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Attractiveness of alternative fuel trucks with regard to current tax and incentive schemes in Germany: a total cost of ownership analysis

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Summary

Alternative drivetrains for heavy-duty vehicles pledge tremendous and partly ad-hoc potential for cutting greenhouse gas emissions from road freight transport in the EU. However, this transition is costly for federal governments while cost-effective operation for logistic companies is arguable. Therefore, our comprehensive cost analysis aims to evaluate all feasible options, including different energy carriers, with a consistent modeling framework, and from both federal and company perspective. Our results demonstrate short-term cost-efficiency for battery electric trucks and plug-in hybrid trucks for companies due to subsidies. In the long term, fuel cell, plug-in hybrid and battery electric trucks are cost-competitive with diesel vehicles, both from a company perspective and from a federal perspective.

Keywords: alternative fuel, heavy-duty, subsidy, taxation, truck

1 Introduction

Heavy-duty trucks and busses are responsible for approximately one quarter of the EU's greenhouse gas emissions in the transport sector [1]. To reduce greenhouse gas emissions from trucks, EU legislation defines a 30 % CO2 emissions reduction for newly sold trucks in 2030 compared to today's level [2]. To achieve this target, the introduction of zero emission vehicles (ZEV) is necessary [3].

Meanwhile, various alternative drivetrains can significantly reduce truck emissions. The ones most often discussed are battery electric trucks (BET), fuel cell electric trucks (FCET), hydrogen trucks with an internal combustion engine (H2T), but also natural gas trucks (GT) or diesel trucks (DT) running on synthetic or biogenic fuels. On top, some manufacturers position plug-in hybrid trucks (PHET) as a possible interim solution. For rapid market diffusion, cost-effective operations are crucial that may include both federal and company perspective. While diesel trucks serve as cost benchmark for companies [4], federal planners aim to decarbonize heavy road transport as cost-efficient as possible.

In fact, various studies already compared the cost-effectiveness of alternative drivetrains. [5, 6] concluded that long-haul BET and FCET were not yet economically feasible in California. In their reference scenario [7] came to the same result for Germany. However, due to the decline of battery prices current studies predict cost-competitiveness for alternative drivetrains. An initial total-cost-of-ownership (TCO) comparison of DT and BET can be found in [8]. While [8] don't include a strong focus on subsidies, [9] find that depending on the policy measures BETs are already cost-competitive in some European countries. They will reach cost-competitiveness even without subsidies during this decade for all the considered countries. While the previous studies are limited to either BETs or FCETs as alternative drivetrains [10] compares the TCO of DT, GT, BET, PHET, and FCET and the implications of different support policies for alternative drivetrains on TCO. They conclude that BET in the heavy-duty long-haul segment can be promising depending on the policy measures of the countries. H2T as a possible future technology is considered by [11]. According to their techno-economic assessment, FCET and H2T are cost-competitive compared to DT in mid- and long-term perspective for Germany. However, the comparisons are usually not fully comprehensive as some drivetrains or energy carriers are missing, either the federal or company perspective is assumed, and any cross-paper comparison is limited due to different assumptions.

Thus, we aim to compare the cost-effectiveness of BET, FCET, H2T, GT, PHET, and DT with a comprehensive TCO analysis and a consistent modeling framework from both a federal and a company perspective in Germany from 2020 until 2050. For this, we use current policies and detailed cost estimations for the most relevant vehicle components. Tractor-semitrailer combinations serve as our showcase. First, we present our methodology and our data in section 2. Section 3 contains the results. Finally, we discuss our findings in section 4 and conclude with the most important insights.

2 Methodology and Data

2.1 Methodology

We start by introducing our component cost modeling. Afterwards we present our TCO formula.

2.1.1 Meta-analyses

As stated in [12], exemplary for batteries, there are typically four prediction methods (i.e., technological learning, literature-based projections, expert elicitations, and bottom-up modeling) to derive cost assumptions. We focus on literature-based projections yet incorporate influences of technological learning, which in literature is also referred to as learning curve or experience curve analysis.

The latter theory assumes a fundamental relationship between technology costs and one or more learning parameters. This relationship typically exhibits decreasing unit costs with a cumulative increase in production volume (single factor) due to different mechanisms such as decreasing waste, lower purchasing prices for raw materials, decreasing proportion of overhead costs, and process automation. Generally, there are steeper gradients at the beginning (higher contribution of labor costs) and progressively smaller gradients later on as the share of material costs grow [13]. The typical modeling assumes a power-law equation.

We consider six key drivetrain components in our cost modeling: (1) battery system, (2) fuel-cell system, (3) H_2 storage or fuel tank, (4) power electronics, (5) IC engine, and (6) electric motors. The cost modeling covers 2010 to 2050 and focuses on specific costs that allow for adaptation to the technical vehicle specifications. Our process starts with aggregating and standardizing previously published predictions to increase forecast accuracy and minimize individual projections' uncertainty. All costs are considered as direct manufacturing costs. We proceed with statistical evaluations (i.e., median, lower and upper quantile, and standard deviation) per year. To account for heterogeneities and variances, we use three cost scenarios (i.e., high, medium, low) for each component. We calculate our final cost assumptions based on the temporal evolution of the calculated lower quantile (low), the median (medium), or the upper quantile (high). We use regression to harmonize their temporal evolution and ensure a consistent trend per cost scenario. To approximate single factor technological learning, we use power-law regression functions. We limit this regression to years with at least five sample points. Note that predictions earlier than 2015 have limited validity (small sample size, mathematical characteristics of power-law functions).

2.1.2 **Economic calculations**

For the economic evaluation, we follow the procedure as described in [11]. Our TCO calculation covers all relevant costs over the vehicle service life T from vehicle purchase until resale and differentiates between capital expenditures (CAPEX) and operational expenditures (OPEX). Future payments are discounted to eventually compare the net present value of different drivetrains [EUR2020]. Overall, our formula is given below and adopted from [14]:

$$TCO \; = \; I_0 - S_0 - \frac{RV_T}{(1+i)^T} + \sum_{t=1}^{T} \frac{\mathrm{c_{Ins}} \; + \; \mathrm{c_{Tax}} + VKT * (c_{energy} \; + \; c_{O\&M} \; + \; c_{Toll})}{(1+i)^t} \quad [EUR2020] \qquad (1)$$

This comprises vehicle purchase price I_0 and residual value RV_T, fixed annual costs for insurance c_{Ins} and vehicle tax c_{Tax} and kilometre-dependent costs for energy c_{energy}, operation and maintenance including tires and ad-blue $c_{O\&M}$ and road toll c_{Toll}. Cost calculations from both perspectives, i.e. company versus federal, are differentiated by relevant taxes, subsidies S_0, and interest rate i, as shown in 2.2.4.

2.2 Data

We start by introducing our component cost results. We proceed with techno-economic vehicle parameters, and energy cost assumptions and close with varied parameters for the federal perspective.

2.2.1 Component costs

Six evaluations are shown in Figure 1. Per component, this includes annual boxplots, regression curves for all three scenarios, total sample points, and the R^2-value for the medium scenario. Relevant studies date from 2010 and extend to 2022. Main sources comprise among others [5, 8, 10, 12, 15–21]. Further sources are available on request. The following discussion focuses on rounded medium costs.

Typically, we find massive cost reduction potentials for early technologies and smaller relative improvements yet progressive relative convergence over time. We derive an HV-battery system cost evolution (note: high-energy batteries) from around €240/kWh in 2020, €140/kWh in 2030, to €80/kWh in 2050. We assume the same cost evolution for high-power batteries yet include a scale-up of 50% in 2020 and 20% in 2050. We derive a decrease from €35 to €20/kW for power electronics and HV system components from 2020 to 2050. Electric motors decrease from €32 to €18/kW for the same period. Fuel cell costs are going to decrease from around €180/kW in 2020, €100/kW in 2030, to €55/kW in 2050. H2 storage costs are going to decrease from €20 to €11/kWh from 2020 to 2050. In contrast, we find increasing diesel engine costs from €72/kW in 2020 to €77/kW in 2050. This happens as additional costs to comply with future emission regulations or increase fuel efficiency typically compensate small cost reduction potentials for such mature technologies. Costs are given in EUR2020. Vehicle retail prices are calculated in the next section.

Last, we follow [15, 18], and use a markup factor to scale these direct manufacturing costs to retail prices. This factor is set to 1.425 for early technologies and 1.27 for established technologies. In 2050, we assume all technologies to be established.

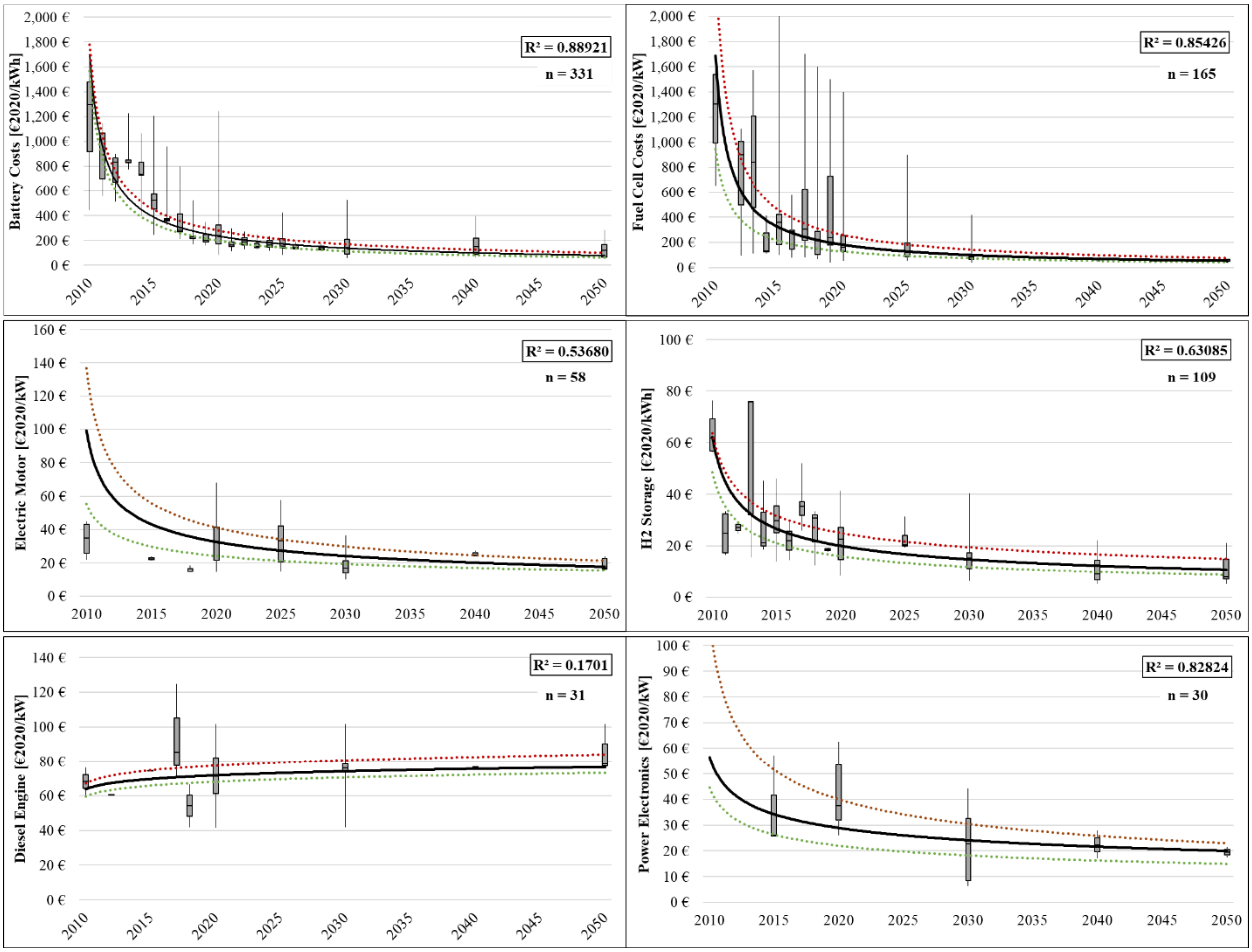

Figure 1: Meta-Analysis - Component costs. Medium cost scenario as solid black line. High (red, dashed). Low (green, dashed). Time scale 2010 to 2050. Own illustration.

2.2.2 Techno-economic vehicle parameter

For all vehicle alternatives, we suppose similar power requirements. Regarding PHETs and FCETs, we applied power shares already known from today's vehicles. To enable a proper comparison, we assumed a target range of 1,000 km for all drivetrains with their respective main drive based on [4, 22]. For PHETs, we additionally consider 65 km battery-electric range, as offered for example by Scania [23]. Range is a crucial cost component for H2Ts, FCETs and BETs. Especially with an increasing expansion of infrastructure, a range of 1,000 km will not be necessary for every application. Therefore, we varied the range for alternative drives between 100 and 1,000 km. By using the assumed range and a self-calculated specific drivetrain-efficiency based on [17, 24, 25], we calculated the necessary capacity of tanks and batteries. Table 1 sums up the most import technical vehicle parameters.

Table 1: Technical vehicle parameter in 2020, 2030 and 2050

Parameter	Unit	DT	GT	PHET	H2T	FCET	BET	Sources
Rated power	[kW]	330	330	300 con. 130 el.	330	330 (180 FC)	330	[26, 27]
Range conv.	[km]	1,000	1,000	1,000	100-1,000			
Range el.				65		100-1,000	100-1,000	
HV battery	[MWh]			0.080 ('20) 0.072 ('30) 0.065 ('50)		0.07	0.15-1.50 ('20) 0.14-1.37 ('30') 0.13-1.25 ('50)	Own assump-tion
H2 tank	[kg]				9-93 ('20) 8-77 ('30) 6-64 ('50)	8-80 ('20) 7-86 ('30) 6-56 ('50)		Own assump-tion
Consumption	[kWh/ 100km]	318 ('20) 265 ('30) 221 ('50)	349 ('20) 298 ('30) 248 ('50)	318 ('20) 265 ('30) 221 ('50)	311 ('20) 259 ('30) 214 ('50)	269 ('20) 226 ('30) 187 ('50)		Own calcu-lation, based on [11, 17, 24, 25]
Consumption electric	[kWh/ 100km]			120 ('20) 110 ('30) 100 ('50)			120 ('20) 110 ('30) 100 ('50)	Own calcu-lation, based on [11, 17, 24, 25]

Table 2 contains tractor purchase prices taking into account the technical specifications explained above and the component costs determined. In accordance with [15, 18], a markup factor of 1.27 was assumed for established technologies. To cover risks and initial costs, the markup factor was increased to 1.425 for new technologies (PHET, H2T, FCET, and BET) in 2020 and 2030 [15]. The numbers do not include costs for a trailer. Increased efficiency is responsible for higher vehicle body prices in 2030 and 2050. The bandwidth reflects the range from 100 to 1,000 km for newly developed drivetrains. In addition to the tractor purchase price, we consider 25,000 EUR2020 per vehicle to equip the vehicle with a trailer.

The residual value is calculated with a regression model, based on [28]. Although the residual value for alternative drivetrains is subject to high uncertainty today, we assume identical residual values for all drivetrains at this point. We assume a residual value of 23 % after 6 years of use.

Table 2: Tractor purchase prices excluding trailer 2020, 2030 and 2050 (without subsidies)

Purchase price	Unit	2020	2030	2050	Sources
Vehicle body	[EUR2020]	60,000	66,100	73,100	[21, 29]
DT	[EUR2020]	115,400	123,900	134,000	Own calculation
GT	[EUR2020]	137,200	140,600	143,900	Own calculation
PHET	[EUR2020]	178,500	164,700	144,800	Own calculation
H2T	[EUR2020]	173,100 - 252,900	158,400 - 208,200	137,000 - 164,000	Own calculation
FCET	[EUR2020]	241,000 - 310,000	187,700 - 231,300	140,600 - 164,100	Own calculation
BET	[EUR2020]	167,200 - 619,300	144,900 - 390,100	121,000 - 235,300	Own calculation

Table 3 contains relevant economic parameters. Vehicle insurance is typically specified relative to the vehicle purchase price. We adopted near-market values from [30]. Since it is uncertain whether the vehicle can be procured again at a reduced price in the event of an insurance claim, the vehicle purchase price without a price reduction is used to calculate the insurance rate. The toll charge takes into account the toll exemption for alternative drivetrains for 2020 [31]. In the long term, we assume that every vehicle will have to pay toll to finance the road infrastructure. Noise-dependent toll components are not relevant for electric drivetrains. For vehicle tax, we considered current tax exemptions and reductions for BET and FCET, but assumed full taxation in 2050. Operation & Maintenance consists of tire costs that are equal for all drivetrains and drivetrain-specific costs for maintenance, repair, and lubricants. For diesel, we determined the costs based on [30]. The drivetrain-specific costs rely on own assumptions, based on [30, 32–34]. Finally, we assumed 6 years of service [32], 120,000 km/a [32], and an interest rate of 9.5 % [35] for all drivetrains.

Table 3: Economic vehicle parameters (incl. trailer) in 2020, 2030 and 2050

Parameter	Unit	DT	GT	PHET	H2T	FCET	BET	Sources
Vehicle insurance	[% VPP]	5.8	5.8	5.8	5.8	5.8	5.8	[30]
Toll charge	[EUR2020/km]	0.183 ('20) 0.183 ('30) 0.183 ('50)	0 ('20) 0.183 ('30) 0.183 ('50)	0 ('20) 0.169 ('30) 0.169 ('50)	0.171 ('20) 0.171 ('30) 0.171 ('50)	0 ('20) 0.169 ('30) 0.169 ('50)	0 ('20') 0.169 ('30) 0.169 ('50)	[31]
Toll share	[%]	92	92	92	92	92	92	[17]
Vehicle tax	[EUR2020/a]	929 ('20) 929 ('30) 929 ('50)	929 ('20) 929 ('30) 929 ('50)	929 ('20) 929 ('30) 929 ('50)	929 ('20) 929 ('30) 929 ('50)	373 ('20) 651 ('30) 929 ('50)	373 ('20) 651 ('30) 929 ('50)	[36]
O&M	[EUR2020/km]	0.17 ('20) 0.17 ('30) 0.17 ('50)	0.19 ('20) 0.19 ('30) 0.19 ('50)	0.16 ('20) 0.16 ('30) 0.16 ('50)	0.19 ('20) 0.16 ('30) 0.16 ('50)	0.18 ('20) 0.14 ('30) 0.14 ('50)	0.14 ('20) 0.14 ('30) 0.14 ('50)	based on [30, 32–34]
Service life	[a]	6	6	6	6	6	6	[32]
Annual mileage	[km]	120,000	120,000	120,000	120,000	120,000	120,000	[32]
Interest rate	[%]	9.5	9.5	9.5	9.5	9.5	9.5	[35]

2.2.3 Energy costs and fuel prices

Energy costs were calculated through vehicle energy consumption and energy carrier prices. For diesel, we followed the analysis in [37] and assume an increasing blend with synthetic diesel to reach climate-neutral transport in 2050. The same applies for gas. For hydrogen, we took into account the current backstop price at refueling stations (9.50 EUR2020/kg including VAT). For the long-term perspective, we referred to the price for climate-neutral hydrogen given in [37]. The electricity price consists of the electricity price itself and the costs for the charging infrastructure. For the latter, we assume 1.22 EUR2020/kWh in 2020 and 0.05 EUR2020/kWh in 2030 according to [9] for fast charging. For overnight charging, we assume 0.04 €EUR2020/kWh in 2020 and 0.03 EUR2020/kWh in 2030. In addition, we assume that BET charge 50% on fast charging infrastructure, while PHET strictly use overnight charging. The electricity price itself stems from [37]. Finally, we assume a maximum total price for public fast charging of 0.44 EUR2020/kWh (0.37 EUR2020/kWh without VAT), as it is planned for the "Deutschlandnetz" for electric cars [38]. Table 4 sums up the energy costs without VAT.

Table 4: Energy costs without VAT at charging / fueling station

Parameter	Unit	2020	2030	2050	Sources
Diesel	[EUR2020/L]	0.98	1.59	2.19	[37]
Gas (liquified)	[EUR2020/kg]	0.97	1.97	2.78	[37]
Hydrogen	[EUR2020/kg]	8.00	8.00	6,59	[37, 39]
Electricity (BET)	[EUR2020/kWh]	0.31	0.26	0.25	[9, 37, 38]
Electricity (PHET)	[EUR2020/kWh]	0.26	0.25	0.24	[9, 37]

2.2.4 Variations for federal perspective

Today, 80% of the vehicle purchase price compared to a diesel vehicle is waived through subsidies for BET, FCET and PHET [40]. We assume that this reduction is only temporary and will not apply in the medium (2030) and long (2050) perspective. This reduction is not applicable in the federal perspective. The toll exemption for GT, PHET, FCET and BET (see Table 3) in 2020 represents a subsidy and is therefore not included in the federal perspective. Also, the cap of the hydrogen and electricity price (see 2.2.3) is not considered in the federal perspective. Additionally, we waived taxes in the federal perspective. Therefore, the fuel prices correspond to those in [37], without the taxes taken into account there. However, levies are taken into account in the federal perspective too, since they are dedicated to infrastructure financing. The vehicle tax from Table 3 is also omitted in the federal perspective. Finally, we reduced the annual interest rate from 9.5% to 4% according to [35].

3 Results

3.1 General results

In this section, we first present our findings from a company and second from a federal perspective. Figure 2 contains the TCO of a tractor-trailer combination equipped with BET, FCET, H2T, GT, PHET or DT for 2020, 2030 and 2050. The stacked bars represent the company perspective. The shaded area indicates cost differences associated with our range bandwidths or the share of electric driving regarding the PHET. The blue bars represent the total results from the federal perspective. Again, the bandwidths represent the range difference (100 km vs. 1,000 km) and the share of electric driving for the case of the PHET.

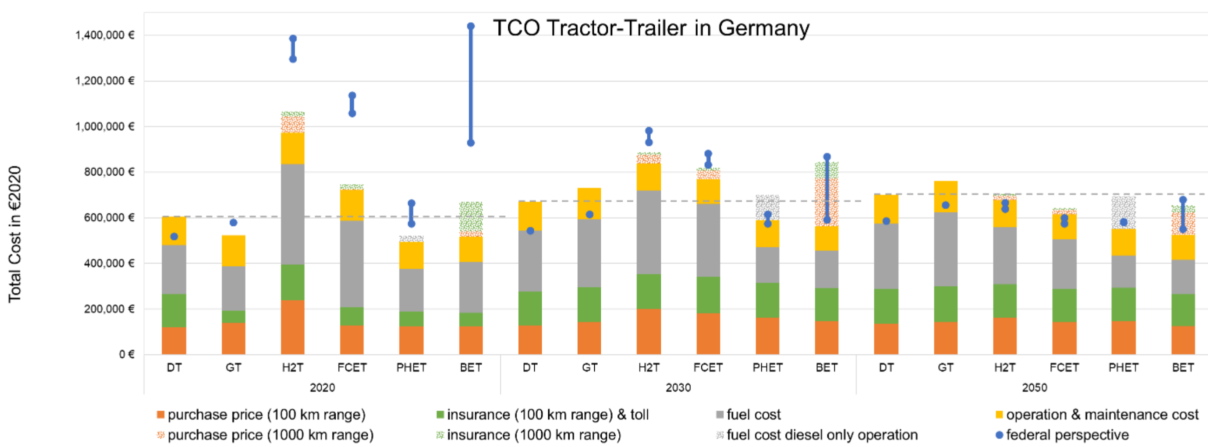

Figure 2: TCO comparison for BET, FCET, H2T, GT, PHET and DT for Germany

3.1.1 Company Perspective

Due to massive subsidies, BET, FCET and PHET are cost-competitive compared to the advanced and mature DT today. BET is the most cost-effective option, when comparing BET and FCET. However, the TCO of a PHET, which is also benefitting of subsidies and toll exemption, is still lower than all other drivetrains, due to smaller batteries. The insurance costs are a relevant cost component for BET with big batteries, since they have to cover the total vehicle price before subsidies. The range of BET and FCET hardly influences the purchase price due to federal subsidies. The H2T receives no purchase price reduction and is not competitive with the DT.

In 2030 BET is - nearly without subsidies - economically competitive to the DT. For example, a BET with 500 km range is 20,000 EUR2020 more expensive than a DT. FCET and H2T are significantly more expensive than a DT. The GT is no longer competitive without toll exemption and gas price reduction. The PHET is still competitive with DT, even with minimal electric driving.

Comparing FCET and BET in 2050, the TCO of BET and FCET are significantly lower than the DT. When designed for a range of 500 km, the BET is slightly cheaper than the FCET. However, the results are very similar considering the high uncertainty of the long-term forecast. H2T and PHET are also competitive with DT.

In general, transport costs are expected to increase in the medium term. In the long term, the use of BET and/or FCET, and possibly PHET with a high electric driving share, can achieve the initial level again.

3.1.2 Federal Perspective

Today massive subsidies are required to finance the vehicle purchase price reduction for BET, FCET and PHET and the cap on the energy costs respectively the underlying infrastructure costs. The absolute amount of required subsidy depend on the size of the battery or the tank. In 2030 subsidies will be significantly reduced, however from a federal perspective alternative drivetrains - except PHET - presumably are not economically competitive compared to the DT. In 2050, this changes and FCET, PHET and BET are economically competitive.

Finally, it can be seen that the federal costs of a DT are consistently lower than the company costs. The delta mainly describes taxes. This is not or nearly not achieved by BET and FCET, which are the promising long-term candidates from a company perspective. This is primarily due to lower absolute taxation, particularly with regard to the energy.

3.2 Sensitivity analysis

Figure 3 illustrates different sensitivity calculations, while we limit to BET, FCET, and DT comparison. The left-hand side visualizes annual break-even mileage for 2030. The range bandwidth are visualized separately. Error bands indicate different component costs (low and high), while the medium scenario is plotted as solid line. We find that the 100 km BET is most cost-effective at any annual mileage. The FCET might be cost competitive versus long-range BET just under 100,000 km/a, while the BET outperforms FCETs afterwards due to lower operating costs. The break-even against the DT is at roughly 220,000 km/a. The long-range BET entails the highest sensitivity toward the component cost variation. The right-hand side shows a parameter variation for 2050, where annual mileage, energy prices and the purchase prices are varied (+-20%). We find strong sensitivity to the annual mileage and energy prices and thus the vehicle operating costs, whereas the purchase price has the lowest sensitivity. The DT is more expensive than both BET and FCET with high robustness. BET and FCET are close and depending on the variation, either one is more cost-effective.

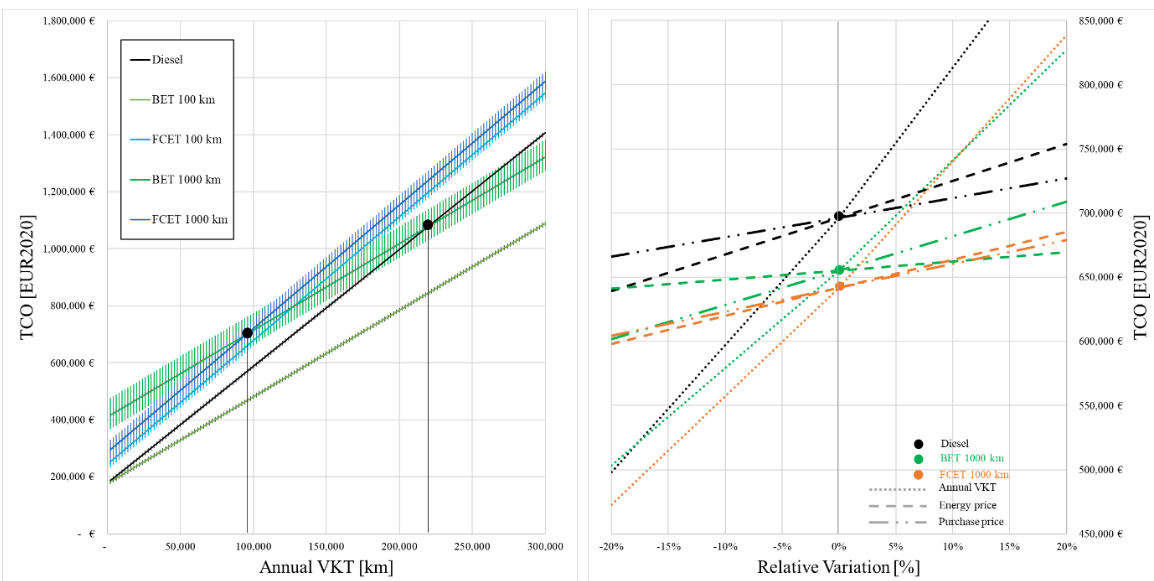

Figure 3: Sensitivity Analysis for BET, FCET, and DT. Left: TCO Comparison 2030 versus annual VKT. Right: Parameter variation +-20% for 2050. Own illustration

4 Discussion and Conclusion

In the following, we discuss some relevant parameters and assumptions and conclude with relevant findings.

Due to the long period under consideration, our parameters are subject to uncertainties. However, the sensitivity analysis shows the competitiveness of BET and FCET against DT in the long term, even when assuming significantly higher capital or operational expenditures. The costs for refueling and charging infrastructure are highly relevant in the short and medium term. They are still subject to major uncertainty, today. In the short term, the price increase of conventional energy carriers due to the war in Ukraine could favor alternative fueled trucks even more. However, support policies have by far the highest influence on the diffusion of alternative fueled trucks in the short term. These measures are currently particularly extensive in Germany, but are also associated with uncertainty, e.g. with regard to the duration. Therefore, we have considered the measures primarily for 2020. Extensions may further favor the diffusion of alternative fueled trucks. Today, insurance costs are of major interest for BET. We calculated conservatively with the full purchase price as basis for the insurance rate. If the reduced price would be applicable, this could further favor BET.

Our analysis focuses on an average vehicle. The sensitivities provide initial insights beyond this. However, in individual cases, the result may differ. For example, we did not consider payload reductions due to heavy batteries.

In summary, we have shown that BET and FCET can be competitive with DT in both the short and the long term. BET, with a plausible range of 500 km is always cheaper than FCET. However, the delta decreases over time. GT and H2T are probably not relevant in the future. PHET could be interesting from an economic perspective. However, the long term environmental effects are not considered in our analysis. Our research from a federal perspective suggest that energy tax from the transport sector could decrease in the medium term. The validation of this effect across the entire fleet, as well as any suggestions for fiscal adjustments, are left for further research.

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