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CO_2 abatement costs of long-haul heavy-duty truck technologies in Germany in 2020 and 2030

A techno-economic analysis based on state-of-the-art research

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1. Relevance and scope of the work

1.1 Introduction: Climate targets and the challenge of long-haul heavy-duty trucks in Germany

In December 2015, all the 197 Parties to the United Nations Framework Convention on Climate Change (UNFCCC) set up the Paris Agreement, which represented the first universal and legally binding global climate change agreement in history (European Commission [EC], 2020). It entered into force one year later and as of today, 189 Parties to the Convention have ratified it, including Germany (UNFCCC, 2020; Federal Ministry of Transport and Digital Infrastructure [BMVI], 2020a). The Paris Agreement states the clear target of keeping global warming well below 2°C and actively trying to limit it to 1.5°C, for preventing the worst consequences of climate change, for instance regarding health, food and water supply as well as biodiversity (EC, 2020a; Masson-Delmotte et al., 2019, pp. 8-9). According to the Intergovernmental Panel on Climate Change (IPCC), for reaching the 1.5 °C target, the world must become a net-zero emitter of greenhouse gas emissions by 2050 (Masson-Delmotte et al., 2019, p. 12). In that framework, the government of Germany set the targets to cut the GHG emissions by at least 55 % by 2030 compared to 1990 and to become extensively GHG-neutral by 2050 (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety [BMU], 2020). However, with a share of about 1.1 % of the global population, Germany emitted almost 2 % of the global carbon dioxide (CO2) emissions in 2018, which demonstrates that the country has a long way to go for achieving its own and the global GHG emission reduction targets (Crippa et al., 2019, pp. 5, 111; The World Bank Group, 2020).

In 2019, Germany emitted GHGs in the amount of 815 million tons CO2 equivalents (MtCO2eq) with the transport sector accounting for a share of about 20.2 % (German Environment Agency [UBA], 2020a). The transport sector requires specific attention, since its GHG emissions are at the approximately the same level as in 1990 of about 165 MtCO2eq, while all the other sectors faced significant reductions in the meantime (UBA, 2020a). However, for complying with the climate targets, the emissions of the transport sector need to decrease by at least 60.6 % by 2030 and by a minimum of 74.5 % by 2050 compared to 2019 (BMU, 2020). With regard to that, it is especially complex to decarbonise long-haul heavy-duty operations due to a variety of factors such as limitations of batteries related to costs and range as well as a lack of suitable infrastructure required for switching to different powertrain technologies (Bründlinger et al., 2018, pp. 38-39, Directorate-General for Research and Innovation (EC), 2017, p. 49). Although the GHG emissions of heavy-duty vehicles are disproportionately high compared to the other vehicle types, road freight activities are expected to increase substantially (Moultak et al., 2017, pp. 1-2). According to the Federal Motor Transport Authority [KBA] (2020, pp. 8), the vehicle fleet in Germany included about 208,000 road tractor units, representing the heaviest weight class of heavy-duty vehicles, which were all based on diesel. Their number continuously increased by on average 3.6 % between 2014 and 2018, which demonstrates the urgent need of finding solutions for being able to get the heavy-duty transport on track with the national and international GHG reduction targets (KBA, 2020, pp. 8).

That raises several questions such as how to decarbonise the heavy road transport, which less polluting technologies are available and at which costs compared to the diesel reference trucks? What does the future cost development of these alternative technologies look like and which kind of governmental market intervention would be required to make them competitive? The subsequent work tries to answer these questions by analysing the true economic costs and climate impact of various combinations of long-haul heavy-duty truck technologies in 2020 and 2030.

1.2 Research questions and general approach

As elaborated above, the upcoming three decades represent important milestones for climate policies both at global and national level. Since this is strongly related to the areas energy and transport, this analysis tries to provide current numbers and future projections of CO2 abatement cost, which could serve as a basis for the further political discussion. Therefore, the following research questions represent the focus of the work:

(1) What are the current total cost of ownership and cradle-to-grave greenhouse gas emissions of long-haul heavy-duty truck powertrain technologies and how will they develop until 2030?

(2) What are the marginal carbon dioxide abatement costs for switching to less polluting technologies in 2020 and 2030 and what are the political implications?

For answering these questions, the approach of this work can be described as a techno-economic assessment (TEA) with environmental considerations in the form of a life-cycle assessment (LCA), and is based on state-of-the-art knowledge of scientific research. According to Zimmermann et al. (2020, p. 15), a

> "TEA generally aims to examine technological feasibility and economic profitability while LCA in general aims to compare environmental impact reductions of technologies. Hence by integrating TEA and LCA results, solutions can be found that balance economic and environmental factors".

In that framework, this work aims to analyse the competitiveness of alternative combinations of powertrain and fuel technologies for long-haul heavy-duty trucks (LHHDTs) by applying a total cost of ownership (TCO) analysis based on the net present value (NPV) method. The environmental impact related to greenhouse gas (GHG) emissions is assessed through a cradle-to-grave LCA. Eventually, integrating the TCO and the LCA result in the carbon dioxide (CO2) abatement costs, which illustrate the economic costs of climate change mitigation in the heavy road transport sector in Germany and are highly relevant for opening political discussions, as initiated at the end of this work.

2. Methodological approach

In line with the components of a typical TEA stated by Lauer (n.d., p. 3), this work provides a cost assessment in the form of the TCO analysis (see chapter 4) and a risk evaluation, which is provided through a sensitivity analysis (in chapter **Error! Reference source not found.**). T he NPV method is characteristic for TEAs for ensuring comparability of the results as well as for assessing the value of a potential investment in the current time value of money before making the decision and for ensuring comparability of the results (University of Cape Town, 2020; Lauer, n.d., pp. 20-21). In the framework of the TCO, basically a modified NPV calculation is applied (see 2.1.3, Equation 1), including an annuity part, which is part of the TEA toolbox as well (Lauer, n.d., pp. 16-17). The LCA results in the opportunity of evaluating the economic costs of climate change mitigation in the heavy road transport sector in Germany through determining the carbon dioxide abatement costs.

The following chapter provides an overview of the basic approach followed in this techno-economic analysis, including the applied methodologies, related assumptions and data sources.

2.1 Total cost of ownership (TCO) analysis

This work aims to analyse the total technology-related economic cost of purchasing and owning a LHHDTs of different combinations of powertrains and energy carriers. The focus lies on the cost perspective from the first owners, as that is decisive for the broad market success of vehicle models (Wu et al., 2015, p. 198). That requires not only looking at the initial purchase price of a vehicle, but rather taking into account the various cost factors occurring before, during and potentially after the subsequent use as well. The TCO method fulfils these requirements and is therefore applied in this work.

2.1.1 Definition and coverage of TCO

The TCO method initially came up in the areas of logistics and supply chain management and has become increasingly popular in academia since the 1990s (Zachariassen & Stentoft Arlbjørn, 2010, p. 7). Ellram (1995, p. 4) defines the TCO method as "a purchasing tool and philosophy which is aimed at understanding the true cost of buying a particular good or service from a particular supplier". 20 years later, Wouters et al. (2005, p. 167) describe it as "a cost accounting application that enables purchasing decision-makers to combine value and price in making sourcing decisions". Referring to that, the buyers of commercial HDTs represent the decision-makers, which are assumed to be cost-minimising private companies. The TCO method is a complex approach, which can be applied to any kind of purchase decision and determines the most important cost drivers of a product (Ellram, 1995, pp. 4, 22). Although the initial purchase price represents a crucial element of the TCO, it is not the only important factor to consider when making investment decisions. Therefore, one main focus in this work lies on identifying the most important cost drivers of the different LHHDT technologies, in line with the definition by Ellram mentioned above. In general, the TCO approach analyses all costs occurring during the whole service life of a good, including the purchase, the use and the disposal (Bubeck et al., 2016, p. 64). For conducting a relevant TCO analysis, it is essential to "identify and compute the necessary cost categories for the product or service in question"

(Hagman et al., 2016, p. 13). In general, TCO be categorized into capital expenditures (CAPEX), representing one-time investment cost at the time of the purchase, operational expenditures (OPEX), covering fixed periodic payments over the service life, and variable cost, which are directly resulting from the active use of the good or service analysed (Bubeck et al., 2016, p. 64; Wittenbrink, 2014, pp. 73, 95).

2.1.2 Scope of this work and assumptions

As the application of TCO to vehicles is a relatively new area in science, there are limitations with regard to its scope (Hagman et al., 2016, p. 12). For analysing customer-centric technology-related vehicle TCO, the cost perspective from the first owners is essential, since this is decisive for the broad market success of vehicle models (Wu et al., 2015, p. 198).

Figure 1: Coverage of the TCO approach in this work

Total Cost of Ownership (TCO)		
CAPEX	OPEX	variable cost
production price	taxes	real fuel use
charging infrastructure	insurances	maintenance
financing & depreciation	driver salary	tolls & other

included in this work   not included in this work

Figure 1 shows the coverage of the TCO approach followed in this work, split up into those three categories. It is important to highlight that, cost related to recycling and disposal are not considered in this work. As several other related scientific works do not include these costs either, it is assumed that their relevance is insignificant and therefore, neglectable (Zapf et al., 2019, p. 42). In addition, all kinds of taxes, fees and subsidies and insurances are excluded from the analysis, as they are not related to the true cost of powertrain technologies, even though there could be differences across technologies due to political measures or other artificial factors.

The CAPEX, or in this case also true vehicle-related acquisition costs, include the production price, financing and depreciation, as well as expenses for required charging infrastructure, which is especially relevant for BEVs due to the need for home-charging.

OPEX, covering all kinds of periodic tax and insurance payments as well as driver salaries, are not included in this work, since they are assumed to be not or only insignificantly based on technology. The amount of taxes, notably the motor vehicle tax, paid results from national policies and is based on the gross weight and the emissions of transport vehicles in Germany (Wittenbrink, 2014, p. 95; German Customs Administration, 2020). Although that means real cost differences for end consumers across powertrain technologies, these are not related to the technologies themselves, but artificially created, for instance for internalising external cost (Kaluza, 2017, p. 519). Insurance costs depend on the specific vehicle and cargo type (Wittenbrink, 2014, p. 95). Salaries for drivers represent a significant share of the total HDT-related cost for companies. However, they are assumed to be technology neutral as well, which implies that the skills required for handling trucks do not significantly differ across the powertrain technologies. In general, the dependence of HDT powertrain technology-related OPEX provides further research opportunities.

With regard to variable cost, this work covers the expenses related to the real fuel use and maintenance. The costs related to fuel use depend on the real average consumption of the vehicle per kilometre, which can significantly differ from the one stated by the producer and is also strongly related to the individual driving behaviour as well as the type of routes taken (Kleiner, 2017a, p. 4; Zapf, 2019, p. 196). Regarding the latter, in related scientific literature it is common to create driving profiles dependent on the shares of urban, regional and long-distance use (see Karlström, 2019, p. 13; Kleiner, 2017a, p. 3). However, as this work focuses on long-haul distances only, it is assumed that the impact of inner-city driving on the total real use is neglectable and therefore, motorway driving cycles are considered only (Kleiner, 2017a, p. 3). Individual driving patterns play a role for the real fuel use as well, but are not considered in this work, as they are assumed to have an insignificant impact on long-haul truck transport only, due to strict speed limitations based on the transport policy (Federal Ministry of Justice and Consumer Protection, 2020, pp. 3, 10). Due to significant differences in materials and components installed across vehicle powertrains, maintenance costs are technology-based and therefore, subject to the subsequent TCO analysis as well (Kleiner, & Friedrich, 2017b, pp. 7-8). Although tolls for heavy-duty vehicles, notably the truck toll, are directly related to the vehicle emissions in Germany, they are still excluded from the analysis due to the same reason as stated for the taxes above (BMVI, 2020b; Wittenbrink, 2014, p. 95).

2.1.3 Calculation methods and data sources

The scope and methods applied in TCO calculations significantly differ among scientific studies (see Bubeck et al., 2016, p. 66; Gnann et al., 2017a, p. 53; Hagman et al., 2016, p. 13; Kleiner, 2017a, p. 6; Wu et al., 2015, p. 199). However, all these studies have in common that they split the cost drivers up into CAPEX as well as operation and maintenance costs, as done in the previous section of this work. In addition, they look at TCO from an investment perspective, which means that the net present value of future cost and revenues related need to be discounted. Considering these findings and the intended scope of the TCO calculation, the subsequent formulas (see Figure 2 below) are mainly based on the approach of Wu et al. (2015, p. 199), but have been adapted and extended, where considered necessary. **Figure 2** shows the formulas which represent the basis for the TCO analysis in this work, where Equation 1 describes the composition of the TCO over the total ownership period (N), which is five years in this case.

Figure 2: Main formulas used for the TCO analysis

Equation 1: TCO over the whole period	$TCO = CAPEX \times CRF \times N + \sum_{n=1}^{N} \frac{VC_n}{(1+r)^n}$
Equation 2: Capital expenditures	$CAPEX = m \times PC - \frac{RV}{(1+r)^N}$
Equation 3: Capital recovery factor	$CRF = \frac{r(1+r)^N}{(1+r)^N - 1}$
Equation 4: real discount rate	$r = f - i + o$
Equation 5: Variable cost	$VC_n = FC_n + MRC_n$
Equation 6: Fuel cost	$FC_n = X_n \times FU_n \times FP_n$
Equation 7: TCO per km	$\frac{TCO}{km} = \left[CAPEX \times CRF + \frac{1}{N}\sum_{n=1}^{N} \frac{VC_n}{(1+r)^n}\right] \div \frac{\sum_{n=1}^{N} X_n}{N}$

The CAPEX represent the first part of the total TCO equation and consist of the difference between the retail price equivalent, which is equal to the total OEM production cost (PC) multiplied with a mark-up factor (m), and the present value of the nominal resale value (RV) after the ownership period, adjusted by the real discounted rate (r). The mark up represents additional cost related to research and development, component integration and vehicle distribution, but also profit margins for OEMs and retailers as well as other factors (den Boer et al., 2013; Kühnel et al., 2018; p. 44). In line with related studies, the mark up accounting for these factors is set to 50 %, leading to a mark-up factor of 1.5 (Burke & Miller, 2020, p. 17; Fries et al., 2017, p. 15; Jöhrens et al., 2020, p. 83; Karlström et al., 2019, pp. 22-24). The nominal resale value is assumed to be 24.9 % after five years for all technologies, except for the battery systems of electric powertrains with little battery capacity, since there is a replacement required (Kühnel et al., 2018, p. 46; see Financing and depreciation).

The capital recovery factor (CRF) represents an annuity method for calculating the financing cost and splits the CAPEX into equal annual payments over the ownership payment (Lauer, n.d., pp. 16-17). The CFR takes into account the real discount rate (r), which represents the time value of money adjusted by future price changes and is therefore calculated by subtracting the inflation rate (i) from the nominal financial interest rate (f) and adding the opportunity cost (o) for companies (Kühnel et al., 2018, p. 47; Wu et al., 2015, p. 199; Zapf et al., 2019, p. 211). The nominal financial interest rate for loans to non-financial institutions is assumed to be 1.652 %, which is derived from the average of the rates in the year 2019 and the first quarter of 2020 (Deutsche Bundesbank, 2020a). Due to the high uncertainty about the future developments of the inflation rate and the opportunity cost, there is a weighted average applied for estimating reasonable values based on the average of the 5- and 10-year growth factors of the proxy variables. This represents an adjustment for the current and past economic cycle, but still considers the development in the past five years more due to path dependency reasons. In the light of that, the inflation rate of 1.267 % was calculated by taking the weighted average of the relative increases of the consumer price index (CPI) in Germany between 2010 and 2020 (Federal Statistical Office of Germany, 2020a). With regard to that, it is important to mention that for the year 2020, the average of the calendar- and seasonally adjusted values for the first quarter of 2020 was applied. Even though more recent data for 2020 exist, these were not considered due to uncertain and possibly exceptional effects of the corona pandemic on price levels. In addition, opportunity costs of 4.596 % were taken into account, approximated by calulating the long-term weighted average of the annual financial return on investing in the DAX index between 2019 and 2010 for avoiding taking into account event-based stock market effects, which compromises the shares of the 30 most valuable companies in Germany (Deutsche Börse, 2020). Considering the corona pandemic, DAX values for 2020 were not taken into account due to the quick reactions of stock prices to economic development. As a result of these factors, a real discount rate of 4.98 % was calculated, covering refinancing costs, investment uncertainties, and time preferences (Wietschel et al., 2019, p. 34). That is in line with the rates used in other related studies with values varying between 3.5 and 8 % (Karlström, 2019, p. 26; Kühnel et al., 2018, p. 47; Zapf, 2019, p. 211; Wietschel et al., 2019, p. 34). For ensuring comparability of the results, that real discount rate is also applied for the years 2030 and 2050. Multiplying the CAPEX with the CRF leads to the real acquisition cost of a vehicle.

The second part of Equation 1 consists of the summed up variable cost (VC) for each year (n) of the total holding period (N), adjusted by the real discount rate (r). The annual VC for a given year (n) represent the sum of the annual costs related to operation, which are in this case equal to the fuel costs (FC), and maintenance and repair costs (MRC). The FC results from multiplying the annual distance driven in kilometres (X), which are set to be 120,000 km every year, with the real fuel use per kilometre in energy units (FU) and the fuel price (FP) per energy unit (Hagman et al., 2016, p. 14). Due to the high volatility of fuel prices (in particular oil-based ones), the calculation is based on annual averages and in general, constant real prices of the energy carriers are assumed over the investment periods (see U.S. Energy Information Administration, 2020).

In the end, the aim is to calculate and compare the TCO per kilometre of the powertrain technologies by dividing the annualised TCO by the annual driving distance (see Equation 7), which in this work amounts to 120,000 km. The analysis is conducted for the years 2020 and 2030. It is assumed that the maximum technical potential for improvements regarding production and maintenance cost as well as fuel efficiency is reached by 2030, so that the only changes affecting the TCO after 2030 are related to the fuel prices only (Fries et al., 2017, pp. 12-15).

The main sources for the modelled vehicle component costs in 2020 and 2030 are Moultak et al. (2017) and Kühnel et al. (2018). However, their numbers were benchmarked against Burke & Miller (2020), Fries et al. (2017), Jöhrens et al. (2020), Karlström et al. (2019) and others, and adjusted in case of significant discrepancies (see chapter 4.1.1 and Appendix III).

With regard to the maintenance costs, the 2020 estimates are based on numbers provided by Kühnel et al. (2018) and Kleiner et al. (2017b). For the year 2030, Wietschel et al. (2017) and Karlström et al. (2019) represent additional sources for the computation of standard values (see chapter 4.2.1 and Appendix V). Complementary benchmarking with related studies, such as Moultak et al. (2017) and Jöhrens et al. (2020) validated the choice of main sources and the related results.

The operational fuel costs are based on estimations by Perner et al. (2018), Zapf et al. (2019), Wietschel et al. (2017; 2019), Jöhrens et al. (2020), Kühnel et al. (2018), Karlström et al. (2019) and Bründlinger et al. (2018) as well as own assumptions (see Appendix VI and Appendix VIII). In general, the lower heating value (LHV) is applied for all calculations related to energy carriers. That implies that combustion processes in engines do not fully utilise the energy content of the resource and produce heat in the form of water vapor as a side product (Harrison et al., 2010, pp. 1-2).

As the various sources analysed mostly use different combinations of currency and base year, all numbers were adjusted to 2020 EUR, in order to establish comparability across them. With regard to that, foreign currencies were adjusted by annual exchange rates as stated by the European Central Bank (2020). In addition, all numbers related to vehicle component cost were converted to 2020 EUR by adjusting for the historical annual increases Producer Price Index (PPI) for industrial products (Federal Statistical Office of Germany, 2020b). For the year 2020, the average of the calendar- and seasonally adjusted values for the first quarter of 2020 was applied, similarly to the CPI calculation mentioned above. On the other hand, the prices of operation costs and energy carriers, such as diesel, hydrogen and electricity, were adjusted by the CPI instead, as they are not specifically related to industrial activity and as heavy duty trucks are assumed to be refuelled at public service stations primarily products (Federal Statistical Office of Germany, 2020a). All conversion rates applied in this work can be found in Appendix II.

2.2 Well-to-wheel (WTW) life-cycle assessment (LCA)

For evaluating the climate impact of the LHHDT technologies analysed, this work conducts an attributional well-to-wheel (WTW) life-cycle assessment (LCA). In general, a LCA is "a tool that can be used to evaluate the potential environmental impacts of a product, material, process, or activity" (U.S. Environmental Protection Agency [EPA], 2020a). In this case, the scope of the environmental impact is limited to GHG emissions and the product analysed are different LHHDT technologies. An attributional LCA evaluates the absolute amount of average direct and indirect emissions related to the consumption of a good, which are in this case different energy carriers (Zapf et al., 2019, p. 121). In contrast to a consequential LCA, it does not consider the marginal effects of fuel switching on the rest of the energy economy.

Usually, a complete LCA consists of a cradle-to-grave analysis which includes all emissions arising during the lifetime of a product, which in the case of vehicles would include the environmental impact of their production and recycling as well as the provision and consumption of energy carriers (Zapf et al., pp. 46-47). However, due to the characteristics of an extremely high annual mileage and energy consumption, the vehicle production plays a minor role and can therefore be neglected when looking at the climate impact of heavy-duty truck technologies (Wietschel et al., 2017, p.28; Sen et al., 2017, p. 116). Therefore, this work focusses on the well-to-wheel GHG emissions, which consist of the well-to-tank (WTT) and the tank-to-wheel (TTW) components, where TTW covers the direct emissions, which result from the internal combustion process in the vehicle engine and are measurable at the tailpipe (Zapf et al., 2019, p. 46; UBA, 2017, p. 146). The WTT factor also takes the indirect, also called upstream chain, emissions into account, which arise at the various stages of producing, processing, transporting and distributing energy carriers (Kühnel et al., 2018, pp. 36-38). The sum WTW GHG emissions simply represent the sum of the TTW and WWT emissions and are the basis for the LCA in this work.

With regard to the scope of GHG emissions covered, the focus lies on the three main gases in terms of climate change contribution, which are carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O). CO2 represents the largest contributor to climate change, accounting for 88 % of the GHG emissions in Germany in 2018, followed by CH4 with a share of 6.1 % and N2O of 4.1 % in CO2eq (UBA, 2020b). However, these GHGs significantly differ from each with regard to their radiative efficiency, which in simple words describes their contribution to global warming, and their lifetime, which states how long they remain in the atmosphere (EPA, 2020b). For being able to compare the impact of the different GHGs on climate change, the Global Warming Potential (GWP) indicator, as determined by the IPCC, measures the relative amount of energy absorbed by a gas per mass unit, compared to the reference gas CO2 (EPA, 2020b). Depending on the timeframe applied, the individual values of the gases can significantly differ, but usually a scope of 100 years is defined. The GWP 100 values of the three main GHGs discussed are shown in **Figure 3** below (Myhre et al., 2013, p. 731).

In general, CO_2 represents the reference with a value of 1 and compared to that, CH_4 and N20 have multiple times the effect on global warming per gram of gas emitted. The lifetime value of CO_2 is not stated as it is not easy to determine, but it is communicated that this gas stays in the atmosphere for up to thousands of years (EPA, 2020b).

Figure 3: Global warming potential of the main GHGs

	GWP 100	*Lifetime in years*
CO_2	1	~
CH_4	28-30	12.4
N_2O	265	121

The GWP 100 values are applied in this work for converting CH_4 and N_2O emissions into CO_2 equivalents and thereby, enabling comparability between the gases involved. That also enables calculating the emission factor of electricity which takes all direct WTT GHG emissions for various kinds of electricity generation and related mixes into account (UBA, 2020, p. 11a) The emission factor states the WTW emission level of energy carriers and generally depends both on the share of renewable energy sources. With regard to that, this work aims to link the emission factors of energy carriers with the real fuel use of the corresponding LHHDTs for evaluating the life-cycle WTW emissions of the different combinations of powertrain technologies and energy carriers.

3. Overview of long-haul heavy-duty truck technologies

This chapter provides an overview of the configurations of the standard vehicles covered in this work, with the different powertrains and related energy carriers they are relying on. Subsequently, estimates for the efficiency of the final energy use are introduced. In the end, the infrastructure needs for upscaling non-established technologies are discussed briefly, as they play a significant role when evaluating the alternatives from a political perspective.

3.1 Overview of powertrains, energy carriers and vehicle configurations covered

This work analyses standard vehicles, which are defined in line with Zapf et al. (2019, p. 95) as synthetic vehicles which share the same basic equipment and only differ through their powertrain technologies. The scope of this work is limited to LHHDTs only, covering vehicles of the highest weight class, which refers to category N3 in Europe and classes 7 and 8 in the United States (EPA, 2020c; European Alternative Fuels Observatory, 2020). In detail, that means a gross vehicle weight (GVW) of 40 tons, of which the minimum curb weight amounts to 12 tons (Moultak et al., 2017, pp. 8, 14). With a market share of 100 %, diesel vehicles were the only technology represented in the long-haul heavy-duty road freight transport sector in Germany in 2018 and therefore, represent the reference technology for the benchmarking (Federal Motor Transport Authority, 2020, p. 4). In line with Kühnel et al. (2018, pp. 16), the payload is assumed to weigh 19.3 tons. In general, the subsequent standard vehicle configuration follows mainly Kühnel et al. (2018), as their assumptions are validated by other studies such as Karlström et al. (2019, p. 23), Kleiner & Friedrich (2017a, pp. 3-4) and Wietschel et al. (2019, pp. 39, 62) and others, which apply very similar vehicle features. In line with Kühnel et al. (2018, p. 26) and Moultak et al. (2017, p. 47), all vehicles are equipped with an engine of 350 kW power. With regard to the powertrains covered, this work generally analyses vehicles based on internal combustion engine, fuel cell, battery and hybrid catenary powertrains. All the powertrains and fuels considered for the analysis of standard vehicles are shown in **Figure 4**.

There are two types of internal combustion engine vehicles (ICEVs) considered, one based on diesel and one on liquified natural gas (LNG). While diesel is based on oil, natural gas takes the same role for LNG (see chapter 4.2.2). Compressed natural gas (CNG) can be neglected as a potential energy carrier, as it is not competitive with LNG when it comes to long driving distances (Wietschel et al., 2017, p. 93). Gasoline is not considered as a relevant fuel, as is not competitive with Diesel for long-haul operation, which are 20 to 35 % more energy efficient according to the U.S. Department of Energy (2020).

In general, there are two viable engine technologies for LNG-based vehicles: positive ignition, which is also called spark ignition, and compression ignition, with high pressure direct injection (HDPI) as the most promising technology (Mottschall et al., 2020, p. 18). The latter requires the injection of natural gas and also diesel, where the diesel share of the total fuel energy accounts for about 5 % (Pate, 2014). Therefore, LNG vehicles with HDPI engines, similarly to Diesel vehicles, require an exhaust fluid for the emission treatment, which is also known as “AdBlue” (Mottschall et al., 2020, pp. 21, 48). However, as the HDPI principle promises a higher fuel efficiency, it is expected to prevail in the future long-haul HDT market, which is why the standard LNG vehicle in this work is based on a HDPI engine as well (Kühnel et al., p. 27).

Related to the ICEVs, biofuels are analysed as a potential renewable alternative to the fossil fuels, where biodiesel could replace diesel and liquified biomethane could be applied instead of LNG. It is assumed that the biofuels, once processed to the final product, represent perfect substitutes for the fossil fuels and therefore, can be fully used by the same vehicles, without any negative effects on the economics (Wietschel, 2019, pp. 44-46). Biofuels are for instance produced on the basis of energy crops, straw, manure or organic waste.

Figure 4: Standard vehicle configurations covered

Powertrain	Energy carrier	Storage capacity	Battery capacity	Estimated range
ICEV	Diesel	286 - 400 l	~ 3 kWh	
	Liquified natural gas (LNG)	205 kg	~ 3 kWh	800 km
	Bioliquids	286 l / 205 kg	~ 3 kWh	800 km
	Synthetic LNG (PtX)	286 l / 205 kg	~ 3 kWh	800 km
FCEV	hydrogen	55 kg	70 kWh	800 km
C-BEV	electricity		175 kWh / 400 kWh	100 km / 250 km
BEV	electricity		600 kWh / 1,200 kWh	400 km / 800 km

Fuel cell electric vehicles (FCEVs) are based on the energy carrier hydrogen, which is stored in high pressure gas tanks (Zapf et al., 2019, p. 84). When in operation, the fuel cells convert the hydrogen into electric energy which is then either directly utilised by the electric engine or flowing into an intermediate traction battery first (Kühnel et al., 2018, p. 30). Considering the rather immature technological status of fuel cells, this work looks at the hybrid version with a battery of 70 kWh capacity and a fuel cell system of 180 kW power, which is sufficient for providing the continuous output required, based on the configuration by Kühnel et al. (2018, p. 30). It is important to highlight that this work only considers hydrogen produced via electrolysis and based on electricity, as the aim is to compare renewable with conventional energy sources.

Battery electric vehicles (BEVs) run entirely on electricity, which is stored in a battery and then processed by the electric engine (Zapf et al., 2019, p. 84). This work analyses two BEV standard models, one with 600 kWh and one with 1,200 kWh battery capacity, which leads to estimated ranges of 400 km and 800 km (Kühnel et al., 2018, p. 30). A significant disadvantage of BEVs is that the batteries are significantly heavier and have a larger volume than conventional energy storage systems, which leads to less payload capacity available and therefore, makes them less attractive for long-haul operations (Wietschel et al., 2019, p. 95; Kühnel et al., 2018, p. 29). However, this factor is neglected in this work, as the same payload is assumed for all standard vehicles analysed, resulting in spare capacity for ICEVs.

Catenary BEVs are hybrid vehicles, with the electric engine conductively retrieving the electricity from either an overhead catenary system via an integrated pantograph or their integrated batteries (Wietschel et al., 2019, pp. 82-83). For that, they require access to an electric road system (ERS) infrastructure, which is not in place on a large scale yet but there are first pilot projects taking place and a significant buildout is planned in the near future (Kühnel et al., 2018, p. 21). For being able to compare the technology potentials of the various vehicle concepts, this work assumes an existing and sufficient infrastructure for O-BEVs representing a real alternative for long-haul heavy road transport. Based on Kühnel et al. (2018, p. 21), two standard C-BEVs are analysed in this work, with battery capacities of 175 kWh and 400 kWh, resulting in driving ranges of 100 km and 250 km.

Other forms of ERS-based vehicle technologies such as conductor rails and inductive electricity transmission are not dealt with in this work, as these technologies are considered to be less mature and cost-competitive than the catenary one (Wietschel et al., 2017, p. 70; Kühnel et al., 2018, pp. 20-21). In addition, it is worth mentioning that there are several types of hybrid vehicles imaginable, such as plug-in hybrid electric vehicles in combination with a diesel or LNG engine, or catenary diesel hybrid catenary vehicles (Wietschel et al., 2019, pp. 82, 98). However, these options are not considered, as they would not sufficiently contribute to the decarbonisation of long-haul transport when still partly running on fossil fuels.

Additional potentially sustainable energy carriers are products of so-called Power-to-X processes, which in a two-step process create synthetic fossil fuel equivalents on the basis of electricity via the intermediate product of hydrogen (Perner et al., 2018, p. 62). An advantage of these energy carriers is the compatibility with existing fossil transport and distribution infrastructure, for instance, synthetically produced methane can be fed into the natural gas grid without any further steps required (Wietschel et al., 2019, p. 8; Zapf et al., 2019, p. 86). However, Power-to-X products are currently not competitive with their fossil or bio-based equivalents and there are high uncertainties regarding their future cost and technology developments (Wietschel et al., 2019, p. 48; Perner et al., 2018, p. 95). Importing these energy carriers from North Africa or the Middle East would currently be significantly cheaper than the domestic production and it is projected that this will be the case in the long term as well (Perner et al., 2018, pp. 82-83).

In general, it is important to consider the different stages of technological development across the powertrain and fuel technologies analysed in the framework of long-haul heavy duty trucks. While Diesel and LNG are the most progressive technologies with technology readiness levels (TRLs) of 9 out of 9, Gnann (2017b, p. 905) states only TRL 5 for BEVs and FVECs and TRL 6 for C-BEVs. With regard to that, TRL 5 means that the technology is validated in a relevant environment, but it is not validated yet, which represents the next step towards TRL 6. Even though the U.S. companies Tesla and Nikola are planning to roll out their first class 8 long-haul HDTs next year, it is uncertain, whether these models will prove themselves under real-world conditions (Smith, 2020). However, a low TRL also means a large potential for technological progress and related cost reductions, which will be analysed in the upcoming chapters.

3.2 Real energy consumption

For analysing the real fuel use, it is essential to define the scope first. This work looks at the final energy use from a consumer perspective, which also referred to as tank-to-wheel (TTW) consumption or battery-to-wheel (BTW) consumption for BEVs. The TTW approach measures the consumption of energy carriers after leaving the last stationary energy system, which for long-haul heavy- duty trucks should mainly be the fuel station and perhaps sometimes private outlets for BEVs (Zapf et al., 2019, p. 179). That implies that no efficiency losses with regard to the provision of the energy carriers are integrated in the further analysis, even though there are significant differences between the technologies (Gnann et al., 2017b,

p. 907). However, as these factors do not directly affect the technology-related fuel costs paid by the consumer at the service station, neglecting these factors seems to be justified.

Based on Kühnel et al. (2018, p. 26), this work assumes an annual driving mileage of 120,000 km for long-haul HDTs and a standard motorway driving profile (see 2.1.2). According to the Federal Motor Transport Authority (2020, p. 8), the average annual mileage of road tractors amounted to about 95,000 km in Germany in 2018. However, as this work considers vehicles used for long-haul operations only, the assumption of 120,000 km driving distance per year seems to be justified. Due to that significant mileage, the need for energy carriers represents an important factor and plays a key role for determining the energy carrier costs in chapter 4.2.2. With regard to the fuel consumption of vehicles, OEMs generally state nominal values, which rely on standardised test procedures, with the most prominent being the New European Driving Cycle (NEDC) and Harmonized Light-duty vehicles Test Procedure (WLTP) for passenger vehicles (Kleiner, 2017a, p. 4). These tests are conducted in laboratories under the same conditions, for instance regarding the driving profile and surrounding temperature, for each vehicle, for establishing comparability and reproducibility (Zapf, 2019, p. 180). For HDVs, the World Harmonized Vehicle Cycle (WHVC) would be applicable. However, studies show significant and systematic differences between officially stated and real fuel consumption based on several empirical observations (Kleiner, 2017a, p. 4; Zapf, 2019, pp. 107-108).

According to Rodríguez et al, (2018, p. 2), the fuel consumption of a vehicle can be described as “the product of the powertrain efficiency (i.e., combined efficiency of engine, transmission, and axles) and the road-load energy demand (i.e., combined effect of aerodynamic drag, rolling resistance, inertial forces, and road grade)”. With regard to the relative importance of these factors, Delgado et al. (2017, p. 59) found that the engine consumes more than 50 % of the total energy use of tractor-trailers, but aerodynamics, tires and braking play essential roles as well.

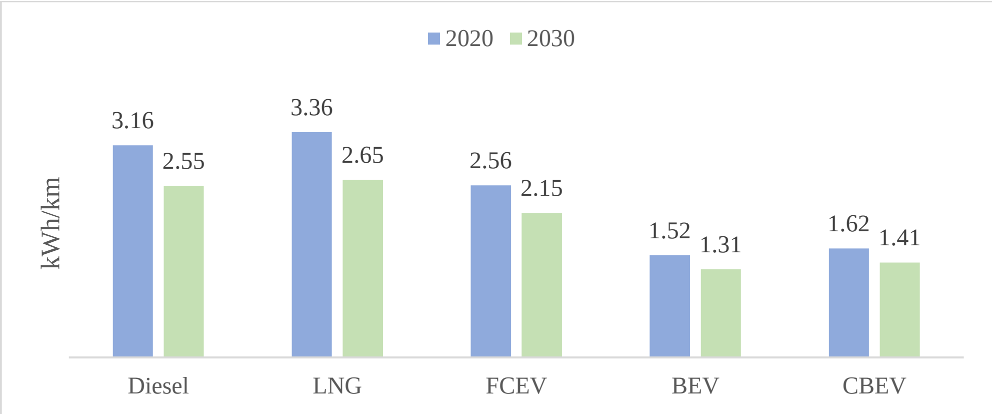
It is also essential to define the energy content of energy carriers, where the higher heating value refers to the gross calorific value, which applies for perfect combustion processes, where all the energy released can be captured and utilised (Harrison et al., 2010, p. 6). However, the lower heating value (LHV) the actual energy which can be extracted from the fuels when taking into account process efficiency losses of the combustion reaction which lead to the emergence of side products of the combustion reaction, primarily water vapor (Harrison et al., 2010, pp. 1-2; Zapf, 2019, pp. 183, 213). Therefore, this work considers the LHVs of all the energy carriers, calculated based on the conversion factors as stated in Appendix II.

With regard to BEVs, it is important to consider charging losses related to the transmission of electricity and the efficiency of the devices themselves as well, since the consumers pay for this excess electricity which is not utilised by the powertrain (Zapf et al., 2019, p. 192). For passenger vehicles, Zapf et al. (2019, p. 192) observe charging losses of 13 %. With regard to large-scale HDVs, a more efficient equipment is assumed and therefore, this work follows the suggestion of Kühnel et al. (2018, p.33), applying an additional electricity consumption of 10 % for BEVs. As the other studies explicitly excluded or did not mention this factor, their fuel efficiency estimates were adjusted accordingly (see Karlström, 2019, p. 14; Moultak, 2017, pp. 15-16). In addition to that, it should be noted that aging batteries potentially consume more electricity for delivering the same output (Kühnel et al., 2018, p.33). However, as this effect is difficult to quantify or even estimate, it remains neglected in this work.

For calculating best estimates for the real consumption of energy carriers by the different powertrains, the related findings of Jöhrens et al. (2020), Moultak et al., 2017, Kühnel et al. (2018), Wietschel et al. (2017), Karlström (2019) and Delgado (2017) were compared with each other (see Appendix VI). The values for BEVs were adjusted by an additional 10 %, as explained above. **Figure 5** shows the values of the real fuel use as applied in this work, resulting from the benchmarking process.

The results show significantly higher TTW energy use of the ICEVs compared with the alternative powertrain technologies. However, Diesel and LNG vehicles are expected to realise the largest efficiency gains of 19.1 % and 21.2 % until 2030. This is due to the implementation of several efficiency improvement measures with significant fuel saving potentials, for instance regarding the tractor tyres and aerodynamics as well as engine optimisation (Delgado et al., 2017, p. 48; Wietschel et al., 2017, p. 94). For long-haul Diesel HDTs, an average real fuel consumption of 3.16 kWh per kilometre is applied in this work, which is in line with the testing program conducted by Rodríguez et al, (2018, p. 12), when also accounting for technological progress since then. Kühnel et al. (2018, p. 33) argue that in theory, LNG vehicles based on HDPI engines could achieve the same efficiency as Diesel trucks, but the other studies looked at assume slightly higher consumption rates in the future as well (see Appendix VI). Therefore, the results of the benchmarking show a 6.3 % higher energy consumption of LNG trucks in 2020, which decreases to a gap of 3.6 % compared to Diesel vehicles.

Figure 5: Real fuel use of HDT powertrains in 2020 and 2030



The TTW energy efficiency of FCEVs is higher compared to the ICEVs, but significantly lower than for BEVs. With regard to the exact value, the assumptions on the total efficiency of the fuel cell system are crucial, which is expected to increase slightly by about 3 % until 2030 (Kühnel, 2018, p.35). Overall, the final energy consumption of FCEVs is calculated to decrease by 16.1 % until 2030.

BEVs are the most efficient of the powertrains analysed, with a TTW energy consumption of less than 50 % of the Diesel vehicle. Although the maximum potential engine efficiency is almost reached, efficiency improvements can still be gained related to the rolling and air resistance as well as the integrated power electronics (Kühnel et al., 2018, pp. 33-34; Wietschel et al., 2017, p. 97). As a result, BEVs show efficiency gains of 13.7 % and CBEVs by 12.9 %. With regard to the CBEVS, the additional air resistance caused by the overhead catenary (pantograph) is assumed to lead to an additional energy consumption of 0.1 kWh/km, which is in line with Jöhrens et al. (2020, p. 82) and Kühnel et al. (2018, p. 32).

4. TCO of long-haul HDT technologies

In this chapter, the main cost drivers of different combinations of powertrain technologies and energy carriers are analysed. With regard to that, the modelled standard vehicles (see chapter 3.1) are aimed to represent the main characteristics technologies as accurate as possible, which is why all cost estimations are based on comprehensive scientific research. It is important to highlight that in cases where studies used for benchmarking significantly differed in their assumptions related to the vehicle features, their numbers were adjusted and streamlined and according to the configurations applied in this work. Until not stated otherwise, all numbers are provided in 2020 EUR. While the vehicle component costs were adjusted by the PPI, the CPI was applied for the operation costs and fuel prices (see 2.1.3). All conversion rates applied in this work can be found in Appendix II.

4.1 Acquisition costs

As described in detail in chapter 2.1.3, the acquisition costs, or here also CAPEX, consist of the difference between the net vehicle acquisition (or purchase) cost and the net present resale value, multiplied with the capital recovery factor. Subsequently, the vehicle purchase costs are split up into its main components first, and the financial adjustment is undertaken afterwards.

4.1.1 Vehicle compontent costs

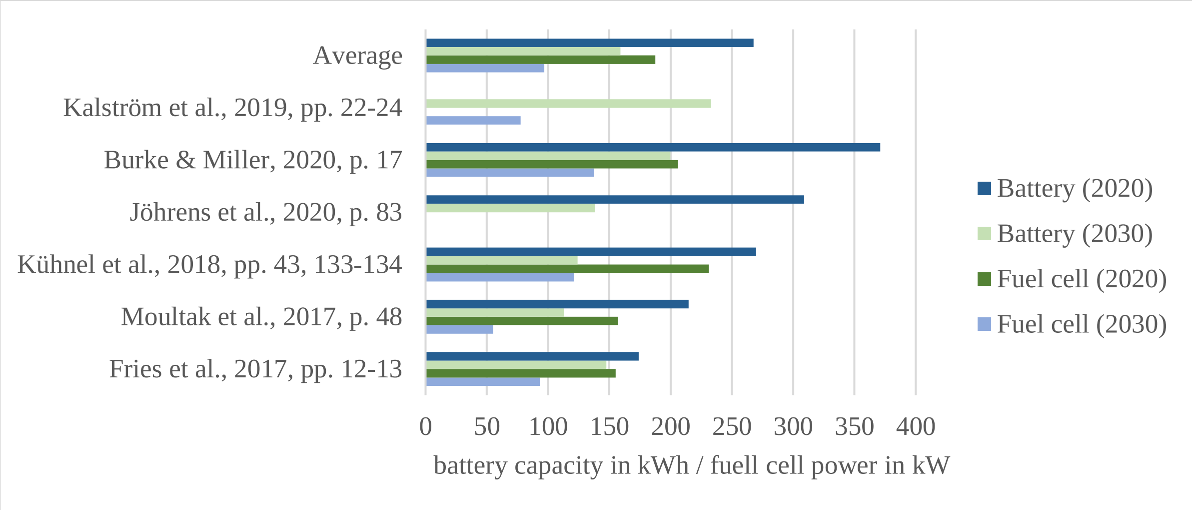
The vehicle component costs are primarily based on Moultak et al. (2017) and Kühnel et al. (2018), two studies published by independent non-profit research institutions, The International Council on Clean Transportation [ICCT] and Öko-Institut e.V., Institute for Applied Ecology (see ICCT, 2020; Öko-Institut e.V., 2020). Both studies have in common that they analysed the complete vehicle cost split up into the main components, but in some parts, they significantly differ in their assumptions and the resulting numbers. Therefore, and for improving the validity of the results of this work, the individual component costs were benchmarked against other studies and adjusted, if considered necessary. With regard to that, there is a special focus on the largest cost drivers of the alternative powertrain technologies, which are batteries, fuel cells and hydrogen storage systems (Moultak et al., 2017, p. 48.; Karlström et al., 2019, p. 25; Kühnel et al., pp. 133-134). For modelling the standard vehicles for the various powertrain technologies, the different technical vehicle configurations, for instance regarding storage or battery capacity, by Moultak et al. (2017) and Kühnel et al. (2018) were streamlined and the values adjusted accordingly, so that the comparability is given. It is important to mention that Kühnel et al. (2018) do not explicitly state vehicle costs for the year 2020, but for 2015 and 2025. Therefore, linear cost developments in that 10-year period are assumed, so that the computed 2020 values represent averages of 2015 and 2025. Comparing these values with other studies showed no significant differences compared to the normal variations, so that this method was validated. In addition, all numbers in Kühnel et al. (2018) were adjusted to the mark up factor of 1.5 instead of the 1.4 assumed in the study (p. 44). For many components, the simple average between these two studies was applied if that seemed to be plausible after comparing with other sources.

In general, the calculated component prices represent the technical production cost multiplied by the mark-up factor of 1.5 (see Calculation methods and data sources). Therefore, the calculated values represent the net prices to the final consumers, also called the retail price equivalent, without taxes or subsidies (den Boer et al., 2013, p. 79-80; Kühnel et al., 2018; p. 44). If taxes and subsidies were included, that would mean an additional mark up, eventually resulting in a resale price of up to twice as high as the manufacturing cost (Fries et al., 2017, p. 15).

Due to the rather low TRL of alternative powertrains compared to conventional ones (see chapter 3.1), and significant related uncertainties of cost developments, it is difficult to estimate the current and future costs of their key vehicle components (Gnann et al., 2017b, p. 905; Kühnel et al., 2018, p. 52). That explains the significant differences in cost estimates across several studies, for instance related to batteries and fuel cells, as shown in **Figure 6** below. However, battery and fuel cell prices are critical for determining the future TCO of electric engine vehicles, as they contribute with a high share to the total vehicle costs (Bubeck et al., 2016, p. 64).

Another critical factor with regard to batteries is their lifetime and the related need for replacement after a certain mileage, which strongly depends on the number of charge cycles required (Kühnel et al., 2018, p. 79). However, based on the comprehensive analysis by Kühnel et al. (2018, pp. 75-79), it is assumed that only the CBEV-100 model requires a replacement of its battery for driving 600,000 km, which takes place in the third year of operation. With regard to CBEV-250 and BEV-400, it is assumed that the batteries hold until the end, but after that, they do not provide significant performance anymore. Due to the least amount of charge cycles required, the battery of BEV-800 is still fully functional after the 600,000 km driven (Kühnel et al., 2018, p. 76). The battery replacement costs of CBEV 100 are not attributed to the acquisition costs as they are depending on the amount of kilometres driven and therefore will be taken into account in the final TCO analysis in chapter 4.3 as additional maintenance costs.

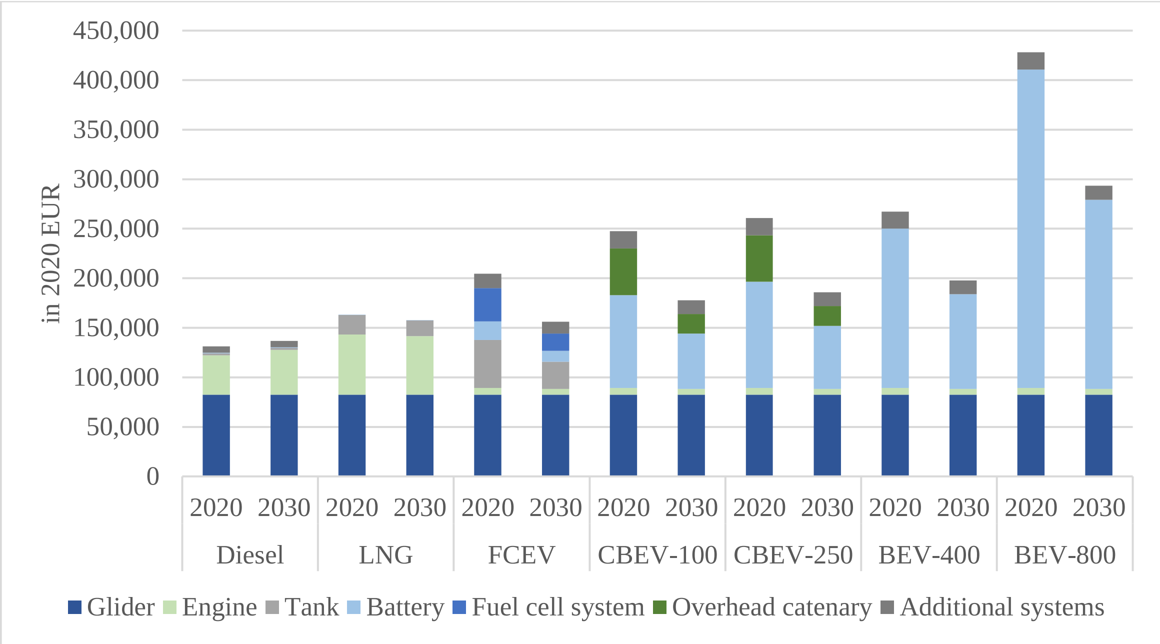
Figure 6: Variations of battery and fuell cell cost projections



With regard to **Figure 6**, the studies chosen for benchmarking the vehicle component costs clearly state the costs they are referring to and represent scientific sources which are themselves based on several other authors and expert opinions. All these numbers were adjusted by the mark up of 50 %, so that they are comparable (as explained in chapter 2.1.3). As the range of cost estimates between all these sources is quite large, applying the simple average seems to be the best valid method for the best estimate, without prioritising or disregarding single studies. That comparison shows that the average of all the studies considered usually lies between the values stated in Moultak et al. (2017) and Kühnel et al. (2018), which demonstrates the credibility of the two main sources. Significant exceptions of this observation are the battery costs in 2030 and the cost for the electric engine, which were underestimated by the main sources in comparison. However, the hydrogen storage costs were overestimated compared to the average of all sources considered. The underlying data of Figure 4 as well as the own estimates for critical components of alternative powertrains are stated in Appendix III.

The results of the process of streamlining technical vehicle configurations and scopes of costs considered as well as adjusting the numbers to 2020 EUR and based on benchmarking are the purchase costs of standard vehicles and their main components across the different powertrains for the years 2020 and 2030, as shown in **Figure 7** below. The underlying data is attached in Appendix IV.

Figure 7: Purchase costs of standard vehicles and their main components



It is important to highlight that the same glider prices are assumed for all standard vehicle technologies. Unfortunately, there is a lack of consent on both the glider component price, ranging from 67,400 to 101,400 EUR in 2020, and its future price development, ranging from decreases of 32.1 % to increases of 10.5 %, in the sources analysed (Burke & Miller, 2020, p. 17; Jöhrens et al., p. 2020, p. 83; Karlström et al., 2019, pp. 23-24; Moultak et al., 2017, p. 47; Kühnel, 2017, p. 133). As the basis for the glider cost evaluation is not discussed in detail, but rather taken as an assumption in all of the sources, the average of about 82,406 EUR applies for the glider price in this work. In addition, it is assumed that there are no real glider price changes by 2030, which means that additional costs related to aerodynamic optimisation and other fuel efficiency measures are set to be equal to cost reductions due to technological progress in the production process across all powertrain technologies analysed.

There is a significant cost advantage of heavy-duty trucks based on Diesel engines, both in 2020 and 2030, with a total purchase price of 131,353 EUR in 2020. Due to efficiency improvements regarding the internal combustion engine, which represents about 1/3 of the total vehicle cost in 2030, the vehicle purchase price increases by about 4.2 % by 2030 (Kühnel et al., 2018, p. 48). Additional systems include the required exhaust treatment system, which is priced at around 6,500 EUR (Fries et al., 2017, p. 13; Moultak et al., 2017, p.47).

In 2020, the total vehicle price of LNG vehicles amounts to 163,274 EUR, which is 24.3 % higher than the Diesel reference. The HDPI engine represents largest powertrain-related cost factor of LNG vehicles, accounting for about 37.1 % of the total purchase cost in 2020, with only marginal cost reductions until 2030 (Wietschel et al., 2017 p. 94). It is important to mention that there are significant differences between the estimations of HDPI engine costs and relative total purchase cost compared to Diesel vehicles (Fries et al., 2017, p. 13; Kühnel et al., 2018, p. 48; Moultak et al., 2017, pp. 47-48). The values calculated here therefore represent best estimates only, which should be taken with caution and could rather represent low numbers compared to other sources. This work calculates with costs of about 173 EUR per kW of HDPI engine power in 2020 and 169 EUR/kW in 2030. Primarily due to significant cost reductions of 19.2 % related to the fuel tank, the total purchase price of LNG heavy-duty trucks decreases by 3.3 % until 2030, reducing the gap to the Diesel vehicles to 15.4 %.

The calculated total purchase price of standard FCEVs is 204,593 EUR in 2020, representing 55.8 % higher costs than for the Diesel reference in 2020. The largest powertrain-related cost drivers are the fuel cells and the hydrogen storage, accounting for 16.5 and 23.6 % of the total vehicle price in 2020. However, the total purchase price is projected to decrease by 23.7 % due to technological progress and scaling benefits from mass market production (Bubeck et al., 2016, p. 64; Burke et al., 2020, p. 17; Wietschel et al., 2017 p. 101). The cost improvements are mainly based on 48.3 % lower fuel cell costs and 43.3 % lower hydrogen storage prices in 2030 compared to 2020 (see **Figure 6** above). In addition, costs for electric engines, representing about 3-4 % of the total purchase price, decrease by 14.7 % and battery prices by 40.5 % until 2030. As a result, the additional total costs of FCEVs are reduced to 14 % compared to Diesel vehicles in 2030 and are even lower than the corresponding LNG vehicle.

All of the electricity-based heavy-duty trucks start at relatively cost high levels and BEVs represent the most expensive models in 2020 with total prices varying between 203.6 % (BEV-400) and 325.9 % (BEV-800) of the Diesel reference value in 2020 (see Appendix IV). Batteries clearly represent the largest cost factors of BEVs and even exceed the costs of the glider. However, as for FCEVs, significant cost reductions are projected by 2030 due to economies of scale based on mass market production, in particular regarding the batteries

(Bubeck et al., 2016, p. 64; Jöhrens et al., 2020, p. 82; Wietschel et al., 2017 p. 97). That results in battery-related cost reductions of 40.5 % by 2030 (see **Figure 6)**. In addition, the electric engine prices decrease by 14.7 % and the costs of additional BEV systems by 20 % until 2030. Resulting from these significant cost reductions, the total purchase prices of BEV-400s decrease by 26% and of BEV-800s by 31.5% until 2030. However, both of these vehicles still remain the most expensive configurations of the models analysed.

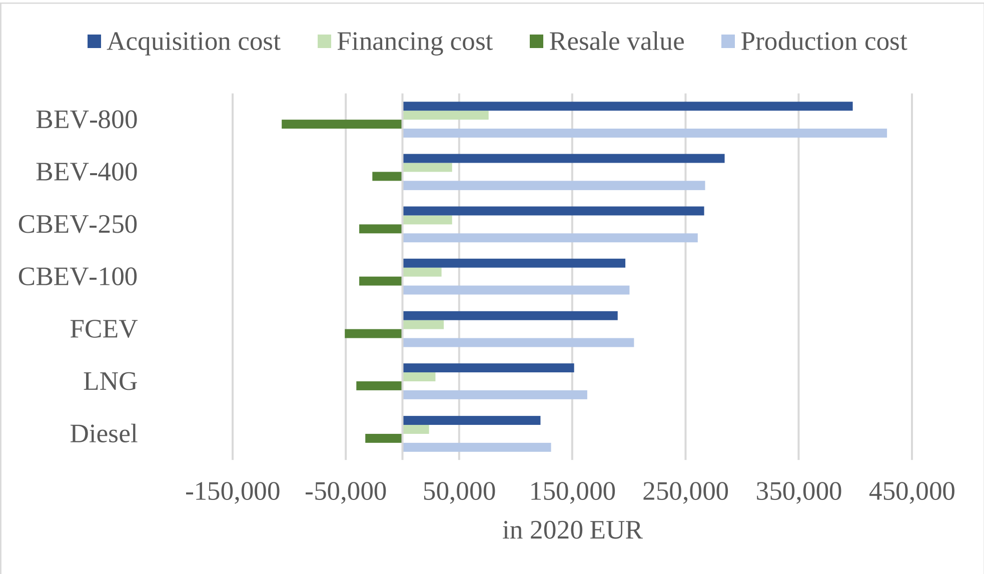
CBEVs dependent on the same variables as the BEV, plus an additional overhead catenary which is priced at 46,845 EUR in 2020. However, the costs for pantographs are projected to drop by 57.8 % until 2030 due to efficiency increases and scale effects to about 19,800 EUR, which is in line with literature (Wietschel et al., 2017, p. 83; Jöhrens et al., 2020, p. 83; Karlström et al., 2019, p. 23). As a result of the significant cost improvements regarding all its main powertrain components, the CBEV-100 becomes the vehicle with the lowest purchase price of the electricity-based models analysed, but still 30 % higher than the Diesel reference. The total purchase price of the CBEV-250 drops by 28.8 % to 185,760 EUR.

4.1.2 Financing and depreciation

Based on Kühnel et al. (2018, p. 46), the nominal resale value generally is assumed to be 24.9 % after five years for all technologies. That is in line or rather a conservative approach compared with Karlström et al. (2019, p. 26), who assume a resale value of 22 % after eight years of ownership. With regard to differences between technologies, Jöhrens et al. (2020, p. 91) apply the same relative depreciation across the different powertrain technologies. On the other hand, Wietschel et al. (2017, p. 86) and Kleiner (2017b, p. 10) do not consider a resale value or only a marginal one of about 3 % of heavy duty trucks with alternative powertrains, as there is no related empirical data or aftermarket available yet. Arguments for at least a lower resale value for alternative powertrains, especially regarding overhead catenary vehicles, mainly rely on the uncertainty about future infrastructure provision Kühnel et al. (2018, p. 46). However, there are also arguments for a potentially even higher resale value of battery-electric heavy-duty trucks in general, due to a higher future durability of batteries, which would imply higher resale values for at least the fully battery-electric vehicles compared to the Diesel ones (Jöhrens et al., 2020, p. 91). Due to the uncertainty regarding the future market development of used-vehicle markets of alternative heavy-duty truck powertrains, this work follows the simplifying approach of Karlström et al. (2019, p. 26) and Jöhrens et al. (2020, p. 91) and assumes the same relative depreciation rate across all technologies. However, is important to highlight that, in line with Kühnel et al. (2018, pp. 46-48, 79, 133), special rules apply for the CBEVs and BEV-400, as their batteries are expected to have no or only significant lifetime left after absolving the 600,000 km. Therefore, the resale value of the batteries of these mentioned vehicles is assumed to be zero after the five years of operation.

Applying the weighted average of past inflation rates and annual financial returns on investments in the DAX as well as taking the nominal interest rate for corporate loans into account (as described in section 2.1.3) results in the calculated real discount rate of 4.98 %. Based on Equation 3 (see section 2.1.3), that leads to a CRF of about 23.08 %.

Figure 8: Structure of the acquisition costs across powertrains in 2020



Merging this information with the vehicle purchase cost as calculated in the previous section allows calculating the total acquisition costs of the different powertrain technologies, as shown for the year 2020 in **Figure 8** (the related numbers and 2030 values are provided in Appendix VII).

The true (or real) acquisition costs stated represent the sum of the production and financing cost minus the nominal resale value, where the NPV adjustments of the resale value were attributed to the financing costs. As both the resale value and the CRF are based on the ame relative numbers for the ICEVs, the FCEV and the BEV-800, their acquisition costs are generally 7.1 % lower than the production price with the nominal resale value accounting for

26.8 % and the financial costs for 19.1 % of the true acquisition costs. As their batteries lose their complete value after the five years (as explained in the previous chapter), the resale value of the remaining three standard vehicles is significantly lower, ranging between 9.4 % (BEV-400) and 20.9 % (CBEV-100). Therefore, their true acquisition costs are higher and in the case of CBEV-250 and BEV-400, they even exceed the nominal production costs by 2.1 % (CBEV-250) and 6.4 % (BEV-400) in 2020. However, with declining battery costs in 2030, the acquisition costs of these three vehicles decrease as well.

4.2 Variable costs

4.2.1 Maintenance and repair

Maintenance costs in general include effort regarding tyres, repair, maintenance and care (Wietschel, 2017, p. 280). Where costs related to tyres are assumed to be equal across the technologies and estimated to amount to 2,46 cents per kilometre, the majority of the remaining maintenance cost drivers are powertrain specific (Wietschel et al., 2017, p. 280).

However, as there has not been an introduction of long-haul heavy-duty trucks with alternative powertrains to the mass market, there is no empirical information regarding their current and future potential maintenance costs available. However, the related literature seems to agree on significantly lower maintenance cost for alternative powertrains compared to ICEVs, especially for BEVs, due to less wearing parts integrated in the vehicles, no exhaust gas treatment system and a lower maintenance intensity in general (Kühnel et al., 2018, p. 56; Zapf et al., 2019, p. 104).

Comparing the maintenance costs assumptions of several studies resulted in best estimates for the years 2020 and 2030, as stated in **Figure 9** in 2020 EUR. These computed values for standard vehicles are primarily based on Kühnel et al. (2018), Kleiner et al. (2017b) for 2020 and complemented by Wietschel et al. (2017) and Karlström et al. (2019) for 2030 (see Appendix V).

In general, the calculated values confirm the in general higher costs for ICEVs compared to alternative powertrains. Both Diesel and LNG vehicles, if they are running on HDPI engines, require exhaust fluid, commonly known as “AdBlue”, for reduced emissions of nitrogen oxides (European Automobile Manufacturers Association, 2020; Mottschall et al., 2020, p. 48). The AdBlue-related expenses amount to 0.0074 EUR/km in 2020 for Diesel trucks and are expected to increase to 0.009 EUR/km by 2030 due to optimisation measures related to the exhaust gas treatment system (Kühnel, 2018, p. 135; Wietschel, 2017, pp. 80-81). For the LNG vehicles based on HDPI engines, a reduced need for AdBlue of 80 % of the corresponding Diesel values is assumed in line with Kühnel (2018, p. 56). Although the exhaust fluid prices are projected to increase, the total maintenance costs of the ICEVs slightly drop by 2030 due to the integration of less complex exhaust systems (Kleiner, 2017b, p. 7). While LNG maintenance costs are the highest ones of the compared powertrains in 2030, they decrease significantly until 2030 and become lower than the expenses for Diesel vehicles.

Figure 9: Maintenance costs per km across powertrains in 2020 and 2030

	Diesel	LNG	FCEV	BEV	CBEV
2020	0.1670	0.1691	0.1609	0.1116	0.1137
2030	0.1650	0.1626	0.1290	0.1098	0.1119

As for internal combustion engine-based vehicles, the maintenance costs for FCEVs are relatively high and amount to more than 16 cents per kilometre in 2020. However, they face the largest cost reduction of the standard vehicles analysed with a relative change of 19.9 % down to 12.9 cents until 2030. In accordance with the literature, BEVs show significantly lower maintenance costs than the other powertrains in 2020 and 2030, accounting for about 2/3 of the expenses related to the Diesel reference vehicle. The additional costs for pantographs of CBEVs are assumed to amount to 0.21 cents and to be constant over time, based on Kühnel (2018, p. 135). It is also important to mention that for the CBEV-100, additional costs for battery replacement arise in the third year of operation, which would amount to 7.8 cents per km in 2020 and 4.64 cents per km in 2030. They are not included in **Figure 9** for methodological reasons, but will be attributed to maintenance costs in the framework of the TCO analysis in chapter 4.3, as they are also depending on the mileage driven (see Kühnel et al., 2018,).

4.2.2 Energy carrier costs

Ah shown in Equation 6 in chapter 2.1.3, the variable fuel costs are the product of the energy carrier price multiplied with the real fuel consumption, as calculated in chapter 3.2.

In general, the scope of what to include in fuel price calculations significantly varies across the related studies. This work looks at the net prices of energy carriers, which are directly related to the technology costs of their provision, including the costs of production or import, transport and provision, as well as margins. As taxes and levies are dependent on political regulations and not market mechanisms, they are explicitly excluded from the calculation.

The price estimates for 2020 are based on observed average energy prices in Germany in 2019, which are assumed to provide the basis for investment calculations in 2020, and related assumptions. For the 2030 prices, the projections are based on literature estimates and own assumptions. The main sources for the benchmarking are Perner et al. (2018), Zapf et al. (2019), Wietschel et al. (2017; 2019), Jöhrens et al. (2020), Kühnel et al. (2018), Karlström et al. (2019) and Bründlinger et al. (2018), as stated more detailed in Appendix VIII. The results of the estimates for relevant energy carrier prices in 2020 and 2030 are shown in **Figure 10**, provided in 2020 EUR. Conversion rates were applied according to Appendix II.

Figure 10: Energy carrier prices in 2020 EUR per kWh

	Diesel	*LNG*	*Hydrogen*	*Electricity*	*Biomethane*	*Biodiesel*
2020	0.0601	0.0404	0.2872	0.0745	0.0932	0.0933
2030	0.0847	0.0450	0.1875	0.0898	0.0932	0.0933

With regard to Diesel, it is important to highlight the high dependency on the oil price, which is why it is highly volatile over time (Ederington et al., pp. 3, 14). The average net price amounted to 59.45 cents per litre in Germany in 2019, consisting of 44.17 cents procurement costs (Mineralölwirtschaftsverband e.V., 2020). This results in technology costs of 6.1 cents per kWh in 2020. The projections for 2030 vary significantly across literature, with total net prices ranging between 8.3 and 9.6 cents per kWh (Perner et al., 2018, p. 80; Wietschel et al., 2017, p. 141). Based on the benchmarking, Diesel commodity costs of 6.7 cents are estimated for 2030 and a total net price of 8.47 cents, which means a significant increase by 40.9 %. This is mainly due to the projected oil price change from 70.9 to 105.9 EUR per barrel, which could be justified by several reasons such as geopolitical and economic developments or a decreasing total supply, for instance due to approaching “peak-oil” (Murphy & Hall, 2011, pp. 56-63). This would result in a price for final consumers of 1.59 EUR/l compared to 1.27 EUR/l in 2020, including the energy tax applicable and the value added tax (Federal Ministry of Finance, 2020).

Similar to the Diesel-oil price relationship, the LNG import price strongly depends on the natural gas price, which is highly volatile as well (Kühnel et al., 2018, p. 52). The 2020 price estimate is based on Eurostat (2020a), who state a minimum wholesale price of 2.2 cents per kWh in 2019, depending on the consumption volume. As there has no real LNG market developed yet, which is shown by only 21 LNG fuel stations in Germany as of 2020, information regarding processing, transport and provision costs is difficult to find (Natural & bio Gas Vehicle Association, 2020). Therefore, related cost in the amount of 1.8 cents are applied, which is based on the 2030 assumptions, but also in line with Kühnel et al. (2018, p. 52). As a result, LNG shows the most competitive technology-related costs per kWh in both years, with lower prices than Diesel by 32.8 % in 2020 and 47.9 % in 2030. The projected natural gas import prices for 2030 significantly vary with values between 2.1 and 3.1 cents per kWh, leading to an average of 2.7 cents per kWh based on five studies (Kühnel et al., 2018, p. 52; Zapf, 2019, p. 265; see Appendix VIII). Taking into account the energy tax and the VAT, end consumers would have to pay 0.87 EUR per kg in 2020 and 0.95 EUR per kg in 2030 (Federal Ministry of Finance, 2020).

For the electricity price calculation, it is important to understand the structure of the end consumer price in Germany first. The gross electricity price paid by households amounted to 30.85 cents per kWh on average in 2019. It consists of the procurement costs, grid fees, the EE-levy for supporting the expansion of renewable energy sources, as well as taxes and additional levies (Federal Network Agency, 2020a). For households, costs of production and distribution amounted to 7.61 cents per kWh and the grid fee to 7.22 cents per kWh (Federal Network Agency, 2020a). For the subsequent calculations, the wholesale price acts as a proxy for the production costs which was 3.74 cents in 2019 (Hein et. al, 2020, p. 5). It is important to mention that the grid fee does not represent the real transport costs on a market basis, as it is determined by monopolistic grid providers as well as by regulation authorities (Federal Network Agency, 2020b). In addition, the grid fees paid by commercial consumers per kWh strongly vary depending on the consumption level, which makes estimating the variable transport costs difficult (Federal Network Agency, 2020b, Eurostat, 2020b). Therefore, this work adopts the assumptions by Kühnel et al., (2018, p. 135) of distribution costs of 3.75 cents per kWh (in 2020 EUR), which include transport costs and margins and do not change in real terms over time. That results in a technological total net price for electric energy price of 7.49 EUR per kWh in 2020. Looking at the future development, the commodity price of electricity is expected to increase to 5.34 cents per kWh, which results in 21.4 % higher net electricity costs in 2030 (Bründlinger et al., 2018, p. 255; Kühnel et al., 2018, p. 135).

The hydrogen price in Germany amounts to 9.5 EUR per kg. However, this is a politically motivated and not market-based price and it is not taxed either (Kühnel et al., 2018, p. 54). As there are currently only about 80 hydrogen fuel stations and no real market existing in Germany, it is difficult to estimate the real production costs and the additional price components (H2 MOBILITY, 2020). Therefore, the price "agreed on" is treated as the total net price basis for the 2020 hydrogen costs of 28.7 cents per kWh. For 2030, the net price for hydrogen based on renewable electricity sources, especially offshore wind energy, is expected to drop by 34.7 % to 18.7 cents per kWh, which is equal to 6.26 EUR per kWh. That is based on assumed electrolyser efficiencies of 70 % (LHV), which is in line with Perner et al. (2018, p. 66) and Wietschel et al. (2019, p. 47). According to Zapf et al. (2019, p. 292-293), renewable hydrogen requires significantly higher transport, storage and distribution costs than the other energy carriers in 2030, especially due to the high costs involved for the fuel stations, With a minimum of about 10 cents per kWh, they even exceed the production costs in 2030 (Zapf et al., 2019, p. 292-293).

With regard to Biofuels, Wietschel et al. (2019, pp. 44-46) and Zapf et al. (2019, p. 294) both assume constant production costs over time, which indicates that the maximum cost reduction potential has already been reached. With regard to biomethane, average productions costs of 7.9 cents per kWh are applied, considering an assumed efficiency of the liquification process of 95 % and related plant costs of 0.7 cents per kWh (Wietschel et al., 2019, p. 48). Adding the transport costs results in a total net price of 9.32 cents per kWh. For biodiesel, Zapf et al. (2019, p. 294-295) assume slightly higher production costs of 8.25 cents per kWh, but by 25.2 % lower transport and provision costs compared to biomethane. As a result, the total net prices of both types of biofuels are estimated to amount for almost the same, with 9.32 and 9.32 cents per kWh.

As of now, PtX technologies based on renewable electricity are far away from being competitive with other energy carriers, as their production costs alone account for more than 20 cents per kWh due to significantly higher transport costs (2019, p.133). For that reason, they are not considered as a part of the 2020 analysis. However, Perner et al. (2017, pp. 81-83) project the synthetic fuels to drastically decrease in future prices, so that they could be imported for about 15.3 cents kWh from North Africa or for 12 cents per kWh from Iceland by 2030 already (the 2030 PtX price projections are attached in Appendix VIII). As synthetic natural gas, in this work referred to as PtX-LNG, is both cheaper to produce and more environmentally friendly (see the comparison chapter 5.1) than its liquid diesel equivalent, it will be the only PtX energy carrier considered in further analysis, as it is assumed that it would rule out PtX-Diesel (Perner et al., 2017, p. 87).

In general, it is important to highlight that biofuels and PtX-LNG are not in the focus of this work, but are rather meant to show up further potential options for decarbonising the heavy-duty road freight transport sector besides the main energy carriers covered.

4.3 Results of the TCO analysis

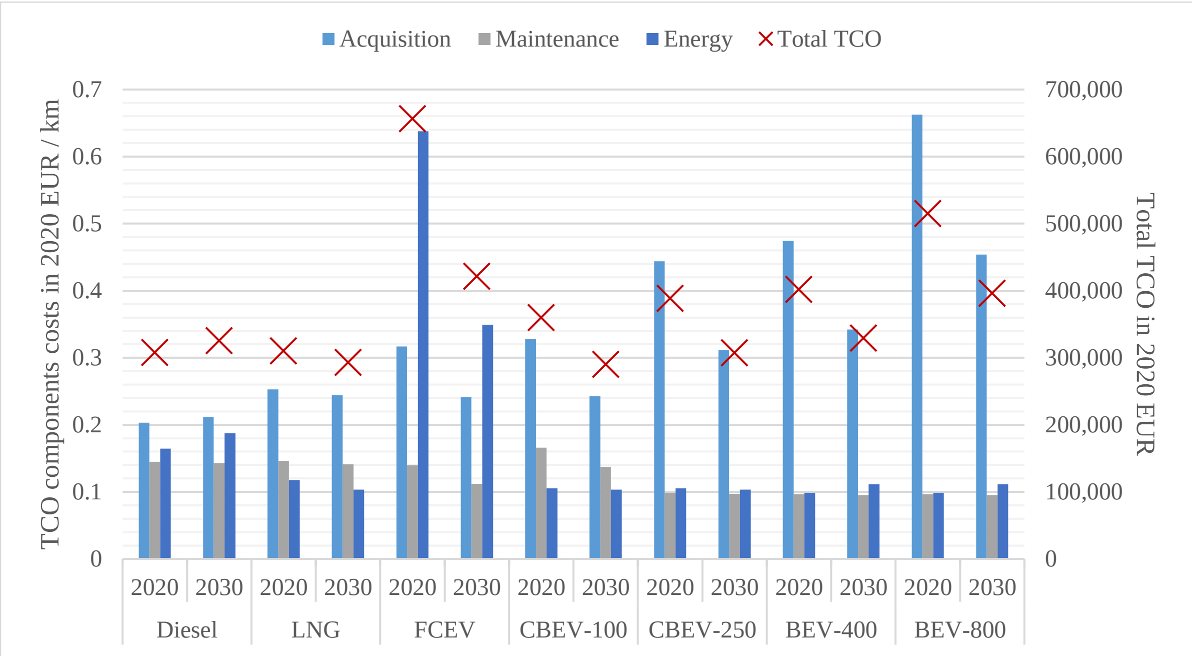
Merging all the information gathered in the previous chapter enables to get an overview of the total cost of ownership of the different LHHDT standard vehicles and thereby, gaining insights into the main cost drivers of the various technologies. The results are shown in **Figure 11**, based on the data from the previous chapters and stated on an aggregate level in Appendix IX. For reasons of readability, biofuels and PtX-LNG are not included in the graphics, but their data are provided in Appendix IX as well.

In 2020, the diesel reference vehicle shows the lowest true economic costs of all standard vehicle models analysed with a TCO of 307,535 EUR. However, it is closely followed by the LNG standard vehicle, which in contrast to the diesel vehicle is projected to face decreasing future costs, so that it eventually shows 9.9 % lower TCO than the diesel reference in 2030.

The largest cost reductions take place related to the FCEVs, which drop by 35.8 % in price by 2030 with their energy costs representing the key driver as they fall by 55.2 %. However, FCEVs still represent one of the most expensive technologies with TCO of 421,557 EUR, only outbid in price by the PtX-LNG vehicle by 4.9 %.

The BEVs and CBEVs also face significantly decreasing costs by 23 % (BEV-800) to 18.1 % (BEV-400) until 2030, where decreasing battery costs are the main contributors leading to the acquisition costs falling by 26.1 % (CBEV-100) to 31.5 % (BEV-800). CBEV-100 becomes the cheapest technology with TCO of 289,865 EUR, which is 1.1% less than for the LNG model, and CBEV-250 reaches the lower costs than the diesel reference, but still faces 4.8% higher TCO than the LNG-vehicle in 2030.

Figure 11: Total vehicle TCO and its main components in 2020 and 2030



With regard to biofuels, they remain at relatively high TCO levels compared to the CBEVs in 2030, but catch up related to the diesel reference, reducing the difference to 3.5 % (biodiesel) and 10.4 % (Bio-LNG).

Figure 12: TCO shares of key components for long-haul HDVs in 2030

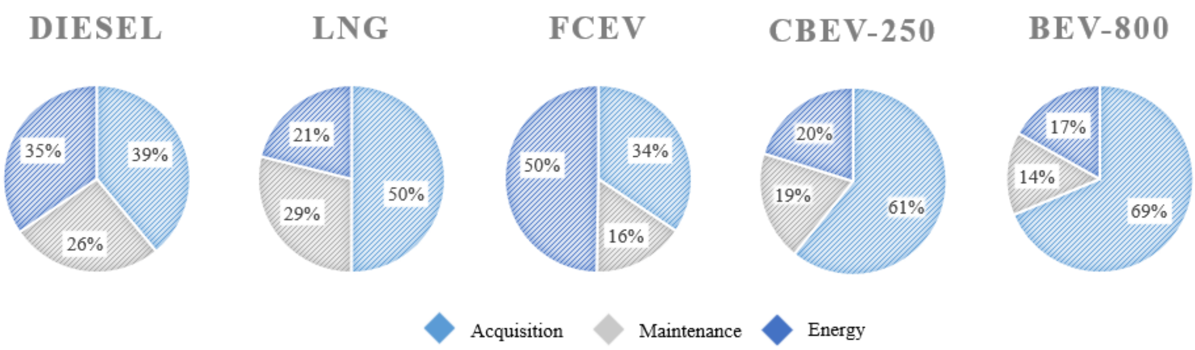


Figure 12 demonstrates the key cost components of the largest representatives of each of the main powertrains-energy carrier combinations analysed in this work. This shows significant

differences between the cost structures of the standard vehicles. As the CBEV and BEV strongly rely on battery costs with a share of over 60 % of the TCO, the competitiveness of FVECs is highly dependent on the hydrogen costs. For LNG vehicles the total acquisition costs represent about 50 % of the TCO. Of these standard vehicles considered, the diesel model is the only one with an almost balanced cost structure.

5. LCA of long-haul heavy-duty truck technologies

This chapter aims to analyse the climate-related impact of the different energy carriers consumed by the modelled standard vehicles. With regard to that, the first step is to conduct a WTW assessment of GHGs emitted over the whole life cycle of the energy carriers, based on related state-of-the-art research. As a result, emission factors will be estimated for eventually being able to evaluate the total climate impact of the vehicle-fuel combinations covered over the five years ownership period.

5.1 WTW analysis of energy carriers

As elaborated in chapter 2.2, the LCA aims to evaluate the impact of the standard vehicles configurated on climate change. Since the GHG emissions related to the vehicle production and disposal are neglectable, this the environmental impact assessment focusses on the WTW emissions of the energy carriers consumed by the different LHHDT technologies (Sen et al., 2017, p. 116; Wietschel, 2019, p. 28).

In that framework, a comprehensive research was conducted for estimating the WTT emissions related to all the steps of the fuel provision as well as the TTW emissions through the consumption. However, the methods applied in research do not seem as streamlined as required for conducting a detailed and accurate analysis. For instance, in Kühnel et al. (2018, pp. 36-39) include CO2 in their WTW analysis only while Zapf et al. (2019, p. 160) exclude N2O, Mottschall et al. (2020, p. 35) highlight the importance of including CH4 emissions, especially with regard to LNG trucks, and Sen et al. (2017, p. 116) demonstrate the non-neglectable role of NOx. One major issue is the lack of transparency on what data the authors exactly use and how they treat them for getting their results. On the basis of these circumstances, this work tries to find a middle way between the different approaches by trying to include the most relevant factors for each energy carrier, which results in estimated WTW values as stated in **Figure 1**. Zapf et al (2018) represent the basis of these values, as they provide the most comprehensive and detailed WTW analysis of the studies looked at. However, whenever possible, their values were benchmarked, mainly against Mottschall et al. (2020, pp. 28-40) and Wietschel et al. (2019, pp. 4, 8) and if considered beneficial for the accuracy of the data, adjusted accordingly. All numbers were converted into grams of carbon dioxide equivalents (gCO2eq).

Figure 13: WTW emissions of energy carriers in gCO2eq per kWh in 2020 and 2030

	Diesel	*LNG*	*Hydrogen*	*Electricity*	*Biomethane*	*Biodiesel*	*PtX-LNG*
2020	337.62	299.04	68.00	401.00	32.40	64.20	61.80
2030	337.62	299.04	37.40	188.00	32.40	64.20	53.00

It is important to highlight that for BEVs, O-BEVs and FCEVs, there are no TTW emissions, so the WTW values stated represent the WTT emissions for the generation and/or production, refining, transport and provision of the corresponding energy carrier (Zapf et al., 2019, p. 160). That also accounts for ICEVs using biofuels and synthetic energy carriers, as they emit (almost) the same CO2 during the operation as was captured for their production beforehand (Zapf et al., 2019, p. 160; Jöhrens, 2020., p. 28).

With regard to the climate impact of electricity, literature tends to significantly underestimate the reduction pathway. For instance, Kühnel et al. (2018, p., 38), Jöhrens et al., 2020, p. 28), Wietschel et al. (2019, p. 4) and Zapf et al. (2019, p. 162) all project the emissions of the electricity mix in Germany to account for around 500 gCO2eq per kWh. Compared to that, German Environment Agency (2020c) estimates the CO2 intensity of the electricity mix in Germany to have accounted for 401 gCO2 per kWh. Unfortunately, they do not sate the remaining GHG emissions but except for gas and hard coal, which together accounted for less than 20 % of the electricity mix in 2019, the other energy sources only have minor impacts on CH4 or N2O (Fraunhofer, 2020; UBA, 2017, pp. 43-62). For that reason and due to further expected GHG reductions in 2020 in line with the climate targets the government of Germany announced (as described in 1.1), the 2019 CO2 electricity emission factor represents the GHG estimation for the GHG emissions of electricity in 2020. With regard to the 2030 projection, the value of 188 CO2eq per kWh by Zapf et al. (2019, p. 161) was adopted, which is in line with Wietschel et al. (2019, p. 8) and represents a rather optimistic estimate compared to other studies, which project numbers in the range between 300 and 413 CO2eq per kWh (Jöhrens et al., 2020, p. 28; Kühnel et al., 2018, p. 38). On the other hand, that scenario remains realistic in the light of the 2030 targets of significantly expanding the share of renewable energy, while also considering phasing out coal power plants and thereby, the heaviest polluting electricity generation technology simultaneously (Federal Ministry for Economic Affairs and Energy [BMWi], pp. 62-65; UBA, 2017; BMU, 2020).

According to Mottschall (2020, pp. 36-37), it is essential to take at least CH4 emissions into account when conducting a WTW LCA for fuels based on fossil sources as well as synthetic and biomethane, as neglecting could lead to significant biases, especially when comparing diesel with LNG vehicles. In general, there is also a high uncertainty about the extent of methane leakage at various stages of the fuel lifecycles with estimates ranging between 0.4% and 12% of the total natural gas produced (Mottschall, 2020, p. 29). That risk of methane but also of nitrogen oxide slip applies similarly to biomethane and synthetic natural gas, and therefore, the other GHGs should not be neglected in these cases (Mottschall, 2020, p. 43). Another important factor is the origin of the imported LNG, as gas extracted by unconventional methods, such as fracking in the U.S, could have a significantly worse climate balance by 24 to 41, which could make LNG more polluting – origin of LNG essential for competitive GHG balance of additional 84.4 to 147.4 gCO2eq per kWh (Mottschall et al., 2020, pp. 29, 37-38).

The estimates for Diesel and LNG were adjusted upwards by the average of the calculated values by Mottschall et al. (2020, p. 28) and Wietschel et al., 2019, (p. 7), since the initial estimates by Zapf et al. (2019, p. 161) were significantly lower than comparable ones by Gnann et al. (2017b, p. 904), Jöhrens et al. (2020, p.) and Moultak et al. (2017, p. 25) and excluded at least N2O. The resulting value of 337.62 GHG emissions per kWh of diesel consumed is close to the average of the five studies mentioned. For LNG, there is a lack of comparability, but benchmarking with Moultak et al. (2017, p. 25) and Mottschall et al. (2020, p. 28) indicates that the updated estimate is still rather law and therefore, applied.

For biomethane, the outdated estimate for 2016 by Zapf et al. (2019, p. 161) was updated by the average emission factor of biomethane in the transport sector in Germany in 2019 of 32.4 gCO2eq per kWh, including CH4 and N2O emissions, as provided by Mottschall et al. (2020,

p. 40). That approximately corresponds to the long-term estimates by Zapf et al. (2019, p. 161) and therefore, is not considered as contradictory.

With regard to biodiesel, hydrogen and PtX-LNG, the estimates by Zapf et al. (2019, p. 161) were adopted, as there was no suitable benchmark available. That could lead to overestimated hydrogen emission results for 2020, as they were not adjusted by the lowered electricity ones. However, they correspond to the initial electricity emissions value in 2030, so that the future analysis is not affected by this. In general, it is worth mentioning that hydrogen starts with higher GHG emissions per energy unit than synthetic natural gas, which is essentially due to significantly more environmental effects of its transport and distribution (Zapf et al., p. 133). However, these emissions are projected to decrease significantly, so that hydrogen becomes more climate-friendly than synthetic natural gas by 2030.

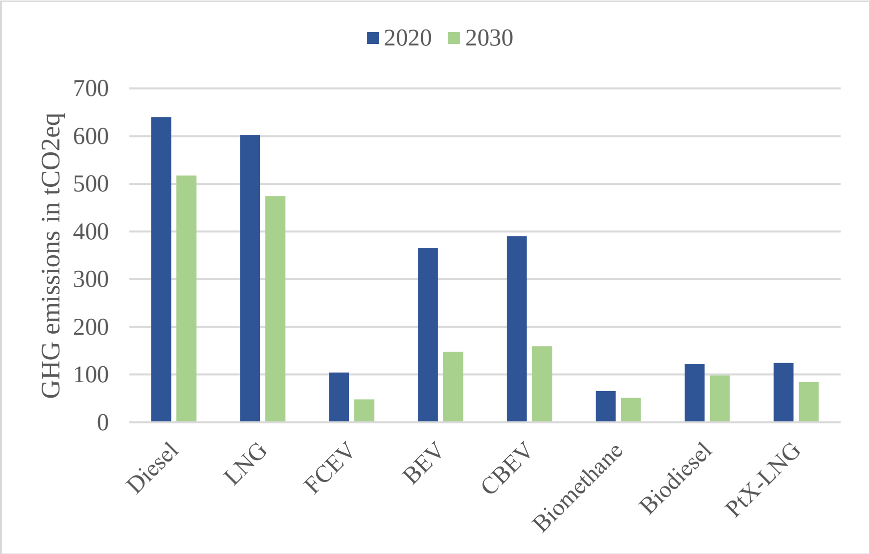
In general, it is important to highlight that all the LCA estimates are based on best knowledge available, considering limited resources. Therefore, these values can indicate environmental characteristics of certain energy carriers only and should not be taken as precise calculations (in contrast to the TCO analysis in chapter 4).

5.2 Total GHG emissions over the ownership period

Based on the thoughts and calculations discussed in the previous chapter, the accumulated climate-impact of the different standard vehicle configurations of LHHDTs over the total ownership period of five years is shown in **Figure 14**. Although there were several simplifying assumptions made the for enabling this, the relative emissions between the different vehicle technologies seem to be close to the findings from Mottschall et al. (2020, p. 37), Kühnel et al. (2018, p. 39), Jöhrens et al. (2020, p. 39) and Wietschel et al. (2019, p. 29). The underlying data are provided in Appendix X.

It clearly stands out that the fossil energy carriers cause the highest accumulated GHG emissions over the holding periods of the vehicles with the WTW emissions by diesel of 640 tons of CO2 equivalents exceeding all alternative powertrains significantly in 2020. Although the diesel emissions decrease by 19.1 % by 2030, their relative change is lower compared to all other technologies besides biodiesel, which decreases by the same share. The emissions of LNG account for about 94.1 % of the diesel ones in 2020 and are expected to fall by 21.2 % by 2030. Here, it is again important to consider that unaccounted methane leakages could result in significantly higher true GHG emissions, even exceeding the ones of the diesel vehicle (see the previous chapter).

Figure 14: Accumulative WTW GHG emissions



CBEVs, BEVs and FCEVs are projected to reduce their GHG emissions substantially by more than 50 % by 2030. However, electricity is expected to still be the least climate-friendly alternative energy carrier by 2030 based on the projected electricity mix developments. However, an alternative scenario with exclusively renewable electricity consumption will be assessed in the framework of the sensitivity analysis. Remarkably, FCEVs are projected to surpass biodiesel and Bio-LNG with regard to climate-friendliness and represent the least polluting of the technologies looked at by 2030.

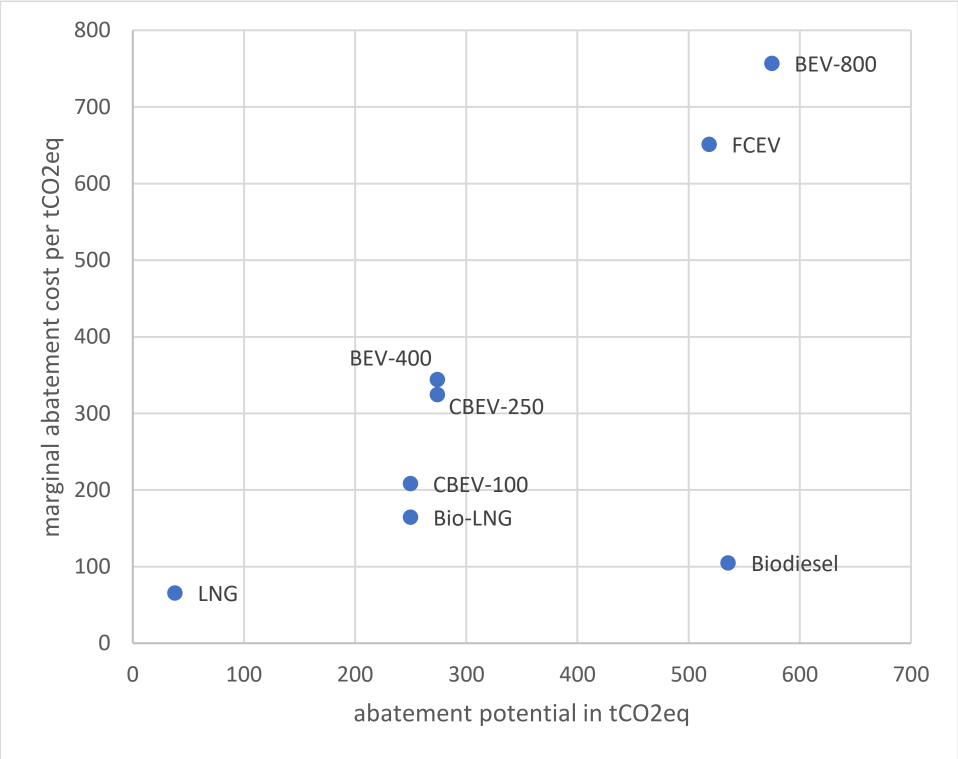
With regard to the biofuels, Bio-LNG represents the least polluting energy carrier in 2020, accounting for a share of 10.2 % of the GHG emissions of the diesel reference vehicle in 2020, with even further decreasing emissions by 21.2 % by 2030. Biodiesel and PtX-LNG start at about the same emission impact level in 2020, but the synthetic fuel is projected to decrease significantly more by 32.4 %.

With both the TCO and LCA conducted for all the standard vehicle technologies considered in this work, the requirements are met for evaluating the CO2 abatement costs in the final step.

6. CO2 abatement costs and political implications

The following two diagrams represent the result of this work, showing the marginal CO2 abatement cost in 2020 and 2030 and related abatement potential. The x-axis represents shows how many tons of carbon dioxide could be avoided by switching from the diesel reference LHHDT to another technology. The y-axis shows the cost of switching to the corresponding technology expressed in potential tons of carbon abated.

Figure 15: Marginal CO2 abatement cost in 2020

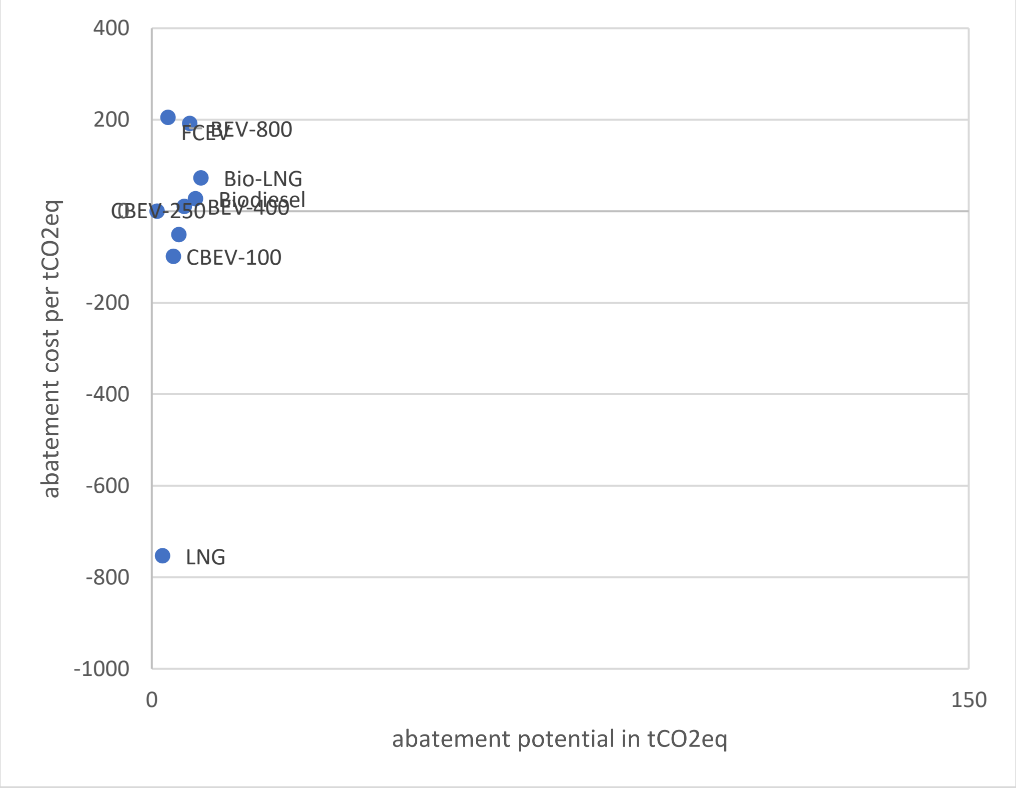


The results for 2020 show that LNG vehicles provide the least carbon abatement cost per tCO2eq avoided, but they also offer the least total abatement potential. However, biodiesel could provide a high abatement potential at low carbon abatement costs and therefore, potentially represent the best available transition technology towards electrification.

It is important to consider that biofuels could never represent the only solution, but rather a part of it, since the resources are very limited and are directly competing with food production. The biomethane potential in Germany represents only a fraction of the theoretical need and the capacities today could supply 25% of the total truck transport demand only (Mottschall et al., 2020, p. 42).

Integrating the social carbon cost rate into these figures would help politicians for deciding on potential political measures required for initiating the decarbonisation of the transport sector, for instance imposing a Pigouvian tax.

Figure 16: Marginal CO2 abatement cost in 2030

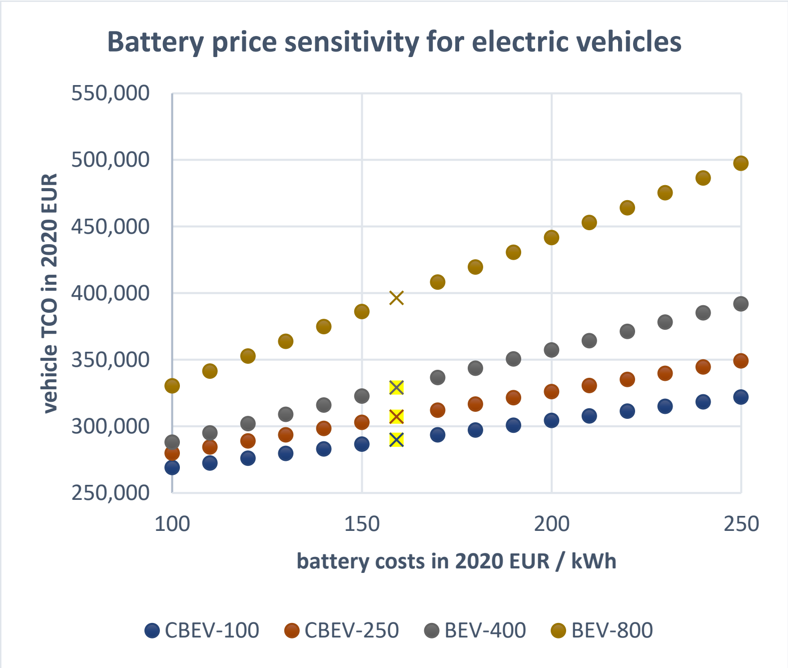


In 2030, LNG even shows a high negative value of CO2 abatement costs, which would mean that fuel-switching would actually be of benefit only for the truck owner – both economically and ecologically. In addition, both of the CBEV technologies provide negative CO2 abatement costs as well and that with a significantly higher abatement potential.

Taking the range issue of the CBEVs into account as well, CBEV probably would represent the most rational purchase decision.

For proofing these findings against potential changes of key parameters, a sensitivity analysis should be subject to further research. For instance, battery costs are the main cost components of BEVs and CBEVs, which is why the total TCO of these vehicles is assumed to be relatively sensitive towards price changes. That is confirmed by **Figure 17** below, which shows significant variations of the TCO related to potential battery price changes from the projected price level in 2030 (highlighted in yellow).

Figure 17: Battery price sensitivity of the TCO of BEVs and CBEVs in 2030



Further sensitivity analysis could cover lower future fossil prices than assumed, which would most likely increase the CO2 abatement costs. Another interesting scenario could include guarantees of low-carbon origin for electricity (GOE) according to the polluter-pays-principle, which would require a price premium (such as 3 ct per kWh) paid for lowering the GHG share of electricity consumed. Furthermore, the effects of changing interest rates could be investigated by modelling a low and a high interest rate scenario.

In addition, there is potential of economies of scale applying to the integration of batteries into a vehicle. As smaller batteries require higher relative performance, the battery cost could decrease with an increasing battery capacity (Zapf et al., 2019, pp. 110-111). Another reason for declining cost increases could be a lower complexity of the process of further implementing batteries once a certain minimum amount of batteries is reached (Kühnel et al., 2018, p. 46). Therefore, the EoS-scenario follows the simplifying assumption of Kühnel et al. (2018, p. 46) that the mark-up factor decreases by 50% to 1.25 for battery capacities on top of a minimum level of 175 kWh. Three BEV technologies benefit this, with their battery cost now reduced to 136.49 EUR/kWh (BEV800), 140.36 EUR/kWh (BEV400) and 144 EUR/kWh (OCBEV250).

The study by Burke & Miller (2020, p. 17) suggests that cost reductions of key parameters for alternative powertrain technologies could further decrease after 2030. Considering this, factors and the in general rather conservative cost estimates with regard to new technologies compared to the lowest estimates, the TP-scenario assumes substantial cost decreases for electricity- and hydrogen-related key components by 2050. Methodologically, the values applied represent the averages of the two lowest 2030 estimates of the sources analysed, which leads to cost of 118.32 EUR/kWh for batteries, 66.42 EUR/kW for fuel cells, 12.14 EUR/kW for hydrogen storage and 14.16 EUR/kW for electric engines.

6.1 Limitations of the results

Infrastructure needs were not taken into account, neither were other externalities such as noise or air pollution.

6.2 Political implications

In mid-2019, the EU finally adopted a CO2 regulation for newly registered heavy-duty vehicles for the first time. Similar to the CO2 emission standards for passenger cars and light commercial vehicles, the regulation requires vehicle manufacturers to reduce the CO2 emissions of their new vehicle fleets over time. The regulation stipulates that the average CO2 emissions of the new vehicle fleet must be reduced by 15 % by 2025 and by 30 % by 2030.

I AM SORRY FOR THIS BEING THE END, BUT I HAD TO HAND IT IN.

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Appendix

I. List of abbreviations

BEV = battery electric vehicle	TRL = technology readiness level
CAPEX = capital expenditures	TTW = tank-to-wheel
CBEV = catenary battery electric vehicle	t = tonne/tonnes
CO2 = carbon dioxide	TTW = tank-to-wheel
DGE = diesel gallon equivalents	U.S. = United States
EUR = euro	VAT = value-added tax
EU = European Union	WTT = well-to-tank
FCEV = fuel cell electric vehicle	WTW = well-to-wheel
GHG = greenhouse gas	
GVW = gross vehicle weight	
HDT = heavy duty truck	
HDPI = high-pressure direct injection	
ICEV = internal combustion engine vehicle	
km = kilometre	
kWh = kilowatt hour	
LCA = life-cycle assessment	
LHHDT = long-haul heavy-duty truck	
LNG = liquified natural gas	
MJ = megajoule	
OEM = original equipment manufacturer	
OPEX = operational expenditures	
TCO = total cost of ownership	
TEA = techno-economic assessment	

II. Technical and economic conversion rates

Technical energy conversion rates

1 kWh = 3.6 MJ	(American Physical Society, 2020)
H2 (LHV): 1 kg = 120.21 MJ	(Essom, 2018; Kühnel, 2018, p. 35)
LNG: DGE = 2.749 kg	(NIST, 2014, p. 5)
LNG (LHV): 1 kg = 48.632 MJ	(Essom, 2018; Kühnel, 2018, p. 35)
Diesel (LHV): 1 kg = 42.791 MJ	(Essom, 2018)
Diesel: 1 litre = 0.840 kg	(Government of Canada, 2018)
Oil: 1 barrel = 159 litres	(American Physical Society, 2020)

Economic rates

Effective loan interest rate for 5 years = 1.652	(Deutsche Bundesbank, 2020a)
DAX 2019 / DAX 2015 = 1.10988	(Deutsche Bundesbank, 2020b)
DAX 2019 / DAX 2010 = 1.98279	(Deutsche Bundesbank, 2020b)
2015 USD / 2015 EUR: 1.1095	(ECB, 2020)
2017 USD / 2017 EUR = 1.1297	(ECB, 2020)
CPI 2015 / CPI 2010 = 1.07199	(The World Bank Group, 2020b)
CPI 2020 (Q1) / CPI 2015 = 1.06267	(Federal Statistical Office of Germany, 2020a)
CPI 2020 (Q1) / CPI 2017 = 1.04209	(Federal Statistical Office of Germany, 2020a)
CPI 2020 (Q1) / CPI 2018 = 1.02434	(Federal Statistical Office of Germany, 2020a)
CPI 2020 (Q1) / CPI 2019 = 1.0095	(Federal Statistical Office of Germany, 2020a)
PPI 2020 (Q1) / PPI 2015 = 1.0460	(Federal Statistical Office of Germany, 2020b)
PPI 2020 (Q1) / PPI 2017 = 1.03496	(Federal Statistical Office of Germany, 2020b)

III. Literature estimates of current and future key component costs of alternative powertrains

		Unit	*Fries et al., 2017, p. 15*	*Moultak et al., 2017, p. 48*	*Kühnel et al., 2018, pp. 43, 133*	*Jöhrens et al., 2020, p. 83*	*Burke & Miller, 2020, p. 17*	*Karlström et al., 2019, pp. 22-24*	*Average*
2020	Battery	EUR/kWh	173.87	214.71	269.87	308.94	371.04		267.68
	Fuel cell	EUR/kW	155.24	157.04	231.09		206.13		187.37
	H2 storage	EUR/kWh	32.60	21.68	30.38		20.62		26.32
	Electric drive	EUR/kW	15.52	17.16	19.72	27.17			19.89
2030	Battery	EUR/kWh	147.48	112.71	123.95	138.17	199.72	232.87	159.15
	Fuel cell	EUR/kW	93.15	55.22	121.09		137.42	77.62	96.90
	H2 storage	EUR/kWh	13.97	17.31	17.46		10.31	15.52	14.92
	Electric drive	EUR/kW	15.52	13.68	14.65	25.46		15.52	16.97

IV. Purchase cost of key standard vehicle components in 2020 and 2030

	Diesel		*LNG*		*FCEV*		*CBEV-100*		*CBEV-250*		*BEV-400*		*BEV-800*	
	2020	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**
Glider	82,406	82,406	82,406	82,406	82,406	82,406	82,406	82,406	82,406	82,406	82,406	82,406	82,406	82,406
Engine	39,687	45,166	60,650	59,049	6,962	5,939	6,962	5,939	6,962	5,939	6,962	5,939	6,962	5,939
Tank	2,047	2,044	19,750	15,962	48,244	27,340								
Battery	513	512	467	455	18,738	11,140	46,845	27,851	107,074	63,659	160,610	95,489	321,221	190,978
Fuel cell system	0				33,727	17,442								
Overhead catenary	0						46,916	19,800	46,916	19,800				
Additional systems	6,700	6,691			14,515	11,773	17,438	13,956	17,438	13,956	17,438	13,956	17,438	13,956
Total vehicle cost	131,353	136,819	163,274	157,873	204,593	156,041	200,567	149,952	260,796	185,760	267,417	197,790	428,027	293,279

V. Literature estimates of current and future maintenance costs per km

	2020		2030			
	Kühnel et al., 2018, p. 135	*Kleiner et al., 2017b, p. 8*	*Wietschel et al., 2017, pp. 79-81, 91-102*	*Karlström et al., 2019, p. 26*	*Kühnel et al., 2018, p. 135*	*Kleiner et al., 2017b, p. 8*
Diesel	0.1591*	0.1675	0.1612*	0.1532	0.1516*	0.1675
LNG	0.1701*	0.1629	0.1516*		0.1584*	0.1629
FCEV	0.2046	0.1173	0.1456	0.1073	0.1456	0.1173
BEV	0.1116	0.1116	0.1137	0.1021	0.1116	0.1116

**including costs for diesel exhaust fluid of 0.0074 EUR/km (Diesel) and 0.0060 EUR/km (LNG) in 2020 and 0.0085 EUR/km (Diesel) and 0.0072 EUR/km (LNG) in 2030 (Kühnel et al., 2018, p. 135; Wietschel et al., 2017, pp. 80-81)*

VI. Literature estimates of current and future fuel use in kWh per km

		Jöhrens et al., 2020, p. 82	*Moultak et al., 2017, pp. 16, 49*	*Kühnel et al. 2018, p. 32*	*Wietschel et al., 2017, pp. 79-81, 93-102*	*Karlström et al., 2019, p. 14*	*Delgado et al., 2017, pp. 30, 38*
2020	Diesel	3.14	3.33	3.00	2.89	3.30	3.30
	LNG		3.61	3.23	3.23		
	FCEV		2.44	2.51	2.50	2.80	
	BEV	1.16		1.43	1.34	1.60	
	CBEV	1.28	1.47	1.53			
2030	Diesel	2.72	2.50	2.40	2.46		2.70
	LNG		2.78	2.38	2.78		
	FCEV		2.11	2.09	2.25		
	BEV	1.06		1.29	1.23		
	CBEV	1.20	1.25	1.38			

VII. Acquisition costs of standard vehicles split up into main components for 2020 and 2030

	Diesel		*LNG*		*FCEV*		*CBEV-100*		*CBEV-250*		*BEV-400*		*BEV-800*	
	2020	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**
Production costs	131,353	136,819	163,274	157,873	204,593	156,041	200,567	149,952	260,796	185,760	267,417	197,790	428,027	293,279
Resale value	32,707	34,068	40,655	39,310	50,944	38,854	49,941	37,338	64,938	46,254	66,587	49,250	106,579	73,027
Financing costs	23,359	24,331	29,035	28,075	36,383	27,749	35,667	26,666	46,378	33,034	47,555	35,173	76,117	52,154
Acquisition costs	122,005	127,081	151,654	146,637	190,032	144,936	186,293	139,280	242,235	172,540	248,385	183,714	397,565	272,407

VIII. Energy carrier prices in Germany in 2020 and 2030

	Diesel	*LNG*	*Hydrogen*	*Electricity*	*Biomethane*	*Biodiesel*
2020	0.0601	0.0404	0.2872	0.0749	0.0932	0.0933
2030	0.0847	0.0450	0.1875	0.0909	0.0932	0.0933

Power-to-X provision: domestically produced and imported

	Diesel	**LNG**
Germany	0.2264	0.2230
North Africa	0.1639	0.1533
Iceland	0.1217	0.1210

Sources: Kühnel et al. (2018, pp. 52-53, 135); Wietschel et al. (2017, p.141); Jöhrens et al. (2020, p. 88); Karlström et al. (2019, pp. 6, 29); Wietschel et al. (2019, pp. 42- 48); Zapf et al. (2019, pp. 272, 275, 278, 294, 295); Bründlinger et al. (2018, pp. 255, 385); Perner et al. (2018, pp. 20, 46-48, 80-83, 87)

IX. Total TCO in 2020 and 2030 (in thousands of 2020 EUR)

	Diesel		*LNG*		*FCEV*		*CBEV-100*		*CBEV-250*		*BEV-400*		*BEV-800*		*Biodiesel*		*Bio-LNG*		*PtX-LNG*
	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030	2030
Acquisition	122.0	127.1	151.7	146.6	190.0	144.9	196.9	145.6	266.4	186.9	284.6	205.2	397.6	272.4	122.0	127.1	151.7	146.6	146.6
Maintenance	86.8	85.8	87.9	84.5	83.7	67.0	99.6	82.2	59.1	58.2	58.0	57.1	58.0	57.1	86.8	85.8	87.9	84.5	84.5
Energy	98.7	112.5	70.5	61.9	382.6	209.6	63.1	62.1	63.1	62.1	59.2	66.8	59.2	66.8	153.2	123.9	162.6	128.2	210.8
Total	307.5	325.4	310.0	293.1	656.3	421.6	359.6	289.9	388.6	307.1	401.8	329.1	514.8	396.3	362.0	336.7	402.1	359.3	442.0

X. Accumulated WTW GHG emissions over the total ownership period in tCO2eq

	2020	*2030*
Diesel	640	518
LNG	602	475
FCEV	105	48
BEV	366	148
CBEV	390	159
Bio-LNG	65	51
Biodiesel	122	98
PtX-LNG	124	84

XI. Marginal carbon abatement costs in 2020 and 2030

2020

	Abatement potential	*CO2 abatement cost*
LNG	37.84	65.84
Biodiesel	535.51	105.07
Bio-LNG	249.85	164.56
CBEV-100	249.85	208.30
CBEV-250	273.91	324.48
BEV-400	273.91	344.25
FCEV	518.36	651.30
BEV-800	574.82	756.70

2030

	Abatement potential	*CO2 abatement cost*
LNG	42.84	-753.32
FCEV	469.32	204.98
CBEV-100	358.14	-99.09
CBEV-250	358.14	-50.90
BEV-400	369.42	10.12
BEV-800	369.42	191.95
Biodiesel	419.16	27.15
Bio-LNG	466.14	72.91
PtX-LNG	433.43	269.14