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Assessing the competitiveness of battery-electric and hydrogen technologies in heavy-duty trucking using fuel-costs

Learning community Energy Transition

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Heavy-duty trucking makes up a significant part of world CO2 emissions and is considered hard to transform. Two technologies are in the starting blocks to decarbonize road freight: Fuel cell and battery electric trucks. The higher competitiveness of hydrogen-powered vehicles for long distances is increasingly challenged. Indeed, battery capacity and lower-cost breakthroughs promote the roll-out of battery-electric trucks and question the infeasibility of electrification of long-haul trucks. Further, more renewables in future scenarios increase the attractiveness of green hydrogen as electricity makes up the highest hydrogen production costs, but battery-electric trucks also profit from cheap electricity prices. The close relationship between electricity and green hydrogen due to sector-coupling is often not considered enough in the debate.

Our study focuses on the role of the two fuels. Therefore, we calculate cost-minimizing electricity prices for BET truck drivers and green hydrogen prices in a competitive market. We find that electricity and hydrogen prices follow the same pattern with increasing renewable penetration, highlighting the sector-coupling aspect. Finally, we estimate the total cost of ownership of both technologies focusing on fuels for 2021 and future scenarios. We show that hydrogen-fueled long-haul trucks are in none of the scenarios cost-competitive over the lifetime of the trucks.

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1. Introduction

The transport sector accounts for approximately one-fifth of global greenhouse gas emissions. European transport emissions increased by 28% between 1990 and 2019 (European Environment Agency, 2021) and by 21% in the US during the same period (Carlier, 2022). Transport is often the most challenging sector to decarbonise as the demand for goods, and car ownership is closely associated with rising population numbers and economic development (Brand, 2021). Trucks and lorries carrying road freight are responsible for almost 30% of all transport emissions and are the second most significant factor contributing to the whole transport sector's emissions next to passenger road vehicles (Ritchie, 2020). Notably, emissions from aviation and shipping have not changed much in the last 20 years, whereas emissions from road freight and passenger vehicles have steadily increased due to rising demand and good flows, especially in developing and emerging markets (International Energy Agency, 2021).

The focus of this study is the heavy-duty trucking sector. Specifically, this comprises commercial vehicles with a total weight of 12 tonnes and above (Plötz, 2022). The typical yearly distance of heavy-duty trucks amounts to 120,000 km with daily mileages of 800 km (Transport & Environment, 2020). Currently, around seven million heavy-duty trucks are operating in the EU, and the number of new registrations is steadily growing. Additionally, heavy-duty trucks are responsible for 5% of total EU emissions with a slightly increasing trend (European Environment Agency, 2018).

Decarbonization of passenger and freight vehicles is a top priority to solve rising emissions in the transport sector. Recent research has focused on ways to curb emissions from the transport sector. Here, the focus has been on finding alternative zero-emission fuels that emit no air pollutants and carbon dioxide. The development and mass roll-out of zero-carbon fuels are critical to a successful energy transition in the transport sector (Gray, McDonagh, O'Shea, Smyth, & Murphy, 2021). The two most promising alternatives are battery-electric and fuel cell trucks powered by hydrogen (Noll, del Val, Schmidt, & Steffen, 2022). On the one hand, the market for passenger cars in the EU increasingly leans towards zero-emission vehicles as they already make up 11% of newly registered passenger cars. This is mainly caused by the mass roll-out of electric cars whereas fuel cell cars are substantially less popular (European Environment Agency, 2021). Recent estimates suggest that 33-40% of new car sales in the EU will be electric vehicles by 2030 (Consultancy.eu, 2021).

However, freight and commercial vehicles and heavy-duty trucks in particular still have a long way ahead on the road towards decarbonisation. The market for zero-emission trucks is much less developed than the market for zero-emission cars, "lagging about ten years behind"(Plötz, 2022). The main question for truck manufacturers and research institutions is whether to focus on electric (BET) or heavy-duty hydrogen trucks (FCET). Electricity seems to be the more economical fuel for smaller commercial vehicles as battery capacity has improved rapidly in recent years (Ars Technica, 2021). However, there is no consensus yet as to which zero-emission fuel - hydrogen or electricity - is more price competitive for long-distance trucking (Plötz, 2022). Only a few years ago, there was a consensus that heavy-duty trucking is almost impossible to electrify. The main problems were the extensive space requirements of batteries and fuel cells for long distances and the insufficient charging infrastructure. Nevertheless, technological progress and political pressures now accelerate the switch to zero-emission alternatives in the heavy-duty trucking industry. More specifically, battery capacity improvements allow longer ranges and the charging times of batteries decreased which enable truck drivers to recharge during their regular brakes (St. John, 2022).

The EU aims to reduce heavy-duty trucking emissions as part of the Green Deal agenda. The emission standard, adopted by the EU Commission in 2019, obliges manufacturers of heavy-duty vehicles to reduce fleet-wide emissions by 15% in 2025 and by at least 30% in 2030 compared to the baseline year 2019. In addition, the proposal also intends to provide credits for manufacturers of low and zero-emission heavy-duty vehicles to comply with the regulation successfully. Overall, the new EU regulation does not determine whether truck manufacturers should build FCET or BET as long as the emission reduction goals are fulfilled (European Commission, 2019). However, current reviews suggest that the emission levels proposed by the EU are not enough to achieve the climate targets set in the EU Green Deal. To stay on the right track towards a decarbonised transport system, the emission reduction target for 2030 needs to be increased to 65%, and from 2035 onwards, only zero-emission heavy-duty vehicles should enter the market (Transport & Environment, 2022).

Truck manufacturers know that the future of heavy-duty trucking is either hydrogen or electricity because emissions need to decrease rapidly. Ultimately, costs will decide which fuel type gains the larger market share. Heavy-duty and long-distance trucking remains the most competitive sector. Whereas BET is already less costly than conventionally powered trucks in short and medium freight applications, the high initial capital costs of zero-emission long-distance trucks reduce their current competitiveness (Noll et al., 2022). Recent studies expect decreasing costs for zero-emission heavy-duty trucks over the next decade. Some scholars suggest higher price competitiveness for BET (Noll et al., 2022; Transport & Environment, 2020) although other researchers indicate lower costs for FCET in the long haul segment (Hunter et al., 2021). This current indecisiveness in the literature is reflected by truck manufacturers investing both in FCET and BET. In fact, the three largest truck manufacturers do not agree which fuel technology is optimal for the zero emission heavy-duty segment. Daimler and Volvo primarily focus on assembling FCET due to the longer ranges and faster refuelling times. Volkswagen, on the other hand, invests solely in BET due to lower costs and the more developed charging infrastructure for electric vehicles. In addition, the British manufacturer Tevva bets on both technologies and builds BET with a hydrogen tank as backup in order to allow longer ranges (Huet, 2022).

It has to be emphasized that different price scenarios yield different results. In particular, future fuel prices for hydrogen and electricity are critical in determining the total costs for heavy-duty trucks. More precisely, the operating costs for heavy-duty trucks become more critical with increasing mileages and amount to approximately 75 % of a truck's total costs (Noll et al., 2022). Fuel costs are the major component of the overall operating costs and thus determine the price competitiveness of zero-emission heavy-duty trucks. Concerning that, international disparities can drive fuel prices for hydrogen and electricity. Countries with higher renewables in the electricity mix or better hydrogen production capacities might be more suitable for the roll-out of either BET or FCET (Noll et al., 2022).

Further, fuel prices for hydrogen and electricity are highly interrelated. It should be noted that we solely regard renewable hydrogen and renewable electricity as we focus on zero-emission heavy-duty trucks. Green hydrogen is produced with electrolysis powered by renewable energy. As renewable electricity prices vary throughout the day, electrolyser plants will maximise production capacities when renewable electricity prices are lowest (see Section 3.4). The mass deployment of renewables in the upcoming years will lead to a decline in renewable electricity prices. Rising costs for fossil fuels and the EU's goal to become more energy independent are the primary triggers for the expansion of renewable electricity plants (IEA, 2022). Consequently, the production costs of green hydrogen will also drop as electricity is the main cost component of green hydrogen production. Besides, other factors such as electrolyser efficiency and capital costs determine the price of green hydrogen, but electricity prices are the main driver in green hydrogen price competitiveness (IRENA, 2020).

In this study, we explore scenarios for different renewable shares in the electricity mix and general electricity demand (see Section 3.4). Overall, a high renewable scenario lowers the cost of electricity and hence that of green hydrogen as well. Our analyses shed more light onto the relationship between renewable hydrogen and renewable electricity prices in different scenarios and how that affects the total costs of BET and FCET.

FCET vs BET - Which zero-emission heavy-duty truck is more price competitive? How is this influenced by the degree of penetration of renewables, and the resulting electricity and hydrogen prices?

We perform a total cost of ownership (TCO) analysis to analyse the competitiveness of FCET and BET. The TCO comprises capital and operating costs over the lifespan of a heavy-duty truck and "is a way of assessing the long-term value of a purchase" (Twin, 2021). In addition, we explore various scenarios for future renewable electricity developments. This allows us to pursue sensitivity analyses for fuel prices of green hydrogen from renewable electricity prices. Our method provides a comprehensive TCO calculation of BET and FCET with an in-depth analysis of zero-emission fuel prices for different scenarios.

To answer the research question, we proceed as follows: The second section gives an overview of current TCO literature in the heavy-duty trucking segment and existing regulations for zero-emission trucks. The third part illuminates our method and presents the data sources. Section four presents the results for the TCO in different scenarios, which we discuss in section five. Further, section five concludes this study and explains the limitations of our analysis.

2. Literature review

2.1 Overview of TCO studies

Although comparative TCO studies first emerged for passenger vehicles, there has been increased attention to heavy-duty trucks. Indeed, various articles now calculate the TCO of heavy-duty BET and FCET compared to combustion engine trucks. The research papers differ in the scope, the parameters used, and the geographical region they focus upon.

Noll et al. computed the TCO for long-haul zero-emission and conventional trucks in ten European countries (2022). The results indicate that FCET is less competitive than BET in nine out of ten countries due to high fuel cell and hydrogen costs. FCET are only competitive with the other truck classes in Switzerland caused of road tolls for higher emission vehicles.
Another study found higher price competitiveness for long-distance BET compared to FCET as well (Transport & Environment, 2020). The applied method is closer to our approach as it computes the TCO based on renewable electricity and green hydrogen prices. The other parameters are derived from the French market.

There have also been TCO studies about heavy-duty FCET and BET in other countries and regions besides Europe. Hunter et al. (2021) found that heavy-duty BET are more price-competitive than FCET in the US. This applies to the baseline year 2018 and, to a lesser extent, to 2025. Assuming that initial capital expenditures shrink in the upcoming years and fuel costs for hydrogen and electricity decrease, the long-term scenario suggests lower TCO for FCET than BET. However, this finding depends on falling hydrogen prices due to expanded production capacities and improved R&D in FCET manufacturing. Further, the scenario analyses yield similar results for different annual mileages.
Moreover, Mao et al. (2021) explored the TCO parity of FCET and BET with conventional trucks in three Chinese cities: Shanghai, Shenzhen and Beijing. According to their calculations, BET is more price-competitive than FCET in the heavy-duty seg-

ment in all three examined cities. More precisely, heavy-duty BET will reach price parity with diesel trucks in 2030 and 2022 if the Chinese government installs policy measures such as fossil fuel pricing and purchasing subsidies for zero-emission vehicles. On the other hand, heavy-duty FCET will only achieve price parity with diesel trucks in the long term and not before 2030. However, the right financial incentives from policymakers could bring price parity in 2025.

Overall, the literature does not uniformly yield similar results for the TCO of FCET and BET. More specifically, electrification of passenger and smaller freight vehicles is already underway as batteries are more price competitive and efficient for smaller distances. However, the heavy-duty and long-distance segment remains the hardest to electrify today. The long daily mileages require powerful and large batteries and sufficient fast-charging infrastructure to enable efficient trucking. Here, fuel cells could be superior to batteries due to the smaller size and faster recharging time (Plötz, 2022).

Additionally, the price competitiveness of heavy-duty FCET and BET heavily depends on the geographic location and the related policy measures. As mentioned above, national policies substantially influence the TCO for zero emission trucks, so they artificially alter the actual costs. Noll et al. (2022) argue that purchase subsidiaries, road toll exemptions and fossil fuel taxation are the three main drivers of price competitiveness for FCET and BET. Different national legislation, constant progress in battery and fuel cell production and green hydrogen and renewable electricity prices that are hard to predict lead to varying TCO results for zero-emission trucks. Hence, there is no definite consensus yet in the literature on whether FCET or BET will dominate the heavy-duty trucking market.

Current research shows operational costs (OPEX) are more critical for truck operating firms than capital expenditures (CAPEX). OPEX account for 75% of the total TCO of a heavy-duty FCET. The TCO for a heavy-duty BET comprises around 50% OPEX and 50% CAPEX due to higher initial battery costs. This shows that the OPEX are the primary determinant of price competitiveness for zero-emission heavy-duty trucks. Here, fuel costs - hydrogen or electricity - account for a significant share of total OPEX. In addition, the longer distances heavy-duty trucks cover per year, the more critical OPEX become as part of the total TCO calculation (Noll et al., 2022). Thus, our study examines the importance of fuel costs in the long-distance trucking segment by exploring scenarios for future green hydrogen and renewable electricity prices.

Our study adds to the TCO literature by shedding more light on the price competitiveness of heavy-duty FCET and BET in the Netherlands. Furthermore, we illuminate the direct relationship between hydrogen and electricity prices as fuel prices are one of the critical drivers of TCO competitiveness. In addition, our analysis solely regards green hydrogen and renewable electricity because these are the primary fuel options for a zero-emission transport sector. Specifically, we compute the TCO for four scenarios with differing renewable shares in the total energy mix and varying demand. This more nuanced approach contributes to the current literature as we explore several projections for future electricity and hydrogen prices.

2.2 EU regulations for zero emission heavy-duty trucks

As mentioned above, the decarbonisation of the transport sector is a significant component of the EU Green Deal. Hence, the European Commission requires truck manufacturers to reduce CO2 emissions from heavy-duty vehicles by 15% in 2025 and 30% in 2030. In addition, the EU provides funding for manufacturers of zero-emission heavy-duty trucks to accelerate the switch to alternative fuels. However, there are no emission standards for the years until 2025. During that time frame, truck manufacturers still have an incentive to build lower emission vehicles as this facilitates access to credits and mitigates the risk of paying a fine if the emission reduction goal is not achieved by 2025. More precisely, truck operating firms have to pay 4,250€ for excess CO2 emissions per vehicle from 2025 onwards and 6,800€ beginning in 2030 (European Commission, 2019).

Critics of the regulation argue that the emission targets are not ambitious enough and threaten the rapid decarbonisation of the transport sector (Transport & Environment, 2022). Others claim that heavy-duty FCET and BET are not a safe investment for truck manufacturers without a sufficient charging infrastructure as they rely on a comprehensive network of charging and refuelling stations. As a potential solution, EU member states' and national governments should provide more incentives for building a charging infrastructure for FCET and BET. This will facilitate the switch from conventional to zero-emission heavy-duty trucks across Europe (Carroll, 2022).

2.3 Market for zero emission heavy-duty trucks

The market for zero-emission trucks is much less developed than the market for zero-emission cars, "lagging about ten years behind"(Plötz, 2022). At the beginning of 2022, around 15 million battery-electric and plug-in hybrid and 25,000 fuel cell cars will be on the road worldwide. Compared to these numbers, there are only 30,000 battery-electric trucks in stock and only a few thousand fuel cell trucks (mainly buses) on the market. However, policy regulations, technological advancements and financial incentives push manufacturers to develop and scale up the production of zero-emission trucks (Plötz, 2022).

Overall, the European market for zero-emission trucks is still at an early stage of development. On the other hand, China has the largest market share and accounts for more than 90% of all sold zero-emission trucks and buses. This demand is driven by policy measures such as financial incentives and specific targets for the share of zero-emission vehicles in the national fleet (Mao & Rodríguez, 2021). In contrast, the European share in the zero-emission heavy-duty market amounted to 3% in 2020. Additionally, the race towards zero emissions in the heavy-duty segment in Europe leans towards battery-electric trucks. More than 97% of new zero-emission heavy-duty vehicles are powered by electricity, whereas hydrogen-powered trucks and buses are still scarce. Currently, 75% of zero-emission heavy-duty trucks in Europe operate in Germany, France and the Netherlands. However, experts estimate that other countries and manufacturers will soon increase the share of heavy-duty FCET and BET due to reductions in battery and fuel cell costs and upcoming EU emission standards (Basma & Rodríguez, 2021).

Truck manufacturers worldwide increasingly develop and build zero-emission heavy-duty vehicles. Research progress, price drops and policy incentives now enable the decarbonisation of long-haul freight trucks - a sector many thought impossible to electrify due to battery capacity and fuel tank size constraints. The number of commercially available zero emission heavy-duty trucks increased by 56% (39 to 61 models) between 2020 and 2022. The US, Canada, China and, to a lesser extent, the EU account for the rapid development of new models (Sporring, 2022).

Several known vehicle manufacturers such as Nikola, Volvo, Hyundai, Daimler, and Mercedes Benz have developed and already assembled the prototypes for heavy-duty FCET. On the other hand, Volkswagen, Freightliner, Tesla and Rivian primarily focus on building heavy-duty BET to decarbonise the long-distance freight segment (Noll et al., 2022).

3. Method and Data

To determine the best choice for future sustainable trucking, we apply the total cost of ownership method, which considers financial parameters over a truck's lifetime. The country of our analysis is the Netherlands, as we have access to the most up-to-date and reliable electricity data and the CAPEX and OPEX parameters - excluding electricity and hydrogen prices - are comparable with other Western European countries (Basma & Rodríguez, 2021). Further, we only consider heavy-duty trucks with daily distances of up to 800 km. According to the European Commission, commercial vehicles with a total mass of 12 tonnes and above are classified as N3 (TransportPolicy, n.d.). Similarly, the US system classifies trucks with a weight of 12 tonnes and above as class 7 and class 8 heavy-duty vehicles (Fullbay, n.d.). We add to existing TCO literature about fuel cell and battery electric trucks' cost competitiveness by examining the role of electricity and green hydrogen prices. The prices of both energy carriers are highly interrelated due to sector coupling. In essence, electricity can be used to fuel BET directly or to power electrolysis, the chemical process of generating hydrogen for FCET. The cost of electricity is the most significant cost component in the production of green hydrogen and is, thus, the decisive factor for green hydrogen competitiveness (IRENA, 2020).
The year 2021 will be taken as a baseline, and future scenarios vary between medium and high renewable energy share of total Dutch energy consumption and between a low and high increase in demand.

The section will be structured as follows: First, we explain the underlying TCO method, relevant parameters, and the data we use to calculate the TCO for both technologies. From there, we state our approach to calculating electricity and hydrogen prices. To highlight the link between electricity and green hydrogen prices, we explain the data separately for the baseline and future scenarios and show the impact of more renewables in the electricity mix.

3.1 TCO

The variables for determining the TCO can vary across countries and studies. For the calculation, we will use the following formula:

$$TCO_j = CAPEX_j + \underbrace{\sum_{t=1}^{T} DW_t + M_t + T_t + \underbrace{[(D_t * EC_j) * F_j]}_{TotalFuelCosts_j}}_{OPEX_j} \tag{1}$$

Here, $CAPEX_j$ denotes the initial capital expenditure in EUR consisting of the powertrain, energy storage, and the rest of the truck. Subscript j denotes the technology type. The $OPEX_j$ consists of the sum of driver wages DW_t, maintenance and repair cost M_t and the road tolls T_t. Subscript t denotes the period and is defined as one year. Capital T denotes the lifetime of a truck. Further, D_t represents the annual distance by the truck multiplied by the energy consumption EC_j of BET and FCET in terms of kWh/km. Finally, F_j stands for the two different fuel costs. The sum of distance, energy consumption, and fuel costs is defined as $TotalFuelcosts_j$. For the calculation and to show the impact of fuel costs on the TCO of both technologies, we assume that $CAPEX_j$ and $OPEX_j$ excluding $TotalFuelCosts_j$ are paid upfront for the lifetime of the trucks and only control for fuel costs change.

3.1.1 CAPEX and OPEX parameters

For this study, we use CAPEX and OPEX parameters for BET and FCET from recent research. In particular, we take constant values for the net purchase price of the truck, road tolls, maintenance costs and driver wages. We excluded other country-specific parameters such as subsidies, scrappage values and CO2 taxation. Consequently, we receive the least distorted results for our TCO analysis as we leave out parameters that could change temporarily due to political will or other circumstances. In addition, we assume an annual distance of 120,000 km and a daily mileage of 800 km for long haul FCET and BET based on industry data from the European Commission (Transport & Environment, 2020).

Purchase prices for BET and FCET in the long haul sector are often overstated and can amount to 300,000 € and above for both technologies (Noll et al., 2022). However, the rapid decline in battery prices enables the production of trucks that will cost substantially less. On the other hand, manufacturers are promoting upcoming low-carbon trucks that seem very cost-competitive with conventional diesel-powered trucks. For instance, Tesla announced that the electric semi-truck would cost 141,000 - 170,000 € depening on the range once it is officially launched (Stopford, 2022). We assume the most sensible values taking into account technological developments and take 167,000 € for a heavy-duty BET and 139,000 € for a heavy-duty FCET (Transport & Environment, 2020).

Regarding the operational costs, the following three parameters - excluding fuel costs - are essential in determining the TCO. First, yearly road charges for heavy-duty low-carbon trucks amount to 1250 € in the Netherlands (Noll et al., 2022). Costs for maintenance and repair are estimated to be around 33 - 50 % lower for low-carbon trucks compared to diesel trucks and amount to 0.1324 € / km (Basma & Rodríguez, 2021). This value results in 15888 € annual maintenance costs, which is comparable with estimates from other studies (Transport & Environment, 2020). Furthermore, driver wages in Western Europe typically amount to 50,000 € annually (Noll et al., 2022).

To further determine the fuel costs in the TCO analysis, we make assumptions about the energy consumption of BET and FCET. Most studies find significantly more energy-efficient low-carbon trucks than conventional diesel-powered trucks. Vehicle and drivetrain characteristics are similar for both FCET and BET. Thus, energy consumption for the two zero emission trucks are the same before accounting for the efficiency losses from the conversion of hydrogen into electricity in the fuel cell. Hence, total energy consumption for FCET is considerably higher than that of BET. Besides, research estimates expect efficiency improvements due to manufacturing progress in battery and fuel cell design. We derive our values from a Transport & Environment paper (2020) and propose an energy consumption rate of 1.15 kWh / km for heavy-duty BET and 1.95 for heavy-duty FCET.
Consequently, a heavy-duty FCET with an annual mileage of 120,000 km and energy consumption of 1.95 kWh / km demands 234,000 kWh worth of hydrogen in a year. Similarly, a heavy-duty BET needs 138,000 kWh worth of electricity in a year. The assumptions for CAPEX and OPEX parameters are summarized in table (1):

Parameters	**BET**	**FCET**
Initial capital expenditure (CAPEX)	167000€	139000€
Drivers wages (DW)	50000€	50000€
Maintenance (M)	15888€	15888€
Road tolls (T)	1250€	1250€
Annual distance (D)	120,000 km	120,000 km
Lifetime (T)	10 years	10 years
Energy consumption rate (EC)	1.15 kWh / km	1.95 kWh / km

Table 1: Assumptions and parameters for TCO-analysis

To assess the cost-competitiveness of BET and FCET, we primarily focus on fuel costs. The following sections explain our approach to calculating electricity and hydrogen prices while highlighting the connection between these two.

3.2 Electricity price

Electric-powered trucks need to be recharged twice a day (range 400-800 km), and the driver must take two daily breaks by Dutch laws. Following this, we assume that the truck driver is price sensitive and optimizes his behaviour by combining brakes and recharging the cells when spot prices are lowest. Denote the lowest electricity price on day t as p^{c1_t} and the second-lowest as p^{c2_t} Further, for T=365 days per year, the relevant average yearly electricity fuel price p^e for a given scenario is then given by:

$$p^e = \frac{1}{2T} \sum_{t=1}^{T} p^{c1_t} + p^{c2_t} \tag{2}$$

As a sensitivity analysis, we also consider the situation where truck drivers are price-insensitive and drive and charge according to a fixed pattern. In particular, a truck driver in the Netherlands and the rest of the EU is allowed to drive 9 hours maximum per day and has to do a mandatory break of 45 minutes after 4.5 hours (Morgan, 2022). The average speed for heavy-duty trucks in Europe amounts to 90 km/h (Arbeiterkammer Österreich, n.d.). If we assume these numbers, the distance after 4.5 hours is 400 km, which is possible for the current generation of BET without recharging. The new Volvo BET has a range of 440 km, the upcoming Tesla Semi is expected to reach 400 km in the basic, and over 1000 km in the high-class version and the BET by Freightliner reaches 390 km. However, it takes approximately 90 minutes to charge 80 % of these trucks' batteries ((Morgan, 2020); (Volvo, 2022)). There is a road map for installing megawatt charging stations every 50 km along the main highways in Europe that would significantly reduce charging times. This infrastructure plan is only a draft for the upcoming years, and for now, we take the current fast-charging standard of up to 350 kW (Plötz, 2022). Thus, we assume the typical truck driver starts the work day at 8 AM, drives for 4.5 hours until 12.30 PM, then takes a mandatory break of 90 minutes to charge batteries to approximately 80 % and then continues driving for 4 hours between 2 PM until 6 PM before recharging for the next day.

Denoting the electricity prices at those times at day t by, respectively, p^{p1_t} and p^{p2_t}, the relevant yearly average electricity fuel price p^e for a given scenario is then given by:

$$p^e = \frac{1}{2T} \sum_{t=1}^{T} p^{p1_t} + p^{p2_t} \tag{3}$$

3.3 Hydrogen price

Hydrogen is a gas that can be extracted from either natural gas using steam methane reforming (SMR) or water using electrolysis. One refers to hydrogen as grey if produced using natural gas and blue if the emitted carbon is captured and stored. Further, hydrogen is referred to be green if it is produced using electrolysis and renewable electricity. Our study will focus on green hydrogen to show the relationship between green hydrogen and electricity production.

As there is not yet a liquid hydrogen market, we calculate hydrogen prices by assuming that producers and suppliers of green hydrogen compete in a competitive market with sufficient other suppliers, hence, taking prices as given. Following, the supplier sets the price for hydrogen such that the marginal cost (MC) are equal to the average total cost (ATC):

$$p^h = ATC = MC \tag{4}$$

The marginal costs calculate how much it costs to produce one more unit of hydrogen, whereas the average total cost shows how much it costs to produce a certain amount of hydrogen. Figure (1) illustrates the relationship between different cost types in a competitive market:

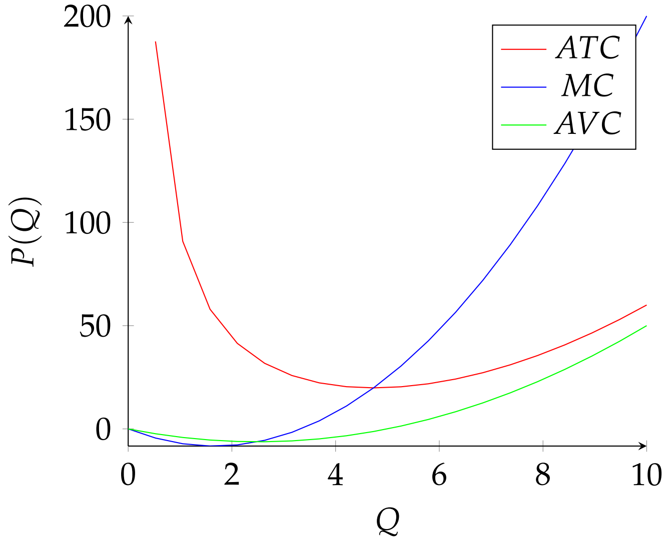

Figure 1: Relationship between different cost types in a competitive market

The intersection of ATC and MC gives the equilibrium hydrogen price P^* and hydrogen quantity Q^*. The reason behind setting the price equal to the marginal cost and the average total cost of the optimal quantity is that otherwise, the producer has an incentive to deviate to get the total market demand. However, deviating and undercutting a component means we see ourselves left to the intersection where the producer makes a loss as the revenue is insufficient to cover all costs. Following this, the producer sets the price to cover the average total cost and does not make a loss. Left to the intersection, the producer makes a loss because the revenue is not enough to cover all costs. Right to the intersection, the producer makes a profit. The AVC curve follows the ATC curve but stays beneath it. The average total costs are calculated by adding the average fixed costs (AFC) to the average variable costs(AVC):

$$ATC_q = AFC_q + AVC_q \tag{5}$$

Here, the average fixed cost is calculated by dividing the fixed costs by the produced quantity:

$$AFC_q = \frac{FC}{q} \tag{6}$$

For the fixed costs of an electrolyzer, we take data from Perey and Mulder (2022) who estimate the CAPEX of an electrolyzer to 1250 €/KWh. Assuming a capacity of 1 MW and a lifetime of 20 years leads to a yearly CAPEX of 62500€. For simplicity, we ignore discounting rates. Further, to show the relationship between hydrogen and electricity prices, we will assume that the operational expenditure for the operation of an electrolyzer is fixed and makes up a fixed portion of the fixed costs over a year, hereafter referred to as fixed CAPEX. Perey and Mulder (2022) states that 1,5% of CAPEX are OPEX per year, leading to a fixed CAPEX of 81250 euros that are used hereafter as fixed costs. Further, the electrolyzer needs a stock replacement of 30% of CAPEX after ten years which is also added to the fixed CAPEX. This leads to an overall fixed CAPEX of 100000€. Further, we assume that the electrolyzer runs all year round, setting the maximal produced quantity to 8760 MWh per year.
The AVC can be calculated by taking the integral of the marginal costs of producing quantity q denoted in MW/h and divide it by quantity q:

$$AVC_q = \frac{\int_0^q MC_q}{q} \tag{7}$$

The marginal costs of a hydrogen supplier here depend solely on the electrolyzer's fuel costs and electricity. The rational hydrogen producer will produce hydrogen when electricity prices are lowest. Following, the marginal costs curve of producing hydrogen resembles the inverse of the price-duration curve. The price duration curve plots electricity prices on the spot market from highest to lowest per hour of the year.
An electrolyzer is not entirely efficient, and the marginal costs have to be multiplied by a conversion factor η. Perey and Mulder (2022) estimate the conversion factor of an electrolyzer to $\eta = 0.75\%$, meaning that one MWh input for an electrolyzer results in 0.75 MWh of hydrogen:

$$MC_q = \frac{PD_q^{-1}}{\eta} \tag{8}$$

Assumptions for the electrolyzer are summarized in table (2):

Assumptions	Electrolyser
Initial capital expenditure (CAPEX)	1250 (€/kW)
Yearly OPEX (%/CAPEX)	1,5%
Lifetime	20
Capacity	1 MW
Operating hours per year	8760
Stock replacement costs (once after 10 years)	30%

Table 2: Assumptions for CAPEX and OPEX of an electrolyzer by (Perey & Mulder, 2022)

3.4 Data for baseline and future scenarios

Green hydrogen and electricity prices are, as argued, closely related to each other due to sector coupling. The green hydrogen price closely follows market developments in the electricity market. However, electricity prices are not fixed but change depending on supply and demand. The demand changes throughout the day depending on how much energy is needed. The supply side also varies, depending on how many plants are needed to satisfy demand. Here, those plants produce energy and satisfy demand first with the lowest marginal costs. The supply curve in the electricity market is called merit-order and describes the arrangement of production types from lowest marginal cost to highest marginal cost. The last plant or plant type needed to satisfy the demand for a given time is called the price-setting plant, as its marginal costs determine the price in the electricity market. However, depending on the demand, the price-setting plant can switch temporarily, and, hence, different electricity prices occur depending on the price-setting plant and its marginal costs (Mulder, 2021).
One way to visualize these developments in electricity markets over a year is to sort hourly electricity prices from highest to lowest, called a price-duration curve. As data for the year 2021, which is used as the baseline (hereafter referred to as Base), we use day-ahead electricity prices for the Dutch electricity market provided by ENTSO-E (ENTSO-E, 2021).

Electricity prices temporarily change through either change in demand or supply. However, due to lower marginal costs, more renewables can permanently lower the average electricity price in the electricity market. To show the effect of more renewables in the energy mix, we also consider future scenarios with different predicted increases in renewable energy. Therefore, we use model predictions by Veenstra, Li, and Mulder (2022). The authors model electricity prices per hour per day for four different scenarios for the Dutch electricity market. The first scenario (hereafter referred to as scenario 1) shows a medium increase in renewables and a low increase in demand (ML). The second scenario (hereafter referred to as scenario 2) shows the same increase in renewables but assumes a high demand increase (MH). The medium renewable scenarios reflect an increase in renewables necessary to be in line with the Dutch Climate Agreement targets. The third scenario (hereafter referred to as scenario 3) shows a high increase in renewables and a low increase in demand (HL). The last scenario (hereafter referred to as scenario 4) shows a high increase in renewables but a high increase in demand (HH). The high renewable scenarios reflect predicted amounts of renewable energy in 2050. Figure (2) shows the price duration curve for the baseline as well as future scenarios:

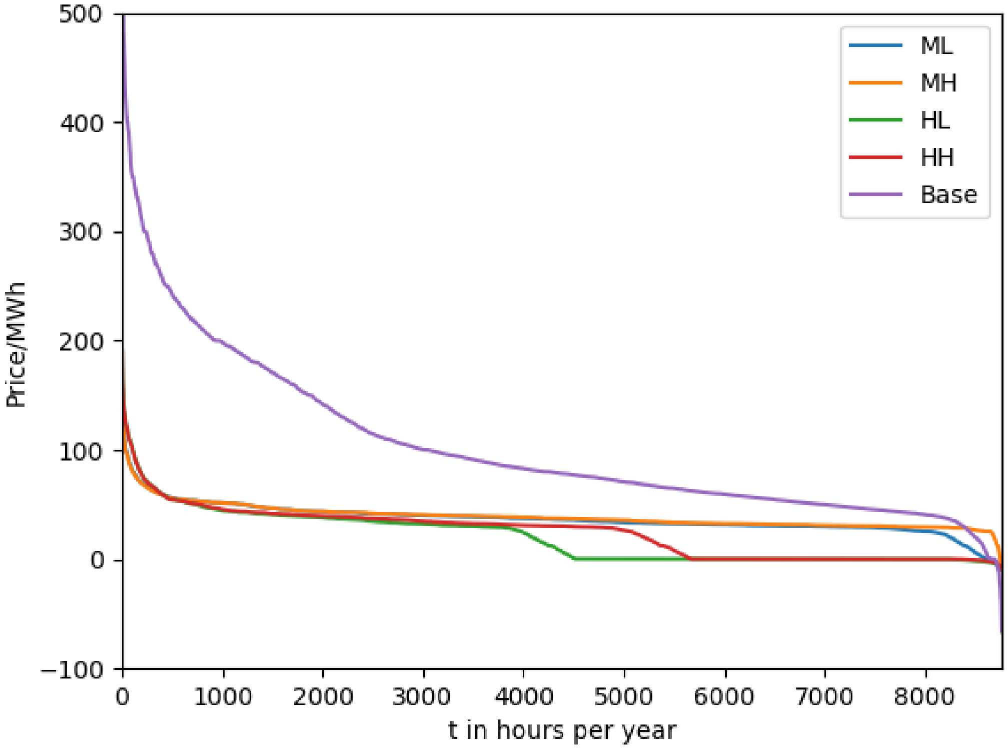

Figure 2: Price Duration Curves for the baseline and future scenario

It is directly visible that scenarios with high shares of renewable energy, i.e. considered future scenarios, have a significantly lower price-duration curves than the baseline scenario. However, the baseline scenario is, most likely, upward-biased due to shortages and tensions in electricity markets due to the Corona Pandemic. However, we also see that the high renewable scenarios differ significantly from the scenarios with only a medium increase in renewables. Further, we see that a high increase in renewables leads to electricity prices of zero throughout a large part of the year due to marginal costs close to or equal to zero.

4. Results

To determine the competitiveness of BET and FCET trucks, we will first state the electricity prices in the baseline and future scenarios. We will also show the sensitivity of electricity prices for sensitive and insensitive truck drivers. Afterwards, we will discuss the results for hydrogen prices in the baseline and future scenarios. Finally, we will use the results and discuss the competitiveness of BET and FCET by comparing the TCO of both technologies in the baseline and future scenarios for the Netherlands.

4.1 Electricity price

As argued, electricity prices make up a significant part of the TCO. Following, we assume that the truck driver reacts to price changes and incorporates them into his decision-making. Figure (3) shows the results for the year 2021 for the Netherlands as a price duration curve taking the average electricity price per day as determined by equation (1) for the price-sensitive truck driver and the price-insensitive truck driver by equation (2):

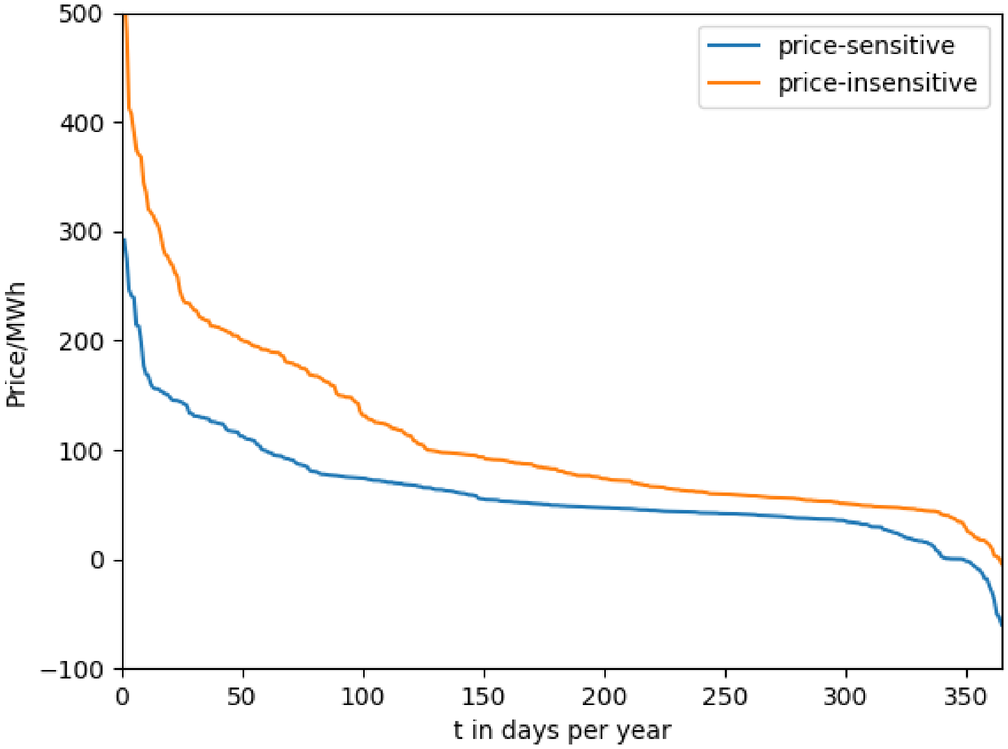

Figure 3: Electricity-fuel-price duration curve for electric trucks for different price-sensitivities in the baseline scenario

Figure (3) shows that optimizing and price-sensitive behaviour differs significantly in the baseline scenario. The yearly average electricity price of the price-sensitive truck driver is $p^e = 61.75$ €/MWh, while it is almost twice as significant for the price-insensitive truck driver $p^e = 110.35$ €/MWh.

Similar to figure (3), figures (4)-(7) show the average price differences for the price-sensitive and the insensitive truck driver as price-duration curves in the different future scenarios:

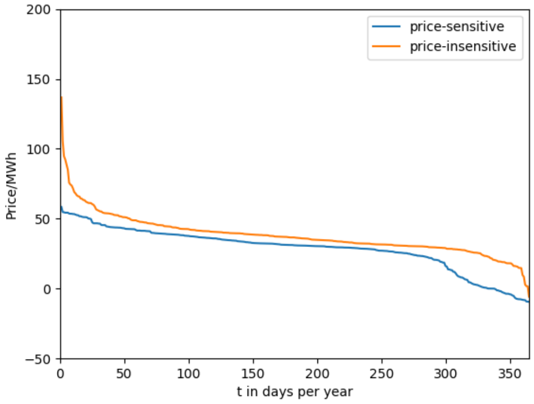

Figure 4: Electricity prices for Scenario 1

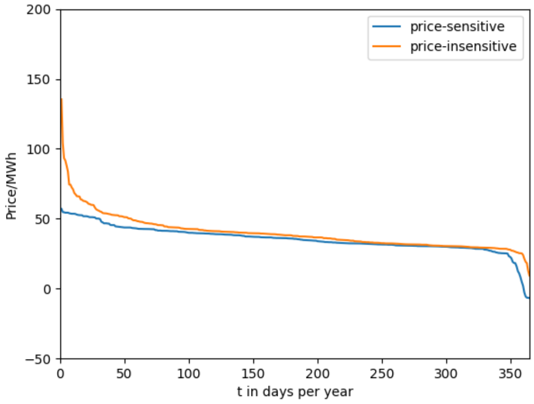

Figure 5: Electricity prices for Scenario 2

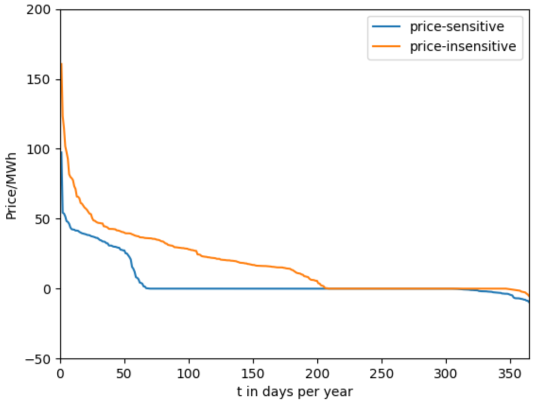

Figure 6: Electricity prices for Scenario 3

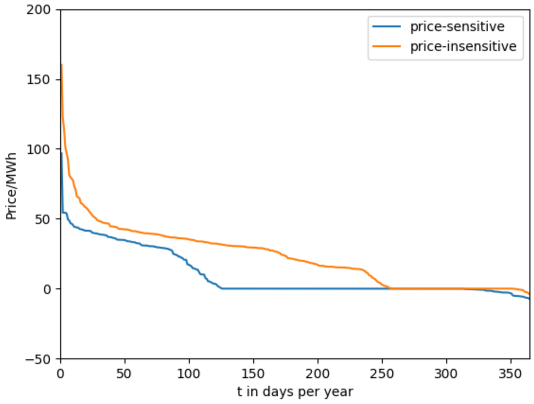

Figure 7: Electricity prices for Scenario 4

The impact is similar for future scenarios. However, the absolute magnitude is different. In the first scenario, with a medium increase in renewables and a low increase in demand, the average electricity price for the price-sensitive truck driver is $p^e = 28.71$ €/MWh while it is $p^e = 38.11$ €/MWh for the price-insensitive truck driver. The smallest average price difference is in the second scenario with a medium increase in renewables and a high increase in demand with an average electricity price of $p^e = 35.53$ €/MWh for the sensitive truck driver compared to $p^e = 39.87$ €/MWh for the insensitive truck driver. On the contrary, the price differences increase again for the scenarios with a high increase in renewables, being $p^e = 5.29$ €/MWh for the sensitive and $p^e = 17.57$ €/MWh for the insensitive truck driver in the low increase scenario. Again, the average electricity prices are slightly higher in the high-demand scenario with $p^e = 9.87$ €/MWh for the sensitive and $p^e = 23.01$ €/MWh for the insensitive truck driver.

The significant price difference for truck drivers between the baseline and future scenarios must be interpreted cautiously. While the future scenarios assume regular developments in the Dutch energy market, the data for the baseline scenario reflect uncertainties and shortages in international energy markets due to the corona pandemic and are upward-biased. However, the overall result of significantly different average electricity prices is the same for all scenarios, leading us to prefer the price-sensitive average electricity prices in the TCO calculations.

4.2 Hydrogen price

Contrary to the electricity prices, there is not yet an existing market for hydrogen, making it impossible to use real-life market data. However, as stated in the method section, we mirror a competitive market and show a competitive hydrogen producer's behaviour and price setting. Figure (8) shows different cost curves of a hydrogen producer and the corresponding competitive price and quantity in the baseline scenario for the Netherlands:

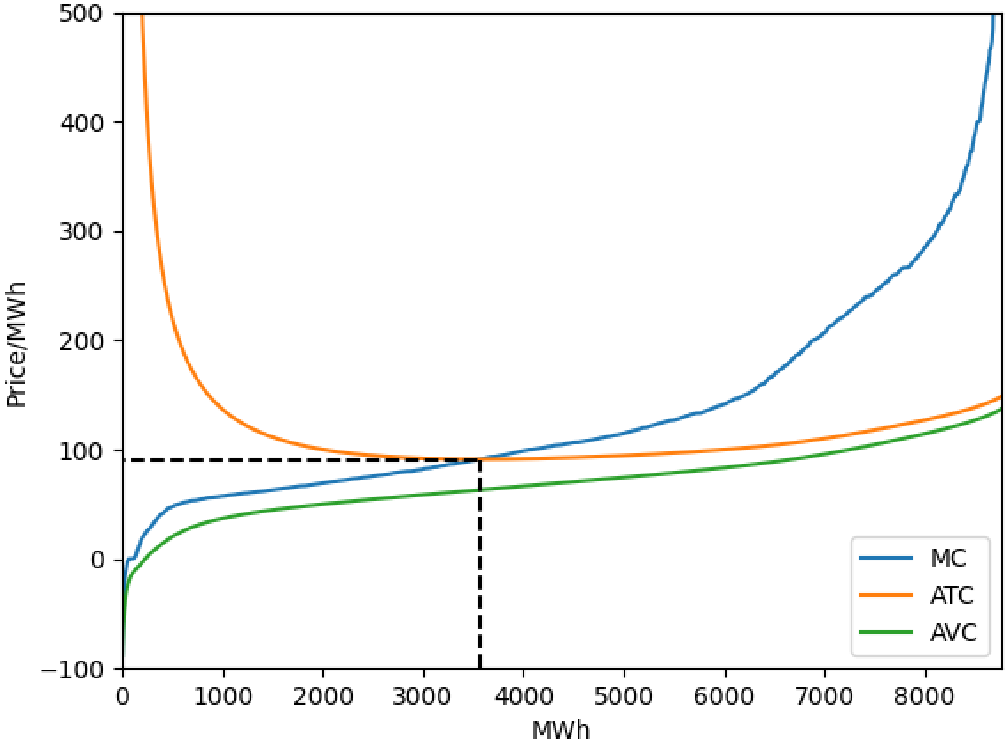

Figure 8: Hydrogen price in the baseline scenario

In the baseline scenario, the green hydrogen price in a competitive hydrogen market would be $p^h = 91.02$ €/MWh[4]. It is important to note that, contrary to the electricity prices, there is only one hydrogen price. This is due to the fact that hydrogen is a storable good and, hence, hydrogen producer make use of any arbitrage possibility which leads to one price over a year.

Due to the sector coupling, this hydrogen price, similar to the average electricity prices in the baseline scenario, must be interpreted with caution due to an upward bias resulting from the Corona Pandemic.

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[4] Perey & Mulder (2022) find a higher hydrogen price of 101.21 €/MWh, however we assume a lower average electricity price

Similar to the baseline scenario in figure (8), figures (9)-(12) show the hydrogen price and other relevant cost curves in the different renewable energy and demand scenarios:

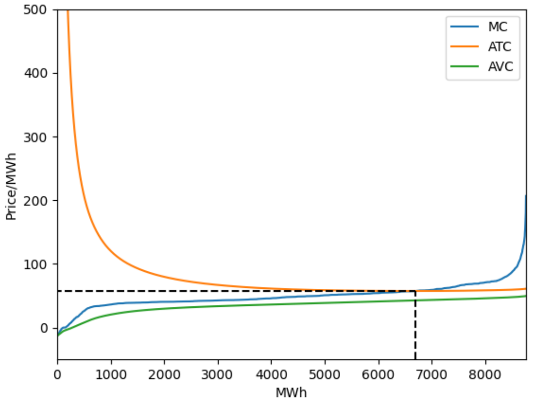

Figure 9: Hydrogen price for Scenario 1

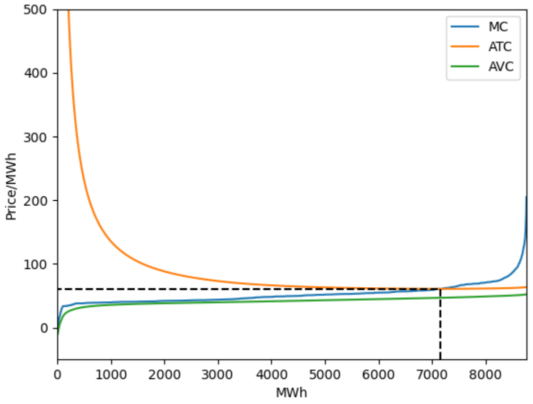

Figure 10: Hydrogen price for Scenario 2

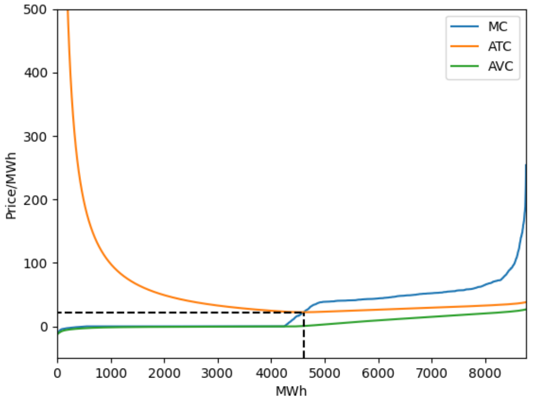

Figure 11: Hydrogen price for Scenario 3

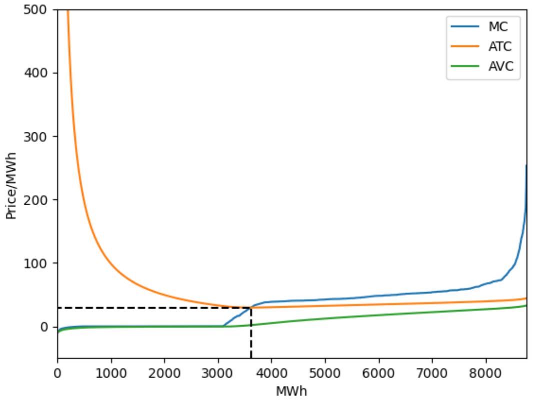

Figure 12: Hydrogen price for Scenario 4

Figure (9) shows the first scenario with a moderate increase in renewable and a low increase in demand. The Hydrogen price is $p^h = 57.44$ €/MWh in equilibrium. Similarly, figure (10) shows the second scenario with a moderate share of renewable but high demand. However, the price difference due to higher demand is slight, with an equilibrium price of $p^h = 60.72$ €/MWh. The third scenario shows the hydrogen price in a high renewable, low demand scenario. The difference is significant compared to the moderate renewable scenarios and drops to a hydrogen price of $p^h = 22.31$ €/MWh. The difference between high and low demand in the high renewable scenarios is also small, as in the moderate scenarios. The hydrogen price increases to

$p^h = 29.59$ €/MWh in the high-demand scenario.

4.3 TCO

Finally, to add to the TCO literature, we start by calculating the TCO for BET and FCET long-haul trucks for the baseline scenario using electricity prices for the price-sensitive truck driver and hydrogen prices in a competitive market. Therefore, as stated in the method section, we assume that CAPEX and OPEX are paid upfront for the whole lifetime of the truck:

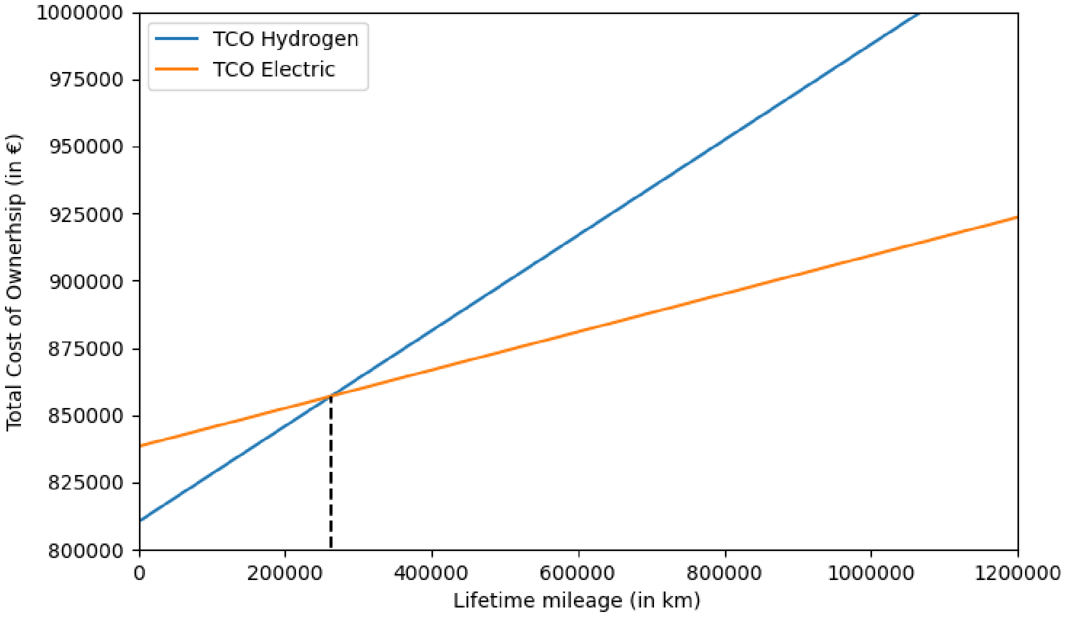

Figure 13: TCO with $p^e = 61.75$ €/MWh and $p^h = 91.02$ €/MWh

Figure (13) shows the development of the TCOs only controlling for the costs due to energy consumption keeping other parameters constant[5]. The interface of the two graphs marks the break-even points where both technologies are equally costly. It is essential to highlight that it cannot be interpreted from the graph that left to the break-even point, the entrepreneur would choose FCET as the entrepreneur would choose another model for short distances with different CAPEX and OPEX. Figure (13) shows that, even though the FCET truck has lower costs initially, the difference in fuel prices makes the BET truck more attractive over the lifetime of the trucks. The break-even point in the baseline scenario is roughly after two years, assuming a yearly mileage of

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[5] Maintenance and tolls could go up with more mileage but these CAPEX parameters do not drive differences between BET and FCET trucks

120,000km.

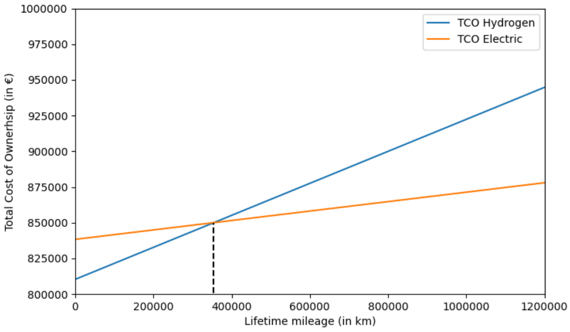

Figure 14: TCOs for Scenario 1

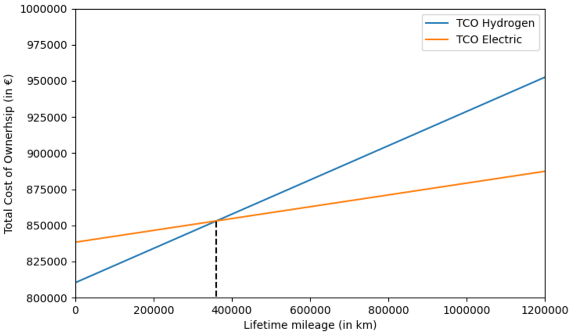

Figure 15: TCOs for Scenario 2

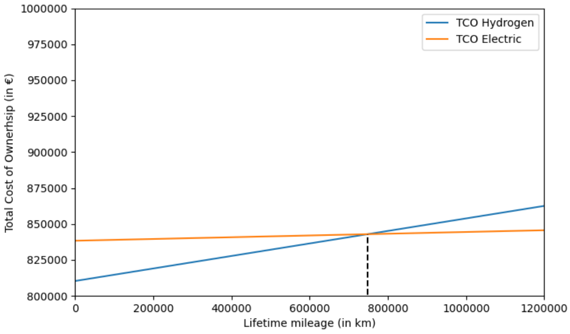

Figure 16: TCOs for Scenario 3

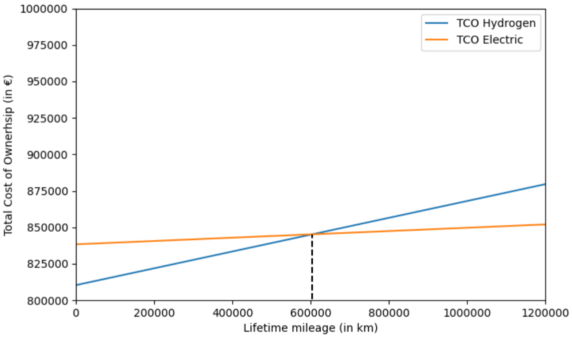

Figure 17: TCOs for Scenario 4

The figures (14)-(17) show the TCO for the future scenarios. In the medium renewable scenarios, the TCO curve is flatter than the baseline scenarios due to the lower fuel weight for the overall costs. Furthermore, in the high renewable scenarios, the weight of fuel costs decreases even more compared to the medium renewable scenarios.
With less weight on fuel costs in the TCO calculation, the importance of other OPEX and CAPEX parameter increase. As driver wages, maintenance and road tolls are the same for BET and FCET (see 3.1.1), the initial CAPEX become more critical.
With lower fuel costs, the break-even point slightly increases for the medium renewable scenarios. This effect further increases in the high renewable scenarios. It shows that an abundant amount of cheap energy increases the attractiveness of BET and FCET trucks. However, taking the whole lifetime of the trucks and a yearly mileage of 120,000km into consideration, the BET trucks are the more attractive choice in the long-haul segment throughout all scenarios.

In the baseline scenario, the weight of fuel costs of annual OPEX of the trucks makes up 9% for BET, and 21% for FCET, respectively. Our findings differ significantly from estimates of other papers (See Transport & Environment (2020) with 28% for BET and 41% for FCET). This further reduces to 0.86% for BET and 6,1% for FCET in the future scenario with the lowest fuel costs (Scenario 3).
Our findings show that the BET long-haul trucks are the optimal choice out of a cost perspective in all future scenarios due to sector coupling. However, our findings also show that the relevance of fuel costs for the cost-competitiveness reduces in scenarios with an increasing share of renewable in the overall electricity mix.

5. Discussion and conclusion

To answer the research question of whether Dutch entrepreneurs should prefer fuel cell trucks or battery-electric trucks for future long-haul trucking and how this depends on the degree of renewables that influences electricity and hydrogen prices, we used the TCO calculations with a particular focus on fuel prices. We will first summarize our key findings and interpret them. Further, we discuss the assumptions and limitations of our findings.

Contrary to popular beliefs, we find that FCET is neither in the baseline nor future scenarios competitive against BET in the long-haul segment. Fuel costs drive the TCO of both technologies. Higher penetration of renewable and lower electricity prices lower green hydrogen prices in future scenarios. However, lower electricity prices also benefit BET and, hence, higher renewable penetration does not change the overall competitiveness of both technologies.

Our results add to the current TCO literature for zero-emission heavy-duty trucking in the EU. Specifically, our research sheds light on the price competitiveness of heavy-duty trucks powered exclusively by green hydrogen or renewable electricity. This approach is consistent with the EU Green Deal to decarbonize the transport sector and with the Dutch government's ambitions to promote the roll-out of zero-emission vehicles. Overall, our results primarily reflect the current consensus in the literature that heavy-duty BET is more price-competitive than FCET over the lifetime (Hunter et al., 2021; Mao & Rodríguez, 2021; Noll et al., 2022). Similarly, our findings align with a study that based the TCO analysis on green hydrogen and renewable electricity prices as well (Transport & Environment, 2020).

The core of our analysis is the calculation of TCO, focusing on fuel costs over the lifetime of the two trucks. The calculation of both fuel costs plays a significant role in the calculation. Our findings are driven by the differences in hydrogen and electricity fuel prices, which are interrelated and driven by the amount of renewable penetration. The scenarios we consider differ between a medium and high increase in renewable and, further, between a low and high increase in demand. We see that electricity prices decrease significantly in scenarios with higher penetration of renewables. Further, lower demand also leads to lower electricity prices, here visualized as price-duration curves. The first scenario considers 2021 as a baseline. We see a large part of the period with high electricity prices in the price-duration curve. Further, we see negative electricity prices for a short period. The considered average paid electricity price for the baseline scenario is 61.75 €/MWh. The hydrogen price in the baseline scenario is 91.02 €/MWh. The second scenario with a medium increase in renewable and a low increase in demand showed a significantly lower price-duration curve than the baseline. Here, we see less time with high electricity prices and more time with low electricity prices. The considered average electricity price in the second scenario is 28.71€/MWh, and the hydrogen price is 57.44 €/MWh. The price-duration curve in the third scenario with a medium increase in renewable but a high increase in demand closely follows the price-duration curve of the second scenario. However, we see a shorter period with low electricity prices compared to the second scenario. This is also reflected in the considered electricity price, which is slightly higher at 35.53€/MWh. The hydrogen price also increases to 60.72 €/MWh. The fourth scenario with a high increase in renewables and a low increase in demand differs fundamentally from the previous scenarios. The price-duration curve in this scenario is zero or close to zero throughout a large part of the considered period. The considered average electricity price is the lowest, at 5.29 €/MWh. Also, the hydrogen price is the lowest for this scenario, at 22.31€/MWh. The last scenario with a high increase in renewables and a high increase in demand also differs from the baseline and medium renewable scenarios. However, compared to the fourth scenario, the period with low electricity prices is lower. Again, this is reflected in the considered average electricity price of 9.87 €/MWh. The hydrogen price follows the pattern and also increases to 29.59 €/MWh.

The average paid electricity price significantly differs between the sensitive and insensitive truck driver. Depending on the future scenario, the difference varies from a few euros per MWh to three times as much. Further, we find that with higher penetration of renewables, electricity prices decrease significantly in the future compared to the baseline scenario. We conclude that truck drivers will consider electricity price movements as it significantly reduces costs and, hence, use these in the TCO calculation. However, we assumed that the truck driver is highly sensitive and reacts to marginal price changes. This sensitivity is limited for two reasons: First, the truck driver will not charge if this means that the truck driver has to charge an additional time to reach the daily mileage. Second, the truck driver might not be fully flexible in choosing optimal prices due to pickup and delivery time windows. Following this, the truck driver might be less sensitive as assumed. However, the substantial price difference between sensitive and insensitive prices shows that the truck driver will incorporate price differences, primarily since the prices are known a day ahead, but the precise sensitivity is out of the scope of this paper. Further, we see that, except for the baseline scenario, which is upward biased, the electricity price for the insensitive truck driver is beneath the hydrogen price in all future scenarios. Consequently, taking the more conservative electricity price would not change the competitiveness over the lifetime of both trucks.

For the green hydrogen price, we find that green hydrogen prices decrease significantly with higher penetration of renewables in future scenarios and follow the same pattern as the electricity prices. However, we find that the hydrogen prices are significantly higher than both electricity prices throughout all scenarios, exempting the average electricity price the insensitive truck driver pays in the baseline scenario. Due to the sector coupling, we conclude that green hydrogen prices will be higher than electricity prices in future scenarios with higher renewable penetration. The possibility of increasing the competitiveness of hydrogen is limited as it depends on the productivity of an electrolyzer. As the most significant cost component of green hydrogen is electricity, the possibility of increasing hydrogen competitiveness through efficiency is limited (IRENA, 2020).

For green hydrogen, there is only one price throughout the year due to the fuel's storable characteristic, limiting the possibility of a truck driver behaving strategically. Nevertheless, one may argue in favour of FCET that the refuelling takes minutes compared to the 45 minutes BET need to recharge. Less time spent recharging translates into higher efficiency and finally into higher profits. However, due to the legally mandatory break of 45 minutes every 4.5 hours, the technological advantage of faster refuelling does not translate into an economic advantage. Not considering the advantage in favour of FCET does not bias our results.

The findings for the two fuels in the TCO calculations show that, due to the sector-coupling, the BET outperforms FCET in the baseline and future scenarios. This is because FCETs face an inherent efficiency loss. Electricity needs to be converted to hydrogen and back to electricity where a lot of electricity is lost in the conversions. This disadvantage of FCETs is impossible to overcome by lower electricity prices, as this directly benefits BETs as well.
The break-even point shifts to the right with higher renewable penetration due to lower electricity prices and, hence, lower weight of fuels in the TCO calculation. However, this effect does not change the overall result in the scenarios. Further, it must be highlighted that FCET is not to be preferred left to the break-even point as an entrepreneur would not choose a heavy-duty truck for such distances. The result of the TCO analysis can only be interpreted by considering the whole lifetime of the trucks. We assumed a yearly distance of 120,000 km for our TCO calculations based on data from the European Commission (European Commission, 2019). However, long-distance truck drivers can also reach yearly mileages up to 210,000 km depending on the location and type of goods carried. In such cases, our results indicate that heavy-duty BET becomes more price competitive with higher distances than FCET. BET is more efficient than FCET, which lowers operating costs over the lifetime. This effect grows with higher annual distances.

Naturally, our TCO calculation comes with some limitations. First, we excluded relevant cost parameters such as national policies (especially subsidies) and infrastructure costs. The current charging infrastructure for BET and FCET is insufficient to power the mass roll-out of zero-emission vehicles. Hence, future projections differ enormously in predicting the availability and price of charging green hydrogen or renewable electricity. Studies attempted to specify annual infrastructure costs (Noll et al., 2022; Transport & Environment, 2020) but we did not include this parameter due to cost uncertainties. Second, TCO analyses sometimes included discount factors to account for the decreasing value of trucks (Noll et al., 2022). However, trucks differ in their total lifetime and the yearly distances travelled. In addition, battery cell technology has improved steadily, making it hard to predict when the battery needs to be replaced in upcoming zero-emission truck models. Hence, uncertainty is involved in quantifying a specific discount factor; thus, we decided to exclude it.

Overall, one needs to be aware of these methodological limitations when reviewing our results. Still, our research sheds light on the price competitiveness between heavy-duty FCET and BET, emphasizing the role of fuel costs. To conclude, we find lower TCO for BET compared to FCET in all four scenarios for the Dutch market. According to our results, different shares of renewables in the energy mix, price-sensitive or insensitive behaviour of the truck driver and overall demand influence the absolute TCO for zero-emission trucks. Nevertheless, heavy-duty BET remain more price-competitive than FCET over the lifetime in all four scenarios for the Dutch market.

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