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Technology extrapolation and total cost of ownership evaluation of battery and fuel cell electric heavy-duty vehicles

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Executive Summary

While it is immanently clear that future transportation must be decoupled from carbon dioxide emissions, currently there is no singular drivetrain technology that is bound to prevail in heavy-duty trucking. As economic efficiency is the guiding principle for trucking operators, this paper examines the differences in total cost of ownership for battery and fuel cell electric vehicles. Several scenarios including technological advances such as High Power Charging are laid out and analyzed based on Monte Carlo simulations. Notably, battery electric trucks show by far the lowest overall costs and there are little to no scenarios where this mechanism changes. Hence, it is quite probable that battery-electric trucks will prevail their hydrogen-powered peers throughout the current decade.

BEV (battery electric vehicle), commercial, fuel cell vehicle, freight transport, heavy-duty

1 Pathway to Zero-Emission Trucking

Representing less than 5% of vehicles in the European Union, about 25% of the correlating CO2 sector emissions are produced by heavy-duty vehicles such as trucks and buses. However, electrification has not yet resulted in significant sales figures regarding carbon-intense long-haul applications. To aid the transition, the European Commission has laid out a detailed strategy to reduce fleet emission based on the so-called Vehicle Energy Consumption Calculation Tool [1]. Vehicles are mandatorily simulated regarding their energy demand, fuel consumption, and carbon emissions while achieving a good correlation to real-world testing. Consequently, Commission Regulation 2017/2400 was issued, setting incentives for low emission vehicles and carbon reduction targets of 30% until 2030 [2]. Then, weighting factors are applied to the different vehicle classes, clearly favoring long-haul applications with about 80% significance. This correlates to their average annual mileage of about 120000 km and, therefore, high carbon emissions.

It is important to note that such steep carbon emission reductions can not be realized with internal combustion engines. Either hybridization, hydrogen, or electrification is necessary to avoid business threatening penalties. Overarching trends such as CO2 taxes and entry bans further underline the starting transition to low emission vehicles. Then, which technology will shape the coming decade? Unlike passenger cars, only a few viable vehicles are available, and no architecture seems to be dominating currently. This paper will only explore fully electrified architectures because both hybridization and low-carbon fuels pose mid-term scenarios at best. Battery electric vehicles may offer a viable opportunity to reduce carbon and energy intensity. However, for heavy-duty vehicles, expensive batteries with several tons of weight are required, thus worsening product attributes such as payload. Some manufacturers are venturing into fuel cell electric vehicles, aiming for a higher driving range, however consuming significantly more energy on a macroeconomic basis.

Right now, the trucking industry is on the verge of the most significant transformation since its inception. Within only a few decades, the fossil fuel age will end, thus, leading to the dominance of carbon-neutral technologies. At the same time, immense challenges are looming as economic efficiency is the guiding principle for trucking operators and main buying criteria. However, if a technology simultaneously decreases cost and carbon dioxide, fast and widespread adoption is inevitable. Therefore, this paper examines technological advances of zero emission drivetrains throughout the current decade and merges all information into a total cost of ownership calculation.

2 Total Cost of Ownership Methodology

To assess the economic viability of different drivetrains, zero-emission technologies will be compared to diesel architectures on a total cost of ownership basis. As laid out previously, this is especially important due to the cost sensitivity of the heavy-duty trucking industry - electric drivetrains will only prevail if they are less expensive than conventional technologies. Finally, economic potentials of electromobility are to be shown with a particular focus on the variables with the highest overall impact while handeling uncertainty with a Monte Carlo approach. Generally speaking, the analysis covers the period from 2025 onwards and is based on typical vehicle characteristics, usage patterns, and holding intervals of commercial vehicles. In the context of this study, the influence of further technological progress shall be assessed in an excurse covering 2030 and onwards.

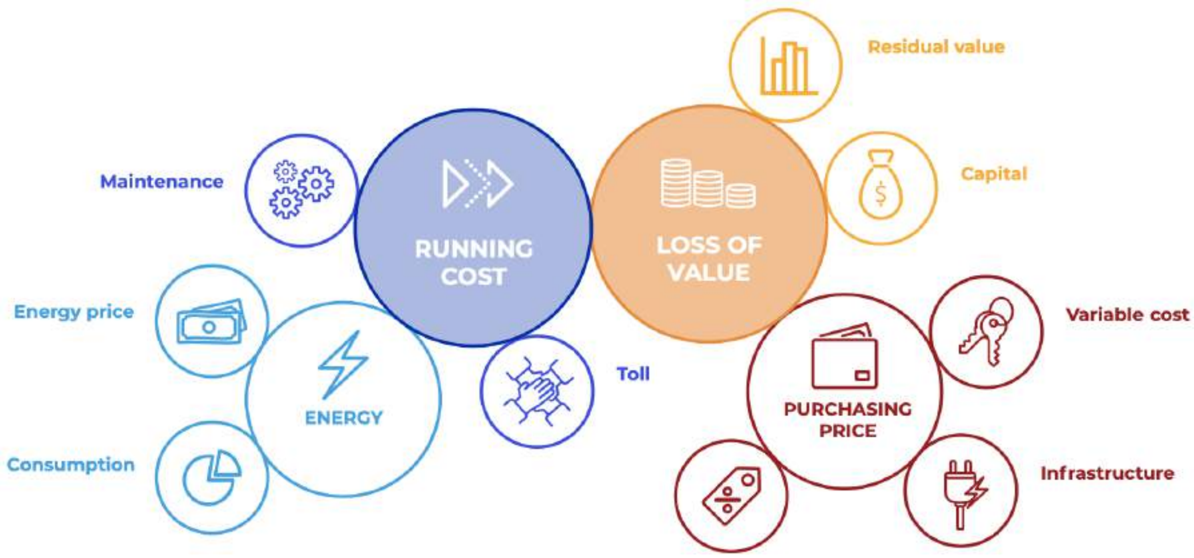

Figure 1: Methodical approach to total cost of ownership

2.1 Approach and limitations

Generally speaking, a TCO approach enables the cost-wise comparison of different investments and is used by most fleet managers. In addition to the purchasing cost for the vehicle and eventually, infrastructure, operating costs such as maintenance, repair, and servicing costs are considered. For better clarity, the analysis is split between one-time and recurring positions, particularly loss of value and running cost. In the following, the total cost approach is used to identify economic potentials for the use of electric trucks and to quantify the remaining cost differences between different drivetrains. As an extension, vehicle purchases in 2030 shall be assessed, too. For the sake of complexity, inflation is disregarded in the following study.

Worth notably, costs due to the truck driver are disregarded in the study. Both BEVs and FCEVs are most meaningfully charged or refueled in the mandatory 45 min steering brake. If this is not possible, liquid hydrogen architectures could yield lower idle times and thus, costs. This could influence the business case in a real-world scenario, but as the LH2 architecture is currently nonexistant, future work is needed. For example, a position paper by ACEA describes the likely technical parameters of such a refueling station and indirectly reveals that the process takes up to 40min per truck [3]. Then, the different zero-emission drivetrain technologies yield roughly the same idle times and costs. As both vehicle architectures and infrastructure mature, more research is needed to aggregate driver costs.

Lastly, it must be noted that the study emphasizes on a very distinct set of vehicles in Europe. While long-haul tractor and rigid vehicles yield the greatest share of total emissions in heavy-duty trucking, it is only a fraction of the total market. The analyzed dynamics are bound to change with different input parameters such as mileage or consumption. For example, electric construction vehicles are prone to higher total cost of ownership compared to their ICE-peers as running costs are significantly lower percentage-wise. While the core findings about TCO should be roughly the same, different requirements from other markets could render BEVs less useful. In other words, while battery-electric vehicles are likely to be competitive on a cost-basis, greater daily mileages in the United States of America could be a limiting factor. Hence, similar research is needed for other countries.

Notably, the distinct characteristics of electric vehicles require adjustments in user behavior and infrastructure, which can considerably influence user acceptance. However, this effect can also be observed conversely: Freight customers are increasingly enforcing carbon-neutral transportation schemes, thus pressing for battery and fuel cell electric vehicles. Still, the total cost of ownership analysis provides essential indications about the economic potential. Adding to the societal cost of technology, regulatory guidelines, and freight customer demand, worthwhile assertions regarding the trucking industry's future can be drawn.

2.2 Loss of value

The definition of typical vehicles in the respective conventional and battery-electric variants forms the basis for the derivation of acquisition and operating costs. In addition, further fixed and infrastructure costs are discussed, and the methodical procedure for deriving the residual vehicle value is explained.

2.2.1 Capital cost

First and foremost, commercial vehicles are assessed as economic goods. Therefore, to decrease capital expenditures and save liquidity for other opportunities, one naturally tends to vehicle financing. It is estimated that such a loan yields interest rates of 2,5%. Furthermore, if a more expensive zero-emission vehicle is purchased, opportunity costs of about 4% for the price difference arise. This is meaningful as the trucking operator could grow the existing business and earn revenue. Consequently, capital expenditures and opportunity costs are incorporated into the total cost of ownership analysis.

2.2.2 Infrastructure

Generally speaking, it is feasible to operate all three drivetrain technologies on public infrastructure only. This premise is reflected throughout the study and forms the basis for energy price assumptions. In such a scenario, infrastructure is handled by third parties, and the costs are incorporated in the asking price for diesel, electricity, or hydrogen.

However, the operation of battery electric vehicles blends exceptionally well with overnight charging infrastructure. A BEV with about 600 kWh installed battery capacity can easily be recharged with 40kW overnight and operate on a radius of up to 500 km throughout the workday. This allows for hub-to-hub transportation and operation around a base depot while accessing low electricity prices for medium-sized non-household customers. Since most industrial parks are connected to the medium-voltage grid, even multiple charging stations should not result in high-priced changes to the infrastructure. For example, the Quantron LRM17 charging station with 44 kW is available for about 14,500 € [4]. Prices are expected to decline over the coming decade; however, uncertainty regarding the electrical installation shall be incorporated. Thus, infrastructure costs of 25,000 € are estimated for every vehicle. Similarly, 180 kW charging stations are available for roughly 40,000 € and can serve several vehicles at once. Again, the assessed infrastructure costs should be sufficient for this scenario as well.

2.2.3 Incentives

Currently, the Federal Ministry of Transport and Digital Infrastructure supports the market ramp-up of HDVs with zero-emission powertrain systems on a technology-neutral basis. To achieve economic competitiveness with combustion engine vehicles, freight companies can receive subsidies totaling 80% of the additional capital expenditures [5]. For this subsidiary directive, funds of about 1600 mio€ are available until the second half of this decade. Still, for the 2025 scenario, it is estimated that the maximum incentives will only be half of the current values. This is due to the fast pace of technological progress and the attractive total cost of ownership for zero-emission vehicles [6]. To better handle uncertainty, values ranging from zero to 40% are assumed. For the 2030 scenario, no incentives are incorporated into the study.

2.2.4 Vehicle purchasing price (ICE)

For the TCO analysis, internal combustion engine vehicles serve as a baseline and are stripped of their powertrain for further analysis. Worth notably, the bottom-up vehicle cost is based on data from Kühnel et al. [7]. For example, the variable cost of a diesel-powered 4x2 tractor is estimated at 60,000 €. Furthermore, roughly 40% of that can be attributed to the ICE powertrain architecture. This leaves the base vehicle at roughly 36,000 €, which is transferred to BEV and FCEV vehicles. Finally, adding the markup factor of 50% to account for research and development, manufacturing, distribution, and the profit margin, a customer net price of 90,000 € is established. This correlates to listings on TruckScout24 and is possibly higher than fleet purchasing prices of large customers.

It is assumed that the vehicle price will remain steady up to the year 2030, excluding inflation. However, manufacturers are pressed to install more efficient technology in their vehicles. Furthermore, cost increases due to Euro 7 emission standards are looming for the coming decade. Therefore, following Meszler et al., price increases of 3,700 € in 2025 and 6,800 € in 2030 are assumed for the more sophisticated drivetrain technology [7]. Still, price increases could potentially be higher as most truck manufacturers have announced their core belief in electric powertrains over diesel ones [8]. Accordingly, the number of produced vehicles is reduced, and thus customer net prices increase.

2.2.5 Vehicle purchasing price (BEV)

As for battery-electric heavy-duty vehicles, an operating radius of about 500 km shall be assessed. In combination with high power charging, the daily mileage expands to about 800 km, thus being sufficient for over 90% of todays' trucking routes in Europe. Frequently in literature, batteries of up to 2,000 kWh are incorporated without considering fast charging [9]. This is a crucial difference from the 600 kWh in this study and significantly increases the total cost of ownership. Furthermore, batteries are repeatedly underestimated: Today's price levels and cycle stability were not expected until 2030 [7]. Battery technology progressed amazingly fast during the last years, and this trend is expected to hold throughout the current decade [10]. For example, modern batteries are prone to outlast the vehicle structure itself, which was inconceivable a few years ago. Concluding, state-of-the-art battery-electric vehicles have a fundamentally different business case than assessed in the past.

Adding to the base vehicle cost of about 36,000 €, it is meaningful to analyze and extrapolate battery prices. This is the largest share of the total vehicle cost and thus dominant regarding further calculations. As with other input parameters prone to uncertainty, a price range is established based on metastudies and other information. Whereas there is no optimal battery technology for all market segments, Lithium-iron phosphate (LFP) batteries are emerging for commercial vehicles due to lower costs and their inherently uncritical supply chain. This is especially meaningful as the electrification of heavy-duty vehicles is estimated to require more than twice the total battery capacity of passenger cars [11]. In one of the most comprehensive metastudies available, the Advanced Propulsion Centre UK estimates that this low-cost cathode material could yield battery prices of 83 €/kWh in 2025 and 66 €/kWh in 2030 [10]. Accordingly, a 4x2 tractor vehicle will likely be equipped with about 50,200 € worth of batteries in 2025. While this is still significantly more expensive than a diesel powertrain, previous studies have concluded battery prices more than thrice this value [7]. For a worst-case scenario, a 40% premium is added to the battery costs mentioned above.

Notably, Tesla has announced to significantly undercut the metastudy prices in its Battery Day 2020 [12]. Although the statements are bold, they must be taken seriously as previous battery price predictions have been overachieved. Due to a holistic approach to cell design and manufacturing, anode and cathode materials, and vehicle integration, battery prices of roughly 45 €/kWh are expected in 2025 [12]. As no prediction for 2030 was made, and the 2025 statements were quite bold, half of the price reduction mentioned in the Advanced Propulsion Centre's metastudy is applied. This leads to battery price estimations of about 40 €/kWh in 2030. In both cases, Tesla's cost per kilowatt marks the lower boundary of the study. Concluding, a long-haul tractor vehicle would be equipped with a battery worth 27,000 € in 2025. Notably, this is less than the price estimation of a diesel powertrain in the same year. Due to additional electric peripheral components, a BEV would still yield a higher customer net price than its ICE peer. However, this difference shrinks quickly and is expected to be negligible at the end of this decade.

In the last step, components specific to an electric drivetrain must be added to the previous costs. For example, AC/DC converters, electric motors including their inverters, HV-coolant pumps, etcetera add to the variable costs and hence the customer net price. Nevertheless, these components contribute insignificantly compared to the HV-batteries, and thus, the analysis effort shall be kept low. According to Kühnel et al., a battery-electric HDV yields peripheral costs of about 30,000€ [7]. For the sake of complexity, an interval of +-30% around this estimation is utilized in the study.

Summing up, battery-electric 4x2 trucks will likely yield customer net prices between 126,300€ and 202,400€ in 2025. This equals a price premium of only 34% compared to an internal combustion engine vehicle in a best-case scenario. On the other hand, prices could be more than twice as high. Notably, this cost estimation is lower than with most studies available and underlines the fast improvement rate.

2.2.6 Vehicle purchasing price (FCEV)

To holistically assess the customer net price of an FCEV, particular emphasis must be put on the fuel cell and its peripheral components. In addition to that, similar components as in battery-electric vehicles are used for the electric powertrain. Notably, most studies assume the HV-batteries to be identical in their cell chemistry and purchasing cost [7]. However, the battery must be significantly smaller due to the vehicle layout, and higher coulomb rates are necessary for effective recuperation and driving power. These power cells are likely to be twice as expensive as the batteries mentioned before. While only 10% of the BEVs capacity is installed, this still sums up about 11,650 € in 2025. For the sake of complexity, a price span of +-30% is established and incorporated into the TCO assessment. For 2030, the same improvement rate as for energy cells is applied. The remaining electronic components shared between a BEV and an FCEV are assessed to be two-thirds as expensive as mentioned above. For example, charging infrastructure within the vehicle is nonexistent or rated for significantly lower power levels.

Furthermore, fuel cell-specific peripheral components are needed, whereas hydrogen tanks yield the most significant influence. For passenger cars, carbon fiber pressurized tanks are used and readily available. However, due to high payloads and mileages, this approach only leads so far in heavy duty-trucking. Even at pressure levels of 700 bar, the technology cannot compete with today's ICE vehicles. According to the Advanced Propulsion Centre UK, such tanks yield costs of about 313 €/kg H2 in 2025 [13]. Additionally, the American Department of Energy concludes that pressurized hydrogen tanks could drop to about 237 €/kg in a bullish future scenario [14]. By 2030, a technology change to liquid hydrogen tanks is anticipated, which reduces the cost to about 172 €/kg [13] and dramatically increases the vehicle's range. However, due to the novelty of such a system, little information is available about the possible costs at production start. In 2013, the U.S. Department of Energy concluded that cryo tanks could be available for about 257 €/kg when produced in series. Hence, this value will be used for the 2025 price prediction. Concluding, a combination of technological progress and production volume increases could reduce automotive hydrogen storage prices by about 60%.

The high power fuel cell yields the greatest percentage of overall vehicle cost; thus, particular emphasis must be put on the assessment. Notably, only proton-exchange membrane fuel cells are considered in this study as they dominate automotive applications. Fuel cell price estimations vary by a significant amount and are prone to subjectivity and subjective assumptions. For example, the U.S. Department of Energy concludes that technological progress and large-scale production of 100,000 fuel cells per year leads to systemic costs of about 68 €/kW [15]. This significantly differs from other metastudies such as the one created by the Advanced Propulsion Centre UK, where systemic prices of about 184€/kW are estimated [13] in 2025. Corrected for the different production volumes, this equals more than twice the DoEs predictions. Other studies remark that production volumes of only 10,000 fuel cell trucks can be reached until the end of this decade. According to an analysis of Transport & Environment, this leads to systemic costs of about 309 €/kW in 2025. As per the vast deviation, estimations from the U.S. Department of Energy or other overly optimistic studies are ruled out completely. Accordingly, 167 €/kW is established as a best-case scenario, whereas 309 €/kW forms the upper boundary for 2025.

Notably, not a single European truck manufacturer intends to produce heavy-duty fuel-cell electric vehicles in the first half of this decade. Still, the hydrogen industry has announced plans to establish a fleet of 100,000 FCEVs in the commercial sector until 2030 [16]. While it can be assumed that this is an optimistic scenario, the resulting production targets are still not sufficient to achieve the cost levels of various studies. Considering that a total of 274,000 new heavy-duty vehicles were registered throughout the European Union in 2019, it is not likely for truck manufacturers to achieve yearly production volumes of 50,000 units or more [17]. This is especially true in the context of other competing technologies such as purely battery-electric drivetrains. For example, battery-electric passenger cars dominate FCEVs in technical specs, customer prices, TCO, and sales volumes. As there is no sign of a trend reversal, fuel cell technology is likely confined to the trucking industry and thus, lacks resources and production volumes. Also, as the car industry has shown, there is an imminent threat of losing further production volumes. Concluding, prices of 99 €/kW are estimated in a best-case scenario for a yearly production of 50,000 units in 2030 [18]. The preceding lower boundary is established as a worst-case scenario to account for uncertainty regarding technological progress and production volumes. For the sake of complexity, peripheral fuel cell components such as the elaborate cooling system, activated carbon air filters, as well as pumps and compressors, are estimated at 10% of the fuel cell and hydrogen storage cost.

Concluding, customers are likely to pay between 193,700 € and 312,800 € for a heavy-duty FCEV in 2025. Notably, a best-case scenario equals more than twice the price of ICE vehicles and about 54%

more than BEVs. Even after considering significant production volume increases for the 2030 scenario, customer net prices are still at least 30% higher than a BEV. Hence, there is no realistic mid-term scenario where fuel cell electric vehicles reach cost parity with their zero-emission peers. Uncertainty about fuel cell production volume increases only worsens the deviation.

2.2.7 Residual value

As a five-year holding period of the initial buyer is assumed, the vehicle's residual value is of great importance for the economic evaluation. Frequently, the residual value is an indispensable part of the following vehicle's financing or leasing rate calculation. For example, one study suggests a residual value of about 25% after 600,000 km mileage for a standard tractor vehicle [7]. Notably, total mileages of about 1,2 million kilometers and lifecycles of up to 10 years can be expected. However, there is little to no scientific information available for crosschecking or other vehicle mileages. Hence, a simple empirical study was conducted.

For this cause, information from the leading online marketplace for commercial vehicles in Europe was gathered. TruckScout24 serves 35 countries and has shown 689 inserts of 4x2 tractor vehicles in Germany at the time [19]. In order to create comparability, only vehicles registered between 2014 and 2016 were analyzed. This roughly compares to the five-year holding period, which serves as an assumption in this study. The following diagram results if all vehicles are arranged in order of kilometers. Most vehicles show mileages between 600,000 km and 900,000 km, which supports the holding period assumption. Polynomic interpolation of the point cloud allows for estimations about the residual value subject to the total mileage. For example, increasing the daily operation from 400 km to 800 km results in a 40% lower residual value. This effect will be included in the total cost of ownership analysis. Also, assuming customer net prices of about 90,000 € for a standard 4x2 tractor unit, a residual value of roughly 35% can be assumed after 600,000 km.

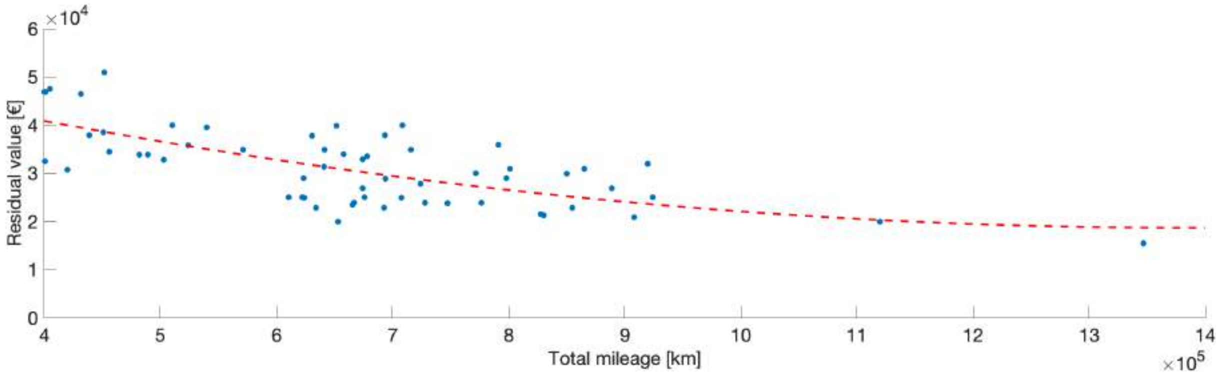

Figure 2: Analysis of residual values for 4x2 tractors based on Truckscout24 [19]

2.3 Running costs

As running costs generally dominate the business case of heavy-duty vehicles, they are most significant for this analysis and will be explored in great detail [20]. Generally, energy consumption yields the most significant influence and is assessed according to the specific powertrain. As this involves great uncertainty, metastudies and statistical information from the European Union are used. Furthermore, HDVs commonly contribute to public infrastructure costs due to levied toll. Governments can easily adjust this value to incentivize or penalize certain drivetrains; thus, the effects of tolls are assessed. Lastly, the different powertrain technologies vary in their reliability and maintenance costs. This directly influences the business case and represents an important buying criterion. Notably, there are additional running costs; however, they only show minor influence or apply equally to all three drivetrains. For example, the difference in insurance and vehicle taxes amounts to only several hundred euros and is disregarded.

2.3.1 Diesel price

Generally speaking, prices for conventional fuels are determined by world market prices, exchange rates, and taxes. Thus extrapolations into the future have often been notoriously wrong. However, one of the most extensive studies commissioned by the German government in 2014 shows excellent accuracy almost a decade later [21]. Diesel prices of 1,57 €/l were predicted for 2020, whereas this average level was approximately reached not even one year later. Additionally, different scenarios due to varying diesel prices across Europe are introduced.

The study concludes diesel prices for German consumers at 1,66 €/l in 2025 and 1,76 €/l in 2030. Corrected for the value-added tax and eventual price reductions for commercial fleet operators, trucking diesel prices are assumed to be 1,17 €/l in 2020, 1,25 €/l in 2025, and 1,33 €/l in 2030. In October of 2021, commercial diesel in Germany is priced at 1,18 €/l without VAT [22]. However, as heavy-duty trucking is a globalized venture, deviations throughout Europe must be accounted for. Austria's fuel prices are among the lowest in continental Europe at 1,05 €/l. Thus, this value is used as the lower end in the study. It is not adjusted for increasing CO2 prices nor time to better account for price fluctuations. This is especially meaningful as the demand for diesel fuel is estimated to decline sharply throughout the coming decade. Consumption could decrease by as much as 25% in the coming decade due to electrification and more fuel-efficient vehicles, thus leading to declining princes [21]. Several Scandinavian countries invoke the highest diesel prices in Europe with up to 1,41 €/l [22]. Transforming these current diesel prices according to the study's findings, roughly 1,51 €/l in 2025 and 1,60 €/l in 2030 can be assumed as the upper limit.

2.3.2 Electricity price

Like diesel, electricity pricing shows great uncertainty over the coming decade and is vastly diverse throughout the European Union. Whereas Scandinavian countries have access to inexpensive, low-carbon electricity, German consumers pay a hefty premium. Furthermore, commercial customers often receive more favorable rates depending on consumption due to numerous exceptions and tax reliefs [21]. As battery-electric long-haul trucks consume more than 150 MWh per year and companies are likely to operate more than one, non-household consumer prices can certainly be assumed. However, these rates only apply for depot charging - opportunity charging along the route will be covered later. According to the statistical office of the European Union, medium-sized consumers utilizing between 500 MWh and 2000 MWh per year were charged 0,125 €/kWh on average in 2020 [23]. Electricity prices were highest in Germany with 0,182 €/kWh and lowest in Sweden with 0,059 €/kWh. Thus, the spread of up to 308% heavily influences the business case of electric vehicles and will affect their market potential unevenly. For comparison, diesel prices only deviate by a maximum of 34%.

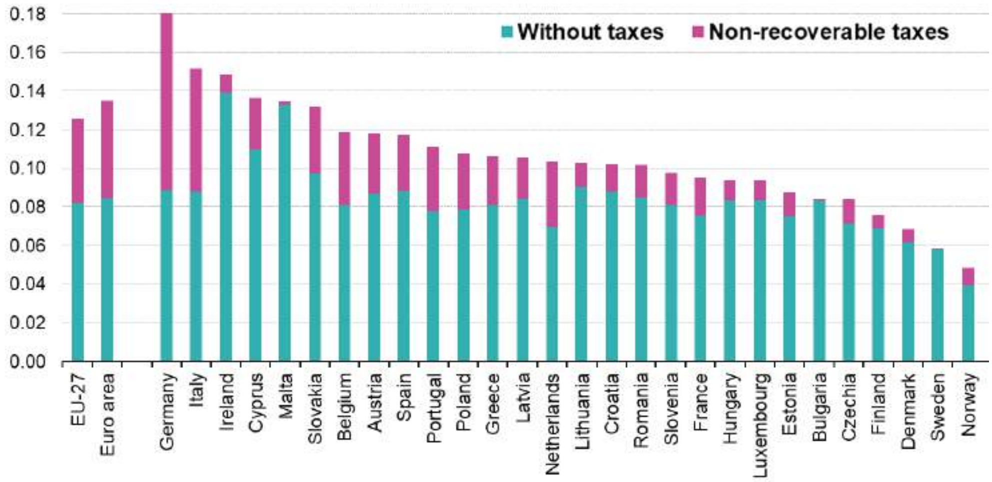

Figure 3: Electricity prices for non-household consumers in €/kWh (2020) [23]

Following the methodological approach for diesel price extrapolation, the values above are transferred [21]. In the reference forecast, despite inexpensive electricity generation from renewables, rising CO2 and fuel prices lead to increased wholesale prices until 2025 in Germany. However, electricity prices are estimated to decrease after 2025 due to declining "Erneuerbare Energien Gesetz"-surcharges (EEG). This surcharge shall reduce the difference in cost between renewable and carbon-intensive electricity production. As laid out, this gap is estimated to decrease; thus, the EEG-surcharge will also shrink. Despite the rising electricity demand, this trend is estimated to continue throughout the subsequent decades [21]. Concluding, medium-sized non-household German consumers could see an increase in electricity prices of up to 20% until 2025. In the period until 2030, costs are assumed to decrease slightly by about 5%.

For the other country-specific electricity prices, a simplified approach based on historical prices is established. According to Eurostat, electricity rates for non-household customers have increased by 4,6% over the last five year-period on an inflation-adjusted basis [23]. Notably, the EU27 average price decreased excluding taxes and adjusting for inflation. Only after adding taxes and governmental levies, rising levels can be observed. Nonetheless, electricity prices of 0,131 €/kWh in 2025 and 0,137 €/kWh in 2030 are assumed for EU27 non-household consumers. The same logic applies for the lower bounds of the analysis, Swedish electricity prices are estimated at 0,062 €/kWh in 2025 and 0,065 €/kWh in 2030.

Current battery technology does not allow 4x2 heavy-duty vehicles to cover all routes observed in the market. However, energy prices for on-demand charging shall be assessed now. According to the Charging Interface Initiative, high-power charging (HPC) will be capable of delivering up to 2 MW on highly frequented routes [24]. Naturally, this service will be drastically more expensive than depot charging but allows actual long-haul trucking. With a utilization rate of 50% and power draw according to common state-of-charge (SoC) curves, it can be estimated that one HPC station already qualifies for large-scale energy prices. This is especially true as multiple charging stations utilize capital costs more efficiently and thus, are the most reasonable business decision. Therefore, electricity prices for HPC providers could be as much as one-third lower than the values laid out above [25]. However, significant capital expenditures, maintenance, land usage, and profit intentions will lead to vast markups for trucking customers. For the sake of complexity, it is estimated that HPC prices will be thrice as high as the electricity prices of non-household customers mentioned above. For example, one of the largest energy providers in Germany bills 0,55 €/kWh for DC Charging with up to 350 kW [26]. Roughly, this equals thrice of current mid-sized, non-household consumer electricity prices. Finally, this approach is applied to all country-specific energy rates and adjusted with up to 70% utilization rates. This is meaningful as customers are naturally incentivized to rely on depot charging due to drastically lower costs.

2.3.3 Hydrogen price

While literature and expert groups are convinced that hydrogen will play a vital role in tomorrow's energy industry, its importance for street transport is highly controversial. As hydrogen is a secondary energy carrier, its production requires the useage of primary energy through electrolysis. Green electricity is likely to be rare throughout the coming decade as more and more industries decarbonize. Also, hydrogen can be produced from natural gas in which hydrogen is chemically bound. Today, 96% of the global hydrogen supply is produced using fossil energy carriers [27]. While this production method is relatively cheap, it produces at least as much carbon dioxide emissions as todays diesel based transport infrastructure. Thus, this scheme is fully disregarded in the following assessment.

In 2021, hydrogen can be bought at filling stations for 9,5 €/kg or 0,285 €/kWh. Notably, this is an artificial price with political motivation. When hydrogen is actively used in the transportation industry, an accurate market price is established that covers costs, taxes, and profit margins. Similar to fuel cell price estimations, hydrogen price yields must be assessed carefully as there is significant guesswork and subjectivity involved. As this is one of the most critical points of the study, various resources are used to derive a price range for green hydrogen. Thus, various production paths, such as wind and solar energy as well as centralized and decentralized schemes, are incorporated. Subsequently, transportation cost is assessed. According to McKinsey, decentralized production could yield hydrogen prices of about 4 €/kg in 2030 [28]. Notably, the very optimistic hydrogen council estimates that offshore wind parks will produce H2 at about 5,2 €/kg [29] by 2025. Accounting for advances in renewable energy and electrolyzer technology, prices of 3,4 €/kg could be viable in the long-term. Furthermore, one of the most comprehensive studies by Prognos AG embodying price ranges in different years is incorporated. For example, hydrogen prices between 4,9 €/kg and 7,1 €/kg are predicted in 2030 excluding transportation [30]. In 2025, price estimations range from 5,3 €/kg to 7,9 €/kg.

The scenarios above only care for the production of green, low-carbon hydrogen. However, there is a significant effort needed for the logistics process up to the filling station. This covers liquefaction, storage, and transport with abled trucks. Höhnlein et al. estimate costs of 1 €/kg for distances less than 150 km [31]. Accordingly, costs connected to the filling stations accumulate at about 0,5 €/kg. Michaelis et al. [32] concluded that hydrogen transportation in a decentralized scheme yields costs of 1,7 €/kg, and filling stations account for 1 €/kg. Hence, the logistics process for European Hydrogen production can be estimated at 1,5 €/kg to 2,7 €/kg. Likely, economies of scale and technological progress are to reduce these values. Thus, a 40% deduction is applied to the 2030 scenario.

Often, very favorable scenarios about globalized liquid hydrogen production schemes are outlined. Therefore H2 production in countries with very favorable conditions for renewable energy shall be briefly discussed. According to the International Energy Agency, the MENA region (Middle East and North Africa) could be an attractive hub for inexpensive, green hydrogen production [27]. This is mainly due to the high capacity factory of solar panels and thus low costs of green energy. In the long term, green hydrogen could be produced for about 1,9 €/kg [27]. Notably, alkaline electrolyzer capital expenditures (CAPEX) were estimated at 390 €/kW with electrical efficiency ratings of 74%. The same study concludes that in 2030, efficiencies between only 65% and 71% can be achieved. Also, capital expenditures are estimated twofold the level mentioned above. According to the hydrogen council, the electrolyzers' higher CAPEX is likely to increase production cost by roughly 0,6 €/kg [29]. Due to the superior energy density of liquid hydrogen, this is the only meaningful scenario for a globalized production based on renewables. However, there is a major drawback: The liquefaction process implies significant losses, accounting for 30-45% of the hydrogens' total energy content. Concluding, in an optimistic 2030 scenario, liquid hydrogen production prices in the MENA region can be estimated between 3,4 €/kg and 4,1 €/kg. Accordingly, dedicated tankers able to transport cryogenic hydrogen on long-routes are to serve import terminals within Europe. Only then, the logistics processes mentioned above could serve the refueling stations. Despite the significant technical and economic uncertainty involved, it can be concluded that such a supply chain yields cost at least as high as mentioned above. Thus, green hydrogen production in the MENA region yields prices between 4,3 €/kg and 5,7 €/kg. Notably, the minimal price estimation does not differ from the offshore wind scenario. Therefore, it can be concluded that there is little to no financial benefit from MENA hydrogen production but vast technological and economic hurdles. This may change in the coming decades but is unrealistic for the 2020s and early 2030s.

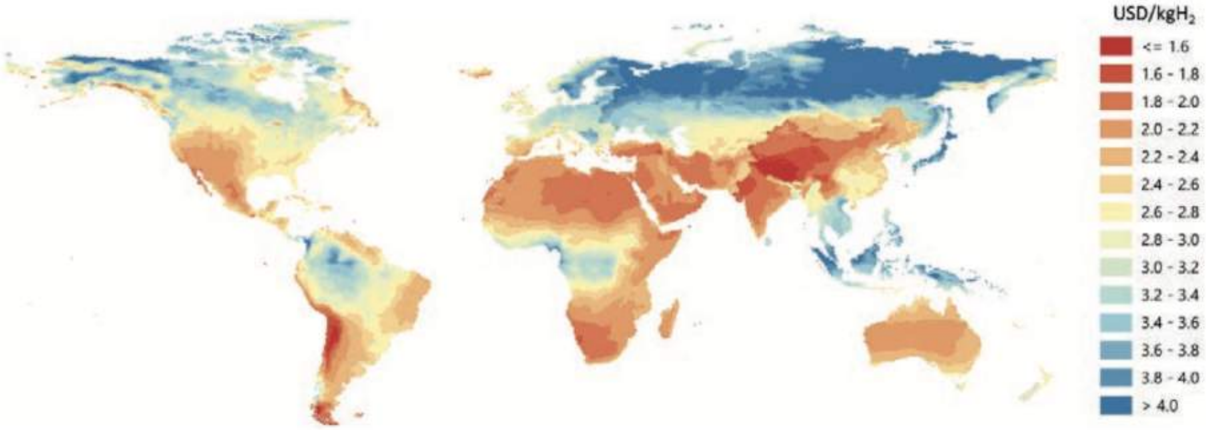

Figure 4: Estimated long-term production cost of green hydrogen [29]

2.3.4 Maintenance

The costs for vehicle maintenance, care, and repair include, among other things, fluid changes and inspections following the manufacturer's specifications. In addition, wear-and-tear repairs such as brake pad and tire replacement or faulty component repairs must be considered, especially for high mileage vehicles. The TCO models' assumptions for internal combustion engine vehicles are based on an endurance test from 2016 by the freight company Fehrenkötter [33]. Heavy-duty tractors from seven different manufacturers have shown maintenance costs of roughly 0,135 €/km throughout 320,000 km each.

A significant reduction in maintenance costs is estimated for battery electric vehicles due to fewer wear parts. Nowadays, the whole electric powertrain is designed for a vehicle lifetime and must not be replaced. In contrast to former studies, this also applies to the batteries and drastically decreases maintenance costs. On the other hand, diagnostics and part replacements due to random faults are probably more expensive due to high voltage levels. Therefore, special precautions must be taken, and service can only be done by certified staff. Nevertheless, the Vehicle Technology Office of the American Department of Energy estimates that about 40% of maintenance costs can be saved compared to ICE vehicles [34]. This study focuses on light-duty vehicles but is one of the newest and most comprehensive ones. Hence, the results are adopted for commercial vehicles in the following calculation.

Estimating the maintenance cost of fuel cell electric vehicles is a more complex and uncertain task. Generally speaking, the system architecture is more intricate compared to a battery-electric vehicle. It also features a larger number of moving parts such as pumps and compressors. Notably, this effect is only amplified if vehicles use liquid hydrogen as a propellant. Handling chemicals at -253°C is a daunting task, requires cutting-edge technology, and creates unforeseen challenges. While technological progress is bound to decrease fuel cell maintenance costs by up to 60% in the coming decade, this can not easily be transferred to liquid hydrogen commercial vehicles [35]. Lacking scientific and real-world evidence due to the novelty of the system architecture, maintenance costs in the context of long-haul FCEV can only be estimated. Certainly, expenses will be higher compared to battery-electric and combustion engine vehicles. In the context of this study, maintenance costs are estimated to be 50% higher than for current diesel trucks.

2.3.5 Toll

The truck toll represents another major cost component and is a distance-based road usage charge for heavy commercial vehicles. Most European countries have some sort of toll system, whereas there are initiatives for harmonization. At first, the German truck toll shall be evaluated before an outlook can be provided. The toll fee is adjusted according to the vehicle's axle configuration as well as its weight and emission class. For example, standard long-haul 4x2 tractors are billed 0,183€ for every kilometer traveled on federal highways and motorways. Hereby, infrastructure cost forms the biggest lever totaling about 92% of the toll fee. On the other hand, air and noise pollution costs are allocated at only 1,4 cents per kilometer and are subject to the vehicle's emission class. This tolling scheme incentivizes trucking operators to deploy modern ICE vehicles on long-haul jobs. Notably, zero- and low-emission drivetrain technologies are exempt from the tolling scheme for an indefinite period. Currently, this applies to gas-powered combustion engine vehicles as well as battery-, plug-in hybrid- and fuel cell electric vehicles. As tolling fees quickly accumulate in long-haul trucking due to high mileages, this is a desirable incentive for the ramp-up of low-carbon technologies and marks the lower boundary in the TCO calculation.

On a European basis, directive 2017/275/EU introduces a tolling scheme for commercial HDVs according to their carbon dioxide emissions. An implementation is very likely as all EU transport ministers have agreed on a compromise [36]. While it is unclear when the new regulation will be legally valid, it is clear that it will be established in all member countries. According to a study on behalf of the Federal Ministry for Transport and Digital Infrastructure, a tolling scheme based on energy efficiency and carbon dioxide emissions could yield differences of up to 310% between zero-emission and conventional ICE vehicles [4]. As laid out in chapter 2.1, the emissions of future heavy-duty trucks can easily be assessed with the VECTO tool and must be reported for every individual vehicle. Thus, toll fees can be adjusted on a vehicle-specific basis, too. Notably, diesel-powered 4x2 tractors are likely to be rated for vehicle efficiency class 1 or 2 in 2025 [4]. Battery and fuel cell electric vehicles are prone for efficiency class 7 and thus, tolling fees of 7,8 cents per kilometer. Other studies conclude that Germany is expected to set the fees for ZEVs higher at around 75% of today's rates. Hence, roughly 14 cents per kilometer will be the upper boundary condition.

3 TCO scenario assessment

3.1 400km mileage per day in 2025

For the first of four scenarios, the different technologies are assessed based on a daily mileage of 400km. This is easily feasible with a 40t battery-electric truck in 2025 and thus, the study's baseline. At the same time, use cases with similar action radii allow for overnight charging. A relatively small 40kW charging station is sufficient to recharge the truck outside the operation hours. Due to that, trucking operators can utilize inexpensive electricity rates for medium-sized commercial customers. Both the diesel- and hydrogen-powered vehicles can drive longer distances - the study will consider this in the subsequent chapter. Notably, this range can also be handled by a vehicle with compressed hydrogen tanks. Then, the vehicle cost is changed slightly, and inefficiencies due to liquefaction can eventually be decreased. Accordingly, this effect is incorporated into the scenario, and the following figure can be derived.

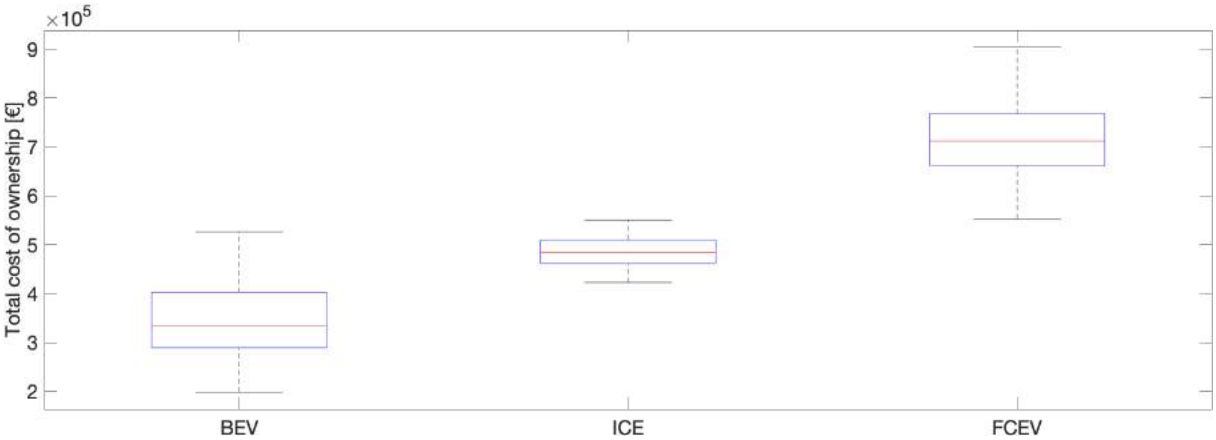

Figure 5: TCO assessment for 400km daily mileage in 2025

Surprisingly, the battery-electric truck yields the lowest total cost of ownership throughout its entire confidence interval. This finding is contrary to most studies and papers, possibly due to incorporating the latest data regarding battery technology and an emphasis on depot charging. The latter is a very attractive option as an investment of roughly 25,000€ per truck allows access to electricity for commercial customers. Then, recharging is estimated to be less than one-third as expensive than on the road. However, approximately in the upper third of the box plot, scenarios of up to 20% charging on highways are incorporated. Only then, BEVs yield similar costs compared to ICE vehicles. In every other scenario, battery-electric trucks show significant cost savings and thus business advantages. As laid out earlier, margins in the transport industry are generally very slim - electrification will therefore be inherently attractive. For example, in the median scenarios, TCO reductions of approximately 31% can be estimated. This is a massive opportunity in an industry that is familiar with low single-digit fuel efficiency improvements annually. Worth notably, trucking operators in Sweden will benefit disproportionately due to low electricity and high diesel prices. Hence, the total cost of ownership is likely to decrease by over 50%. Throughout the appropriate confidence intervals, the operation of a BEV is at least 13% cheaper than a diesel-powered truck. However, the variation between different scenarios is significantly larger as electricity prices in Europe differ by more than 300%.

Still, battery electric vehicles are a meaningful business decision throughout Europe due to the lower total cost of ownership. Consequently, this vast discrepancy could even influence the way the trucking industry is working. Due to low fuel prices in Eastern Europe, routes with up to 2000km are often served without refueling or reversing. With battery-electric trucks, hub-to-hub operations could be the cheaper option. The study will lay out this mechanism in the coming chapter.

As laid out previously, singular vehicle consumption values are derived from the DIVe platform. Hence, the inherent variation for internal combustion engine vehicles is solemnly due to fuel prices. Notably, not one scenario matches the confidence interval of battery electric vehicles. Only diesel prices as low as 0,67€/l would lead to cost parity regarding the 75th percentile. With climate change due to carbon dioxide emissions and governments enacting steep reduction goals, this will not happen. For comparison, diesel prices of 0,25€/l barely yield the same TCO as the battery-electric vehicles' median scenario. Hence, it is safe to conclude that battery electric vehicles prevail over their diesel-powered peers in a 400km scenario.

On the other hand, fuel cell electric vehicles are significantly more expensive throughout their confidence interval than the two other drivetrain technologies. For example, the median total cost of ownership scenario is 46% higher compared to ICE trucks. This is a substantial green premium, and thus, it cannot be anticipated for the technology to succeed. Compared to battery-electric trucks, the situation worsens as an FCEV is likely to yield more than twice the total cost of ownership. Notably, not even the most optimistic FCEV scenario intersects the worst-case estimations regarding BEVs. Thus, it is safe to conclude that battery-electric vehicles pose the most meaningful business decision on a total cost of ownership basis.

3.2 800km mileage per day in 2025

Now, all vehicle technologies are compared based on an 800km daily operation radius. As the figure below clearly shows, this mileage is sufficient for the vast majority of day-to-day operations. The data was derived from real-world trips of roughly 10,000 Mercedes-Benz trucks throughout Europe and therefore yields the highest accuracy possible. While an action radius of 400km is sufficient for only less than half of the market, 800km satisfies almost 90%. The remaining multi-manning operations are disregarded in the study as they only represent a minority of the market. While the ICE vehicles easily manage the requirement due to immense diesel tanks, both BEV and FCEV must refuel. Notably, a compressed hydrogen architecture cannot meet the 800km action radius without compromising vehicle parameters such as wheelbase. In a real-world operation, this could force the driver to stop additionally. However, the operator could also handle the refueling stop in the mandatory steering brakes. Hence, this study solemnly focuses on the total cost of ownership, excluding driver-related effects.

The most important difference compared to the first scenario lies in electricity cost. To reach a mileage of 800km, the BEV must recharge alongside the highway network at an HPC station. As this charging network is currently being built up, costs can only be estimated. However, according to the methodology laid out in the previous chapter, significantly increased charging fees are assumed. As a result, a 70% HPC charging quota with prices of up to 0,55€/kWh in Germany yields the worst-case scenario. Notably, this is a vast difference compared to the high-power charging operators' electricity prices of approximately 0,12€/kWh and therefore implies sufficient safety margin. The effects on TCO are shown in the figure below.
It is immanently clear that battery-electric vehicles yield the lowest total cost of ownership throughout the confidence interval. However, cost parity with the 25% percentile of ICE vehicles is established for the very upper limit. Notably, this is an unlikely scenario, as most target variables yield cost savings for a BEV. For example, the median TCO value of a battery-electric truck is approximately 15% lower than its ICE peer. This is surprising as significantly more expensive electricity rates are incorporated due to high-power charging utilization. Notably, trucking operators are inherently incentivized to charge at their depot and not alongside the highway. Else, there are scenarios where a high HPC utilization rate

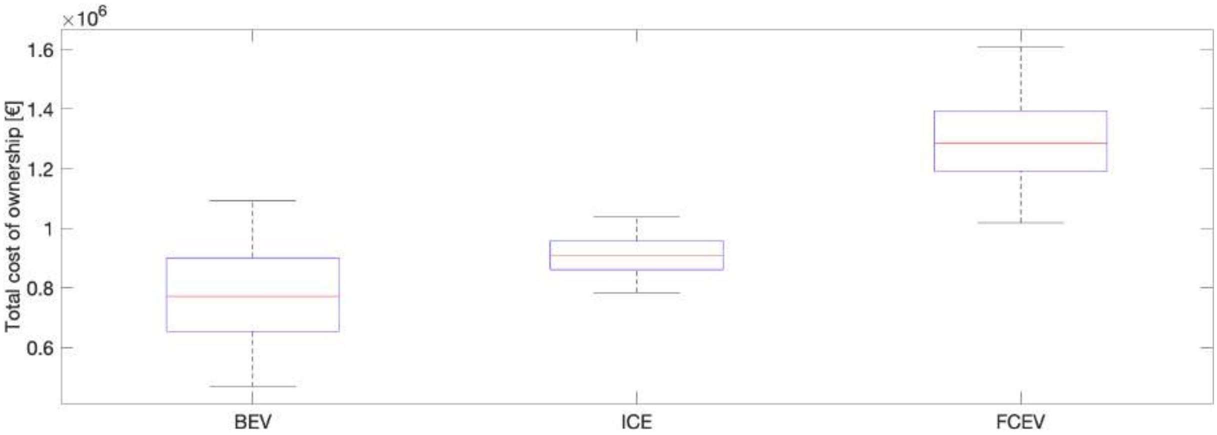

Figure 6: TCO assessment for 800km daily mileage in 2025

yields a higher total cost of ownership compared to diesel vehicles. However, this is only true for countries with expensive electricity rates, such as Germany. There is no such scenario for a BEV operated in Scandinavia - BEVs prevail ICE vehicles in any combination. Hence, battery electric vehicles pose a meaningful business decision in long-haul trucking, too. This is a vital opportunity in an industry with slim margins and will likely induce market pressure favoring BEVs.

It is worth noting that the dynamics between diesel- and hydrogen-powered vehicles are essentially the same. This is because an increased daily mileage does not induce higher fuel costs. Hence, the interpretation of scenario 1 is still valid.

Still, the operation of a battery-electric vehicle is estimated to be approximately 40% cheaper than with an FCEV. For comparison, in the 400km scenario, this value was at 54%. Consequently, vastly increased energy prices due to HPC worsen the BEVs standing relatively. However, battery-electric trucks still prevail over their hydrogen-powered peers by a significant margin. Hence, the study concludes that FCEVs will not compete in electrified long-haul trucking on a cost-based assessment.

3.3 400km mileage per day in 2030

Generally speaking, the longer estimation horizon induces increased uncertainty and thus more significant variances. Other than that, the figure below is quite comparable to scenario 1. Especially the electric vehicle architectures have seen steep decreases in manufacturing cost due to technological progress and economies of scale. This is true for battery- as well as fuel cell electric vehicles. Notably, the situation could look drastically different if one technology prevails over the other by mid of decade. However, as this is difficult to assess, both architectures are handled as if they were in series production by 2030.

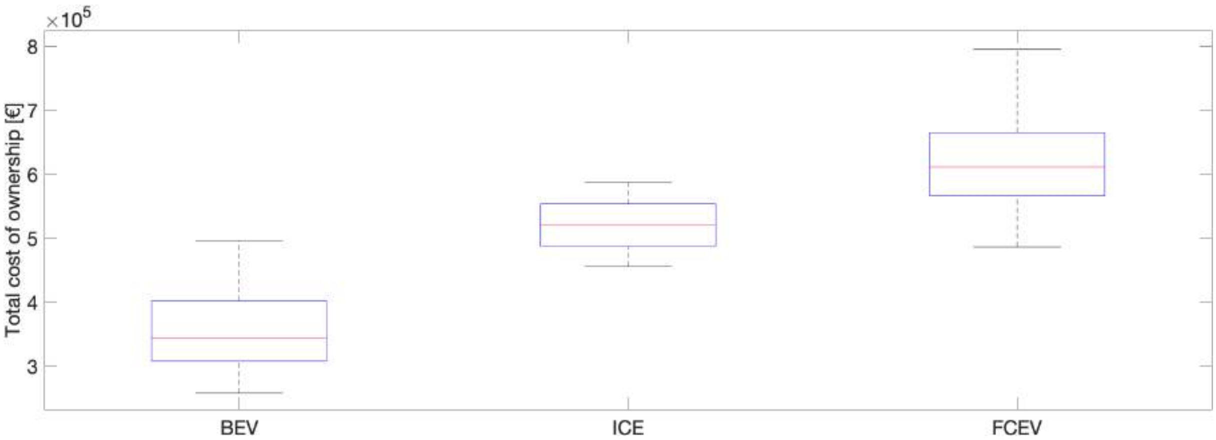

Figure 7: TCO assessment for 400km daily mileage in 2030

Despite the decreased manufacturing costs, the operation of a battery-electric truck is virtually as expensive as in the 2025 scenario. This is due to several reasons: As the economic viability is demonstrated with novel BEVs (as seen in scenario 1), it is improbable that there are still incentives. Also, zero-emission vehicles are likely to pay their toll share in a 2030 scenario. This is necessary as an ever-increasing amount of diesel-powered trucks is replaced with ZEVs, and hence, tax revenues decline. Furthermore, electricity price increases are probable throughout most of the European Union. However, this effect should not be significant, as renewable energy generally is the cheapest option available. Furthermore, as laid out in chapter 4.2, electricity prices decreased in the 2010s when deduction taxes. Concluding, even when it is probable that governments will reduce incentives until 2030, battery electric vehicles are still the most economical option. Furthermore, technological progress in battery production decreases operation cost throughout the confidence interval. For example, the cost savings increased to 34% in the 2030 scenario compared to diesel vehicles.

On the other hand, diesel-powered trucks are likely to have a worsened economic stance compared to the 2025 scenario. For example, the median operation cost increased by approximately 8%. This is due to higher diesel prices and particularly the incorporation of carbon dioxide fees. Also, the toll for ICE vehicles is likely more expensive at the end of this decade. Adding to these effects, combustion engines will be more costly than currently due to mild hybridization and ever-advanced exhaust cleaning. In fact, this could be worsened with the Euro 7 standard.

Fuel cell electric vehicles have seen the most significant decrease in their corresponding total cost of ownership. Compared to the 2025 scenario, a reduction of approximately 102,000€ can be estimated. Percentage-wise, this equals a considerable 14% deduction. Unfortunately, FCEVs are still more expensive than ICE vehicles throughout the entire confidence interval. Notably, there are a few scenarios where hydrogen-powered trucks show a lower total cost of ownership, but their occurrence is improbable. The median TCO, for example, is still approximately 17% higher with FCEVs. Compared to battery electric vehicles, FCEVs yield roughly 80% higher total cost of ownership. As with the other three scenarios, it is improbable for fuel cell electric vehicles to be competitive with BEVs cost-wise. Also, in the 400km scenario, there is little to no advantage regarding the other relevant objects of the customer buying criteria. While FCEVs can be faster refilled on the road, this is nowhere comparable to the influence of an 80% TCO increase.

3.4 800km mileage per day in 2030

As laid out earlier, high power charging is a vital element for daily mileages above 400km. Notably, purpose-built battery-electric trucks could yield enough battery capacity to cover 800km without recharging at the end of this decade. However, this consumes large quantities of resources and ties up battery production capacities. While this technological improvement is not embodied in the study, it could still improve the stance of BEVs in reality. Such a vehicle would not rely as much on high power charging, thus yielding a lower total cost of ownership.

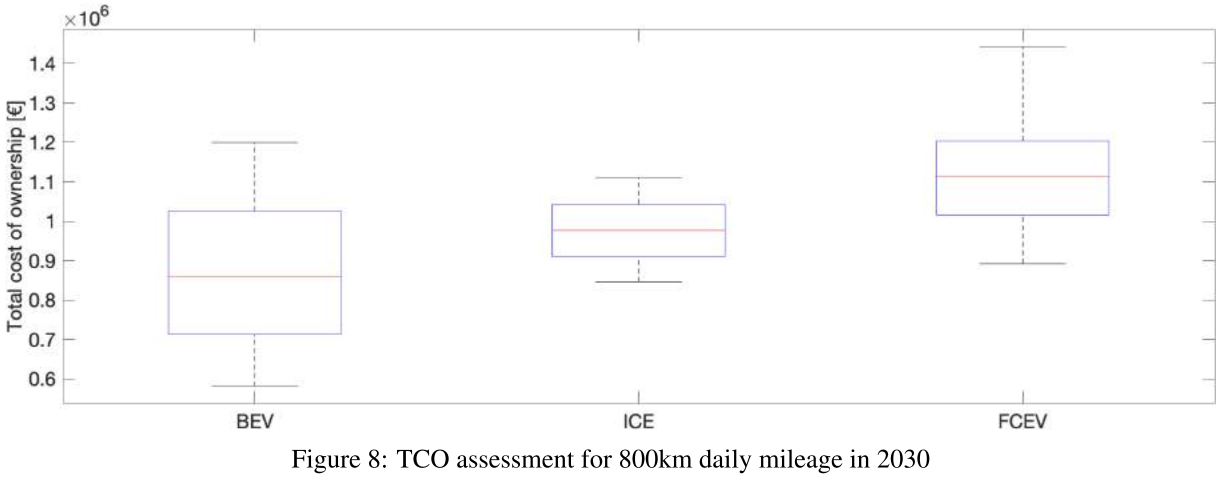

Figure 8: TCO assessment for 800km daily mileage in 2030

Still, battery-electric trucks show the lowest TCO values throughout most of the confidence interval. Only when HPC is utilized heavily in countries such as Germany, ICE vehicles could be cheaper. However, it is inherently clear that most trucking operators throughout the European Union will still see significant operation cost decreases. For example, the median scenarios show a 12% deduction in favor of BEVs. Compared to the 2025 assessment, rising energy prices and discontinued governmental subsidies have led to roughly 10% more costs for battery electric vehicles. Contrary to the 400km scenario, these effects have not been compensated by technological progress.

Fuel cell electric vehicles show the most remarkable transformation of all three powertrain technologies. Due to reduced hydrogen prices and technological progress regarding fuel cells and hydrogen tanks, the total cost of ownership decreased by more than 167,000€. This equals a cost reduction of 13% within five years. While an FCEV is still the most expensive option throughout most of its confidence interval, the 25th percentile has reached cost parity with the upper boundary of both diesel and battery-electric trucks. This is an important milestone and clearly shows how technological progress influences the stance of technology. At the same time, it also highlights the intrinsic limitations of fuel cell electric trucks. Even with opportunistic input parameters, an FCEV still yields approximately 30% higher cost than its battery-electric peer. Under no circumstances, cost parity, nor TCO advantages, can be established throughout the European Union. Adding to that, none of the hydrogen infrastructure necessary is currently available. Contrarily, at this moment, a high-power charging network for trucks is built up.

4 Parameter Sensitivity Analysis

Now that the total cost of ownership is simulated across different powertrain technologies, daily mileages, and timescales, it is meaningful to identify the input parameters with the greatest contribution. For that, the cause-effect framework is reused and slightly adjusted. Every parameter is positively and negatively varied by 30% around its median value while the other subjects remain constant. Notably, one cannot expect that parameters lie within the range mentioned above. It is a mere theoretical construct to identify critical parameters for the technologies' success. For the sake of complexity and to not repeat the statements, only 400km and 800km scenarios are assessed for 2025.

4.1 Medium mileage scenario

As the following figure depicts, electricity cost is the main contributor for a battery-electric vehicle operating 400km daily in 2025. In absolute values, a 30% increase leads to roughly 29,600€ additional TCO. Surprisingly, there is quite a big gap to the second largest contributor. Toll, as well as battery prices, nearly yield the same influence with 13,900€ and 15,700€. Even for the low mileage scenario, this is roughly half the electricity cost and underlines the importance of depot charging for the commercial success of BEVs. Subsequently, peripheral EV parts show influences of only 9,400€ and thus, are of lesser importance. The same is true for governmental incentives, as the sensitivity analysis yields 7,500€. Contrary to popular belief, the next generation of battery-electric trucks is not submissive to stimuli. Technological progress has led to significantly lower vehicle costs as well as greater efficiency and range, thus rendering incentives near to pointless.

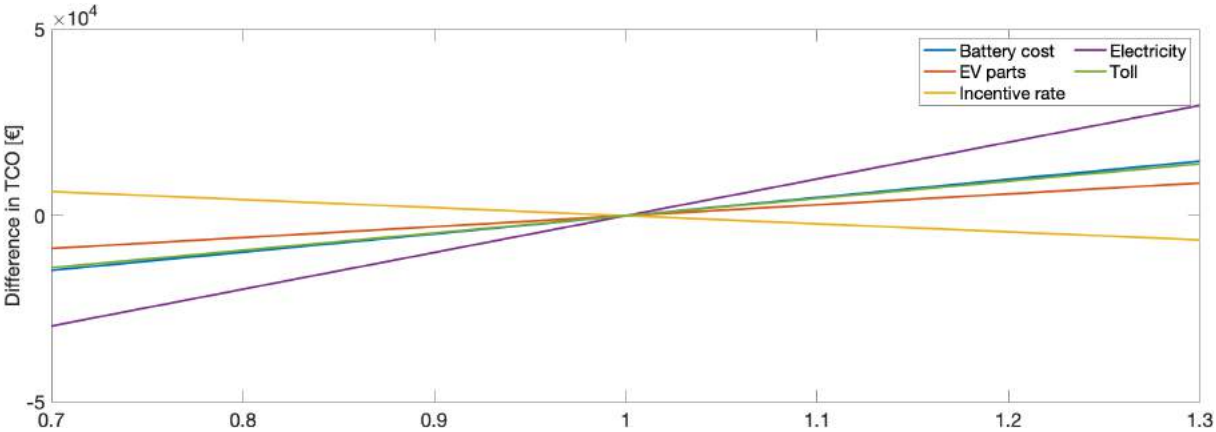

Figure 9: Parameter sensitivity analysis of BEVs for 400km daily mileage

Similarly, hydrogen yields the most substantial influence on a fuel cell-electric vehicles' total cost of ownership by far - a 30% increase results in 111,300€ more operating cost. This finding is very significant and underlines the greatest problem of FCEVs: Due to higher inefficiencies in the powertrain architecture, hydrogen prices can either support or rule out the entire business case. As laid out previously, there is vast uncertainty involved regarding the hydrogen infrastructure necessary for the operation of such vehicles. Also, its prices cannot be estimated accurately as green hydrogen is likely to be a rare resource in the decarbonization of several industries at once. However, combined with the massive TCO contribution, all these soft effects are likely to influence fuel cell electric vehicles negatively. Compared to the influence of hydrogen prices, all the other input parameters become negligible. For example, cost-wise advances in fuel cell technology contribute less than one-fifth compared to hydrogen.

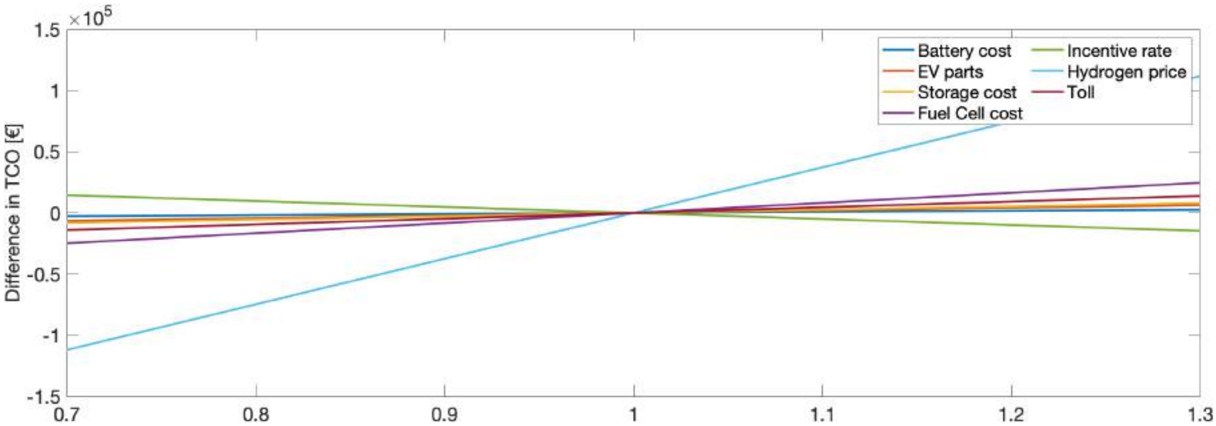

Figure 10: Parameter sensitivity analysis of FCEVs for 400km daily mileage

4.2 High mileage scenario

Different than in the 400km scenario, high power-charging is utilized for battery-electric vehicles. As laid out, this significantly increases electricity costs and, therefore, the parameters' contribution. This effect can be seen in the figure below, as a 30% electricity price deviation leads to 61,900€ higher operational costs. This is more than twice as in the previous scenario. Simply put, the effects of higher median electricity prices and increased daily operation radii superimpose. Notably, the latter leads to a higher contribution of toll costs; thus, approximately 37,400€ are estimated. Again, this is significantly higher than in the previous scenario. All input parameters connected to the loss of value, such as battery costs, remain constant but are of lesser importance. Concluding, running costs show far greater contribution with higher daily mileages. This underlines the necessity for an affordable high-power charging network. Else, trucking operators are incentivized to operate trucks with far greater batteries at the end of the decade. Then, cheap overnight charging is enabled, thus improving the business case. As resources are likely to be scarce, the high-power charging strategy is wiser for society.

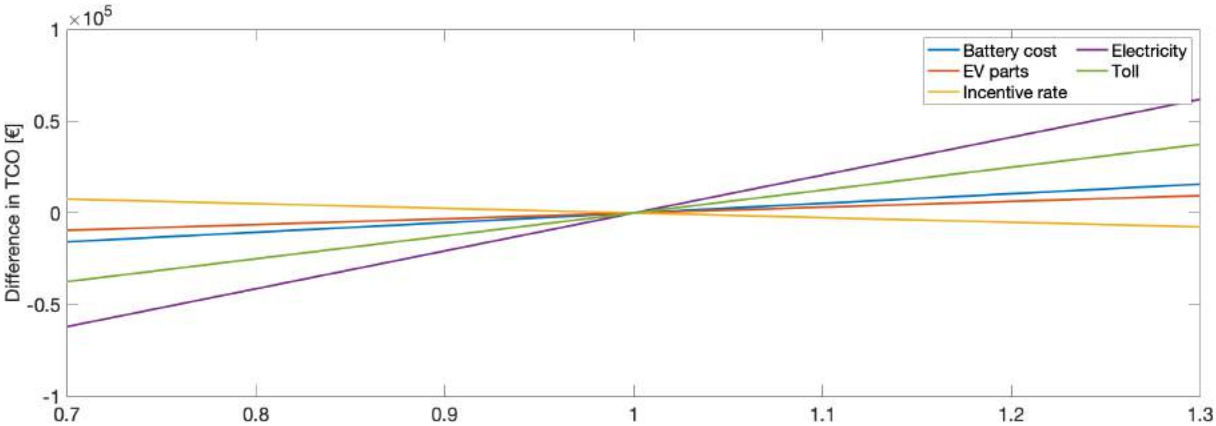

Figure 11: Parameter sensitivity analysis of BEVs for 800km daily mileage

Lastly, the study shall assess LH2 fuel cell-electric vehicles in long-haul usage. This is especially meaningful as a big part of the industry is convinced FCEVs will prevail over BEVs in such a scenario. It is immanently clear that hydrogen prices show the most significant contribution to the overall total cost of ownership. As seen in the figure below, the absolute influence of 222,600€ is precisely twice as high as in the 400km scenario. Unfortunately, this amplifies the effect of hydrogen prices making or breaking the business case. While there is good reason for a vivid hydrogen economy and thus low prices, the inherent uncertainty is vast and the infrastructure non-existent. It must be clear that technological and economic improvements on the vehicle only show a minor influence on the business case. Also, truck OEMs are strongly dependent on third parties regarding the hydrogen infrastructure and resulting prices. While high-power charging stations can be built with somewhat limited CAPEX, this is improbable for hydrogen production and distribution facilities. Notably, due to higher vehicle costs, governmental incentives yield a greater influence than for BEVs. Still, 14,600€ is vanishingly small compared to the effect of H2 prices.
In conclusion, battery-electric vehicles show a lower influence of energy prices on the total cost of own-

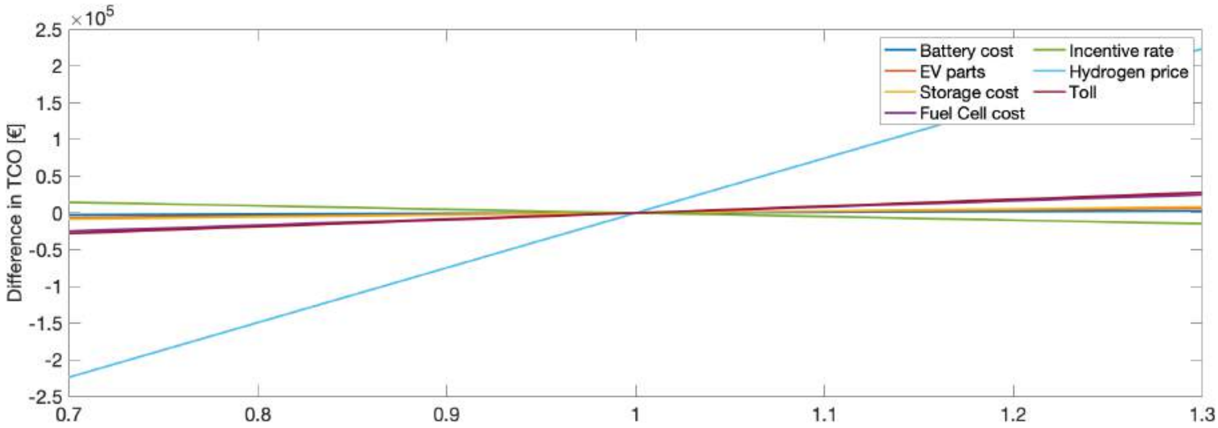

Figure 12: Parameter sensitivity analysis of FCEVs for 800km daily mileage

ership than FCEVs. This likely improves the BEVs' market stance as electricity and hydrogen prices are subject to fluctuations and uncertainty. Also, technological improvements yield a more potent influence for battery-electric trucks. Combined with the findings that hydrogen-powered trucks yield a higher total cost of ownership throughout the coming decade in every possible scenario, this is a significant disadvantage for FCEVs and almost improbable to catch up.

5 Conclusion

While it is clear that the trucking industry must decarbonize and avert from internal combustion engines, most previous studies have come to the conclusion that battery-electric vehicles merely pose a solution for distribution vehicles and hydrogen-powered truck are likely to cover long-haul applications. As the pace of technological progress is immensely quick, said reasoning is tested and challenged throughout the paper. For the assessment, a special emphasis is laid on total cost of ownership as this is a prime criterium for customers‘ buying decisions. Hence, a framework based on purchasing price, energy usage, maintenance and governmental incentives is established and discussed from a methodological point-of-view. As technological progress is closely linked to the TCO assessment, improvements and step-changes for batteries and fuel cells are discussed, too. Notably, the analysis is conducted for European markets and therefore focussed on 4x2 tractor vehicles.

Embedded into MATLAB, the methodolical cause-effect framework yields TCO estimations subject to the different technologies in 2025 and 2030. As the input parameters' uncertainty establishes a range of possible values, the same holds for the total cost of ownership. Due to the Monte Carlo-analysis approach, the different drivetrain technologies can be compared according to defined confidence intervals and median scenarios. It is immanently clear that battery electric vehicles are most meaningful for trucking operations with 400km in 2025 and 2030. Entry barriers regarding infrastructure are particularily low as 40kW charging stations allow for overnight charging in the home depot. For as little as 25,000€ operators qualify for industrial electricity prices - the resulting TCO is simply unreachable for other technologies. In median scenarios, cost reductions of approximately 31% compared to internal combustion engine vehicles are expected to create massive market pressure favoring BEVs. This is particularily true as the heavy-duty trucking industry is subject to low single digit operating margins. The whole trucking industry is likely shaken on its path towards zero-emissions as such steep cost reductions were not seen previously. Thus, the transition from ICE to battery-electric vehicles is prone to happen faster as anticipated in previous studies. Technological progress will massively improve the business case in the next five years and unheard daily mileages will be possible.

Notably, fuel cell electric vehicles are estimated to be significantly more expensive throughout their confidence interval compared to the other drivetrain technologies in the 2020s. On the one hand, this is due to doubled or tripled customer net prices compared to conventional trucks. For example, fuel cell technology is expected to yield high prices throughout the coming decade as the passenger car industry almost solemnly focuses on BEVs. Adding to this point, the necessary system architecture is vastly more complex, elaborate and thus, costly compared to battery-electric drivetrains. On the other hand, while hydrogen is expected to get cheaper in the 2020s due to multiple industries' decarbonization efforts, there is no scientific reasoning for hydrogen prices able to reach cost parity with BEVs. Also, it is reasonable to expect that a global LH2 infrastructure to be a vastly more daunting task than the implementation of charging stations. While it is inevitable that a significant hydrogen economy will emerge in the long-term, it is not reasonable to assume that fuel-cell electric HDVs will be meaningful in the coming decade.

However, liquid hydrogen-powered vehicles can store vast amounts of energy and thus operate for over 1,000km without refueling. This could pose a vital option for the utilization of FCEVs in long-haul trucking as the BEVs' mileage of roughly 500km only suffices 50% of the daily operations. Counteracting this effect, by mid 2021, the first high-power charging stations have been built up. It will enable operators to recharge their battery-electric HDVs in a mere 30 minutes from 10 to 80%. While electricity costs are expected to soar with this on demand charging, BEVs still show the lowest total cost of ownership compared to both diesel- and hydrogen-powered trucks. Worth notably, this is a novel finding and has not been incorporated in literature. Moreover, it completely changes the initial assessment of FCEVs being most meaningful for long-haul operations. Also, it clearly established that truck OEMs have a inherent interest in HPC charging stations as a mean of vertical integration. In such a scenario, long-haul customers are able to operate with lowest TCO, OEMs guard their business against competition while generating vastly more revenue and society profits as BEVs are the most ecological option - in game theory, this is called a nash-equilibrium. Thus, battery electric vehicles are incredibly likely to prevail over the other drivetrain technologies.

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