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Cost analysis of Plug-in Hybrid Electric Vehicles including Maintenance & Repair Costs and Resale Values

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Abstract

This paper analyses the cost competitiveness of different electrified propulsion technologies for the German auto market in 2020. Several types of hybrid electric vehicles including parallel hybrids (with and without external charging) and a serial range extended electric vehicle are compared to a conventional car with SI engine, a full battery electric vehicle and a hydrogen powered fuel cell vehicle. Special focus lies on the maintenance and repair cost and the expected resale value of alternative vehicles, which have been integrated within one extensive total cost of ownership model.
The assessment shows that the current TCO gaps for alternative drivetrains will decrease significantly by 2020 mainly driven by the reduction in production cost. Furthermore hybrid electric vehicles will profit from lower maintenance and repair cost and a higher expected resale value compared to conventional cars.
Therefore, hybrid electric vehicles will be an attractive option in particular for users with high annual mileages, who can benefit from the low operating cost of EVs in combination with unlimited driving range.
The analysis concludes that there will not be one dominant powertrain design in the midterm future. Hence, automakers have to manage a wide portfolio of competing drivetrain architectures, which will increase the risk and complexity of strategic decisions.

Keywords: Total cost of ownership, maintenance and repair cost, resale value, hybrid electric vehicle

1 Introduction

Driven by ambitious CO_2 reduction targets set by politics and the growing awareness for fuel economy by the customer, automotive OEMs are increasingly required to develop energy efficient vehicles. In this context electrification of the automotive powertrain is potentially a highly effective lever to reduce greenhouse gas emissions and energy usage of passenger cars. A variety of propulsion concepts including hybrids (HEV), plug-in hybrids (PHEVs), extended range electric vehicles (EREVs) battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) are examined. Hybrids and plug-in hybrids derived from them can come in many combinations of powertrain configurations and a mix of electric and internal combustion engine power.
In this paper plug-in versions of HEVs with two levels of electric drive power – PHEVs (grid-connected HEVs) and EREVs – are examined. By combining all-electric driving capability at limited top speeds for limited distances with unrestricted

range (like ICEs), plug-in hybrid electric vehicles offer a very promising alternative to conventional drivetrains. In addition, the EREV, a vehicle capable of electric driving at all speeds, also using an ICE to increase range and power is examined.

The higher initial purchase price and lower running cost of vehicles using electric drivetrains require a life cycle perspective when comparing them to conventional vehicles and to one another. Previous total cost of ownership (TCO) analyses usually exclude maintenance and repair cost (M&R) as well as the resale value of a car [1] [2] [3] [4] [5]. Since the resale value of an average car accounts for over a third of its initial purchase price, this approach might lead to incorrect conclusions [6]. The objective of this paper is therefore a holistic cost assessment of numerous options for use of electric drive, with a special focus on PHEVs.

2 Methodology

For our estimates of vehicle attributes for the year 2020, this assessment explores the life cycle cost of one HEV, two PHEVs, and a single EREV configuration in the German market. These are also compared to conventional ICEs and a full electric BEV as well as a fuel cell vehicle (FCV) in the time frame to 2020. These vehicles each use a different battery pack in terms of kW and kWh capability. To predict energy consumption in different driving patterns vehicle simulations have been carried out with a model previously known as PSAT [7] [8] which has been updated and renamed Autonomie (http://www.transportation.anl.gov/modeling_simulation/PSAT/autonomie.html). Aside from the FCEV, batteries are the most expensive part of an electrified drivetrain. Battery costs are calculated using the DLR battery cost model [9]. For all other major powertrain components more approximate top-down assessments of 2020 cost developments are made.

Furthermore, exogenous parameters such as oil prices and taxation are included in the TCO analysis. M&R costs are estimated on a component level differentiated by powertrain type and vehicle size depending on mileage and mean times between failures (MTBF). The resale value of a car is forecasted based on an extensive analysis of the DAT [11] database covering all car models in the German market.

The Total Cost of Ownership (TCO) over four years of ownership is calculated. TCO includes the sum of purchase price, energy cost, maintenance and repair, other operating costs (e.g. motor tax, inspection), less the estimated resale price, after depreciation. A battery cost model is a critical submodel used in predictions of purchase price. The maintenance and repair and depreciation models are discussed in some detail, while cost estimates from other models are presented without supporting details. For values on energy consumptions we used preliminary estimates provided by the team of analysts working on vehicle simulations within the IEA implementing agreement Task XV.

Table 1: Definition of vehicle parameters (Consumptions are given for NEDC)

Parameter	**Unit**	**ICE**	**HEV**	**PHEV15**	**PHEV30**	**EREV**	**BEV**	**FCEV**
Vehicle architecture		Gasoline engine, 2-wheel drive (identical for all), automatic transmission	Parallel hybrid with 2 clutches, automatic transmission	Parallel hybrid with 2 clutches, external charge unit, 16 km AER	Parallel hybrid with 2 clutches, external charge unit, 32 km AER	Series hybrid with gasoline engine as range extender, external charge unit, 86 km AER	Central electrical traction motor, single-speed transmission, charge unit	Central e-motor, 700 bar hydrogen storage
Power combustion engine	*kW*	105	68	65	67	72	-	-
Power e-motor	*kW*	-	25	34	34	98	98	98
Battery pack storage	*kWh*	-	1	2.8	5.4	17	25	2
Pack cost	*EUR*	-	760	835	1,545	4,010	5,600	1,160
Curb weight	*kg*	1,220	1,271	1,288	1,307	1,511	1,621	1,683
Electric consumption	*Wh/km*	-	-	43	62	103	128	-
Fuel consumption	*l/100 km*	6.0	3.2	2.0	1.4	1.0	-	[1.0 kg H_2 /100km]

2.1 Assessment of maintenance and repair cost for electric vehicles

As mentioned above, previous studies on life-cycle-cost of alternative powertrains do not incorporate maintenance and repair cost. Hence, our goal is to assess these costs on a Euro per km level. Our model differentiates M&R costs regarding scheduled and unscheduled maintenance. Three different vehicle sizes (according to historical German vehicle fleet compositions classified into small, medium, and large vehicles) are taken into account in the model supporting the analysis in this paper. In order to compare different types of powertrains, the drivetrains themselves can be defined according to the considered vehicle configuration (Table 1). Six different drivetrain architectures have been examined:

- Conventional internal combustion engine vehicles (ICV), in this case configured as an spark-ignited (SI) engine,
- parallel hybrid electric vehicles (HEV), designed with torque-adding electric machine flange-mounted to the six-speed automatic gear, 2 clutches, also available as plug-in hybrid with two different battery sizes (PHEV15 and PHEV30),
- plug-in series hybrid electric vehicles (EREV),
- battery electric vehicle (BEV) and
- fuel cell electric vehicle (FCV).

None of the HEVs or PHEVs in the model use the two electric machine “split parallel and series” design used by Toyota. Based on mean times between failures / replacements (MTBF), component costs as well as required labor input for replacing the components are assessed for more than 30 drivetrain components, ranging from spark plugs to Li-ion batteries. The vehicles are defined by the type of powertrain (e. g., whether they use a parallel or a serial configuration), the vehicle size (e. g., small, medium, or large) the battery size, the power-level of the fuel cell system, the shares of CD (charge depleting) vs. CS (charge sustaining) driving including recuperative braking, and the output power and energy provided by both the internal combustion engine (ICE) and the e-motor.

Hence, the costs for maintenance and repair $C_{M\&R}$ can be expressed as a function of the MTBF, the replacement costs of the spare part C_i, the time it takes to replace the part T_i and the corresponding labor costs C_{labor}. The calculation steps for all types of powertrains j and all vehicle sizes k can be summarized with (1).

$$C_{M\&R,j,k} = \sum_{i=1}^{n=31} MTBF_{i,j,k} * \left(C_{i,j,k} + T_{i,j,k} * C_{labor}\right) \ \forall j,k \quad (1)$$

Hence, mathematically, the MTBFs are assumed to be identically distributed over the lifetime of a vehicle. Costs and MTBFs for replacement parts of conventional diesel and gasoline engines are taken from the ADAC database [10]. For hybrid drivetrains, these values have been adjusted according to their share of CS vs. CD driving as well as their share of regenerative braking vs. mechanical breaking. For new parts such as the Li-ion battery, the fuel cell system, power electronics, or electric motors, individual costs and MTBFs have been incorporated, depending on the configuration of the drivetrain.

For Li-ion batteries, MTBF have been calculated utilizing a newly developed lifetime model. This model calculates both the MTBF between repairable failures and the lifetime of a traction battery depending on the driving range, the SOC limits of the battery within the given drivetrain architecture, as well as the number of cells connected in parallel and in series.. Real driving profiles collected in the extensive database Mobility in Germany (MiD) 2008 have been used as input [11]. According to the model, battery lifetimes of 489,000 km for the BEV, 922,000 km for the EREV, 451,000 km for the PHEVs, and 1,324,000 km for the non-plug-in hybrid have been assumed.

For the fuel cell system, 400,000 km have been assumed as maximum lifetime. This figure has been derived based on published operating hours and service lifetimes of automotive fuel cell systems. [12] reports a lifetime of more than 7,300 hours, whereas [13] indicates a mileage based lifetime of more than 200,000 km and hence exceeding the regular lifetime of a vehicle. [14] predicts mileage based lifetime of 247,000 km. According to [15] the hydrogen storage tank lasts around 300,000 miles or about 483,000 km.

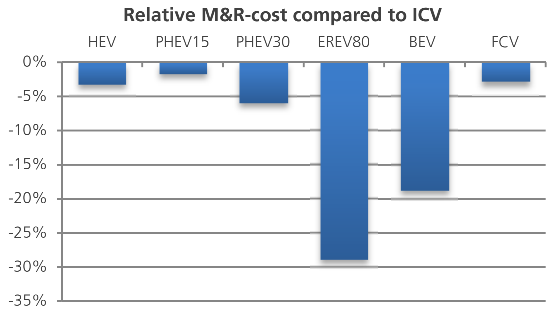

Figure 1: Relative maintenance and repair cost, compared to conventional SI vehicle

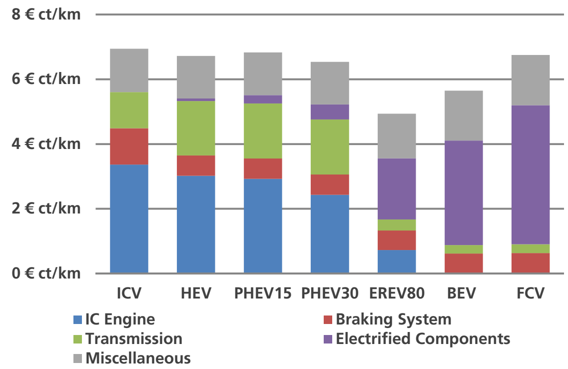

Figure 3: Aggregated distribution of maintenance and repair cost

Power electronics (PE), including both AC/DC and DC/DC converters are assumed to have a service life of 200,000 km in full-electric mode. As mentioned above the set-up of the model incorporates the share of full-electric driving and hence allows the user to adjust the service life of power electronics accordingly. The assumed lifecycle of on-board charging units is 300,000 km of full-electric driving.

As a result, the model is capable of comparing various powertrain configurations and main cost drivers can be identified. For this paper, we focus on the medium size segment. Furthermore, we put an emphasis on different plug-in hybrid configurations. As mentioned above, the results for these configurations are compared to ICVs as well as BEVs and FCVs (Figure 1).

The comparison of the six electrified drivetrain architectures to a conventional SI-vehicle shows that all powertrains are estimated to have lower costs for maintenance and repair. Especially in the small vehicle segment, the model results (not shown here) predict that electrically propelled vehicles have significantly lower M&R-costs. Due to the significantly reduced complexity of the drivetrain, the strongest cost reduction of over 25% can be seen for EREVs, as is illustrated in this paper's example. Despite the different set up of the three parallel hybrids, no significant cost differences can be identified (Figure 3).

However, when comparing the main drivetrain

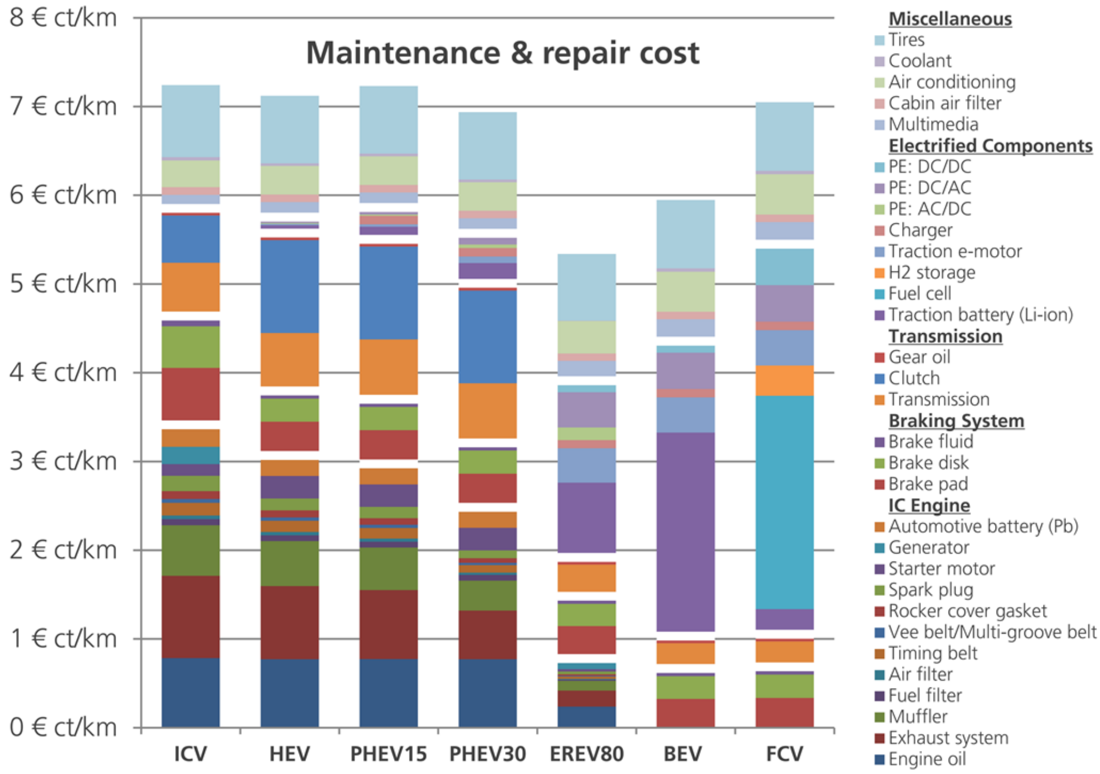

Figure 2: Composition of M&R cost based on all 31 assessed drivetrain components

component groups, the main cost drivers can be located. Although all parallel hybrids show nearly identical overall M&R costs, the share of different parts of the drivetrain architecture varies significantly. In case of the $PHEV_{15}$ cost reductions due to a lower usage of the combustion engine are entirely compensated by higher expenses for electrified drivetrain components.

By comparing the share of all 31 individually assessed components, it can be seen that M&R-costs for full electric vehicles like BEVs and FCVs tend to be driven by major components such as the traction battery or the fuel cell system, whereas conventional ICVs as well as hybrids do not have a particular component accounting for a significant share of the overall M&R-cost (Figure 2). Due to the reduced complexity of drivetrain components used the serial hybrid shows the lowest overall M&R cost. As mentioned above, all parallel hybrids show nearly identical M&R-costs.

2.2 Assessment of resale value

Besides taking into account M&R costs it is essential to evaluate the resale value in order to comprehensively assess the life cycle cost of a vehicle. As mentioned above, the resale value of today's vehicles in Germany accounts (on average) for 36% of the initial purchase price. However, data on alternative powertrains for this issue is very rare. In order to identify the resale value for alternative vehicles, we developed a new model taking into account a variety of input parameters, such as the purchase price of the vehicle, the type of powertrain, the age of the vehicle, the overall vehicle-miles-traveled, and technology costs.

The model applies a 2-step approach. First, resale values of conventional SI vehicles are analyzed in detail, based on historical German vehicle data. By applying multiple regressions functional dependencies for the input parameters are identified. Second, in order to assess future values of alternative vehicle concepts, the results are transposed to the new powertrain architectures, mainly taking into account varying lifetime expecations and their impact on utilization costs.

The regression model for the resale values of conventional vehicles shows that linear dependencies can be found between the resale value RV and both the annual vehicle miles traveled VMT as well as the initial purchase price P. The resale value can be expressed as (2)

$$RV_{j,k} = P - \left[\left(P * m_{1,j} + c_{1,j} \right) * VMT_k + P * m_{2,j} + c_{2,j} \right] \quad (2)$$

where m and c are depending on the vehicle size j. The overall residual value is influenced by the annual VMTs of customer k.

Analyzing the very limited data base for resale values of hybrid vehicles, results show that HEVs have a significantly higher resale value than their conventional SI counterparts after a holding period of 4 years (Table 2).

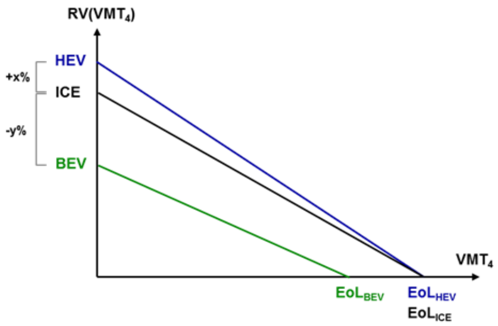

Figure 4: Methodology for the assessment of resale values of electrified powertrains

In contrast, BEVs are expected to show faster depreciation rates than conventional vehicles. [16] lists a resale value for BEVs 28% lower than for comparable SI-vehicles, whereas [17] anticipates 44% lower resale values. The strongest depreciation is predicted by [18], who sees resale values down to 10% of the initial purchase price after 5 years. All sources base their assessments on the still unclear life cycle expectations of traction batteries and the corresponding risks car owners / buyers have to take. However, as of today, no used BEV market has been established in Germany, and hence, no empirical data is available. Figure 4 shows the structure of the calculation for the assessment of resale values after a holding period of 4 years, based on the linear regression model. For the following TCO analysis, x has been set to 15%, whereas y has been set to -10%.

Table 2: Comparison of resale values of currently available HEVs in Germany [10]

		Relative resale value			
Model	**$P_{purchase}$**	**10,000 km**	**20,000 km**	**30,000 km**	**40,000 km**
Toyota Auris 1.8 Hybrid life	23,950 €	48.9%	42.7%	37.5%	32.3%
Toyota Auris 1.6 life, 3T	19,750 €	42.6%	37.3%	32.7%	28.2%
Delta ICE_{HEV} vs. ICV	21.3%	14.7%	14.7%	14.7%	14.7%
Honda Insight 1.3 Hybrid	20,950 €	47.7%	41.7%	36.6%	31.5%
Honda Civic 1.4	17,790 €	42.4%	37.1%	32.6%	28.1%
Delta ICE_{HEV} vs. ICV	17.8%	12.3%	12.3%	12.3%	12.3%
Mercedes S400H	87,097 €	38.3%	36.0%	33.0%	30.6%
Mercedes S350	81,742 €	31.9%	30.0%	27.5%	25.5%
Delta ICE_{HEV} vs. ICV	6.6%	20.1%	20.1%	20.1%	20.1%

2.3 TCO analysis

The TCO assessment covers all types of expenses accruing for a vehicle owner including one-time cost (e.g., purchase price, expected resale value) as well as operating cost (e.g., fuel/energy, vehicle tax, general/exhaust inspection, maintenance, and repair). The annual mileage, holding period and use characteristics (i.e., share of electric driving) are adjustable to facilitate the economic comparison for different types of users as well as to perform sensitivity analyses. Although the underlying models are designed to deal with multiple years the assessment in this paper will focus on 2020. For a more detailed description of the TCO model see [19].

The production cost of the powertrain components are based on DLR analyses and a proprietary McKinsey study [20]. In this study, the future cost development of over 60 drivetrain components have been projected by consolidating industry data, expert interviews, and economic forecasts. The basic car body, interior, and chassis (excluding powertrain) is assumed to be identical for all examined vehicle concepts. For the most expensive and crucial part of electric powertrains, the traction battery, the same data that has been calculated for the M&R-model with the DLR battery cost model has been used. (In this analysis NMC has been selected as cell chemistry for high-energy storages and NCA for high-power configuration.) A learning curve for the price development of Li-ion batteries has been derived by applying the cost model for different output levels. The analysis indicates a cost decrease of 12% for a doubling of the cumulated production of high energy batteries, which are used for PHEVs, EREVs, and BEVs. This implies that the battery price (for a BEV) will decrease from ca. EUR 860 per kWh on pack level in 2010 to below EUR 225 per kWh, if the national target of 1 million EVs in 2020 set by the German government will be achieved.

For all other external influence factors realistic scenario assumptions have been made based on various sources (see Table 3). With regard to regulation the CO_2 emission target of the European Union is applied which sets penalties for vehicles exceeding 95 g CO_2/km (corrected by a weight-dependent factor) in the year 2020. Direct monetary incentives (except the motor vehicle tax reduction for EV holders) are currently not planned from government side in Germany and therefore are not incorporated in the TCO model.

3 Results

In a first step the total costs of ownership of the selected drivetrain architectures have been calculated assuming the average German holding period of 4 years and an average yearly driving distance of 10,000 km. The cost break-down for a midsize conventional car with a gasoline engine versus different hybrid architectures, a full battery electric car, and a fuel cell vehicle are summarized in table 4. This comparison shows that the purchase price rises with an increasing share of electrification which is mainly driven by the expensive traction battery accounting for one third of total production cost of a BEV. As expected, for hybrid cars the higher acquisition costs are partly

Table 3: Relevant scenario parameters

Scenario parameter	Unit	Value 2020	Source
Oil price	USD/barrel	118	IEA Energy Outlook 2011 (Current Policy scenario)
Gasoline retail price	EUR/l	1.67	DLR analysis based on IEA scenario
Electricity cost	EUR/kWh	0.24	BMU study 2010
Hydrogen price	EUR/kg	7.85	EU-Coalition study
CO_2 targets	g CO_2/km	95	Legal regulation European Union
CO_2 penalties	EUR / g CO_2	95	Legal regulation European Union
Battery pack cost (high energy)	EUR/kWh	225	DLR battery cost model (NMC, 25 kWh)
Battery pack cost (high power)	EUR/kWh	760	DLR battery cost model (NCA,1 kWh)
Fuel cell system cost	EUR/kW	100	DLR assumption
Hydrogen storage cost	EUR/kg	350	DLR assumption (700 bar)

offset by the higher expected resale value. Operating costs for electrified drivetrains are lower in all dimensions. Especially energy cost can be reduced by up to 69% through electric driving. Furthermore, electric vehicles generally need less service and maintenance, e.g. no motor oil change and less brake wear due to energy recuperation as shown with the M&R cost model. Additionally, zero-emission vehicles benefit from the vehicle tax exemption and are not required to pass a regular exhaust inspection. This assessment shows that by 2020 EVs will become cost competitive in comparison to conventional vehicles. Including CO_2 penalties HEVs and PHEVs even show a TCO advantage of ca. EUR 2,500 against ICEs. For full battery electric vehicle a TCO gap of EUR 4,000 remains after consideration of resale value and operating cost. However, this gap decreases below EUR 1,000, if the mileage a user drives per year, doubles from 10,000 km to 20,000 km. To better understand this effect on the cost competitiveness of different powertrains a sensitivity analysis has been performed, where the annual mileage has been varied between 5,000 and 20,000 km (see figure 2). The results clearly state that the electrified powertrains profit from their lower running cost the more the car is used. While for example an EREV will not pay off for a user driving 5,000 km a year (8% higher TCO compared to ICE), for a user with 20,000 km annual mileage the higher purchase price is offset by 19% lower operating cost resulting in a TCO advantage of 6% compared to a conventional car.

In principle this effect also holds true for full electric vehicles (BEV), as they have the lowest operating cost of all assessed concepts. However, their limited driving range and long charging time will not allow realizing large mileages in most use cases. So over the next decade BEVs will only be interesting for niche markets (e.g. car sharing within cities) or for customer with great willingness to pay for environmentally friendly driving.

Table 4: Cost break-down for different powertrain options
(Assumption: annual mileage 10,000 km, holding period 4 years)

Costs type (in EUR, year 2020)	**ICE**	**HEV**	**PHEV 15**	**PHEV 30**	**EREV**	**BEV**	**FCEV**
Purchase price*	27,946	29,963	30,805	31,941	37,093	36,390	46,456
Resale value	-9,503	-11,916	-12,252	-12,704	-14,756	-10,335	-15,809
Net depreciation	18,443	18,047	18,554	19,237	22,337	26,054	30,647
Energy cost	4,016	2,142	1,739	1,564	1,637	1,235	2,587
Maintenance & repair cost	2,892	2,720	2,704	2,692	2,124	2,348	2,548
Other operation cost (e.g. motor tax, inspection)	330	160	160	160	160	53	53
Total cost of ownership	**25,680**	**23,069**	**23,157**	**23,653**	**26,257**	**29,690**	**35,835**

*excluding CO_2 penalties

In the long run also fuel cell vehicles (FCV) show potential, since they promise zero emission driving with longer driving ranges than BEVs and relatively short refueling times of their hydrogen storage. But according to this analysis FCVs will not become a viable option from a cost perspective by 2020. Mainly driven by the costly production of the fuel cell system FCVs show 27% to 49% higher TCOs than comparable ICEs. Furthermore a sufficient H_2 infrastructure has to be in place to achieve broad acceptance by the market.
Hence, in the mid-run hybrid electric vehicle (especially PHEV with external charging) will be become the preferred choice for many car buyers due to their low running cost in combination with unlimited driving range.

4 Conclusions

The presented work demonstrates a comprehensive approach towards total cost of ownership for a range of vehicles using different degrees of electric drive, including initial cost, operating cost, maintenance cost, and resale values of different powertrain configurations. Several models assessing the different parts of lifetime costs are integrated within one TCO-model. The results indicate that no single electric drive option dominates. The least TCO powertrain option varies according to customer use patterns, initial costs, and aggregate operating costs, suggesting that automakers may want to develop a portfolio of electric drive alternatives.
When comparing different sensitivity analyses regarding annual mileages, plug-in hybrid vehicles seem a favorable option for a wide range of customers. However, since the results strongly depend on a variety of inputs such as economical and technical parameters, a careful assessment of these inputs has always to be taken into consideration.

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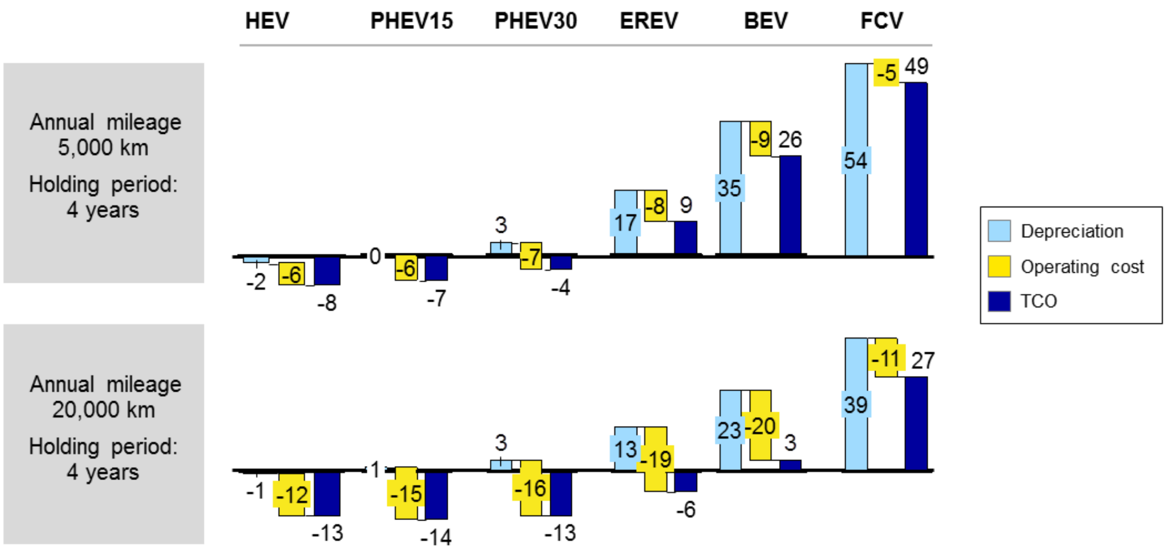

Figure 6: TCO comparison of electrified powertrain architectures relative to ICE (in %) in the year 2020 for users with different annual mileages

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