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A comprehensive techno-economic evaluation of fuel cell electric trucks

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ABSTRACT

Climate change is compelling all industries to adopt new approaches to energy storage. In road freight transport, diesel must be replaced as the dominant fuel for heavy-duty trucks. Battery-electric and fuel cell electric technologies are considered promising alternatives. For long-distance applications, fuel cell electric powertrains appear particularly advantageous due to their higher gravimetric energy density compared to batteries. This paper examines the current development status of fuel cell electric trucks (FCETs) and identifies the key challenges that must be addressed. All currently available and announced FCET models are analyzed, revealing that a new generation of vehicles with longer ranges and improved efficiency is poised to enter the market. The paper also explores infrastructure and economic barriers. Although the capital expenditures (CAPEX) and operational expenditures (OPEX) of FCETs currently exceed those of internal combustion engine (ICE) trucks, incentives such as fuel subsidies and reduced tolls are helping to close the gap. As infrastructure continues to develop, operational strategies must increasingly incorporate navigation and refueling planning. The findings demonstrate that FCET operation in Central Europe is feasible, albeit more complex than the operation of conventional ICE trucks.

1. Introduction

In the face of climate change, CO_2 emissions must be significantly reduced. According to data from the German Federal Environment Agency (Umweltbundesamt, 2022), the transport sector accounted for approximately 20% of Germany's total greenhouse gas emissions in 2022. Of these, 35.5% were emitted by commercial on-road vehicles (Bundesministerium für Umwelt et al., 2021). While commercial vehicles represent only about 4 million of the 60 million vehicles in Germany, heavy-duty trucks account for roughly 200,000 of them (Kraftfahrtbundesamt, 2022), yet they are responsible for over 25% of the transport sector's total emissions (Umweltbundesamt, 2023). This implies that decarbonizing just this small fraction of the fleet could cut the sector's emissions by a quarter, making truck electrification a particularly effective strategy.

To address this challenge, several propulsion technologies have been explored. Hybridizing diesel powertrains can reduce fuel consumption by up to 9%, while both diesel and natural gas vehicles offer only limited greenhouse gas reduction potential (Heidt et al., 2019). Beyond fossil fuels, storing energy either in batteries or as hydrogen enables three zero-emission alternatives: battery-electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and hydrogen combustion engines. However, hydrogen combustion systems cannot eliminate CO_2 emissions entirely and generally fall short of fuel cell efficiency (Neugebauer, 2022). BEVs use batteries and electric motors, while FCEVs also integrate a fuel cell as a secondary energy converter. This additional component introduces new degrees of freedom in vehicle energy management, which can positively impact overall efficiency and operability.

The energy storage capabilities of these technologies differ substantially. Batteries offer an energy density of approximately 0.27 kWh/dm^3, whereas compressed hydrogen can reach 0.8 kWh/dm^3 at 35 MPa and 1.3 kWh/dm^3 at 70 MPa (Klell et al., 2018). Consequently, FCEVs are more suitable for long-distance applications, as they can achieve longer ranges with the same energy storage volume. Truck configurations, however, vary significantly depending on application requirements. The meta-study by Sharpe and Basma (2022) categorizes vehicles by sleeper/day cab design and average daily mileage. According to their findings, fuel cell truck retail prices in the U.S. ranged from US$ 949,400 to US$ 629,100 between 2018 and 2020, while battery electric trucks ranged from US$ 210,600 to US$ 949,400. In Europe, retail prices for both technologies hover around US$ 400,000 (Sharpe and Basma, 2022). Due to limited and outdated data, Rout et al. (2022) estimate current purchase costs at approximately US$ 406,000 for FCEVs and US$ 543,000 for BEVs. Other studies rely on component-level pricing (Mu et al., 2024; Danielis et al., 2025; Basma and Rodríguez, 2023).

This paper specifically focuses on fuel cell electric trucks (FCETs), distinguishing them from the broader FCEV category. Despite their

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theoretical advantages, several barriers hinder the widespread deployment of FCETs. One major challenge is the limited hydrogen refueling infrastructure, as highlighted by Drawer et al. (2024). While hydrogen tanks provide higher volumetric energy density than batteries, the current driving range of FCETs remains constrained, particularly for very long-haul operations. Economic viability poses another significant challenge. The production and operation of FCETs remain costly due to the high price of fuel cell systems and hydrogen supply infrastructure. Low manufacturing volumes further inflate per-unit costs. In addition, hydrogen quality and supply chain reliability present logistical challenges. Recent studies from Zhao et al. (2024) emphasize the importance of hydrogen purity and station availability for successful FCET operation. Our total cost of ownership (TCO) framework builds on the infrastructure considerations outlined by Zhao et al. (2024), adapting them for European FCET applications. To compete economically with conventional and alternative powertrain technologies, FCET TCO including acquisition, operation, maintenance, and disposal must be substantially reduced (State of California Air Resources Board, 2015; Neuhausen et al., 2022).

This paper provides a comprehensive overview of the FCET landscape as of Q1 2024, focusing on technical configurations, market readiness, and operational limitations. We begin by outlining the basic architecture and key components of FCET powertrains, including advancements in hydrogen storage and fuel cell technologies. Next, we analyze the European market, cataloging current and announced FCET models. The discussion then turns to hydrogen refueling infrastructure, assessing regional gaps and long-distance transport challenges. By integrating vehicle performance data and infrastructure status, we identify key barriers to adoption such as fuel availability, TCO competitiveness, and the need for integrated operational planning. Finally, we propose actionable recommendations aimed at enabling successful FCET integration under real-world conditions.

2. Methodology

This study employs a multi-layered qualitative and quantitative analysis to assess the viability of zero-emission heavy-duty trucks, with a primary focus on FCETs. The methodological approach is structured around four key components:

Data sources and benchmarking approach:. Publicly available technical data from OEM specifications, academic literature, and meta-studies were gathered to characterize and compare available and announced FCET models. To contextualize the findings, two representative BEV models are also included in the benchmarking. Key technical parameters such as vehicle weight, fuel cell power, battery capacity, motor output, and hydrogen storage volume are compiled and compared through summary tables and charts.

Cost structure analysis:. Capital expenditure (CAPEX) estimates for critical powertrain components fuel cell systems, hydrogen storage tanks, batteries, and electric drivetrains are derived from up-to-date meta-analyses. All costs are normalized to 2024 values and converted to a unified currency base (US$). Table 1 presents the component-level unit cost estimates used in the analysis.

Operational and infrastructure considerations:. Beyond technical specifications, qualitative aspects of FCET operability are evaluated. These include compatibility with existing and planned hydrogen refueling infrastructure, range limitations, and downtime associated with refueling. Operational constraints are discussed in the context of current infrastructure deployment strategies, regional readiness, and system reliability.

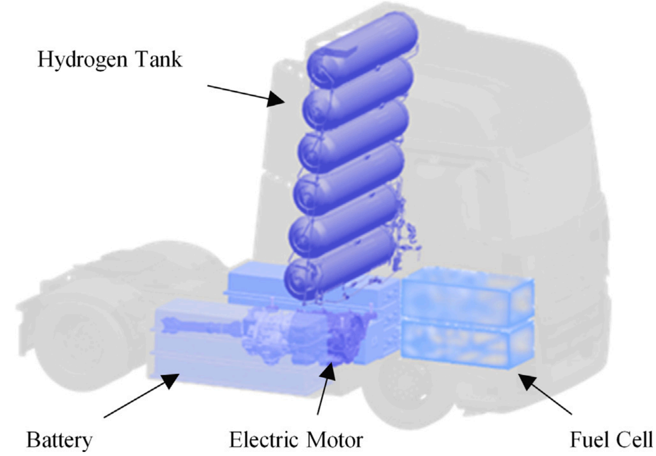

Fig. 1. Integration concept of an FCET as presented in the SeLv project (Kampker et al., 2023).

Total cost of ownership perspective:. The analysis includes a qualitative evaluation of TCO, incorporating both CAPEX and operational expenditures (OPEX). Key factors include vehicle acquisition cost, fuel consumption, maintenance, and infrastructure availability. While a dynamic TCO model is not applied, insights are drawn from synthesizing available cost data and real-world usage scenarios. This framework facilitates a holistic comparison between FCETs and BEVs across various logistics applications.

3. Technical fundamentals of FCET

This chapter provides an overview of the general layout and component costs of the FCET powertrain. At a fundamental level, a FCET consists of four main components: a hydrogen storage system, a fuel cell unit, a battery pack, and an electric motor. A representative integration concept of these components is illustrated in Fig. 1.

3.1. Hydrogen tank

Currently, two technologies are under consideration for refueling and storing hydrogen in mobile applications: gaseous hydrogen and subcooled liquid hydrogen (sLH2). Ahluwalia et al. (2010) further differentiates between cryo-compressed and subcooled hydrogen, where cryo-compressed hydrogen allows for lower boil-off due to reduced evaporation gas. Pressure tanks for gaseous hydrogen are already in use and, depending on their design, can operate at pressures of up to 35 MPa or 70 MPa (SAE International, 2015). These tanks achieve energy densities of 0.8 kWh/dm^3 at 35 MPa and 1.3 kWh/dm^3 at 70 MPa (Klell et al., 2018). Subcooled liquid hydrogen (sLH2), a newer technology currently being introduced by Daimler Truck AG (2024b) and Linde, represents an alternative approach. As its name suggests, sLH2 refers to hydrogen stored in liquid form, which allows for significantly higher energy densities of approximately 2.2 kWh/dm^3 (Klell et al., 2018). To achieve this state, hydrogen must be cooled to −245°C or below and maintained at that temperature (Shell Deutschland, 2017; H2 Mobility, 2021).

The costs associated with hydrogen storage tanks vary depending on the technology and pressure level. For pressure tanks designed for 35 MPa or 70 MPa, costs range from approximately 400 US\$/kg H_2 to 700 US\$/kg H_2 for medium- and heavy-duty applications (Shin and Ha, 2023; Houchins et al., 2022). Although 70 MPa tanks can store roughly 1.5 times more hydrogen compared to 35 MPa tanks, their higher storage capacity requires a thicker carbon fiber layer, resulting in comparable costs per kilogram of hydrogen at both pressure levels. Consequently, the tank weight for medium- and heavy-duty trucks is approximately 10.4 kg C/kg H_2 (kilograms of carbon

Table 1
Summary of FCET component costs (with US$ 1 = € 0.96).

Component	Specification	Cost (average)	Source
Hydrogen tank	35 MPa	ca. 410 $\frac{US\$}{kg\ H_2}$	Houchins et al. (2022)
Hydrogen tank	70 MPa	ca. 450 $\frac{US\$}{kg\ H_2}$	Houchins et al. (2022)
Hydrogen tank	sLH2	ca. 200 $\frac{US\$}{kg\ H_2}$ + US$ 10,000	Shin and Ha (2023) and Ahluwalia et al. (2023)
Fuel cell	PEM	ca. 500 $\frac{US\$}{kW}$	Sharpe and Basma (2022) and Basma and Rodríguez (2023)
Battery	NMC	ca. 370 $\frac{US\$}{kWh}$	Sharpe and Basma (2022)
Battery	LFP	ca. 140 $\frac{US\$}{kWh}$	Henze (2020) and Amol A. Phadke et al. (2021)
E-Motor & Inverter	–	ca. 40 $\frac{US\$}{kW}$	Basma and Rodríguez (2023)

per kilogram of hydrogen) for 35 MPa tanks and 14.8 kg C/kg H_2 for 70 MPa tanks (Houchins et al., 2022). Data on the costs of sLH2 storage tanks remains limited. However, Shin and Ha (2023) estimate that the costs for sLH2 tanks range between 200 US$/kg H_2 and 270 US$/kg H_2. Ahluwalia et al. (2023) investigates configurations, performance, and costs of sLH2 storage tanks, determining a minimum tank cost of 174 US$/kg H_2 to 183 US$/kg H_2, with additional balance-of-plant costs of approximately 10,000 US$.

3.2. Fuel cell

In a FCET, the fuel cell serves as the primary energy source. Typically, plug-in charging is not considered a relevant energy supply for such vehicles. As a result, the fuel cell must meet the vehicle's entire energy demand. This is achieved through the electrochemical oxidation of hydrogen with oxygen from the air, converting chemical energy into electrical energy. For mobile applications, proton-exchange membrane (PEM) fuel cells are commonly used due to their dynamic power response and relatively low operating temperatures (Kampker and Heimes, 2024).

The efficiency map of PEM fuel cell systems can be divided into three distinct sections (Pischinger and Seiffert, 2021). At low power demands, the fuel cell itself operates with high efficiency. However, the base power demand of the balance-of-plant (BOP), required to maintain cell operation as well as the activation losses on the cell level, significantly reduces the system's overall efficiency (Section 1). As power increases, the fuel cell's efficiency decreases due to Ohmic resistance, but the relative power demand of the BOP diminishes, resulting in a plateau in system efficiency (Section 2). At even higher power levels, diffusion effects within the cell lead to a marked decline in efficiency, causing a continuous reduction in system efficiency (Section 3) (Klell et al., 2018). A quantitative representation of the fuel cell system efficiency map is provided in Fig. 2, where the three sections are displayed in the efficiency map of a Toyota Mirai. The data was measured based on the fuel cell stack power output by Lohse-Busch et al. (2020). The peak efficiency of fuel cell systems typically occurs at power demands ranging from 50% to 70% of the system's maximum capacity (Tschöke, 2019).

Fuel cell costs exhibit considerable variability. Sharpe and Basma (2022), in a meta-analysis, reported unit costs for fuel cells in 2020 ranging from 175 US$/kW to 1250 US$/kW. The market is expected to undergo significant cost reductions over the coming years. Daimler Truck AG (2021) projects a 90% decrease in fuel cell prices between 2021 and 2030. Similarly, Sharpe and Basma (2022) forecast a 52% reduction in average costs, from 500 US$/kW in 2020 to 240 US$/kW by 2030. Further analysis by Basma and Rodríguez (2023) estimates production costs for fuel cell stacks at 826 US$/kW in 2023, with a projected decline of 64% to 300 US$/kW by 2030.

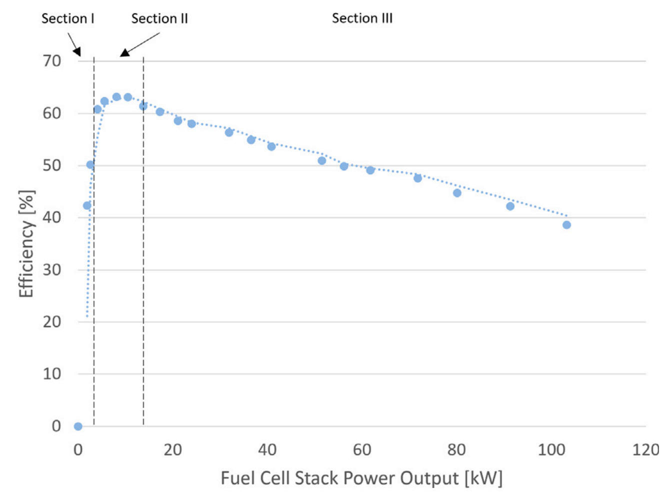

Fig. 2. Quantitative efficiency map of the Toyota Mirai fuel cell system according to Lohse-Busch et al. (2020).

3.3. Battery

The battery in the FCET powertrain functions as a buffer. When the fuel cell is unable to supply sufficient power, the battery compensates for the deficit. This situation can arise during rapid changes in power demand or when the demand exceeds the peak power capacity of the fuel cell. Additionally, the battery can store energy recovered from the motor during regenerative braking, allowing for improved energy efficiency. The performance of the battery is characterized by its maximum continuous and peak power capabilities for charging and discharging (Lain et al., 2019). Lithium-ion batteries used in vehicle applications are generally classified as either high-power or high-energy types. High-power batteries, such as lithium-iron-phosphate (LFP) batteries, are named after their cathode chemistry and are characterized by high gravimetric power-to-energy ratios. In contrast, high-energy batteries, such as those with lithium-nickel-manganese-cobalt (NMC) cathodes, exhibit lower gravimetric power-to-energy ratios (Lain et al., 2019). This means that, for batteries with equal energy capacity, high-energy cells provide lower peak power output than high-power cells, but offer higher gravimetric energy densities. These differences in cell chemistry also influence the cost, mass, and volume of batteries in vehicle applications. Compared to NMC batteries, LFP batteries have lower energy densities but are safer to handle and rely on less expensive materials (Kampker and Heimes, 2024). Consequently, an LFP battery tends to be larger and heavier than an NMC battery of equivalent energy capacity.

As the battery market expands and technologies evolve, precise battery cost estimates remain difficult. A meta-study by Sharpe and Basma (2022) distinguishes between power and energy batteries for truck applications, estimating average system-level prices of 370 US$/kWh for power batteries and 150 US$/kWh for energy batteries by 2025. Similarly, Amol A. Phadke et al. (2021) reports a battery price of 150 US$/kWh, while Henze (2020) identifies a pack-level price of 137 US$/kWh for high-energy batteries. Bhardwaj and Mostofi (2022) consolidate findings from various sources and estimate the price of high-energy batteries at approximately 135 US$/kWh. Based on these values, this paper assumes a reference price of 140 US$/kWh for high-energy LFP batteries.

3.4. Electric motor unit

The electric motor unit comprises both the inverter and the motor itself. The inverter converts direct current (DC) from the battery and fuel cell into alternating current (AC) to power the motor. The motor then transforms this electrical energy into mechanical power, which propels the truck. This process also works in reverse during regenerative braking: the motor provides mechanical resistance to decelerate the vehicle while converting mechanical energy back into electricity. The inverter then converts this energy back into DC to be stored in the battery. However, energy conversion in both directions is subject to inherent losses (Kampker and Heimes, 2024).

The design of the electric motor is determined by technical requirements such as payload capacity, peak velocity, and climbing ability. Two key parameters are critical: motor power, which influences maximum speed, and motor torque, which determines the maximum gradeability or the maximum payload that can be moved (Kampker et al., 2022). Three main topologies are used in electrified vehicle drivetrains: central motors, electric axles (motors near the wheels), and wheel hub drives. While wheel hub drives offer higher efficiency compared to central drives, they are mechanically more complex and require advanced cooling systems. Central drives, on the other hand, are the most cost-effective solution (Kampker et al., 2019). Since trucks are designed for a variety of applications including long-haul transport, mid-distance distribution, and short-distance delivery their powertrain configurations must be tailored to meet the specific performance and operational needs of each use case (Neuhausen et al., 2022). The cost-per-power ratio of electric drives used in electrified trucks is analyzed in Basma and Rodríguez (2023). According to the authors, the average reported cost of electric drives in 2020 was approximately 60 US$/kW. This figure is expected to decrease to 25 US$/kW by 2030. For the purposes of this paper, the electric drive cost is estimated at 40 US$/kW.

3.5. Component cost

Based on a review of current literature, average costs for key FCET powertrain components were identified. Table 1 summarizes these values along with their corresponding technical specifications and sources.

4. Hydrogen refueling

To keep FCETs in operation, a robust and compatible hydrogen infrastructure is essential. The specific infrastructure needs of each truck depend primarily on the onboard hydrogen storage technology. As introduced earlier, two main refueling technologies exist: compressed gaseous hydrogen (CGH2), available at 35 MPa and 70 MPa, and subcooled liquid hydrogen (sLH2) (H2 Mobility, 2021; Daimler Truck AG, 2024b). These systems are not compatible with one another. CGH2 is managed at pressures up to 87.5 MPa and temperatures between −40 °C and 85 °C, while sLH2 operates at much lower pressures (0.5 MPa to 1.6 MPa) and temperatures below −245 °C (H2 Mobility, 2021; Shell Deutschland, 2017).

Several standards govern the design and operation of CGH2 fueling stations. ISO 19880 outlines general safety requirements (International Organization for Standardization, 2020b), while ISO 17268 specifies pressure levels (International Organization for Standardization, 2020a). SAE J2600 defines the vehicle-nozzle interface (SAE International, 2019), SAE J2601 standardizes the refueling protocol (SAE International, 2016), and SAE J2799 covers communication protocols between vehicle and station (SAE International, 2015). No standards currently exist for sLH2 fueling, though developments are underway (Daimler Truck AG, 2024b). Hydrogen purity is another critical concern. According to ISO 14687, hydrogen used in fuel cells must be at least 99.97% pure (International Organization for Standardization, 2025). Impurities such as carbon monoxide, sulfur compounds, or moisture can severely damage fuel cell membranes, reduce efficiency, and shorten system lifespan. As such, high standards of hydrogen purity must be maintained throughout the entire supply chain (Klell et al., 2018).

Hydrogen can be sourced in multiple ways: from natural reservoirs, through electrolysis powered by renewable energy, or from fossil sources such as natural gas (Nationaler Wasserstoffrat, 2022). Depending on where the hydrogen is produced, it can be transported in gaseous form via pipelines or vessels, as liquid hydrogen in specialized tanks, or chemically bound (e.g., in ammonia) (Shell Deutschland, 2017).

To enable seamless FCET operation, significant infrastructure expansion is required (Shell Deutschland, 2017). As of today, 83 CGH2 stations at 35 MPa and 170 at 70 MPa are operational in Europe, predominantly in Germany, the Netherlands, Belgium, and Switzerland (H2 Mobility, 2023). Fig. 3 shows the current distribution of 35 MPa fueling stations. Stations in operation are shown in blue, while planned or under-construction stations are in green. No public sLH2 station is yet operational; the first is expected to open in summer 2024 (Daimler Truck AG, 2024b). Additionally, 46 new 70 MPa and 70 new 35 MPa CGH2 stations are currently planned (H2 Mobility, 2023). Compressed hydrogen faces challenges in delivering high-volume fuel at high pressure. Current stations often cannot dispense more than 8 kg at 70 MPa (H2 Mobility, 2021). This limitation is also reflected in fuel prices: in Germany, the average price for 35 MPa hydrogen is approximately € 13.50 (ranging from € 9.99 to € 15.75), while for 70 MPa hydrogen it averages € 15.00 (H2 Mobility, 2023).

Looking ahead, infrastructure development is guided by Regulation (EU) 2023/1804 on the deployment of alternative fuels infrastructure (AFIR) (Europäisches Parlament und europäischer Rat, 2023). This regulation mandates hydrogen stations along the TEN-T (Trans-European Transport Network) core roads by 2030. According to AFIR, stations must be located within 10 km detour distance from TEN-T roads and spaced no more than 200 km apart. They must provide at least 1 t/day of hydrogen at 70 MPa. Urban nodes of the TEN-T network must also be equipped with at least one public station. To meet these goals, a minimum of 661 stations, 237 along the core network and 424 in urban nodes, must be operational by 2030 (Europäische Union, 2021).

5. Techno-economic evaluation framework

When designing a FCET, manufacturers must define a configuration that satisfies both technical and economic requirements. Technically, the truck must meet operational demands such as speed, acceleration, payload, and range to fulfill customer expectations. Economically, the vehicle must offer a competitive TCO to be a viable alternative to conventional and battery-electric drivetrains. Bhardwaj and Mostofi (2022) defines TCO as the sum of capital and operational expenditures over the vehicle's holding period. Various studies (Earl et al., 2018; Basma and Rodriguez, 2021) break TCO down into vehicle and powertrain costs, fuel costs, maintenance, road charges, driver wages, insurance, and taxes. These components are typically grouped into two categories:

- **CAPEX** – initial capital expenditures, including vehicle purchase, financing, and fixed annual costs, less residual value.
- **OPEX** – ongoing, mileage-dependent operational expenditures such as hydrogen fuel, tolls, insurance, and maintenance.

While CAPEX is largely fixed, OPEX increases proportionally with annual mileage. As a result, cost-effectiveness in long-haul operations hinges on minimizing OPEX through drivetrain efficiency and reduced fuel consumption (Geng et al., 2014). Since wear-related maintenance tends to be powertrain-independent, the primary lever for reducing OPEX lies in lowering hydrogen use and fuel costs.

The annual OPEX can be expressed as:

$$\mathrm{OPEX} = (\mathrm{Cons}_{H_2} \cdot \mathrm{Cost}_{H_2} + \mathrm{Toll} + \mathrm{O\&M}) \cdot \mathrm{YCD} \quad (1)$$

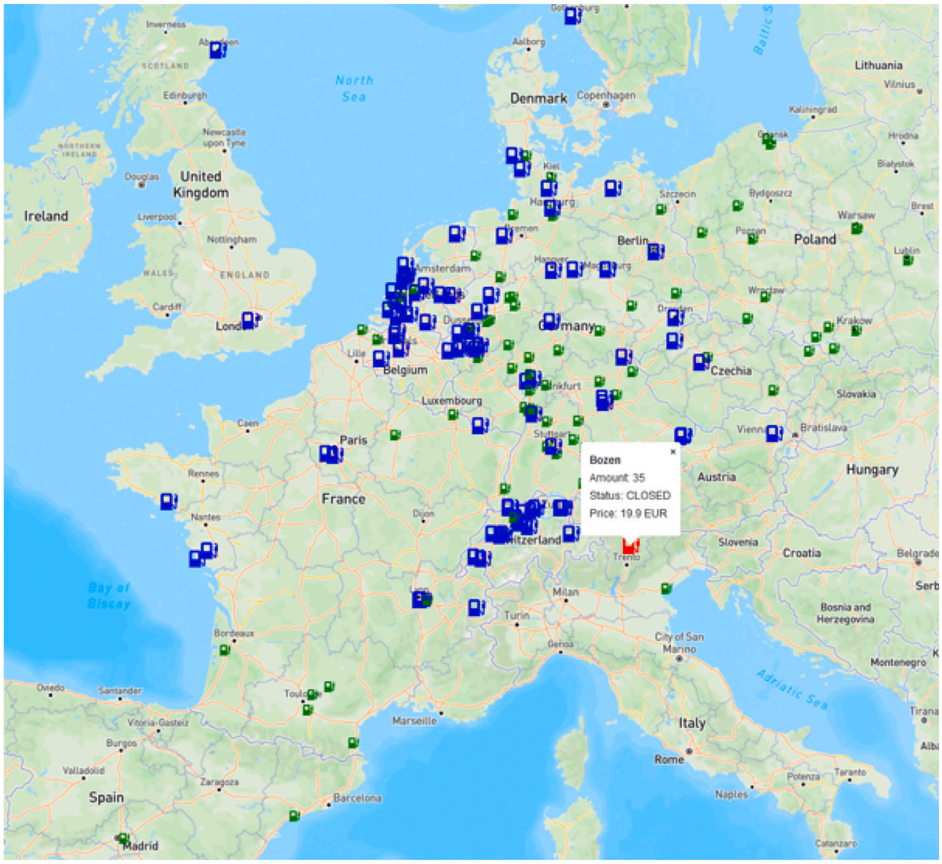

Fig. 3. Hydrogen fueling infrastructure in Europe at 35 MPa pressure level (H2 Mobility, 2023).

where $Cons_{H_2}$ is hydrogen consumption per kilometer, $Cost_{H_2}$ is the hydrogen price per kilogram, Toll is the average toll per kilometer, O&M includes insurance, servicing, and fixed taxes, and YCD is the yearly mileage.

Total cost of ownership (TCO) is then calculated as:

$$TCO = CAPEX + OPEX \cdot HP \tag{2}$$

with HP representing the truck's holding period in years.

To reflect real-world usage scenarios, this analysis includes three mileage cases (50,000 km, 100,000 km, and 150,000 km per year), based on assumptions from Neuhausen et al. (2022). Moultak et al. (2017) reports an average of 115,000 km per year for long-haul trucks in their first three years. Basma and Rodríguez (2023) further differentiate between trucks with daily driving distances of up to 500 km (return-to-depot) and up to 1000 km (non-returning), resulting in average annual mileages of 119,000 km and 201,000 km, respectively, during the first five years. This study assumes a five-year holding period, consistent with Basma and Rodríguez (2023).

The TCO model applied in this paper builds on existing frameworks such as those by Zhao et al. (2024) or Basma and Rodríguez (2023) and expands them for application to fuel cell trucks under European conditions. It serves to illustrate how drivetrain efficiency, fuel consumption, and infrastructure availability affect the economic viability of FCETs. While simplifying certain real-world uncertainties such as downtime, residual value volatility, or component failure risks, it captures key cost dynamics relevant for fleet operators. Lowering hydrogen consumption and fuel cell system costs improves OPEX and CAPEX simultaneously, which is essential for making FCETs competitive in long-distance logistics applications.

6. Interim conclusion

The preceding chapters outlined the framework for FCET operation, emphasizing the interdependencies in powertrain design imposed by limited chassis space. While integrating components such as inverter, motor, and gearbox is relatively straightforward (Kampker et al., 2022), achieving sufficient range and power remains a multidimensional challenge. Vehicle range is primarily determined by hydrogen storage capacity and fuel consumption, both of which are in turn influenced by fuel cell power, battery size, and operational strategy. For instance, larger batteries can relieve the fuel cell and enhance system efficiency (Pell et al., 2022), but simultaneously reduce the space available for hydrogen tanks (Lain et al., 2019). Economic constraints further shape FCET architecture. CAPEX and OPEX dominate the TCO, with their relative significance depending on the specific use case. Long-haul applications prioritize low operating costs due to high annual mileage, whereas regional operations may favor lower upfront investments. Achieving an optimal balance between drivetrain design and cost drivers is therefore critical for enabling economically viable FCET solutions. Our TCO model, as presented in the previous chapter, builds on the foundational cost structure outlined by Zhao et al. (2024), but extends it to accommodate the unique characteristics of fuel cell electric trucks in the European context. This includes real-world mileage scenarios, hydrogen price sensitivity, and infrastructure availability constraints. The benchmark shows how different manufacturers resolve this design tension through varying system configurations. The subsequent analysis section builds on these findings, assessing to what extent investments in fuel cell power or battery capacity translate into operational advantages. It also explores whether FCETs can currently be considered a robust solution under prevailing cost and infrastructure conditions.

7. Benchmark analysis of FCEV as of 2024

The following sections present an analysis and evaluation of the current FCET market as of Q1 2024. Initially, all currently available and announced FCET models are introduced. In the subsequent sections, these vehicles are analyzed with respect to their market maturity, CAPEX, and OPEX. Finally, their operability is assessed.

7.1. FCEV market

As of Q1 2024, seven companies have announced or are actively marketing FCETs in the European market. The publicly available data on vehicle specifications are summarized in the following sections and in Table A.1.

7.1.1. Hyundai - Xcient Fuel Cell

The *Xcient Fuel Cell*, introduced by Hyundai Motor Company in 2021, is a heavy-duty truck with a towing capacity of up to 42 tons. It features a 180 kW fuel cell powering an electric motor with a maximum output of 350 kW. Energy is stored in a 72 kWh battery. The hydrogen storage system consists of tanks with a capacity of 31 kg at a maximum pressure of 35 MPa (Hyundai Motor Company, 2022). According to a press release from 2020, the Xcient achieves a maximum range of 400 km with 32.09 kg of hydrogen in the 4×2 configuration and a total mass of 34 tons (Hyundai Motor Company, 2020), corresponding to a fuel consumption of 8.02 kg/100 km.

7.1.2. Hyzon - HyMax series

Hyzon Motors Company currently offers three FCET models in Europe: the *HyMax-160*, *HyMax-250*, and *HyMax-450*, named after their respective motor power outputs (Hyzon Motors, 2021). The HyMax-160, with a gross vehicle mass (GVM) of 24 tons, includes an 80 kW fuel cell, a 70 kWh battery, and a continuous motor output of 160 kW (Hyzon Motors, 2023). The truck has a standard hydrogen tank capacity of 30 kg at 35 MPa, providing a maximum range of 400 km and a fuel consumption of 7.5 kg/100 km (Klimafreundliche Nutzfahrzeuge, 2023a). The HyMax-250 and HyMax-450 models, designed as trucks and tractor-trailers, have a GVM of up to 46 tons and a fuel cell power of 120 kW (Hyzon Motors, 2021). With a battery capacity of 120 kWh, the reported hydrogen consumption is 10.3 kg/100 km (Hyzon Motors, 2023; Hylane GmbH, 2023b,a). Additional hydrogen tanks, each holding 5 kg, can be modularly added or removed, allowing a maximum capacity of 60 kg (Hyzon Motors, 2021, 2023). However, in mid-2024, Hyzon announced its withdrawal from the European market (Hyzon Fuel Cell, 2024).

7.1.3. Paul - PH2P Truck

Paul Nutzfahrzeuge GmbH (2022) produces the *PH2P* truck, a heavy-duty FCET with a GVM of 24 tons, powered by an 80 kW fuel cell (Paul Nutzfahrzeuge GmbH, 2022). Series production began in 2024 (Paul Nutzfahrzeuge GmbH, 2024). The truck features a usable battery capacity of 60 kWh and a drive power of 120 kW. Its 30 kg hydrogen tank, operating at 35 MPa, supports a maximum range of 450 km (Paul Nutzfahrzeuge GmbH, 2022), with fuel consumption reported at 6.67 kg/100 km.

7.1.4. Nikola - Tre FCEV

The *Nikola Tre FCEV*, a product of the joint venture between Nikola Corporation and Iveco Group (IVECO Group, 2023), was scheduled for release in 2023 on the U.S. market as a tractor-trailer with a GVM of 37 tons (Nikola Motors, 2023a). The first European deliveries are expected in 2024 or 2025 (Räth, 2024). The truck includes a 200 kW fuel cell, a 164 kWh battery, and a 400 kW electric motor. With a 70 kg hydrogen tank at 70 MPa, the vehicle has a stated range of 800 km, corresponding to a fuel consumption of 8.75 kg/100 km (Nikola Motors, 2023b). To mitigate infrastructure limitations, Nikola also offers a trailer-mounted mobile refueling station (Nikola Motors, 2023c).

7.1.5. Quantron - QHM FCEV 44-1000

Quantron AG manufactures the *QHM FCEV 44-1000*, a heavy-duty tractor-trailer available since Q3 2023. It features a 240 kW fuel cell, a 124 kWh battery, and a electric motor with a continuous power of 420 kW. The simulated range is 700 km with a 54 kg hydrogen tank at 70 MPa (Quantron AG, 2023), resulting in an estimated fuel consumption of 7.71 kg/100 km.

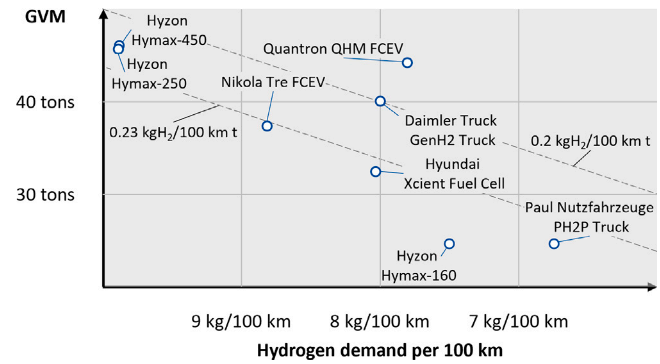

Fig. 4. Efficiency of FCET.

7.1.6. Daimler Truck - GenH2 Truck

Daimler Truck AG has announced the *GenH2 Truck*, a fuel cell-electric tractor-trailer expected by 2027 (Daimler Truck AG, 2021). The vehicle will include a 300 kW fuel cell from Cellcentric, a joint venture with Volvo Trucks (Cellcentric, 2020). Together with a 55 kWh buffer battery, the system powers a 460 kW electric motor. Designed for 80 kg of liquid hydrogen, the range is 1,000 km. In a 2023 demonstration, a prototype covered 1,047 km at a total weight of 40 tons (Daimler Truck AG, 2023b).

7.1.7. Volvo Trucks

Volvo Trucks is developing an FCET expected to enter the market in the late 2020s. As of Q1 2024, little technical information is available, apart from plans to incorporate a 300 kW Cellcentric fuel cell and to achieve a range of 1,000 km (Volvo Trucks, 2022).

7.2. Conclusion - Market situation 2024

The vehicle characteristics discussed above are summarized in Table A.1. Where fuel consumption data were unavailable, it has been estimated. It becomes clear that, apart from Hyundai, no major OEM has yet launched FCETs at scale in Europe by 2024. Companies such as Hyzon Motors and Paul Nutzfahrzeuge remain niche manufacturers without large-scale serial production capabilities (Klimafreundliche Nutzfahrzeuge, 2023b; Paul Nutzfahrzeuge GmbH, 2022). The subsequent section provides a detailed technical benchmarking and categorization of these vehicles.

8. Technology and market assessment

The previous section outlined the currently available and announced FCETs in the European market as of Q1 2024, highlighting notable differences in their characteristics. FCETs are available in two main configurations: motor cars and semi-trucks. Motor cars offer more packaging flexibility due to their greater vehicle length, which facilitates component placement. However, the GVM varies significantly by configuration. While semi-trucks support up to 40 tons total mass, some motor car concepts are limited to much lower GVMs. For instance, the PH2P Truck from Paul Nutzfahrzeuge has a GVM of only 24 tons including a trailer (Paul Nutzfahrzeuge GmbH, 2022). Fig. 4 illustrates the relationship between GVM and fuel efficiency. Lighter trucks generally exhibit better fuel efficiency due to lower rolling and slope resistance. Efficiency gains in the latest generation of FCETs are also evident. Despite a higher GVM, both the QHM FCEV and the GenH2 Truck demonstrate comparable fuel efficiency to the Xcient Fuel Cell. One way to quantify these improvements is through fuel consumption per ton per 100 km. As shown in Table A.3, older FCETs typically consume about 0.23 kg/100 km t, while newer models approach 0.2 kg/100 km t.

Clear distinctions also exist in hydrogen tank capacities and supported pressure levels. Available FCETs are typically equipped with 35 MPa tanks storing about 30 kg of hydrogen. In contrast, announced

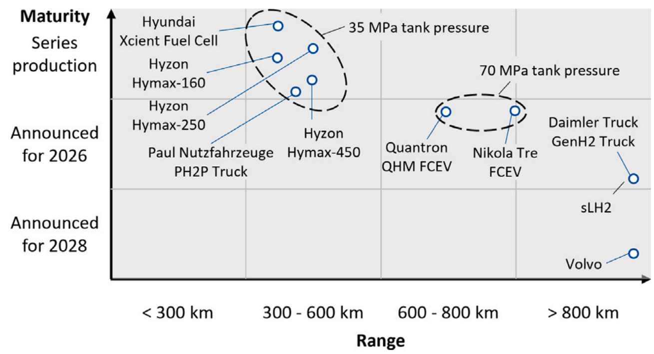

Fig. 5. Maturity and range of FCET.

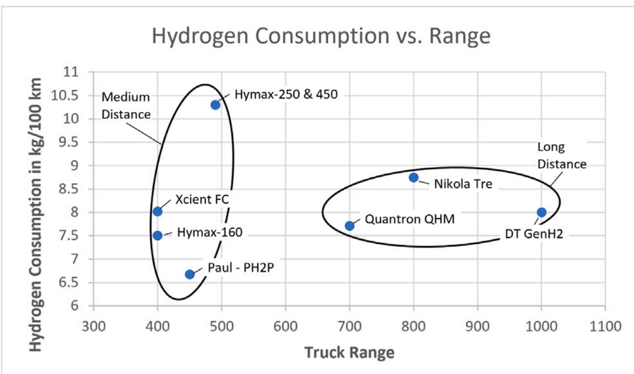

Fig. 6. Comparison of range and hydrogen Consumption.

models are either equipped with 70 MPa tanks or utilize sLH2 technology, allowing storage capacities of up to 80 kg. Fig. 5 shows the correlation between vehicle availability, range, and fuel storage technology. Three clusters are visible: (1) market-ready trucks with ranges of 400 km to 500 km using 35 MPa tanks, (2) trucks announced for release in 2024 with 700 km to 800 km range and 70 MPa tanks, and (3) long-range vehicles (> 1000 km) expected later in the decade, such as the GenH2 Truck, which employs sLH2 storage.

The analysis reveals a generational shift: early FCETs were optimized for shorter distances, characterized by lower GVMs, reduced hydrogen capacity, and less efficient drivetrains. In contrast, next-generation FCETs are tailored for long-haul applications. These newer models combine extended range, improved fuel efficiency from relatively lighter tank systems and advanced drivetrain components, and higher motor power, making them more suitable for demanding operational requirements.

When evaluating the relationship between GVM, fuel consumption (Fig. 4), and the interplay between market maturity and vehicle range (Fig. 5), two operational clusters can be identified. Fig. 6 plots hydrogen consumption against vehicle range, revealing two distinct groups: vehicles with ranges below 500 km, categorized as *medium-distance* (MD) trucks, and those exceeding 700 km, classified as *long-distance* (LD) trucks. Notably, there is a 200 km range gap between these two segments. All MD trucks, with the exception of those manufactured by Hyzon, feature a GVM below 35 tons and are configured as motor cars. This suggests a design focus on urban and regional delivery applications. These vehicles are expected to operate with lower annual mileage compared to LD trucks, which are optimized for long-haul operations exceeding 700 km in range and typically feature higher GVMs and semi-truck configurations.

9. Evaluation of FCET TCO

Following the vehicle-level analysis of FCETs their cost structures are evaluated. Several assumptions are necessary for this assessment. While component-level costs have been addressed earlier, the final assembly costs must be estimated. The meta-study by Basma and Rodríguez (2023) proposes a markup factor of approximately 1.4 on component costs to account for assembly and manufacturer margin. Additionally, an average hydrogen price of€ 13.50, (approximately US$ 14.00) is assumed for operational cost calculations. This section is divided into two parts: First, CAPEX and OPEX are calculated and compared across different vehicle configurations. Thereafter, a comprehensive total cost analysis is presented.

9.1. CAPEX of the analyzed FCET

In the following, the CAPEX of the analyzed FCETs is evaluated as part of the overall TCO assessment. Understanding the CAPEX structure is essential for assessing the upfront investment barriers to FCET adoption and for comparing different drivetrain technologies. Based on the component costs summarized in Table 1 and the vehicle data in Table A.1, the CAPEX of the FCETs is calculated and displayed in Fig. 7. Detailed results are provided in Table A.4. The analysis shows that MD trucks have significantly lower CAPEX compared to LD trucks. While the CAPEX for LD trucks ranges between US$ 280 000 and US$ 300 000, the CAPEX for MD trucks lies between US$ 110 000 and US$ 200 000. The component costs for LD trucks are up to three times higher than those for MD trucks. For example, the fuel tank expenditure for MD trucks is approximately US$ 12 000, whereas LD trucks range between US$ 18 000 and US$ 32 000. Notably, the reduced cost of sLH2 tanks lowers the overall CAPEX for the *GenH2 Truck*, making its tank costs 17% less with 14% more capacity compared to that of the *Nikola Tre FCEV*. A major contributor to the higher CAPEX in LD trucks is the investment in larger fuel cells. While fuel cells in MD trucks (except the *Hyundai Xcient*) cost around US$ 50 000, those in LD trucks range from US$ 100 000 to US$ 150 000. Battery costs vary from US$ 20 000 to US$ 60 000 across both truck types, with no clear distinction between MD and LD vehicles. Among the analyzed trucks, the *GenH2 Truck* has the lowest battery costs at approximately US$ 20 000, whereas the *Nikola Tre* features the highest battery costs, at around US$ 60 000. Investment in electric motors is relatively small compared to other components, ranging from US$ 5000 for the *PH2P Truck* to US$ 18 000 for the *HyMax-450*. Assembly costs, assumed as a percentage of total component costs, scale proportionally with the overall investment. In summary, the primary factors influencing CAPEX are the costs of the fuel cell and the battery. Fuel cell costs significantly impact the CAPEX of LD trucks, while battery costs vary across both MD and LD configurations. As financing is directly tied to vehicle costs and residual values cannot yet be reliably estimated, these elements are excluded from the CAPEX analysis. While CAPEX outlines the investment burden, the following section focuses on OPEX to assess the operational cost dynamics that determine long-term economic viability.

9.2. OPEX of the analyzed FCET

As discussed in the section on efficiency and economy, the OPEX of FCETs primarily depends on fuel costs. In this section, OPEX is modeled as a function of hydrogen cost. Given the variability in annual mileage reported in the literature, this study adopts a stepwise approach, analyzing OPEX at intervals of 50,000 km (Neuhausen et al., 2022). This enables an evaluation under varying operational scenarios. Based on truck efficiencies and mileage values, the OPEX of the analyzed trucks is calculated and compared. To illustrate the impact of OPEX and efficiency on TCO in MD and LD applications, two representative trucks are examined. For LD operations, the HyMax-250 and the Quantron FCET are compared. While the HyMax-250 has a US$ 100, 000 lower CAPEX, it exhibits higher fuel consumption than the Quantron truck. Fig. 8 displays the resulting total cost comparison. For lifetime mileage up to 300,000 km, the HyMax-250 maintains lower total costs. Beyond this point, the Quantron becomes more cost-effective due to its lower

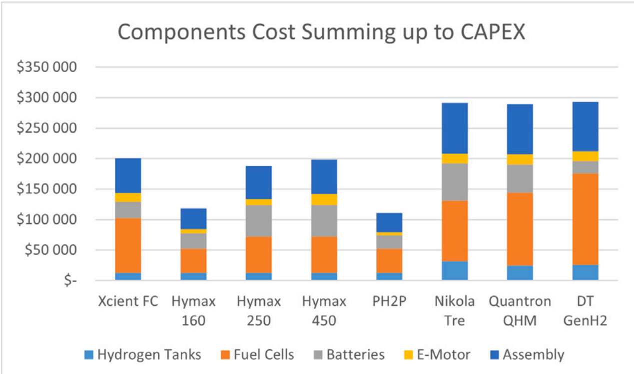

Fig. 7. Structure of FCET CAPEX.

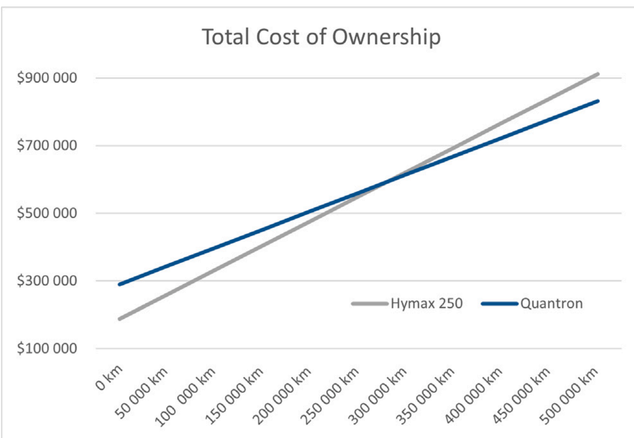

Fig. 8. Impact of hydrogen consumption on the total truck costs ("Long Distance").

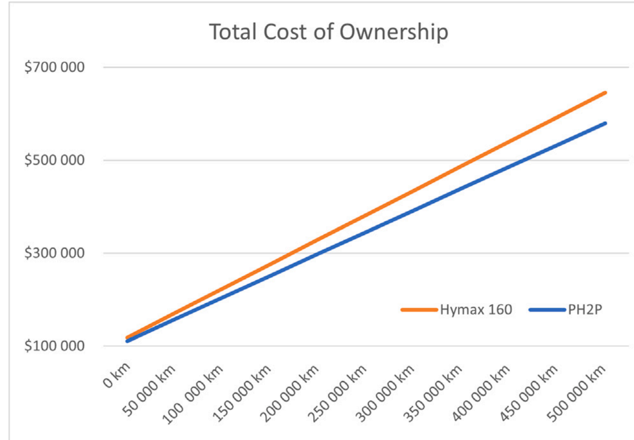

Fig. 9. Impact of hydrogen consumption on the Total Truck costs ("Medium Distance").

fuel consumption. Assuming an annual mileage of 150,000 km for LD trucks (Neuhausen et al., 2022), the Quantron reaches a break-even point after two to three years.

For MD trucks such as the HyMax-160 and the PH2P Truck, fuel efficiency also plays a critical role. Fig. 9 presents their total cost as a function of lifetime mileage. Despite nearly identical CAPEX (US$ 120, 000), the HyMax-160's higher hydrogen consumption leads to increased OPEX, resulting in a higher cost per kilometer than the PH2P. These examples demonstrate that, besides component costs, OPEX and efficiency are key determinants of total costs. This is especially relevant for high-mileage operations, long holding periods, or applications with uncertain lifetime mileage. The analysis assumes constant hydrogen prices; at lower hydrogen prices, the Quantron's break-even point would shift to higher mileage.

To give an idea of the advantages and disadvantages of FCET, they are compared with BEV trucks. As reference the electric MD and LD truck from Daimler Truck are used. Both the *eActros 300* (MD) and the *eActros 600* (LD) represent common BEVs in their classes. The eActros 300 has a net battery capacity of 336 kWh and a continuous motor power of 330 kW. The range is specified by the manufacturer at 220 km. The consumption of the truck can therefore be calculated as 110 kWh/100 km. With a charging power of up to 160 kW the battery can be filled from 20% to 80% state-of-charge (SOC) within 75 min. Daimler Truck AG (2024a) The eActros 600 has a net battery capacity of 600 kWh and a continuous motor power of 400 kW. The range is specified by the manufacturer at 500 km. The consumption of the truck can therefore be calculated as 120 kWh/100 km. With a charging power of up to 400 kW at the CCS-standard the battery can be filled from 20% to 80% state-of-charge (SOC) within 60 min. For the mega watt charging standard (MCS), that is still under development, the manufacturer specifies the charging time at 30 min with a maximum charging power of 1000 kW. Daimler Truck Schweiz AG (2023) While the eActros 300 is powered by a NMC battery (Carla Westerheide, 2025)the eActros 600 contains a LFP battery (Daimler Truck AG, 2023a). Their component setups lead to CAPEX of approximately US$ 193, 000 for the eActros 300 and US$ 140, 000 for the eActros 600. This shows the impact of the cheaper LFP cell chemistry. Regarding the OPEX of BEV trucks the electricity price is based on Lanz et al. (2022), who determined the cost of charging in Germany at an average of US$ 0.62 per kWh. Thus OPEX per 100 km of these BEV trucks range around US$ 74 for the eActros 600. The Quantron in comparison ranges around US$ 108. This cost gap is opposed by the downsides of batteries when it comes to charging. As the BEV supply the fastest charging rates in between SOC of 20% to 80% they are usually operated merely there. Therefore the trucks only supply a realistic range of 300 km (eActros 600) and 132 km (eActros 300) to allow for a charging time of 60 min or rather 75 min. When comparing the distance based TCO with the ranges of the trucks as shown in Fig. 10 the benefits of the technologies are visible. The diagram shows the trucks with the lowest TCO at the driven distance and supplying range without refueling or recharging. Due to the low CAPEX the PH2P truck is the cheapest truck for a total operation below 150 000 km and a required range of 450 km. With higher CAPEX but lower OPEX the TCO of the eActros 600 is best for ranges between 450 km and 500 km at all driven distances. When the total driven distance exceeds 150 000 km and the required range is below 500 km the TCO of the eActros is the most economic as well. Above a required range of 700 km the Daimler Truck GenH2 has the best TCO. For ranges between 500 km and 700 km the TCO of the GenH2 is better for total driven distances up to 150 000 km, from there on the Quantron truck is more economic. To generalize this one can say that the low CAPEX of small FCET make them a suitable solution for low lifetime distances, while the low OPEX of BEV trucks manifest for longer total distances of operation. As the supplied range of FCET is larger compared to BEVs they come to play when long ranges are required.

To contextualize FCETs, they are compared with BEV trucks using Daimler Truck's electric MD and LD models as references: the *eActros 300* and *eActros 600*. The eActros 300 features a net battery capacity of 336 kWh, continuous motor power of 330 kW, and a range of 220 km, implying a consumption of 110 kWh/100 km. With a maximum charging power of 160 kW, its battery can charge from 20 % to 80 % SOC in 75 min (Daimler Truck AG, 2024a). The eActros 600 includes a 600 kWh LFP battery and a 400 kW motor. Its range of 500 km corresponds to a consumption of 120 kWh/100 km. Charging at 160 kW the CCS (Combined Charging System) standard reduces 20% to 80% SOC time to 60 min. For the Megawatt Charging Standard (MCS), that is still under development, the manufacturer specifies the charging time

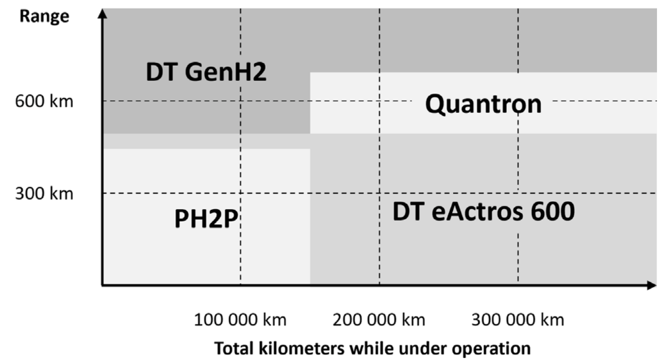

Fig. 10. Minimum TCO compared between distance and range.

at 30 min with a maximum charging power of 1000 kW. Daimler Truck Schweiz AG (2023) The eActros 300 uses NMC cells (Carla Westerheide, 2025), while the eActros 600 employs LFP technology (Daimler Truck AG, 2023a). These battery chemistries influence CAPEX: US$ 193,000 for the eActros 300 versus US$ 140,000 for the eActros 600. OPEX for BEVs is estimated using an average charging cost in Germany of US$ 0.62 per kWh (Lanz et al., 2022), equating to approximately US$ 74/100 km for the eActros 600. In comparison, the Quantron FCET has an OPEX of about US$ 108/100 km. However, BEVs have charging limitations: their fastest rates are achieved between 20% and 80% SOC. As such, operational strategies often target ranges of 132 km (eActros 300) and 300 km (eActros 600) between charges. Fig. 10 compares TCO across trucks with different CAPEX, OPEX, and ranges. The PH2P is most cost-effective for operations below 150,000 km with a maximum range of 450 km. The eActros 600 has the lowest TCO for ranges between 450 km to 500 km and high lifetime mileage. Beyond 700 km range requirements, the GenH2 Truck becomes favorable, although for mid-range operations (500 km to 700 km) and moderate lifetime mileage, the Quantron is more economical. In general, MD FCETs are suited for lower total mileage, while BEVs excel in high-mileage, short-range operations. FCETs' superior range makes them attractive for long-haul applications.

10. Operability

The preceding sections outlined the FCET manufacturers active as of Q1 2024 and the vehicles currently available. Most of these trucks offer shorter ranges than those announced for the coming years. Both range and efficiency are critical parameters for FCET operations. Given identical hydrogen tank capacities, a less efficient truck will yield a shorter range. In practice, two main operational modes must be considered: scheduled service and charter service. Scheduled (or depot-based) services operate from a fixed base and typically refuel at a dedicated station on-site or nearby. This type of operation allows for a predictable, star- or circular-shaped route network that returns to the same depot. Charter service, by contrast, involves flexible routing between customers without regular returns to a base. Consequently, these trucks must refuel en route, resulting in more linear routing patterns. Understanding these modes is key to assessing FCET operability. Scheduled services depend on one or a few refueling stations, enabling localized FCET deployment. In these cases, infrastructure reliability becomes critical: any failure at the primary station can halt operations unless a backup station exists within the truck's remaining range. While long vehicle ranges are not strictly necessary for depot-based operations, shorter ranges limit flexibility and increase vulnerability to single-point failures. Notably, even one refueling station can enable scheduled FCET operations within a defined radius, and additional stations within that radius further expand the operational range. Charter service poses greater infrastructure demands. Trucks in this mode travel across regions or countries and typically require refueling mid-route, since a single tank rarely covers the full distance between customers. Low vehicle range increases the number of required refueling stops, which often involve detours, time losses, and reduced profitability. Furthermore, Europe had only 83 hydrogen refueling stations by September 2024, most of which are located near highways or in major urban centers. Fig. 11 illustrates the road distances between 35 MPa hydrogen stations in central Europe. Three dense clusters are evident: the western Netherlands, North Rhine-Westphalia, and northern Switzerland, where inter-station distances are under 50 km. Outside these areas, distances quickly increase to several hundred kilometers. For example, the nearest station to Paris is in Belgium, roughly 280 km away. The next-closest stations, in Germany and Belgium, are over 300 km distant. This example underscores the importance of precise infrastructure knowledge for planning FCET routes. Compounding the issue, most stations currently feature only one nozzle. A malfunction of a single component can render the entire station inoperable, substantially increasing the required backup range. With an average inter-station distance of around 150 km (see Fig. 11), this distance should be factored into routing decisions as a contingency buffer. The figure includes nearly all hydrogen stations in Europe, excluding a few in Great Britain and northern Europe. From this distribution, several takeaways emerge regarding charter service operability: trucks must be able to reach both their destination and the next refueling station. The hydrogen network cannot be deviated from significantly, as this introduces risk. Assuming fuel availability at each station, charter FCET operations are feasible within a corridor spanning northern Germany, eastern Austria, southeastern France, and Belgium. However, travel to and from Paris especially from southeastern France or western Germany requires vehicle ranges exceeding approximately 600 km. Thus, Paris currently lies outside the bounds of the central European hydrogen network. Further infrastructure expansion is essential for full charter service viability.

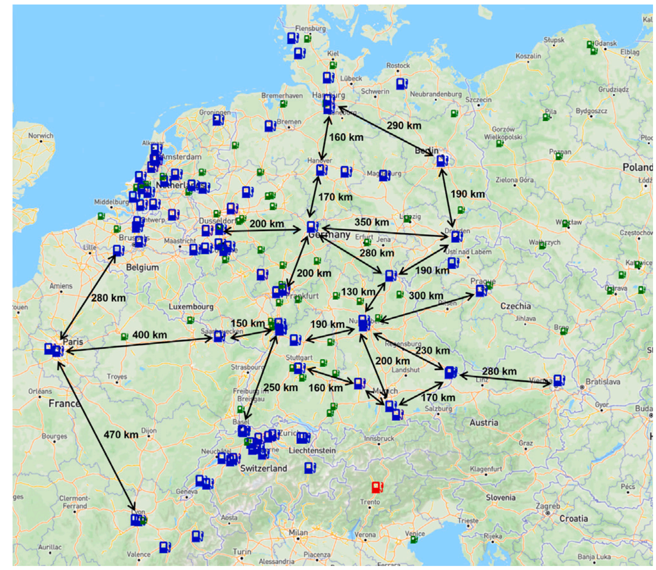

Fig. 11. Road distance between hydrogen fuel stations in central Europe (35 MPa).

11. Conclusion

The economic evaluation performed in this study highlights that both CAPEX and OPEX critically influence the viability of FCETs. Particularly, fuel consumption and thus the efficiency of the entire drivetrain and the fuel cell system significantly affects the economic competitiveness of FCETs. To establish FCETs as a viable alternative to conventional diesel and BEVs, substantial reductions in key component costs, especially for fuel cells and hydrogen storage tanks, are necessary. Furthermore, enhancing the efficiency and lifespan of fuel cell systems will substantially reduce OPEX, enabling significant economic benefits. Both the limited number of available FCET models and the sparse hydrogen fueling station network underline that FCET technology remains in an early developmental stage. The high initial costs of FCET vehicles and hydrogen fuel lead to low market demand, perpetuating a "chicken-and-egg" scenario that hampers further technological maturity and widespread adoption. Additionally, the limited ranges of currently available FCET models, typically around 500 km, significantly restrict operational flexibility, especially for long-distance freight transport. To overcome operational barriers, a crucial first step involves implementing real-time information systems for hydrogen fueling stations. Such systems, following models like those proposed by Gerboni et al. (2021), would offer fleet operators and drivers timely, accurate updates on station functionality, hydrogen availability, and potential outages. Gerboni et al. demonstrate how integrating infrastructure availability into vehicle routing decisions can enhance reliability and utilization of electric freight vehicles. While their work focuses on BEV applications, the underlying principles of infrastructure-linked decision support are equally critical for FCET operations, where fueling opportunities are even more limited and station failures can result in route infeasibility. This enhanced transparency would significantly reduce operational uncertainty, thereby building trust and increasing reliability. Moreover, holistic operational planning, integrating detailed route planning with real-time operational data, can optimize FCET usage, enhance fuel efficiency, and further reduce OPEX. Utilizing advanced data analytics and predictive modeling to align refueling strategies with logistical demands can greatly enhance operational feasibility, particularly in areas with limited infrastructure. Advancements in FCET technology itself remain crucial. Expanding vehicle range and enhancing drivetrain efficiency, particularly improving fuel cell performance, can bridge the gap between FCET and traditional internal combustion engine trucks. These technological advancements must systematically address both technical limitations and economic barriers to achieve widespread adoption. Comparisons with battery-electric vehicles in this research underscore distinct operational profiles: BEVs generally exhibit lower operational costs for medium-range operations, whereas FCETs offer advantages for longer routes due to shorter refueling times and greater operational flexibility, assuming appropriate infrastructure. Therefore, decisions between BEV and FCET technologies should align closely with specific operational needs, infrastructure conditions, and long-term cost projections. Lastly, significant expansion and redundancy in the hydrogen refueling network remain imperative. A denser, more resilient infrastructure will mitigate current operational constraints imposed by sparse fueling availability and reliability concerns. Incorporating redundancy measures, such as backup refueling capabilities, would further enhance reliability and operational confidence. Future research should emphasize practical implementation, empirical validation of operational strategies, and robust economic evaluations comparing FCETs with alternative technologies across diverse logistic scenarios. Through targeted innovation, comprehensive planning, and coordinated infrastructure expansion efforts, FCET technology can substantially contribute to achieving a sustainable, decarbonized future in freight transportation.

12. Summary and outlook

Based on a benchmark analysis of current FCETs and BEVs, this study has evaluated the technical design, cost structure, and operational constraints of zero-emission drivetrains for heavy-duty freight. Drawing from publicly available specifications and a qualitative TCO comparison, the paper identifies key trade-offs in drivetrain design, vehicle range, energy efficiency, and economic feasibility. The results demonstrate that neither FCETs nor BEVs represent a universal solution; instead, each technology requires context-specific operational alignment and cost optimization. A central finding is that the limited range of current FCETs, coupled with sparse hydrogen refueling infrastructure, poses considerable barriers to widespread adoption. Depot-based services with dedicated refueling stations face fewer operational constraints; however, charter services experience significant limitations due to insufficient redundancy in refueling networks. This underscores the need for real-time transparency regarding hydrogen availability and the integration of refueling logistics into comprehensive operational planning. To enhance FCET adoption, several critical areas require attention. Firstly, advancing operational planning systems, improving fuel cell efficiency, and reducing component and operational costs is essential. In particular, the study highlights that reducing both CAPEX and OPEX is crucial to achieve economic viability. CAPEX can be addressed by lowering fuel cell system and hydrogen storage component costs through economies of scale, improved integration and further research. On the OPEX side, increasing fuel cell system efficiency, particularly under real-world duty cycles is key to reducing hydrogen consumption and lowering TCO. These efficiency gains directly translate into lower fuel demand, fewer refueling stops, and improved operational flexibility. Extending the vehicle range beyond current limitations and boosting overall drivetrain efficiency will help FCETs become economically competitive with ICE trucks, especially for long-haul logistics. Significant expansion and redundancy of the hydrogen refueling network remain crucial. Enhanced infrastructure density and reliability directly address current operational constraints. Incorporating redundancy measures, such as backup fueling capabilities, will further increase operational confidence among fleet operators. Future research should prioritize practical implementation, empirical validation of operational strategies, and robust economic evaluations of FCET versus alternative technologies in diverse logistics scenarios. Through targeted innovation, coordinated infrastructure expansion, and operational excellence, FCETs hold strong potential to become a cornerstone of sustainable, decarbonized freight transportation.

CRediT authorship contribution statement

Maximilian Bayerlein: Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julius Hausmann:** Writing – review & editing, Supervision. **Heiner Heimes:** Supervision. **Achim Kampker:** Supervision, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT-Open AI 4.0 in order to improve formulation and for spell checking. After using this service, the author reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maximilian Bayerlein reports financial support was provided by Federal Ministry for Digital and Transport. Prof. Achim Kampker reports financial support was provided by Federal Ministry for Digital and Transport. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Detailed truck data

(see Tables A.1–A.6).

Table A.1
Summary of the FCET data.

FCET model	Market entry	Config.	GVM	Fuel tank Cap.	Fuel cell power	Net battery Cap.	Electric motor power	Range	Hydrogen Cons.
Hyundai Xcient Fuel Cell[a]	2021	Motor car	42 t	31 kg (35 MPa)	180 kW	72 kWh	350 kW	400 km	8.02 $\frac{kg}{100\ km}$
Hyzon HyMax-160[b]	2021	Motor car	24 t	30 kg (35 MPa)	80 kW	70 kWh	160 kW	400 km	7.5 $\frac{kg}{100\ km}$
Hyzon HyMax-250[c]	2021	Motor car & semi truck	46 t	30 kg (35 MPa)	120 kW	140 kWh	250 kW	490 km	10.3 $\frac{kg}{100\ km}$
Hyzon HyMax-450[d]	2021	Motor car & semi truck	46 t	30 kg (35 MPa)	120 kW	140 kWh	450 kW	490 km	10.3 $\frac{kg}{100\ km}$
Paul Nutz-fahrzeuge PH2P Truck[e]	2024	Motor car	24 t	30 kg (35 MPa)	80 kW	60 kWh	120 kW	450 km	6.67 $\frac{kg}{100\ km}$
Nikola Tre FCEV[f]	2024	Semi truck	37 t	70 kg (70 MPa)	200 kW	164 kWh	400 kW	800 km	8.75 $\frac{kg}{100\ km}$
Quantron QHM FCEV 44-1000[g]	Q3 2023	Semi truck	44 t	54 kg (70 MPa)	240 kW	124 kWh	420 kW	700 km	7.71 $\frac{kg}{100\ km}$
Daimler GenH2 Truck[h]	2027	Semi truck	40 t	80 kg (sLH_2)	300 kW	55 kWh	400 kW	1000 km	8 $\frac{kg}{100\ km}$
Volvo[i]	until 2030	Motor car & semi truck	n.n.	n.n.	300 kW	n.n.	n.n.	1000 km	n.n.

[a] Hyundai Motor Company (2022, 2020).
[b] Hyzon Motors (2021, 2023) and Klimafreundliche Nutzfahrzeuge (2023a).
[c] Hyzon Motors (2021, 2023) and Hylane GmbH (2023a,b).
[d] Hyzon Motors (2021, 2023).
[e] Paul Nutzfahrzeuge GmbH (2022, 2024).
[f] Nikola Motors (2023a,b,c).
[g] Quantron AG (2023).
[h] Daimler Truck AG (2021, 2023b), Cellcentric (2020) and Julian Hoffmann (2023).
[i] Cellcentric (2020) and Volvo Trucks (2022).

Table A.2
Summary of the BEV data.

BEV model	Market entry	Config.	GVM	Net battery Cap.	Electric motor power	Range	Energy Cons.	Charging time (CCS) (20% to 80% SOC)
Daimler Truck eActros 300[a]	2023	Motor car & semi truck	40 t	336 kWh	330 kW	220 km	110 $\frac{kWh}{100\ km}$	75 min
Daimler Truck eActros 600[b]	2024	Motor car & semi truck	44 t	600 kWh	400 kW	500 km	120 $\frac{kWh}{100\ km}$	60 min

[a] Daimler Truck AG (2024a, 2023c).
[b] Daimler Truck Schweiz AG (2023) and Daimler Truck AG (2023a).

Table A.3
Fuel consumption per ton per 100 km.

	Mass	Consumption	Consumption per mass
Hyundai Xcient Fuel Cell	34 t	8.02 $\frac{kg}{100\ km}$	0.236 $\frac{kg}{100\ km\ t}$
Hyzon HyMax-160	24 t	7.5 $\frac{kg}{100\ km}$	0.313 $\frac{kg}{100\ km\ t}$
Hyzon HyMax-250	46 t	10.3 $\frac{kg}{100\ km}$	0.224 $\frac{kg}{100\ km\ t}$
Hyzon HyMax-450	46 t	10.3 $\frac{kg}{100\ km}$	0.224 $\frac{kg}{100\ km\ t}$
Paul Nutzfahrzeuge PH2P Truck	24 t	6.67 $\frac{kg}{100\ km}$	0.278 $\frac{kg}{100\ km\ t}$
Nikola Tre FCEV	37 t	8.75 $\frac{kg}{100\ km}$	0.236 $\frac{kg}{100\ km\ t}$
Quantron QHM FCEV	44 t	7.71 $\frac{kg}{100\ km}$	0.175 $\frac{kg}{100\ km\ t}$
Daimler Truck GenH2 Truck	40 t	8 $\frac{kg}{100\ km}$	0.2 $\frac{kg}{100\ km\ t}$

Table A.4
Calculation of the CAPEX based on component cost of the FCET.

CAPEX [thou.]	Hydrogen tanks	Fuel cells	Batteries	E-Motor	Assembly	Total CAPEX
Hyundai Xcient Fuel Cell	US$ 12.71	US$ 90	US$ 26.64	US$ 14	US$ 57.34	US$ 200.69
Hyzon HyMax-160	US$ 12.3	US$ 40	US$ 25.9	US$ 6.4	US$ 33.84	US$ 118.44
Hyzon HyMax-250	US$ 12.3	US$ 60	US$ 51.8	US$ 10	US$ 53.64	US$ 187.74
Hyzon HyMax-450	US$ 12.3	US$ 60	US$ 51.8	US$ 18	US$ 56.84	US$ 198.94
Paul Nutzfahrzeuge PH2P Truck	US$ 12.3	US$ 40	US$ 22.2	US$ 4.8	US$ 31.72	US$ 111.02
Nikola Tre FCEV	US$ 31.5	US$ 100	US$ 60.68	US$ 16	US$ 83.272	US$ 291.452
Quantron QHM FCEV	US$ 24.3	US$ 120	US$ 45.88	US$ 16.8	US$ 82.792	US$ 289.772
Daimler Truck GenH2 Truck	US$ 26	US$ 150	US$ 20.35	US$ 16	US$ 80.94	US$ 283.29

Table A.5
Calculation of the CAPEX based on component cost of the BEV.

CAPEX [thou.]	Batteries	E-Motor	Assembly	Total CAPEX
Daimler Truck eActros 300	US$ 124.32	US$ 13.2	US$ 55.008	US$ 192.528
Daimler Truck eActros 600	US$ 84	US$ 16	US$ 40	US$ 140

Table A.6
TCO for given mileages based on CAPEX and OPEX.

TCO [thou.]	CAPEX	TCO 50k km	TCO 100k km	TCO 150k km	TCO 200k km	TCO 250k km	TCO 300k km	TCO 350k km	TCO 400k km
Daimler Truck eActros300	192.5	226.6	260.7	294.8	328.9	363.0	397.1	431.1	465.2
Daimler Truck eActros 600	140	177.2	214.4	251.6	288.8	325.9	363.1	400.3	437.5
Hyundai Xcient Fuel Cell	200.7	257.1	313.5	369.9	426.3	482.6	539.0	595.4	651.8
Hyzon Hymax-160	118.4	171.2	223.9	276.6	329.4	382.1	434.8	487.6	540.3
Hyzon Hymax-250	187.7	260.2	332.6	405.0	477.4	549.8	622.3	694.7	767.1
Hyzon Hymax-450	198.9	271.4	343.8	416.2	488.6	561.0	633.5	705.9	778.3
Paul Nutzfahrzeuge PH2P Truck	111.0	157.9	204.8	251.7	298.6	345.5	392.4	439.3	486.2
Nikola Tre FCEV	291.5	353.0	414.5	476.0	537.5	599.1	660.6	722.1	783.6
Quantron QHM FCEV	289.8	344.0	398.2	452.4	506.6	560.8	615.0	669.2	723.5
Daimler Truck GenH2 Truck	283.3	339.5	395.8	452.0	508.3	564.5	620.8	677.0	733.3

Data availability

Data will be made available on request.

References

Ahluwalia, R.K., Hua, T.Q., Peng, J.-K., Lasher, S., McKenney, K., Sinha, J., Gardiner, M., 2010. Technical assessment of cryo-compressed hydrogen storage tank systems for automotive applications. Int. J. Hydrog. Energy 35 (9), 4171–4184.

Ahluwalia, R.K., Roh, H.-S., Peng, J.-K., Papadias, D., Baird, A.R., Hecht, E.S., Ehrhart, B.D., Muna, A., Ronevich, J.A., Houchins, C., Killingsworth, N.J., Aceves, S.M., 2023. Liquid hydrogen storage system for heavy duty trucks: Configuration, performance, cost, and safety. Int. J. Hydrog. Energy 48 (35), 13308–13323.

Amol A. Phadke, Aditya Khandekar, Nikit Abhyankar, David Wooley, Deepak Rajagopal, 2021. Why regional and long-haul trucks are primed for electrification now. URL: https://eta-publications.lbl.gov/sites/default/files/updated_5_final_ehdv_report_033121.pdf.

Basma, H., Rodriguez, F., Battery electric tractor-trailers in the European Union: A vehicle technology analysis, International Council on clean Transportation 2021, 1–20.

Basma, H., Rodríguez, F., 2023. A total cost of ownership comparison of truck decarbonization pathways in Europe: Working paper. URL: https://theicct.org/publication/total-cost-ownership-trucks-europe-nov23/.

Bhardwaj, S., Mostofi, H., 2022. Technical and business aspects of battery electric trucks—A systematic review. Futur. Transp. 2 (2), 382–401.

Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, www.bmu.de, 2021. Klimaschutz in Zahlen–Fakten, trends und impulse deutscher klimapolitik, ausgabe 2021. URL: https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/klimaschutz_zahlen_2021_bf.pdf.

Carla Westerheide, 2025. Mercedes expands eActros 600 line-up and phases out eActros 300/400. URL: https://www.electrive.com/2025/05/13/mercedes-expands-eactros-

600-line-up-and-phases-out-eactros-300-400/.

Cellcentric, 2020. Volvo group und daimler truck AG forcieren entwicklung nachhaltigen transports. URL: https://cellcentric.net/volvo-group-und-daimler-truck-ag-forcieren-entwicklung-nachhaltigen-transports/.

Daimler Truck AG, 2021. Strategy day - inverstor relations. URL: https://group.mercedes-benz.com/dokumente/investoren/praesentationen/daimler-ir-presentation-daimler-truck-strategy-day-may-2021.pdf.

Daimler Truck AG, 2023a. Daimler truck #HydrogenRecordRun: Mercedes–Benz GenH2 truck knackt 1.000-kilometer-marke mit einer tankfüllung flüssigem wasserstof. URL: https://media.daimlertruck.com/go/HydrogenRecordRun.

Daimler Truck AG, 2023b. Erste eActros 300 sattelzugmaschine in deutschland an logistik schmitt übergeben: Serienstart ende des jahres. URL: https://www.daimlertruck.com/newsroom/pressemitteilung/erste-eactros-300-sattelzugmaschine-in-deutschland-an-logistik-schmitt-uebergeben-serienstart-ende-des-jahres-52469011.

Daimler Truck AG, 2023c. Mercedes-benz trucks feiert weltpremiere des batterieelektrischen fernverkehrs-Lkw eActros 600. URL: https://www.daimlertruck.com/newsroom/pressemitteilung/mercedes-benz-trucks-feiert-weltpremiere-des-batterieelektrischen-fernverkehrs-lkw-eactros-600-52428265.

Daimler Truck AG, 2024a. DER eACTROS 300/400. Charged & ready. Nachhaltig, zukunftsorientiert, innovationsgetrieben und leise. URL: https://autowelt-ebert.de/wp-content/uploads/2024/10/eActros300_400_Produktblatt_DE_SCREEN.pdf.

Daimler Truck AG, 2024b. Sicher, schnell und einfach: Daimler truck und linde setzen mit sLH2-technologie neuen standard für flüssigwasserstoff-betankung. URL: https://www.daimlertruck.com/newsroom/pressemitteilung/sicher-schnell-und-einfach-daimler-truck-und-linde-setzen-mit-slh2-technologie-neuen-standard-fuer-fluessigwasserstoff-betankung-52581266.

Daimler Truck Schweiz AG, 2023. Der neue eActros 600. CHARGED TO change. URL: https://www.merbag.ch/media/jzcais5p/web_eactros600_produktblatt_de.pdf.

Danielis, R., Niazi, A.M.K., Scorrano, M., Masutti, M., Awan, A.M., 2025. The economic feasibility of battery electric trucks: A review of the total cost of ownership estimates. Energ. 18 (2), 429.

Drawer, C., Rödl, A., Kaltschmitt, M., 2024. Life cycle assessment of construction and driving operation of a hydrogen-powered truck built from a used diesel truck. Transp. Res. Interdiscip. Perspect. 24, 101020.

Earl, T., Mathieu, L., Cornelis, S., Kenny, S., Ambel, C.C., Nix, J., 2018. Analysis of long haul battery electric trucks in EU. In: 8th Commercial Vehicle Workshop. pp. 17–18.

Europäische Union, 2021. Creating a Green and Efficient Trans-European Transport Network. [Publications Office of the European Union], [Luxembourg], URL: https://transport.ec.europa.eu/system/files/2023-03/Creating_a_green_and_efficient_Trans-European_Transport_Network.pdf.

Europäisches Parlament und europäischer Rat, 2023. Verordnung (EU) 2023/1804 DES Europäischen parlaments UND des rates über den Aufbau der Infrastruktur für alternative Kraftstoffe und zur Aufhebung der Richtlinie 2014/94/EU: AFIR, URL: https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32023R1804.

Geng, B., Mills, J.K., Sun, D., 2014. Combined power management/design optimization for a fuel cell/battery plug-in hybrid electric vehicle using multi-objective particle swarm optimization. Int. J. Automot. Technol. 15 (4), 645–654.

Gerboni, R., Caballini, C., Minetti, A., Grosso, D., Dalla Chiara, B., 2021. Recharging scenarios for differently electrified road vehicles: A methodology and its application to the Italian grid. Transp. Res. Interdiscip. Perspect. 11, 100454.

H2 Mobility, 2021. Wasserstoffbetankung von schwerlastfahrzeugen – die optionen im überblick. URL: https://h2-mobility.de/wp-content/uploads/sites/2/2021/10/H2M_Ueberblick_BetankungsoptionenLNFSNF_TankRast_2021-10-21.pdf.

H2 Mobility, 2023. H2 tanken: Wasserstoffmobilität beginnt jetzt. URL: https://h2.live/.

Heidt, C., Biemann, K., Dünnebeil, F., Jamet, M., Lambrecht, U., Althaus, H.-J., Wüthrich, P., Hausberger, S., 2019. Entwicklung und bewertung von maßnahmen zur verminderung von CO2 -emissionen von schweren nutzfahrzeugen: Abschlussbericht. URL: https://www.umweltbundesamt.de/publikationen/entwicklung-bewertung-von-massnahmen-zur.

Henze, V., 2020. Battery pack prices cited below $100/kwh for the first time in 2020, while market average sits at $137/kwh. URL: https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/.

Houchins, C., James, B., Acevedo, Y., Watts, Z., 2022. Hydrogen storage system cost analysis (2017–2021) (final report). URL: https://www.osti.gov/servlets/purl/1975554.

Hylane GmbH, 2023a. Hyzon HyMax 250 4x2. URL: https://www.hylane.de/mieten/hyzon-hymax-250-4x2/.

Hylane GmbH, 2023b. Hyzon hymax-250 6x2. URL: https://www.hylane.de/mieten/hyzon-hymax-250-6x2/.

Hyundai Motor Company, 2020. Erste brennstoffzellen-lkw hyundai xcient fuel cell kommen nach Europa. URL: https://www.hyundai.news/de/articles/press-releases/erste-brennstoffzellen-lkw-hyundai-xcient-fuel-cell-kommen-nach-europa.html.

Hyundai Motor Company, 2022. XCIENT fuel cell. URL: https://trucknbus.hyundai.com/hydrogen/ko/download/catalog_xcient-fuel-cell_en.pdf.

Hyzon Fuel Cell, 2024. Hyzon to focus on core North American markets and refuse industry and strategically halt Netherlands and Australian operations: Company to continue pursuit of new capital and adoption of market-leading fuel cell technology in North America. URL: https://www.hyzonfuelcell.com/in-the-news/hyzon-to-focus-on-core-north-american-markets-and-refuse-industry-and-strategically-halt-netherlands-and-australian-operations.

Hyzon Motors, 2021. Logistiktag wasserstoff konkret. URL: https://www.k-n-i.de/fileadmin/user_upload/dokumente/20210920-HYZON_Motors_Europe.pdf.

Hyzon Motors, 2023. Hyzon hymax series. URL: https://www.hyzonmotors.com/vehicles/hyzon-hymax-series.

International Organization for Standardization, 2020a. ISO 17268:2020 gaseous hydrogen land vehicle refuelling connection devices. URL: https://www.iso.org/obp/ui/en/#iso:std:iso:17268:ed-3:v1:en.

International Organization for Standardization, 2020b. ISO 19880:2020 gaseous hydrogen — Fuelling stations. 19880. URL: https://www.iso.org/obp/ui/en/#iso:std:iso:19880:-1:ed-1:v1:en:term:3.17.

International Organization for Standardization, 2025. ISO 14687:2025 hydrogen fuel quality — Product specification. URL: https://www.iso.org/obp/ui/en/#iso:std:iso:14687:ed-2:v1:en.

IVECO Group, 2023. Die iveco group und die nikola corporation beschreiten eine neue phase der partnerschaft: Iveco group übernimmt joint venture. URL: https://www.iveco.com/germany/presse/veroeffentlichungen/pages/iveco-group-und-die-nikola-corporation-beschreiten-eine-neue-phase-der-partnerschaft.aspx.

Julian Hoffmann, 2023. Das Ist Dampf. Fernfahrer.

Kampker, A., Heimes, H.H., 2024. Elektromobilität. Springer Berlin Heidelberg, Berlin, Heidelberg.

Kampker, A., Heimes, H.H., Schmitt, F., Backes, T., Betz, M., Hadzovic, T., 2022. Design of an electric drive axle for heavy duty commercial vehicles in the long-haul application under consideration of energy consumption. In: 2022 12th International Electric Drives Production Conference. EDPC, IEEE, pp. 1–8.

Kampker, A., Heimes, H., Schmitt, F., Bayerlein, M., Scheffs, P., 2023. Fixed route refueling-strategy for fuel cell trucks. Conf. Prod. Syst. Logist. 2023 - 2.

Kampker, A., Pandey, R., Gomez, J.G.D., Wessel, S., Treichel, P.-E., Malatyali, I., 2019. Cost optimal design strategy of electric drivetrains for medium heavy-duty vehicles based on product development and production costs. In: 2019 9th International Electric Drives Production Conference. EDPC, IEEE, pp. 1–8.

Klell, M., Eichlseder, H., Trattner, A. (Eds.), 2018. Wasserstoff in der Fahrzeugtechnik: Erzeugung, Speicherung, Anwendung, 4., aktualisierte und erweiterte Auflage ATZ/MTZ-Fachbuch, Springer Vieweg, Wiesbaden and Heidelberg.

Klimafreundliche Nutzfahrzeuge, 2023a. Hyzon hymax-160. URL: https://www.klimafreundliche-nutzfahrzeuge.de/praxis/fahrzeugdatenbank/hyzon-hymax-160/.

Klimafreundliche Nutzfahrzeuge, 2023b. Hyzon hymax-250-450. URL: https://www.klimafreundliche-nutzfahrzeuge.de/praxis/fahrzeugdatenbank/hyzon-hymax-250-450/.

Kraftfahrtbundesamt, 2022. Der fahrzeugbestand im überblick am 1. Januar 2022 gegenüber dem 1. Januar 2021.

Lain, Brandon, Kendrick, 2019. Design strategies for high power vs. High energy lithium ion cells. Batter. 5 (4), 64.

Lanz, L., Noll, B., Schmidt, T.S., Steffen, B., 2022. Comparing the levelized cost of electric vehicle charging options in Europe. Nat. Commun. 13 (1), 5277.

Lohse-Busch, H., Stutenberg, K., Duoba, M., Liu, X., Elgowainy, A., Wang, M., Wallner, T., Richard, B., Christenson, M., 2020. Automotive fuel cell stack and system efficiency and fuel consumption based on vehicle testing on a chassis dynamometer at minus 18 °C to positive 35 °C temperatures. Int. J. Hydrog. Energy 45 (1), 861–872.

Moultak, M., Lutseyn, N., Hall, D., 2017. Transitioning to zero emission heavy-duty freight vehicles. URL: https://theicct.org/wp-content/uploads/2021/06/Zero-emission-freight-trucks_ICCT-white-paper_26092017_vF.pdf.

Mu, Z., Zhao, F., Bai, F., Liu, Z., Hao, H., 2024. Evaluating fuel cell vs. Battery electric trucks: Economic perspectives in alignment with China's carbon neutrality target. Sustain. 16 (6), 2427.

Nationaler Wasserstoffrat, 2022. Wasserstoff farbenlehre. URL: https://www.wasserstoffrat.de/fileadmin/wasserstoffrat/media/Dokumente/2022/NWR-Informationspapier_Farbenlehre.pdf.

Neugebauer, R. (Ed.), 2022. Wasserstofftechnologien. Fraunhofer-Forschungsfokus, Springer Vieweg, Wiesbaden.

Neuhausen, J., Dr. Christian Foltz, Dr. Philipp Rose, Andreas Thalmair, Tobias Kasseroler, Lorenz Kehrbein, 2022. The dawn of electrified trucking: Truck study 2022: Routes to decarbonizing commercial vehicles. URL: https://www.strategyand.pwc.com/de/en/industries/transport/the-dawn-of-electrified-trucking/strategyand-the-dawn-of-electrified-trucking.pdf.

Nikola Motors, 2023a. Battery-electric vs hydrogen fuel cell electric semi trucks: 2 platforms | zero-emissions. URL: http://www.nikolamotor.com/wp-content/uploads/2023/09/FCE021_FCEV_vs_BEV_Brochure.pdf.

Nikola Motors, 2023b. Specifications TRE FCEV. URL: http://www.nikolamotor.com/wp-content/uploads/2023/09/FCE009_FCEV-US-Spec-Sheet-08.29.23.pdf.

Nikola Motors, 2023c. TRE FCEV: The hydrogen fuel cell electric class 8 vehicle. URL: http://www.nikolamotor.com/wp-content/uploads/2023/09/FCE022_FCEV_Brochure_Full_09.25.2023.pdf.

Paul Nutzfahrzeuge GmbH, 2022. PH2p truck. URL: https://paul-nutzfahrzeuge.de/wp-content/uploads/2022/10/PH2P_Truck_V2_web-new.pdf.

Paul Nutzfahrzeuge GmbH, 2024. PH2P trucks von paul group erfolgreich im einsatz: Erste 25 fahrzeuge an kunden ausgeliefert. URL: https://paul-nutzfahrzeuge.de/presse-newsroom/#/pressreleases/ph2p-r-trucks-von-paul-group-erfolgreich-im-einsatz-erste-25-fahrzeuge-an-kunden-ausgeliefert-3309685.

Pell, J., Schörghuber, C., Pretsch, S., Schreier, H., 2022. Optimierte betriebsstrategie für brennstoffzellen-lkw. ATZheavy Duty 15 (1), 26–31.

Pischinger, S., Seiffert, U., 2021. Vieweg Handbuch Kraftfahrzeugtechnik. Springer Fachmedien Wiesbaden, Wiesbaden.

Quantron AG, 2023. Q-heavy info brochure. URL: https://www.quantron.net/wp-content/uploads/2023/05/Q-Heavy_Infobrochure_DE_web.pdf.

Räth, G., 2024. Gründerin lernt lieber LKW fahren, als zeit bei netzwerktreffen zu vergeuden: Sara schiffer hat den LKW-Führerschein gemacht und ein startup gegründet, das wasserstoff-trucks vermietet. Hylane ist der größte abnehmer von wasserstoff an tankstellen in deutschland. URL: https://www.businessinsider.de/gruenderszene/automotive-mobility/gruenderin-lernt-lieber-lkw-fahren-als-zeit-bei-netzwerktreffen-zu-vergeuden-08/.

Rout, C., Li, H., Dupont, V., Wadud, Z., 2022. A comparative total cost of ownership analysis of heavy duty on-road and off-road vehicles powered by hydrogen, electricity, and diesel. Heliyon 8 (12), e12417.

SAE International, 2015. J2600 compressed hydrogen surface vehicle fueling connection devices. J2600. URL: https://www.sae.org/standards/content/j2600_201510/.

SAE International, 2016. J2601 fueling protocols for light duty gaseous hydrogen surface vehicles. J2601. URL: https://www.sae.org/standards/content/j2601_201612/.

SAE International, 2019. J2799 hydrogen surface vehicle to station communications hardware and software. J2799. URL: https://www.sae.org/standards/content/j2799_201912/.

Sharpe, B., Basma, H., 2022. A meta-study of purchase costs for zero-emission trucks: Working paper. URL: https://theicct.org/publication/purchase-cost-ze-trucks-feb22/.

Shell Deutschland, 2017. Shell wasserstoff-studie: Energie der zukunft? nachhaltige mobilität durch brennstoffzelle und H2. URL: https://www.shell.de/about-us/newsroom/shell-hydrogen-study/_jcr_content/root/main/containersection-0/simple/call_to_action/links/item0.stream/1643541262215/1086fe80e1b5960848a92310091498ed5c3d8424/shell-wasserstoff-studie-2017.pdf.

Shin, H.K., Ha, S.K., 2023. A review on the cost analysis of hydrogen gas storage tanks for fuel cell vehicles. Energ. 16 (13), 5233.

State of California Air Resources Board, 2015. Technology assessment: Medium- and heavy-duty fuel cell electric vehicles. URL: https://ww2.arb.ca.gov/sites/default/files/classic/msprog/tech/techreport/fc_tech_report.pdf?_ga=2.266899022.1905277306.1720958491-369376654.1720958488.

Tschöke, H., 2019. Definitionen, architekturen und topologien. In: Tschöke, H., Gutzmer, P., Pfund, T. (Eds.), Elektrifizierung des Antriebsstrangs. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 17–30.

Umweltbundesamt, 2022. Anteil der treibhausgasemissionen nach sektoren des klimaschutzgesetzes (KSG) im Jahr 2021. URL: https://www.umweltbundesamt.de/themen/verkehr-laerm/klimaschutz-im-verkehr#rolle.

Umweltbundesamt, 2023. Bausteine für einen klimagerechten verkehr: Klimaschutzinstrumente im verkehr. URL: https://www.umweltbundesamt.de/sites/default/files/medien/366/dokumente/2023-03_kliv_uebersicht_bausteine_klimavertraeglicher_verkehr.pdf.

Volvo Trucks, 2022. Volvo trucks showcases ner zero-emissions truck. URL: https://www.volvotrucks.com/en-en/news-stories/press-releases/2022/jun/volvo-trucks-showcases-new-zero-emissions-truck.html.

Zhao, J., Burke, A.F., Miller, M.R., Fulton, L.M., 2024. Vehicle choice modeling for emerging zero-emission medium- and heavy-duty vehicle markets in California. Transp. Res. Interdiscip. Perspect. 26, 101169.