain 2020 (2030).

Vehicle taxes [€]	Diesel	Gasoline	Methane	PHEV	BEV
Small	€161	€104	€22	– / €28	–
Compact	€230	€109	€42	– / €30	–
SUV	€295	€175	€91	€10 / €40	–

Table 7. Mixed total energy prices. Liquid fuels in [EUR2020/l]. Methane in [EUR2020/kg].

Fuel	2020	2030	2040	2050
Diesel	1.329	2.030	2.260	2.375
Gasoline	1.400	1.969	2.131	2.082
Methane	1.293	1.961	2.082	1.788

Table 8. Mixed total electricity price for BEVs and PHEVs in [EUR2020/kWh].

[EUR2020/kWh]	2020	2030	2040	2050
BEV	0.342	0.302	0.319	0.327
PHEV	0.314	0.268	0.282	0.291

Table 9. Maintenance and repair costs [EUR2020/km] per segment and powertrain in 2020/2030.

[ct2020/km]	Diesel	Gasoline	Methane	PHEV	BEV
A/B	4.49	4.28	4.92	3.81 / 3.08	2.74
C	5.09	4.85	5.58	4.32 / 3.49	3.10
SUV	5.88	5.60	6.44	4.98 / 4.03	3.58

ent power levels. The latter differentiates between AC charging with 22 kW, DC charging with 50 kW and high power charging (HPC) up to 300 or 350 kW. Prices for domestic and commercial electricity were taken from (Prognos AG et al. 2021). Fees and prices for public charging were determined from empirical studies (e.g. ADAC 2020b). Relative shares taken from Scherrer et al. (2019) were assumed to be segment-independent, whereas a distinction was made between BEVs and PHEVs. Table 8 summarizes the total electricity price.

Maintenance and electric charging infrastructure

Maintenance and repair costs (M&R costs) were determined based on the ADAC vehicle cost calculator (ADAC 2020a), validated with other studies (i.e. Propfe et al. 2012; Letmathe and Suares 2017) and adjusted if necessary to ensure consistency between powertrains in different segments. We assumed these are independent of lifetime and do not change from 2020 to 2030, except for the PHEVs. Overall, our results ranged from 2.74 to 6.44 ct/km, which is consistent with studies from above, although the segments are not identical. Gasoline vehicles were taken as the baseline in line with (Kasten and Maier 2018). Higher costs were derived for gas and diesel vehicles, while the costs for BEVs were lower due to less maintenance-intensive and fewer moving components. PHEVs were in-between gasoline and BEVs, and decreased from 2020 to 2030 due to a higher electric range.

For home charging, we assumed an 11 kW wall box that is priced according to empirical near-market data and literature values (Bünger et al. 2019; dena and Prognos 2020). In total, purchasing costs for a wall box were estimated at about €800 plus an additional €1,200 for its installation. Consistent with NPM (2020), charging power was assumed to be constant through 2030, and more complex installations were not considered, so costs remained the same. For 2020, a corresponding subsidy of €900 from the German federal government was considered. Since we only calculated 7 years of vehicle ownership, but the wall box remains usable afterwards, the costs and subsidy were linearly depreciated over 15 years.

Results

TCO UNDER CURRENT TAX AND INCENTIVE SCHEMES

Current tax and incentive schemes seem to have a positive impact on EVs. Figure 2 shows the TCO of vehicles with different powertrains and fuels in the small car segment. It is striking that BEVs are the most economical alternative in 2020, despite their high purchase prices and the additional costs for a wall box. These costs are more than compensated for by the current purchase price premiums for EVs and charging infrastructure. Furthermore, compared to all other alternatives, BEVs benefit from lower operating costs, including lower energy costs, lower maintenance and repair costs, currently lower insurance costs, and are exempt from vehicle tax. Methane vehicles and PHEVs are in joint second place, but for different reasons. Whereas the purchase price premiums for EVs contribute significantly to the high economic efficiency of PHEVs, methane vehicles benefit from low energy costs. ICEVs represent the most expensive alternative in the small car segment in 2020. Surprisingly, despite their higher purchase prices, diesel vehicles are more economical than gasoline vehicles. The TCO differences between diesel and gasoline vehicles are very small, but there is a striking difference in energy costs.

In 2030, methane vehicles are the most economical alternative. Low energy costs, low taxes and low insurance costs are the main reasons. Due to the assumed short service life and low annual mileage in the small car segment, the high purchase prices of EVs can hardly be compensated by their lower energy costs. Note that we assumed the purchase price premiums for EVs are not extended until 2030 and that a real-world range of 400 km for BEVs is quite high. Furthermore, all ICEVs powertrains undergo mild hybridization. Overall, however, the TCO of all powertrains are very similar in 2030, despite the significantly higher purchase prices of BEVs and PHEVs.

Figure 3 shows the TCO of compact cars with different powertrains and fuels. The results are very similar to the results for small cars: BEVs are the most economical alternative, methane vehicles continue to rank second together with PHEVs. Again, high purchase price premiums for EVs are the reason for their high economic viability and compensate the high acquisition costs. BEVs are characterized by low operating costs. Due to the higher annual mileage of compact cars compared to small cars, the BEVs' advantage of lower energy costs makes a bigger difference. At the same time, in relative terms, the positive effect of purchase price premiums on compact BEVs is lower despite the larger absolute amount. This is due to the significantly higher purchase prices of compact BEVs, which require a large and more expensive battery.

In the case of gas vehicles, it should be noted that, in addition to lower purchase prices, energy costs are also very low and only slightly higher than those of BEVs. Low gas prices are the main reason for this. PHEVs' energy costs are among the highest, which is due to the high share of conventional, gasoline-based driving. Diesel and gasoline vehicles have a comparable TCO and, overall, there is a very similar TCO for all types of compact car.

In 2030, the TCO of all the alternatives continue to converge. Despite the phase-out of purchase price premiums and a significant increase in the range and battery size of compact BEVs, these are still the most economical alternative, while PHEVs and diesel vehicles are the most expensive alternatives in 2030.

Figure 4 shows the TCO of SUVs. In this segment, gas vehicles represent the most economical alternative in 2020, followed by diesel and gasoline vehicles. Despite purchase price premiums, EVs are more expensive. Very high purchase prices and no clear energy cost advantages over ICEVs are the reasons for this result. Moreover, it can be seen that the significant increase in range and thus battery capacity in 2030 compared to 2020 is largely offset by a reduction in battery costs.

The changes in 2030 are relatively small. With ICEVs becoming more expensive due to the CO_2 tax, and only a small cost increase for EVs, there is a tentative convergence of the overall TCO. Gasoline SUVs are the most economical alternative.

COMPARISON OF TCO WITH AND WITHOUT CURRENT TAX AND INCENTIVE SCHEMES

We calculated a scenario without taxes and incentives in order to reveal the influence of taxes, incentives and other regulatory measures. We omitted the following taxes and levies in the TCO calculation to enable a neutral comparison of the technologies:

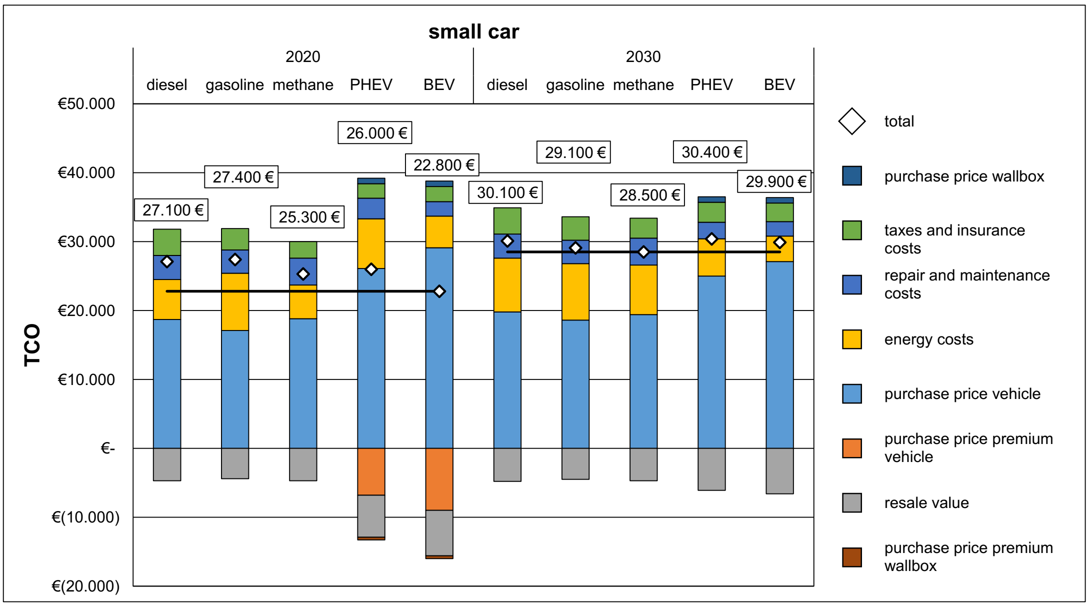

Figure 2. TCO of vehicles with different powertrains and fuels in the small car segment in 2020 and 2030.

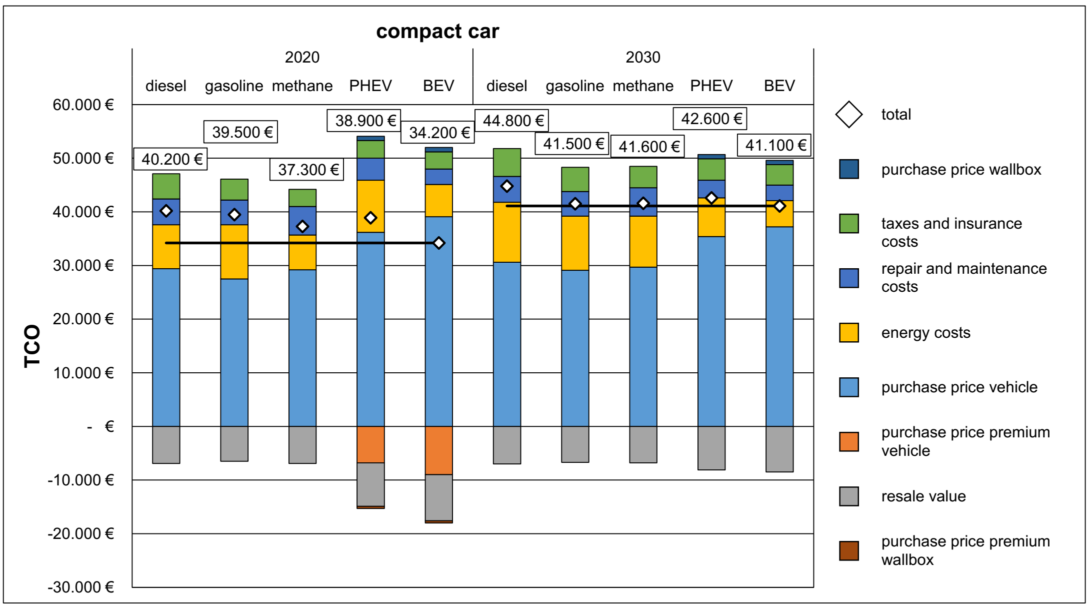

Figure 3. TCO of vehicles with different powertrains and fuels in the compact car segment in 2020 and 2030.

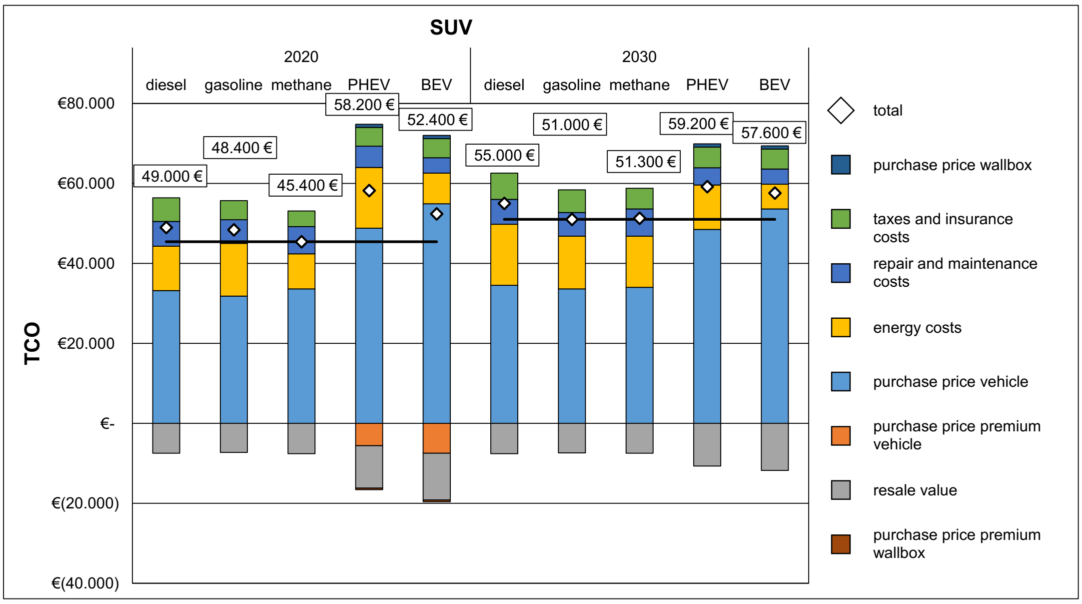

Figure 4. TCO of vehicles with different powertrains and fuels in the SUV segment in 2020 and 2030.

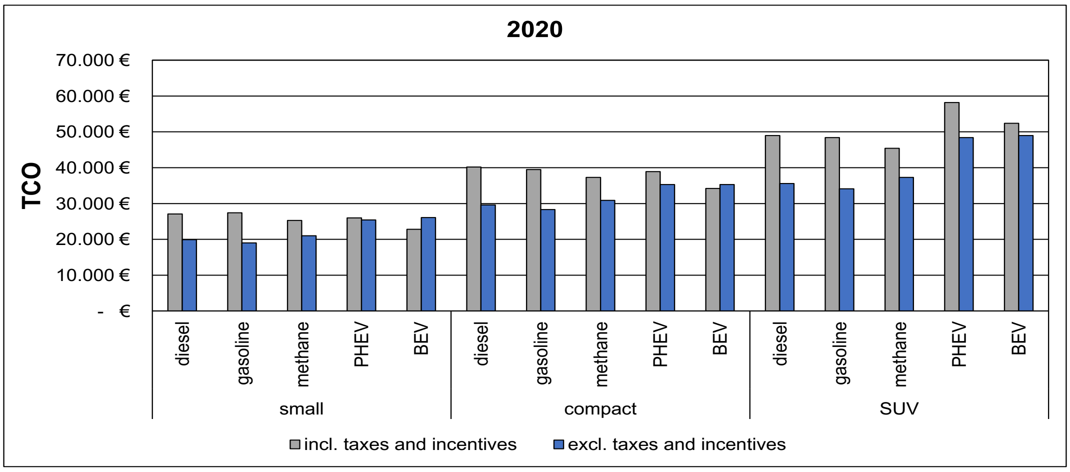

Figure 5. TCO of vehicles with different powertrains in varying segments in 2020, with and without current tax and incentive schemes.

- Value-added tax or sales tax (strong impact on the purchase price, but also on all other cost components)
- Purchase premiums (no subsidies for EVs or charging infrastructure)
- CO_2 tax on conventional and biogenic energy sources
- Energy tax on energy sources
- Vehicle taxes for all segments and powertrains
- Surcharges on electricity (no surcharges on the electricity price such as reallocation charges for the support of renewable energies, of combined heat and power, of grid expansion, of offshore wind energy etc.).

Costs related to the procurement, sales, margins, distribution etc. of energy carriers were still included.

The TCO of vehicles with and without taxes and incentives are depicted in Figure 5. While ICEVs show substantially lower TCO in a non-tax scenario in all segments, EVs show a much lower decrease of TCO, and BEVs even show increasing TCO in the small and compact car segment. Neglecting the positive effect of purchase price premiums cannot be offset by the tax exemption of EVs. Without taxes and incentives, gasoline vehicles are the most economical alternative, followed by diesel and methane vehicles. This is due to neglecting the CO_2-tax among other things. In all segments, the TCO of PHEVs and BEVs in the non-tax scenario are almost the same.

Discussion

Some of our assumptions and parameters need to be discussed. Firstly, we assumed identical annual mileages for all powertrains and fuels. In practice, however, annual mileage varies largely among different powertrains. Diesel vehicles and EVs in particular usually show higher than average annual mileages (KBA 2021b). People tend to buy these cars because of their lower operating costs compared to other ICEVs, and drive them more frequently or over longer distances or both. Nevertheless, our assumption of identical annual mileage is adequate for a fair comparison of powertrains. Secondly, a service life of seven years is appropriate for private customers buying a new car. It has to be noted, however, that only just over half of all car owners actually own a new car (Statista 2021), which indicates that the purchase of a new car is not necessarily the standard case. Usually, cars have more than one owner and are used for much longer. If the entire useful life were used for the TCO calculations, the purchase price would be "amortized" over a significantly longer period, which would significantly improve the economic viability of EVs. Thirdly, electric ranges and thus battery capacities of BEVs and PHEVs have a high impact on the purchase price and consequently on the TCO. Our range assumptions for EVs in 2030 are high and therefore lower figures would further improve the competitiveness of EVs. Here, other studies assume a price reduction of about 30 %, e.g. Stahl (2020). Fourthly, methane vehicles showed high economic viability in our analyses, among other things, due to the high biogas blend and comparatively lower energy prices and high efficiency improvements. Although these models have been available for years, their market diffusion is very low. Obviously, other criteria are relevant for customers buying new cars. Finally, it is debatable whether ICEVs will still be sold in 2030, considering the first bans on internal combustion engines, and whether further efficiency improvements of ICEVs can be realized, considering that an increasing number of OEMs have announced plans to phase-out combustion engines and related research and development. OEMs are focusing to an increasing extent on EVs, expanding the number of vehicle models and improving technical characteristics, which will further increase the attractiveness of EVs.

Conclusions

Our results showed that BEVs and PHEVs currently represent the most economical alternative in the small car and compact car segment, mainly due to purchase price premiums and the low operating costs of EVs. Their high purchase prices, which are largely determined by the battery, are significantly reduced by the subsidies offered, and BEVs can exploit their advantage of low operating costs. Electric SUVs are an exception. Due to their high mass, these require a high-capacity battery, which increases the mass and energy consumption of the vehicle on the one hand, and costs on the other hand. Methane-powered vehicles or gasoline vehicles are more economical for this segment, since they are characterized by lower purchase prices and favourable energy costs. With regard to future developments in the small car and compact car segment, it should be noted that the TCO of all alternatives are very similar, so EVs should become a cost-competitive alternative in the future. We can conclude that purchase price premiums seem to be a good measure to increase the attractiveness of EVs over the next five years or so in order to stimulate the diffusion of EVs. In the long term, however, EVs might become competitive even without direct subsides. The CO_2 tax is another factor, which substantially improves the competitiveness of EVs. It is applicable to conventional fuels and thus to ICEVs and significantly increases their TCO, especially in the medium to long term. Our comparison of TCO with and without current tax and incentive schemes highlights the importance of a far-reaching cost redistribution, if the aim is to increase EVs' attractiveness from a customer perspective. Currently, without considering taxes or incentives, EVs are not very competitive. Our results can be generalized to other countries or user types with some reservations. Other countries have different incentives and tax schemes for private users, while other users, such as company car or commercial fleet vehicle users, show different user behaviour (electric driving share, vehicle service life, annual mileage) compared to private users and are subject to different taxation and incentive schemes (e.g. car allowance in Germany). Energy prices also vary between countries. Nevertheless, our results clearly demonstrate the importance of a redistribution of costs in private motorized transport and of direct incentives to boost EV diffusion. Since car buyers tend to focus on purchase prices rather than on TCO, they might oversee the current TCO advantages of EVs. This suggests action is needed on the part of policy makers, who could implement mandatory TCO labels for cars similar to the energy labelling of cars in Germany.

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