Standardized framework for techno-economic assessment of heavy-duty vehicles: Insights from a state-of-the-art review

Applied Energy 415 (2026) 127883

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apen

Standardized framework for techno-economic assessment of heavy-duty vehicles: Insights from a state-of-the-art review

Trentalessandro Costantino [a,*], Xavier Guichet [b], Ezio Spessa [a]

[a] DENERG - Department of Energy “Galileo Ferraris”, CARS@Polito - Center for Automotive Research and Sustainable Mobility, Politecnico di Torino, C.so Duca degli Abruzzi, 24, Torino, TO 10129, Italy

[b] IFPEN - Institut Français du Pétrole Énergies Nouvelles, 1-4 av. de Bois Préau, Rueil-Malmaison, F-92852, France

HIGHLIGHTS

- Identifies discrepancies in assumptions and key data gaps in TCO studies.
- Highlights the variability of purchase costs and energy carrier costs in HDVs and their impact on TCO.
- Proposes a standardized TCO framework for fair comparison of HDV alternative technologies.

ARTICLE INFO

Keywords:
Total cost of ownership
Heavy duty
Electric trucks
Fuel cell
Alternative-fueled truck
Hydrogen trucks
TCO
HDV
Standardized framework
State-of-the-art review

ABSTRACT

The growing demand for techno-economic evaluations in the heavy-duty vehicle (HDV) sector is reflected in the increasing number of recent publications. Driven by tightening global tailpipe emission targets, many studies focus on technologies that can achieve zero-tailpipe emissions, such as Battery Electric Vehicles, Fuel Cell Electric Vehicles, and Hydrogen Internal Combustion Engine Vehicles, often comparing them with conventional Diesel Internal Combustion Engine Vehicles. However, comparing results across studies remains challenging due to varying assumptions that can drastically alter outcomes. This underscores the need for a standardized methodology to ensure fair and consistent comparisons of these technologies, integrating both technological and economic factors.

This review identifies key discrepancies in assumptions and significant data gaps, particularly in residual values and operational costs. We also examine the most influential cost components within Total Cost of Ownership (TCO) and their wide variability across studies. Specifically, purchase cost represents a significant portion of TCO, with large variations across the studies. Additionally, energy carrier cost, particularly for hydrogen-fueled vehicles, is a major operational expense, often influenced by assumptions regarding both energy consumption and energy carrier prices. In this study we also propose the rationale for a standardized TCO framework that can be applied across different HDV technologies, enabling fair comparisons that account for both technical performance and economic viability. Our findings aim to empower fleet operators, researchers, and policymakers with the insights needed to make informed decisions, even if the approach is focused on the fleet operator point of view. This is essential for accelerating the transition to zero-emission HDVs and achieving global climate goals in a fair and sustainable way.

1. Introduction

The rising greenhouse gas (GHG) emissions pose a significant global concern, contributing to increased solar radiative forcing and global temperature rise, which impacts ecosystems and human societies [1–4]. Global surface temperature during 2011–2020 was about 1.1 °C higher than 1850–1900.

Despite global regulatory efforts to curb emissions, the average global temperature is still projected to rise by 2.5-3 °C [5]. In 2022, among other sectors, the transport sector accounts for approximately 20% of global carbon dioxide (CO_2) emissions [6,7]. A significant portion, over three-quarters, stems from road transport, with 45% attributed to passenger vehicles and nearly 30% to freight transport. Moreover,

* Corresponding author.
Email addresses: trentalessandro.costantino@polito.it (T. Costantino), xavier.guichet@ifpen.fr (X. Guichet), ezio.spessa@polito.it (E. Spessa).

https://doi.org/10.1016/j.apenergy.2026.127883
Received 6 December 2024; Received in revised form 18 December 2025; Accepted 8 April 2026
Available online 17 April 2026

the transport sector is expected to expand in the coming decades as the global population grows and incomes rise, driving higher demand for transportation services, as stated by the International Energy Agency in 2020 [8], and reiterated by the International Transport Forum in 2023 [9]. As a result, the share of CO_2 emissions of the freight transport, in the total global emissions, is expected to increase, given that current transport systems remain heavily dependent on fossil fuels and their associated carbon emissions. Road freight transport is considered a hard-to-abate sector, alongside the aviation sector [10].

In Europe, the goal set by environmental policies is to limit the global temperature rise to 1.5 degrees by the end of the century, in alignment with the Paris Agreement, signed in 2015. On July 14th, 2021, the European Commission adopted a set of legislative proposals outlining how it intends to achieve climate neutrality by 2050, including an interim target of a net reduction of at least 55% in greenhouse gas emissions by 2030 compared to 1990 [11]. Between 1990 and 2018, the European Environmental Agency reported a significant decrease in carbon dioxide equivalent emissions from energy supply, residential, agricultural, and industrial sectors. In contrast, the transportation sector experienced a 33% rise in its emissions [12].

Heavy Duty Vehicles[1] (HDVs) such as trucks, buses, and coaches represent a significant and growing share of transport-related GHG emissions. Together, they account for more than a quarter of road transport-related greenhouse gas emissions in the European Union (EU) and over 6% of the EU's total GHG emissions in 2023 [14]. Despite recent gains in efficiency, emissions from HDVs continue to rise, largely driven by the growing volume of road freight traffic.

To address this, a new regulation has been introduced to strengthen the EU's CO_2 emission standards for HDVs [15]. The new regulation aims to accelerate the shift toward alternative trucks by setting more ambitious CO_2 reduction targets. While the existing goal of a 15% emissions cut by 2025 for heavy lorries over 16 tonnes remains unchanged, new targets have been introduced: a 45% reduction by 2030 (up from 30%), 65% by 2035, and 90% by 2040. These targets will apply to a broader range of vehicles, including medium lorries, heavy trucks over 7.5 tonnes, coaches, and vocational vehicles.

According to the regulatory framework outlined in Art. 3 of the regulation, zero-tailpipe CO_2 emission vehicles are defined as those that either do not have an internal combustion engine or emit no more than 3g CO_2 per tonne-km. Consequently, HDVs classified as ZEV vehicles, defined in this work with zero CO_2 tailpipe emissions, are restricted to Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEVs), and Hydrogen Internal Combustion Engine Vehicles (H2-ICEVs).

In 2023, sales of electric cars in the EU reached 1,627,000 units, representing 15.5% of total car sales, with BEVs clearly dominating and virtually no sales of FCEVs [16].

Regarding trucks, in 2022, sales of ZEVs for VECTO group 5[2] in the EU were almost nonexistent, while for VECTO group 9, they represented only 1% [16]. This shows that, despite the advancement of electric mobility in the car sector, the truck sector is still far behind in adopting ZEVs.

Achieving production and operational costs reduction is essential to make zero-tailpipe CO_2 emission heavy-duty vehicles (ZE-HDVs) competitive with conventional vehicles. Reducing the overall cost of ownership will encourage user adoption and unlock the full carbon reduction potential of these technologies at scale.

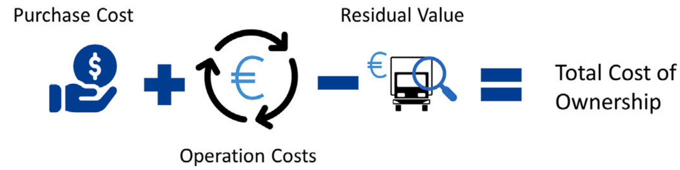

Fig. 1. Total cost of ownership scheme.

TCO provides a comprehensive framework for evaluating the financial implications of owning and operating an asset throughout its entire lifecycle [17]. A crucial aspect of TCO is its focus on the complete lifecycle of the truck, compelling businesses to look beyond the initial acquisition cost and consider expenses that may arise during the asset's useful life, such as maintenance, upgrades, and end-of-life costs [18,19].

Operating costs constitute a significant component of TCO, covering expenses related to energy consumption (i.e., fuel consumption), preventive maintenance and repairs, and any consumables necessary for the asset's proper operation (e.g., urea and lubricating oil). Lastly, the residual value refers to the asset's worth at the end of the ownership period being considered. A representative scheme of TCO can be seen in Fig. 1.

By accounting for all relevant expenses, TCO provides decision-makers with a clearer understanding of the financial implications of their choices. This clarity fosters better-informed decisions that align with long-term business objectives.

Evaluating the entire lifecycle cost of an asset also promotes sustainability, enabling fleet operators to align their decisions with broader environmental goals.

When selecting among various vehicle technologies, TCO becomes an invaluable tool, guiding customers through the complexities of evolving technologies and market dynamics [20].

The widespread adoption of BEVs in HDV applications faces several challenges, including low energy density, compounded weight, material shortages, and extended recharging times. These factors can negatively impact operational efficiency and service provision. Conversely, while FCEVs are currently expected to cost more than BEVs due to the lack of mass production and a lower manufacturing readiness level (MRL) compared to BEVs [21–23], they offer several advantages for HDVs. These include faster refueling times, longer range, better performance in extreme conditions, and lower degradation of fuel cells compared to lithium-ion batteries [24,25].

Recent literature highlights growing interest in the economic assessment of zero-tailpipe CO_2 emission vehicle technologies, though results vary due to the market immaturity and data gaps, particularly in end-of-life, maintenance, and refueling/recharging costs.

The HDV sector spans a wide array of applications, from urban delivery to long-haul distribution, each with distinct operational demands. These varied mission profiles and truck types add complexity to model choices and comparisons, as assumptions tailored to one application may not align with those of another. For example, a techno-economic assessment (TEA) typically starts with the purchase cost of a zero-tailpipe CO_2 emission technology truck, focusing on the production costs of major components like the electric motor, battery pack, fuel cell, and hydrogen tank. However, due to the early-stage market for zero-tailpipe CO_2 emission HDVs, this cost is often estimated and heavily reliant on assumptions, which can significantly affect outcomes.

Similarly, energy carrier cost, one of the most impactful operational expenses, is often based on assumptions. Understanding energy consumption rates and the price of the chosen energy source is crucial for comparing results across studies, as differing assumptions can lead to varying cost estimates. Another important cost is the vehicle's residual value at the end-of-life stage, where fleet operators aim to recover value.

[1] HDVs in this work follow the UNECE definition [13] and include categories M_2, M_3, N_2, and N_3. Since the analysis focuses on freight transport, the relevant HDVs are trucks in categories N_2 and N_3.

[2] Regulation (EU) 2017/2400 of the European Commission mandates the use of a simulation tool (VECTO) to calculate the CO_2 emissions of heavy-duty vehicles. The regulation also defines vehicle groups based on subcategories of category N, which are classified according to the technically permissible maximum laden mass (in tonnes), chassis type (rigid or tractor-trailer), and axle configuration. Group 5 refers specifically to tractor-trailer trucks with a 4x2 axle configuration and a maximum laden mass exceeding 16 tonnes.

Since the secondary market exists for zero-tailpipe CO_2 emission HDVs, this cost is typically speculative.

This review seeks to address these variations by providing a framework for more standardized TEA assessments. Our goal is to systematically explore existing studies, identify the key cost categories influenced by assumptions, and propose a methodological foundation for reliable TEA assessments that can better guide industry stakeholders and policymakers. By establishing a consistent, transparent approach to TEAs across HDV applications and vehicle types, this work aims to enable fair and accurate comparisons among zero-tailpipe CO_2 emission vehicle technologies. Ultimately, this standardized framework may empower decision-makers, foster sustainable practices in freight transport, and support the sector's transition toward decarbonization.

2. Methodology

2.1. Search strategy and selection criteria

The literature review process began with a systematic search across three prominent academic databases: Scopus, ScienceDirect, and Google Scholar. The search strategy was designed to be both comprehensive and focused, utilizing three sets of keywords: 'hdv AND tco', 'tco AND truck' and 'hdv AND economic' to capture all relevant studies on the TCO of heavy-duty vehicles. In total, the initial search yielded 3217 papers: 37 from Scopus, 982 from ScienceDirect, and 2198 from Google Scholar. The period explored is up to October 1st, 2024.

To manage this large volume of literature, a rigorous filtration process was implemented to ensure that only the most relevant and accessible papers were included in the review. The first step involved verifying the availability of the full text for each paper, as having access to the complete content was crucial for conducting a thorough analysis. This ensured that no significant information was excluded due to limited access.

Next, the relevance of each paper to the research topic was assessed. This was a critical step to maintain focus and ensure pertinence to the review's objectives. Abstracts were closely examined, and in cases where they lacked sufficient detail, the introduction and conclusion sections were reviewed. This process enabled a precise evaluation of each paper's relevance to the specific research question.

At the same time, a check for duplicates was conducted, as some papers appeared in multiple databases. Removing duplicates ensured that the dataset was not skewed by repeated entries. This filtration process ultimately reduced the initial pool of papers to a final set of 36 documents.

2.2. Data extraction and classification

After collecting the papers, the second stage of the literature review focused on extracting and classifying all relevant information in alignment with the study's objectives. Data from each paper were carefully grouped into specific categories. The initial fields included the title of the study, the year of publication, and an assessment of whether the study explicitly addressed the TCO.

Key technical and operational aspects were then documented, including the functional unit used in the study, the vehicle lifetime in years, and the lifetime distance of the vehicle. The yearly mileage of the trucks was also noted, along with some specific technical specifications of the trucks under assessment. The powertrain technologies examined in the study were categorized, followed by the discount rate adopted and whether inflation was taken into account.

The heavy-duty vehicle sector includes various configurations, such as the number of axles, gross vehicle weight (GVW), and whether the vehicle is a rigid truck or a tractor-trailer, along with features like the presence of a sleeper cab. These factors were collected, where disclosed, to accurately characterize the trucks reviewed.

From a regulatory perspective, there are differences between Europe and the US. In Europe, Regulation [26] defines truck categories, requiring certification of energy consumption through VECTO simulation software, with specific configurations for each truck type. In contrast, the US classifies truck configurations differently, focusing on GVW rather than the number of axles or other factors [27].

Additionally, the mission profile of the trucks was identified, clarifying whether they were designed for urban delivery, regional transport, or long-haul operations, if disclosed in the study. The studies were further evaluated to determine if they included financial benefits and whether battery or fuel cell replacements were considered over the vehicle's lifetime and the rationale behind these choices. The consideration of external costs (e.g., social costs of GHG emissions, and air pollutant impacts) was also recorded.

From a technical perspective, the truck efficiency (measured in kWh per kilometer) was noted. For hydrogen-powered vehicles, the hydrogen production pathway (grey, blue, brown, green, or pink) and the price of hydrogen (in euros per kilogram) were identified. The electricity mix of the country where the vehicle was operated during its use phase was also taken into account, as was the price of electricity (in euros per kWh). Furthermore, the technical specifications, when disclosed, were collected. In fact, regarding BEV, the battery's nominal energy capacity (in kWh) was noted, as well as the hydrogen tank capacity (in kilograms) for hydrogen-powered vehicles. This detailed classification tried to ensure that all relevant technical, and operational data were systematically collected for comparison across the various studies.

Economic aspects were another critical focus of the review. This included the vehicle's purchase price and personnel costs, as well as the cost of key components like batteries (in EURO/kWh), fuel cell stacks (in EURO/kW), and hydrogen tanks (in EURO/kg). For ICE trucks, the costs of the combustion engine (in EURO/kW) and fuel tank (in EURO/kWh) were documented. Another key aspect considered during the analysis phase was the cost of hydrogen at the pump or the electricity at public fast-charging stations. The analysis examined whether the studies accounted for infrastructure costs and how these costs influenced the final energy carrier price per unit of energy. Maintenance costs were also analyzed, with particular attention to zero-tailpipe CO_2 emission technologies, where maintenance practices remain uncertain due to the limited market penetration of these systems.

Additionally, the residual value, the amount recovered by fleet operators after selling the truck at the end of the ownership period, was thoroughly investigated. Depreciation of zero-tailpipe CO_2 emission vehicles is highly uncertain, as an established second-hand market has yet to develop, given the limited number of trucks reaching their end-of-life or first-use phase. Estimating this residual value presents a research challenge.

In the final step, the TCO was documented, either as a total amount in EURO or as EURO per functional unit. The idea was to try ensuring consistency in the comparison across studies.

2.3. Alternative technologies assessed

The studies analyzed cover a wide range of alternative technologies. Given the strong focus on reducing tailpipe emissions, the most commonly assessed technologies are BEVs and FCEVs. Conventional diesel technology is also almost always included, but typically as a benchmark for comparison. As shown in panel c) of Fig. 2, BEVs are assessed in 28 out of the 36 studies considered, while FCEVs appear in 20 out of 36.

Regarding other alternative technologies, B100 (biodiesel produced from biomass) is examined in only one study [28]. HVO and eDiesel are each analyzed in only one study [28], and hybrid electric trucks (both full and plug-in hybrids) are assessed in four studies [29–32]. Compressed natural gas (CNG) technology is assessed in three studies [29,31,33], while hydrogen-powered internal combustion engine (H2-ICE) technology appears in two recent studies [28,34].

The vast majority of the studies evaluated BEV, and FCEV as alternative technologies to be compared to conventional diesel truck.

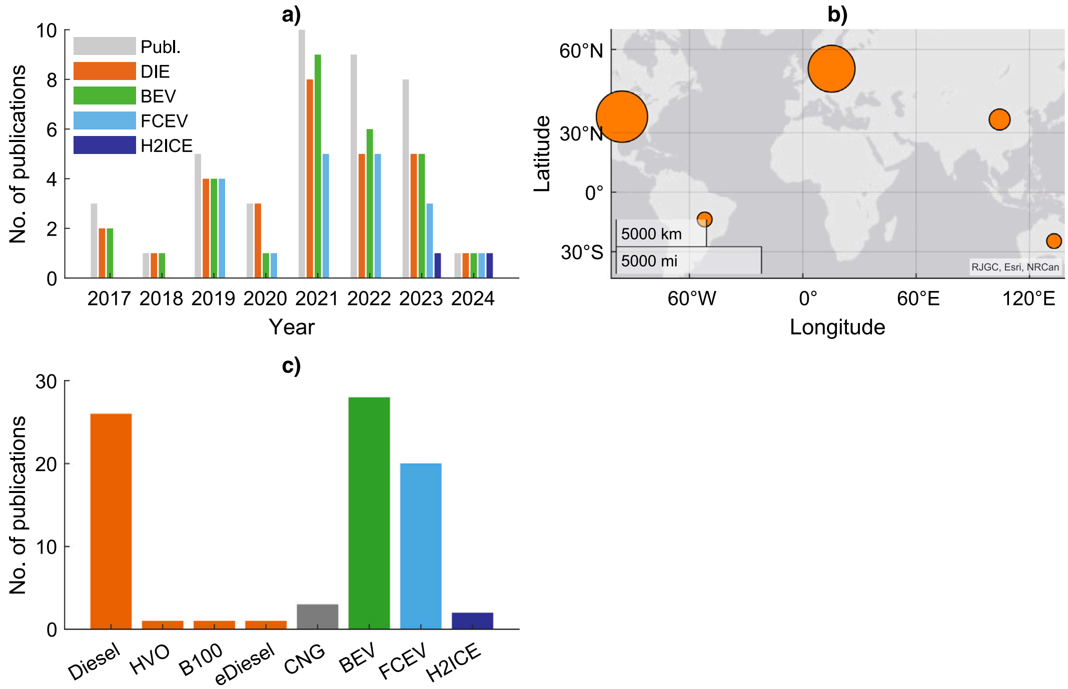

Fig. 2. a) Time distribution with breakdown by considered technologies, b) Geographical distribution, c) Alternative technologies considered.

This indicates that, with the global legislative framework increasingly prioritizing the reduction of CO_2 tailpipe emissions, BEVs and FCEVs are the most frequently studied technologies. Additionally, studies on H2-ICE technology are growing, as it is the third key technology that aligns with zero tailpipe CO_2 emissions goals.

3. Results

3.1. System boundaries, functional unit, and technical parameters

3.1.1. Year of publication and geographical aspects

The development of alternative technologies has accelerated in recent years, with a significant increase in research output. Our review focuses on studies and technical reports published between 2017 and 2024. Notably, the majority of publications have emerged in the past four years, as illustrated in panel a) of Fig. 2, underscoring the rising importance of TEAs in HDV sector. This trend is likely driven by the tightening of global CO2 emission regulations, which is accelerating the transition away from conventional diesel trucks across the globe [15,35,36].

The geographical distribution of these studies provides additional insights. From the data gathered during our document analysis, panel b) of Fig. 2 offers a comprehensive summary of the regional publication landscape. The bubble sizes in the figure represent the volume of publications from each geographic region. Research on the techno-economic aspects of alternative technologies for decarbonizing the HDV sector is global in scope, with significant contributions from Europe, which leads the field also due to recent regulatory frameworks. The United States follows closely, but there are also studies from South America, China, and Oceania.

3.1.2. Functional unit

The functional unit (FU) represents a quantifiable measure of a product based on its end-use application. It plays a fundamental role in sustainability assessments by enabling objective comparisons between different products serving the same function. In this study, the FU serves as a reference point for calculating total monetary costs, ensuring standardized and meaningful comparisons across studies and technologies. The analysis results are presented in panel a) of Fig. 2. In this figure, we also classify the selected studies based on the FU in relation to the vehicle's gross vehicle weight (GVW) to explore how the FU may vary across different weight categories. Specifically, when reported, we distinguish HDVs below 12 tons and above 12 tons GVW. A similar classification is applied to other parameters that influence the FU, such as the annual distance driven, the vehicle lifespan expressed in years, and the total lifetime distance.

Most of the reviewed documents present TCO results in monetary terms, such as euros in Europe, dollars in the USA, and yen in Japan [29,30,37].

In these studies, the FU is the truck itself. While this choice provides a straightforward way to define a functional unit, it can pose challenges when comparing different studies.

Among the few studies that use a functional unit other than the truck itself, distance is the most common alternative, measured in kilometers for non-USA studies and in miles for USA focused studies [20,31,38–43]. Only one study adopted ton-kilometers (ton * km) as the FU [34], aligning its TEA with the most widely used FU for freight transport in Life Cycle Assessment (LCA), as noted in several other studies [44–46].

In the same panel, we can also observe several documents that do not specify a functional unit. This is because not all of the reviewed documents present a complete TCO analysis; some were included for their valuable insights into truck purchase costs or subsystem cost breakdowns [47–55].

We also observe a pattern regarding vehicle size: studies examining vehicles with a GVW below 12 tons tend to adopt the truck itself as the FU, whereas studies on vehicles above 12 tons display the broader variability in FU choices.

3.1.3. Lifetime and annual mileage

Vehicle lifetime is a critical factor in calculating TCO, as it directly impacts costs related to fuel, driver wages, maintenance, and taxes. Selecting an appropriate lifetime is essential to accurately reflect both the state of the art and fleet operators' specific needs. Variations in lifetime assumptions, whether shorter or longer, can significantly influence TCO results.

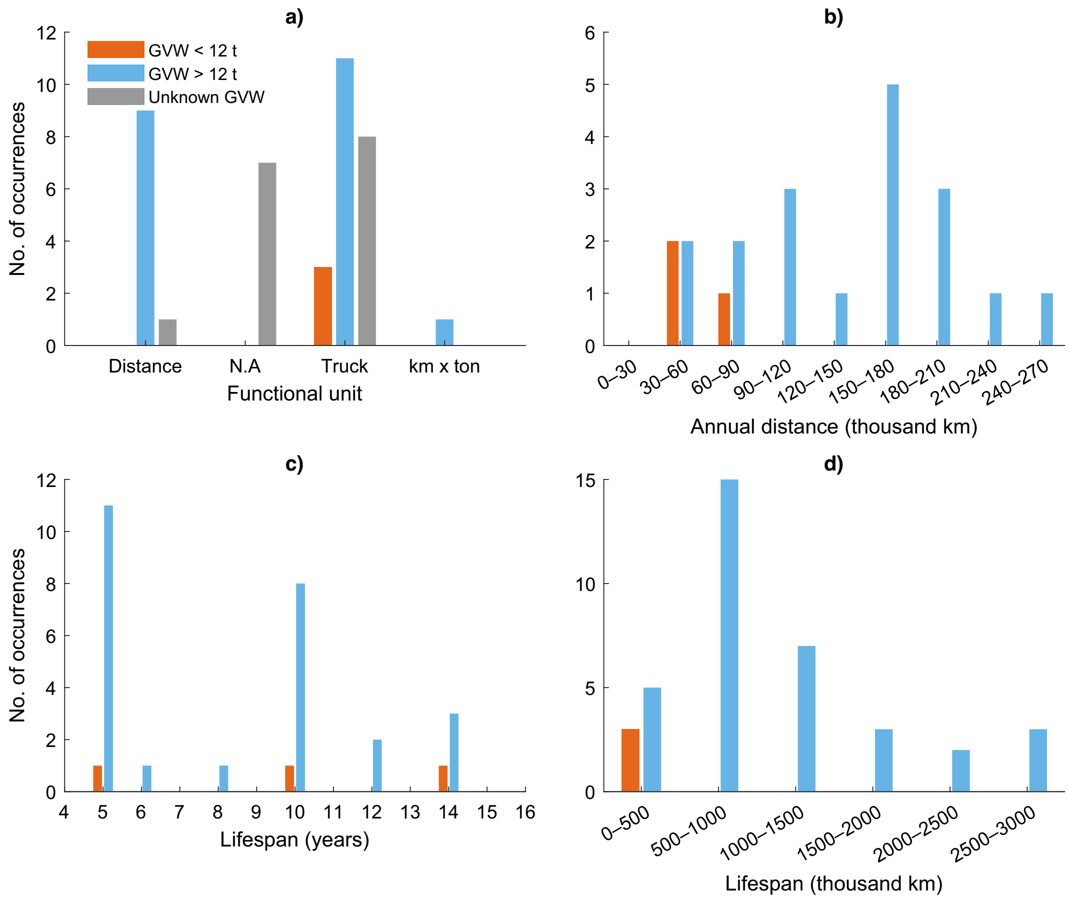

Fig. 3. a) Functional unit chosen, b) Annual mileages, c) Lifespan in years, d) Lifespan in distance.

As shown in panel c) of Fig. 3, there is no universally accepted standard for vehicle lifetime, particularly in the heavy-duty sector. Several studies rely on the first ownership period, typically five years [28,30,33,38,39,41,43,56–59], while others base their calculations on the manufacturer's guaranteed lifetime or the vehicle's actual lifespan [40]. Furthermore, when examining lifetime assumptions by GVW category, we observe that lighter vehicles (GVW below 12 tons), although less represented in the reviewed studies, show a variability in assumed lifespan similar to that of heavier vehicles.

In addition to the ownership period measured in years, the concept of lifetime in terms of distance driven is not standardized in TCO studies, often varying widely based on mission and truck configuration. A truck's distance-based lifetime depends heavily on its daily mission and operating environment. For example:

- Long-haul trucks, primarily used on highways with high maintenance standards, generally last between 500,000 to 1,000,000 kilometers or even more. The Euro 7 proposal [60] supports this, mandating a minimum manufacturer guarantee of 700,000 kilometers.
- Urban and regional freight trucks, operating frequently in congested city areas with frequent stops, typically have shorter lifespans of 300,000 to 500,000 kilometers, as also suggested by the Euro 7 proposal, which sets a minimum of 400,000 kilometers for such vehicles.

Panel d) of Fig. 3 underscores the absence of a consistent standard for lifetime distance across the literature, with over 20 studies omitting this parameter entirely. Among studies that do include lifetime distance, assumptions vary widely, ranging from 320,000 km to 2,511,000 km. This variation reflects the diversity in truck types and missions, as different vehicle classifications and operational profiles naturally result in differing lifetime mileage expectations. The analysis also highlights a distinct trend with respect to vehicle size: for vehicles with a GVW below 12 tons, the reviewed studies consistently assume lifetime mileages within the 0–500 thousand kilometer range. This aligns with the typical operational profiles of lighter commercial vehicles, which predominantly serve urban and regional freight applications and consequently accumulate lower total mileage than heavier HDVs.

Another key assumption in cost assessments is annual mileage, a variable that also shows substantial variation across studies, as illustrated in panel b) of Fig. 3. Annual mileage is intrinsically linked to truck classification and intended mission: urban delivery trucks generally cover fewer kilometers annually, while long-haul trucks log considerably higher mileage. Data extracted from the literature indicates a wide range of annual mileage, spanning from 24,500 km to 273,700 km per year. This variation reflects differences in operational needs and usage patterns across fleets, as demonstrated in studies such as [20,29], where estimates of annual mileage are tailored to fleet operators' specific requirements and the truck's role. A similar pattern emerges for annual mileage: lighter HDVs generally operate below 90,000 km per year, whereas heavier vehicles exhibit much greater variability, with annual mileage ranging from approximately 30,000 to 270,000 km across the reviewed studies.

3.1.4. Battery, fuel cell, H2ICE replacement and maintenance

The analysis reveals that the majority of studies overlook the need for battery replacement in heavy-duty vehicles throughout their evaluation periods. Only a limited number of studies take into account the possibility of battery replacement over the vehicle's operational lifespan [29,34,61]. For example, one study considers two potential vehicle lifetimes, factoring in battery replacement solely for the longer duration [59].

An analysis of the results indicates that when battery replacement is not explicitly addressed, it is generally excluded from the vehicle's life cycle assessment. Presently, there are no standardized minimum requirements for battery durability in heavy-duty vehicles. A working group is currently addressing this gap [62], particularly in light of the increasing market presence of zero-CO_2 tailpipe emission vehicles and the necessity for clear regulations.

Fuel cell replacement is another area that receives scant attention in the literature. Only two studies consider fuel cell replacement over the entire life-cycle of heavy-duty vehicles [29,40].

Regarding H2ICE replacement, only one study [34] has addressed this issue, and it is mentioned only in the supplementary material rather than the main results. The authors suggested that H2ICE replacement has a minimal impact on TCO.

3.1.5. Truck energy consumption

The energy consumption of HDVs is a key input for calculating energy carrier costs, which are derived from the energy consumption per distance driven and the energy carrier price (e.g., hydrogen or electricity price). However, in many studies, this data is not explicitly disclosed. In fact, in 26 out of the 36 documents reviewed, the energy consumption data is not explicitly stated.

When examining the energy consumption of conventional trucks, significant variation is observed, ranging from less than 2 kWh per kilometer [20] to nearly 4 kWh per kilometer [58]. For BEVs, the energy consumption varies between 0.8 kWh per kilometer [63] and 2.51 kWh per kilometer [64]. FCEVs generally exhibit slightly higher energy consumption compared to BEVs, ranging from 1.59 kWh per kilometer [65] to 3.44 kWh per kilometer [20].

These variations arise due to differences in truck configurations and models. Energy consumption in trucks strongly depends on factors such as the number of axles, which increase rolling resistance, and the payload, which significantly influences results as suggested for a previous study [66]. Additionally, the specific mission type or evaluation cycle (e.g., urban distribution, regional transport, or long-haul distribution) further affects energy consumption.

Many studies that report energy consumption for alternative vehicle technologies primarily rely on literature data rather than simulation-based results or real world collected data. For instance, Burke et al. [58] noted that conventional trucks consumed 3.84 kWh per kilometer in 2020, with a projected decrease to 2.94 kWh per kilometer by 2030. Similarly, BEVs were reported to consume 2.25 kWh per kilometer in 2020, reducing to 1.9 kWh per kilometer by 2030. However, these estimates lack validation through simulation tools, which may raise concerns about their accuracy, particularly when specific truck configurations (e.g., VECTO group for Europe or HDV class for the U.S.) are not disclosed.

The study [34] provides an example of using generalized efficiency curves rather than relying on detailed simulated calculations, which used a curve based on average speed and weight, first introduced in Noll [31].

3.2. Economic features and assumptions

3.2.1. Discount rate

The discount rate is fundamental in finance and economics, capturing two main aspects:

- Time Value of Money: Money today is more valuable than money in the future, as current funds can generate returns through investment.
- Risk and Opportunity Cost: It reflects the risk of an investment and the potential returns of alternative options.

In TCO and economic evaluations, the discount rate converts future cash flows to present value, clarifying an investment's current worth. Our analysis shows that some studies omit the discount rate, overlooking essential factors like time value and opportunity cost, and simply summing lifetime costs.

However, many studies apply a discount rate, typically between 7% and 10%, to reflect the higher risks of emerging technologies. This range is reasonable for evaluating alternative technologies in freight transport, as it accounts for the added risks in transitioning from conventional diesel to newer options.

3.2.2. Inflation

A notable portion of the reviewed studies does not account for price inflation, as evidenced by over thirty studies that made no reference to inflation in their analysis. Upon examining these studies, it becomes clear that inflation was not considered. Only a few studies [29,40,59] included inflation, but all applied a fixed rate. The rationale for this fixed rate differed: some studies selected it based on their experience, while others based it on the average inflation rate from previous years.

3.2.3. External costs

In 2019, the European Commission published a handbook to guide the assessment of external costs in the transport sector. It offers methodologies, input values, and cost figures to estimate external costs related to accidents, pollution, and climate impacts, covering marginal, total, and average costs across all EU countries, Switzerland, and Norway. It also includes comparisons with non-European countries and addresses well-to-tank emissions, noise, and congestion [67].

Only one of the analyzed studies considered external costs [29], using the AFLEET software methodology [68] to estimate costs from petroleum use, social costs of GHG emissions, and air pollutant impacts, though without detailing the rationale. This suggests that most studies either omit external costs or lack a standardized method for including them.

3.2.4. Energy carrier cost

The cost of energy carriers is a critical factor in assessing technologies that are not yet widely implemented in the market.

Significant uncertainties arise when examining hydrogen prices, particularly at the pump. Two studies focusing on the European market indicate that the price of green hydrogen at the pump ranged from 8.1 to 11.2 € per kilogram in 2022, with projections for a downward trend in the coming years due to reductions in capital expenditures for electrolyzers [28,57]. These studies advocate for green hydrogen as the optimal pathway for decarbonizing freight transport, highlighting its production from electricity generated by renewable sources.

In the U.S. market, another study cites a hydrogen price of 5 € per kilogram, but does not specify the production pathway used. This raises questions about whether this price is based on steam methane reforming, which has higher CO_2 emissions, or on the more environmentally friendly electrolysis from renewable sources [38]. Additionally, Burke et al. report that in the U.S. market, the price of green hydrogen varied between 10 and 17 € per kilogram in 2020, projecting a decrease to a range of 7 to 12 € per kilogram by 2030, and further down to 4 to 6 € per kilogram by 2040 [39].

Hall et al. [65] considered two distinct pathways—gray and green hydrogen—estimating costs of 5.12 and 9.26 € per kilogram, respectively, in 2020, with projected decreases to 4.17 and 6.88 € per kilogram by 2030 in the U.S. market.

Returning to European studies, three investigations report varying hydrogen costs: 7.98 € per kilogram across ten European countries [31], 13.8 € per kilogram as the reported price at the pump in Bolzano (Italy) in 2022 [51], and 5 € per kilogram in Finland [34].

The reviewed literature often lacks clear differentiation between production costs and infrastructure costs. It is not consistently specified whether the reported hydrogen prices include additional costs such as compression, transportation, storage, and station-specific markups. This ambiguity makes it challenging to determine whether the prices reflect only the cost of hydrogen production or encompass the entire supply chain up to distribution at refueling stations.

Uncertainties also arise when examining electricity costs, particularly concerning the fast charging of heavy-duty vehicles during daily operations. Many of the studies analyzed do not disclose the electricity price per kWh, with only a few reporting specific costs for fleet operators. The reported values range from 0.1 to 0.4 € per kWh [28,30,31,38–40,42,51,58,59,61]. It remains difficult to know whether infrastructure costs are accounted for or if the reported electricity prices consider various fast charging technologies. Given that the reported range aligns closely with non-residential electricity prices in Europe (between 0.20 and 0.30 € per kWh) [69], it is uncertain whether infrastructure costs are included and, if so, how they impact the final electricity costs.

Finally, it is essential to understand that energy carrier cost is derived from the multiplication of energy consumption per distance traveled and the price of the energy carrier. This cost type significantly impacts TCO [40,56]. For example, Alonso-Villar et al. [29] demonstrated that the energy carrier cost is the most influential for each technology, except for BEVs, where only the raw electricity cost is considered, excluding charging infrastructure costs. Gunawan et al. [42] also identified the energy carrier cost as the most influential factor, and Huin et al. [30] similarly highlighted its importance in TCO analysis. Liu et al. [50] and Lyu et al. [61] echoed this finding.

3.2.5. Driver cost

Among the studies analyzed, driver costs are seldom included in the economic assessments of alternative technologies for heavy-duty vehicles (HDVs). In fact, only four studies considered driver costs over the ownership period of HDVs [31,33,41]. However, when included, driver costs are significant and cannot be overlooked, as they constitute a substantial portion of the TCO and play a crucial role in the overall economic evaluation.

For instance, Earl et al. [41] considered a fixed wage for drivers that remained consistent across all assessed configurations, resulting in no analysis of the time spent driving the same distance each day for different technologies. Nevertheless, their TCO analysis revealed that personnel costs account for approximately 30% of the TCO for each configuration analyzed, whether involving internal combustion engines (ICE) or battery electric vehicles (BEV).

Similarly, Noll et al. [31] emphasized the importance of driver costs by examining varying annual driver wages across different countries (Switzerland, Sweden, Norway, Germany, and Italy). They found that driver wages represent a significant cost type, constituting around 20% of the TCO, depending on the specific wages in each country for the technologies considered.

Ravigne et al. [33] also recognized driver costs as a crucial factor, reporting an expense exceeding 250,000 euros in the TCO, which underscores the importance of accounting for this cost type in fleet operations.

3.2.6. Residual value

The residual value refers to the amount of money recovered by the fleet operator after selling the truck at the end of the ownership period. Estimating this value involves considerable uncertainty, particularly for alternative technologies that have not yet reached full market maturity, and therefore lack an established second-hand market. Key factors that influence the residual value include the condition of the battery, fuel cell, and H2 ICE at the end of the ownership period, as well as the proportion of the vehicle's value that the operator can recover when selling the alternative truck.

Basma et al. [57] suggest that the annual depreciation rate for a conventional diesel truck is fixed at 7.5%, meaning that after five years of ownership, the truck loses approximately 70% of its initial value. For FCEVs, it is estimated that the glider and e-axle retain 30% of their initial value, similar to conventional trucks. However, the fuel cell system is estimated to have a residual value of 25%, while the battery retains 15% and the hydrogen tank retains 70%. These values, however, are based on estimations rather than real-world data cause the lack of data related to second-hand market.

Burke et al. [38] report that, after five years, the diesel truck retains 50% of its initial value. The glider and e-axle of a BEV are estimated to have the same residual value, while the battery retains 85% of its initial value. For fuel cell vehicles, the glider is also estimated to retain 50% of its value, with the fuel cell system having a residual value of 50%.

Lyu et al. [61] estimate that conventional trucks retain 35% of their initial value after the ownership period, while BEVs retain 25%. These values are likewise estimations. Ravigne et al. [33] found that conventional trucks retain 24% and CNG trucks retain 10% of their initial value after the ownership period.

Tanco et al. [70] presented a depreciation curve as a function of the ownership period, showing that the residual value drops to 50% after the first two years and further declines to 20% by the end of a 12-year ownership period. Vijayagopal et al. [43] reported that vehicles retain 45% of their value after five years and 0% after 15 years, with no significant differences between the technologies considered.

3.2.7. Purchase cost of the alternative technology trucks

The studies analyzed report varying purchase costs across different technologies, influenced by factors such as truck configuration (e.g., specific VECTO Group or US class) and mission requirements. For instance, achieving a longer range in battery electric vehicles (BEVs) typically requires a larger battery pack, which in turn increases the purchase cost. Similarly, hydrogen-powered technologies such as fuel cell electric vehicles (FCEVs) and hydrogen internal combustion engine vehicles (H2-ICEs) require larger hydrogen tanks to extend their range, further driving purchase cost up. For FCEVs, purchase costs can fluctuate significantly depending on power demands, as the size and cost of fuel cell systems, which are notably expensive, vary with the required power output.

According to the analysis of the studies published in literature, as depicted in the first panel of Fig. 4, the average purchase price for a conventional heavy-duty vehicle (HDV) is approximately €148,000. For BEVs, the average cost rises to €326,000, while FCEVs have a slightly higher average purchase price of €342,000. In contrast, H2-ICE trucks, with an average cost of €213,000, tend to be more affordable than both BEVs and FCEVs. The highest reported cost for a BEV is €640,000, as detailed in Burke's study [58], while the lowest cost for a BEV is documented by Earl et al. [41]. Regarding FCEV trucks, the maximum value comes from Basma et al. [28], and the lowest from Burnham et al. [40]. As for H2-ICE trucks, only two studies provided purchase cost data: Basma et al. [28] reported the highest value at €266,000, while Magnino et al. [34] documented the lowest cost at €159,000.

3.2.8. Total cost of ownership results

In this section, we present the TCO results in kEUR for each study reviewed. We opted to display the results using the FU defined as the entire truck. Since no universal FU was adopted (as discussed in Section 3.1.2), for studies that used a different FU, we converted their results into monetary units by adjusting for the vehicle's lifetime. If the FU was distance-based (e.g., per km or mile), the values were multiplied by the vehicle's lifetime distance. In the case of a study that used ton-kilometers as the FU, we adjusted the result by factoring in both the payload and the vehicle's lifetime mileage.

The complete results are shown in the last panel of Fig. 4 as a box plot for the main alternative technologies considered in this study.

4. Discussion

4.1. TCO results

Starting from the overall results obtained in the studies considered, depicted in the last panel of Fig. 4, our review reveals significant

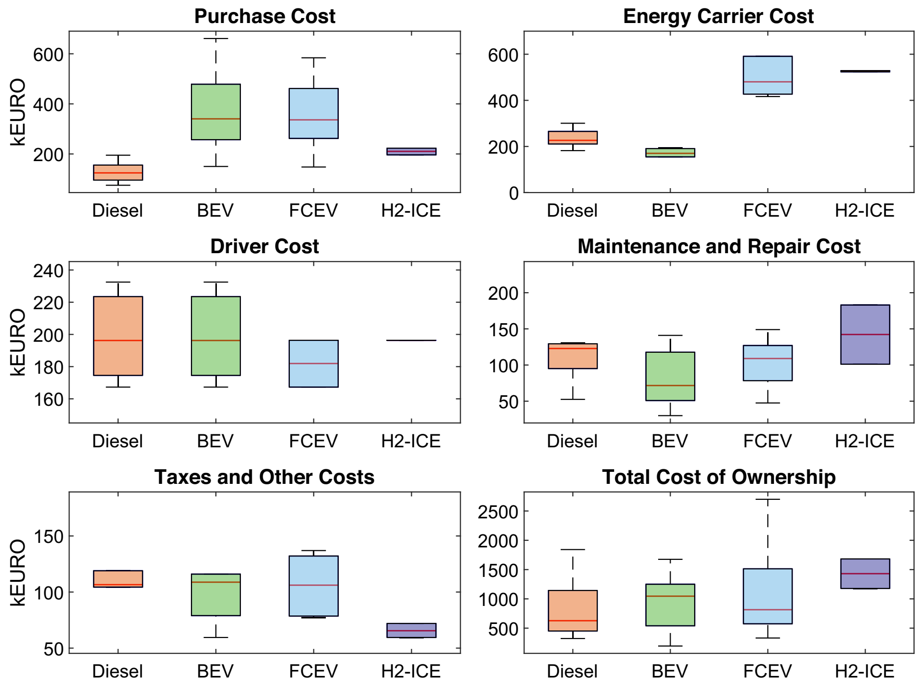

Fig. 4. Boxplots illustrating some of the most important cost types in a TCO evaluation for HDV, based on data extracted from the literature. The six boxplots represent: (1) Purchase Cost, (2) Energy Carrier Cost, (3) Driver Cost, (4) Maintenance and Repair Cost, (5) Taxes and Other Costs, and (6) Total TCO. In each boxplot, the central line marks the median, while the lower and upper edges denote the 25th and 75th percentiles, respectively, offering a comparative view of cost distribution across each category. For H2-ICE technology, the limited number of studies (two documents) results in sparse data. For example, Driver cost is based on a single study, showing no variation.

variability in TCO results, even for conventional technology, which is mature and well-understood. This variability stems from differing assumptions and methodologies across studies, causing notable discrepancies even when evaluating established technologies. The variation is even more pronounced for alternative technologies like BEVs and especially FCEVs, which have not yet achieved widespread market implementation. For instance, TCO estimates for BEVs range from 195 to 1675 k€, while those for FCEVs vary from 331 to 2700 k€. These broad ranges are largely influenced by differences in truck configurations, which directly affect purchase costs, a primary driver of overall TCO, as discussed in Section 3.2.7. Additionally, energy carrier costs contribute to this spread, particularly for FCEVs, as illustrated in the second panel of Fig. 4.

Another factor contributing to TCO variability is the inclusion or exclusion of driver costs, which significantly impact total costs, as detailed in Section 3.2.5 and illustrated in Fig. 5. Furthermore, energy carrier cost introduce considerable uncertainty, particularly for BEVs and hydrogen-fueled trucks, where energy cost is frequently estimated rather than directly observed or simulated. As outlined in Sections 3.2.4, energy carrier costs are calculated by multiplying the raw energy cost by the vehicle's energy consumption. However, these estimates often show considerable variation, particularly for hydrogen, and rarely account for the associated infrastructure expenses, such as compression, transportation, storage, or refueling station markups. This lack of clarity makes it difficult to discern whether reported hydrogen costs represent production costs alone or the full cost at the pump. As emphasized in Section 3.2.4, energy carrier cost is one of the most significant factors in TCO calculations, so any uncertainty in assumptions around this cost element can dramatically alter TCO results, as also depicted in the second panel of Fig. 4 where energy carrier costs make up a substantial portion of the TCO for hydrogen-fueled alternative technologies. This is further illustrated in Fig. 5, which shows the average impact, extracted from the published studies, of energy carrier costs on TCO: for FCEVs, these costs represent up to 50% of the total, and for H2-ICEs, around 46%.

When studies analyze projected TCO over future years, the level of uncertainty increases due to unknown trends in key cost components. For example, while nearly all studies predict a reduction in the costs of alternative trucks compared to today, the future remains uncertain. Given this, it is essential to consider multiple scenarios, ranging from optimistic to pessimistic projections, to conduct a sensitivity analysis on various cost factors. These include purchase costs, energy carrier costs, and the residual value of trucks at the end of their life. Sensitivity analyses seem to be crucial for providing a comprehensive view of potential TCO outcomes, offering a range of values rather than a single estimate, particularly when forecasting into the future.

4.2. *Goal and scope definition*

The variability of the results mentioned above is driven by several factors, including variations in system boundaries, FUs, vehicle lifespan, specific truck configurations, and mission purposes. In fact, our literature review reveals that the detail on specific truck configurations is often overlooked. In the few instances where it is addressed, we observe that in Europe, the most commonly analyzed truck category is VECTO Group 5, which refers to tractor-trailers exceeding 16 tons of weight. This focus is reasonable, as VECTO Group 5 vehicles represent the most commonly sold trucks in Europe [71]. In the USA, among the few studies that specify truck categories, Class 8 trucks, which are also tractor-trailers, are the most frequently assessed type.

This trend highlights a key issue: specific truck configurations are often under-reported in studies, and when included, they tend to focus on the most widely sold models. Properly assessing the TCO of different truck configurations requires knowing the specific configuration details. Different configurations correspond to distinct operational

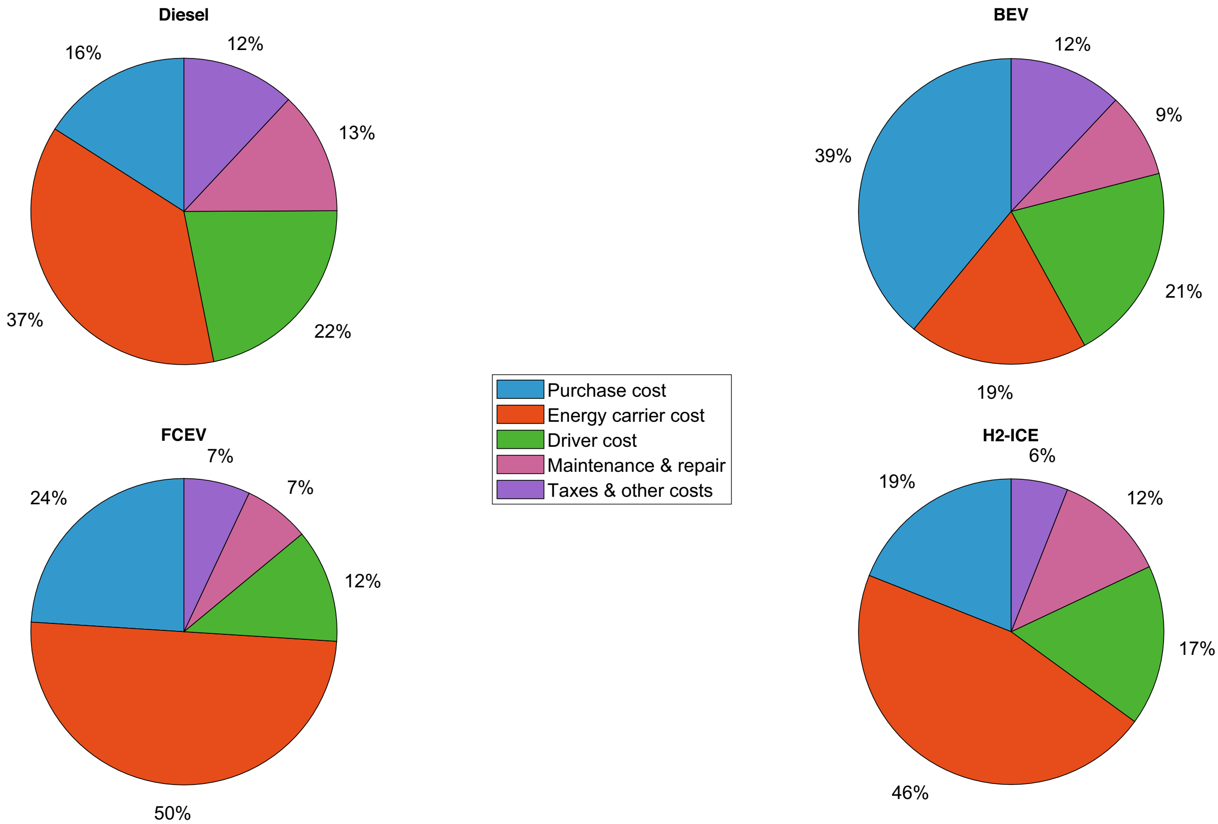

Fig. 5. The charts highlight cost hotspots, with each pie representing: (1) Diesel Truck, (2) BEV, (3) FCEV, and (4) H2-ICE. This comparative view allows for identifying the dominant cost contributors in each technology based on average data extracted from the literature.

missions, making comparisons between trucks with varied purposes less meaningful. To address this, it would be beneficial to categorize vehicle subgroups based on key technical specifications, such as the number of axles, gross vehicle weight (GVW), and whether the truck is rigid or a tractor-trailer. Such an approach would improve the accuracy and relevance of TCO assessments by aligning them with the specific operational roles of each truck configuration. A useful framework for this categorization could be derived from the European Commission's proposal outlined in Regulation [26], specifically in Table I of Annex I, which defines several truck groups based on axle configuration, chassis type, and technically permissible maximum laden mass in tons.

Moving to the choice of FU, there is a lack of consensus regarding the TEA of heavy-duty vehicles in freight transport, as highlighted by our results. Three main FUs emerged from our review: distance-based, truck-based, and transported goods per distance. For truck-based FU, specifying the truck's characteristics (e.g., number of axles, type, mission profile) is crucial for fair comparisons across technologies. However, this FU does not account for potential payload capacity losses of alternative technologies compared to conventional trucks. Additionally, since it does not consider the distance driven, it may result in inconsistencies when comparing results, particularly if the lifetime distance is not disclosed. The distance-based FU similarly falls short in assessing payload loss, as it excludes the amount of transported goods. The FU based on transported goods per distance may offer a more balanced assessment since freight transport is profit-driven but also a social service. It provides a fairer economic comparison by accounting for both distance and goods. However, if fleet operators usually run trucks with lower-than-full payloads, this can mirror the distance-based FU, as the goods volume across technologies would remain similar. Each FU has particular strengths and limitations, and the choice of FU should align with the study's objectives. For example, a distance-based FU may be appropriate for studies focusing on vehicles that are not fully loaded, in line with a specific business model of a fleet operator, while a goods-per-distance FU offers a more comprehensive economic perspective. Overall, the choice of FU highlights the challenges in comparing studies, especially when truck configurations or specific characteristics are undefined.

As reported in Section 3.1.3, vehicle lifetime varies significantly across studies, reflecting the complexity of defining lifetime for heavy-duty vehicles, given the diverse configurations, missions, and tasks they perform.

Vehicle lifetime varies significantly across studies, influenced by the diverse configurations and missions of heavy-duty vehicles. This variability affects comparability, as trucks with higher annual mileage, often operating on highways, experience different wear and costs compared to vehicles used for local deliveries. To address these differences, the European Commission attempted in 2019 to standardize annual mileage values within CO_2 reduction regulations for the heavy-duty sector (Table 4, Annex I [72]). Establishing standard annual mileages by vehicle type and mission could enhance study comparability. Building on this foundation, we could work toward standardizing the annual mileage for each truck group, aligning it with the specific missions they serve for fleet operators. This approach would not only improve comparability but also provide a more accurate basis for assessing the TCO of heavy-duty vehicles across diverse use cases.

4.3. Begin-of-life

The purchase cost, reported in the first panel of Fig. 4, represents aggregated results. Often, these studies refer to trucks of different weights, leading to variability in the size of energy storage systems and powertrain configurations. This illustrates that the purchase cost of alternative technologies remains highly uncertain, as they are not yet widely available on the market, aside from a few models sold globally. Additionally, costs depend heavily on the specific configuration chosen by fleet operators, mission requirements, and the energy storage technology used. For example, some battery chemistries are less expensive than others (e.g., lithium iron phosphate (LFP) batteries are cheaper than nickel manganese cobalt (NMC) batteries [73]). Similarly, fuel cells with higher efficiency tend to be more expensive than those with lower efficiency, and the cost of hydrogen tanks can vary significantly depending on whether they are of Type III, or Type IV [74].

As a major cost component, the purchase cost consistently represents a substantial portion of the TCO for alternative technologies, often exceeding 25%, as reported in Fig. 5. Thus, obtaining realistic estimates is essential for conducting a fair and accurate TCO analysis. Beyond literature review, engaging with OEMs and stakeholders, such as fleet operators, is vital to validate these estimates with empirical data.

Conducting sensitivity analyses on the purchase cost of alternative technology trucks would be beneficial. This approach would account for optimistic and pessimistic scenarios by varying the costs of key subsystems, thereby capturing a broader range of potential purchase costs for these trucks.

4.4. Use phase

Based on average values reported in the literature and shown in Fig. 5, the most impactful cost components during the use phase for the main HDV technologies considered in this study are, in order of magnitude: energy carrier cost, driver cost, maintenance and repair costs, and taxes and other ownership-related expenses.

Energy consumption has a direct impact on the final cost of energy carriers, making it essential to base these estimates on accurate and reliable values. Ideally, this can be achieved through simulations or real-world energy consumption data. When using simulations, they should account for factors such as speed, slope, stops, acceleration, payload, drivetrain characteristics, and specific truck configurations to reflect real-world driving conditions as closely as possible. For European trucks, a way to assess energy consumption can be simulated using specific VECTO cycles tailored to the particular mission the truck is expected to perform. According to the Joint Research Centre (JRC) of the European Commission, fuel consumption measured using VECTO cycles deviated by $\pm 3.5\%$ compared to real-world test results, with a measurement uncertainty exceeding 2% [75]. Due to its strong correlation with real-world performance, VECTO has been recognized as a reliable tool for official vehicle certification. Therefore, it is advisable to use VECTO cycles for simulating the energy consumption of alternative powertrain technologies.

Moving to the energy carrier cost the estimation of these two main energy carriers considered (hydrogen and electricity) is essential, as the operational phase typically has the most significant impact on TCO. Careful consideration of assumptions regarding hydrogen costs at the pump and electricity costs at depots or public fast charging stations is vital to ensure a fair comparison between technologies. Additionally, for BEV, the ratio between the energy recharged at public fast charging and private slow charging stations is influenced by specific configurations, battery sizes, and energy consumption—critical parameters for conducting a comprehensive TEA. Therefore, it is important to clearly disclose these parameters in the study. Furthermore, since there are a lot of uncertainties related to the cost projection of the infrastructure but especially on the raw energy carrier cost (electricity and hydrogen) a sensitivity analysis may be beneficial to display several scenarios and therefore cost trends to give the complete overview of the projected energy cost. It could be beneficial to have a reference scenario but also exploit optimistic and pessimistic scenarios to have a sense of variability of this important cost instead of a single value for future projection since they rely on the assumptions made.

Driver costs are clearly a significant and impactful cost type that cannot be neglected in a comprehensive TCO analysis for heavy-duty vehicles. Given that personnel expenses can constitute a substantial portion of the total ownership costs, it is essential to include them when evaluating different technologies. Neglecting driver costs could lead to an incomplete or misleading economic assessment, as they represent a crucial aspect of fleet operations.

Lastly, the maintenance and the substitution of components have been analyzed. For example, we saw that battery replacement and therefore battery degradation is most of the time neglected in the reviewed studies. Incorporating experimental or simulation data, potentially via empirical models to estimate battery State of Health and determine the precise replacement point, could provide a more accurate and equitable comparison of various technologies.

Also for the FC stack, given the critical role of fuel cells in powering these vehicles, failing to account for their replacement requirements may lead to inaccuracies in cost estimates especially because of the high cost of these systems. Additionally, the lack of TCO models that incorporate fuel cell replacement and aging highlights the need for further research and analysis in this domain. Understanding the factors affecting fuel cell lifespan, the optimal timing for replacement, and the associated costs is essential for informing sustainable fleet management practices and facilitating the broader adoption of fuel cell technology in the heavy-duty vehicle sector.

With regard to the H2-ICE possible replacement or degradation curve of engine efficiency, it could be beneficial to develop an empirical degradation model for engine materials which could aid in better estimating the TCO for this type of technology, even though the cost of this subsystem seems to be not so impactful as referred to in [34] and maybe could be overlooked.

4.5. End-of-life

Residual value is significantly impacted by uncertainties in the second-hand market, particularly for emerging alternative technologies. Current estimates in the literature typically rely on expert assessments, but they often lack a direct link to the remaining life of key components (e.g., battery pack in BEVs and fuel cell stack and H2 tank in FCEVs). A more accurate approach would consider the condition of critical components at the end of the ownership period, such as the battery pack, fuel cell system, and H2-ICE. Estimating the state of health (SOH) of the battery, along with expected performance degradation of the fuel cell and H2-ICE due to aging, may be crucial, as these components experience significant performance loss over time. Factoring in the estimated remaining life of these main components could provide a more precise residual value for trucks with alternative technologies.

4.6. Rationale for a standardized TEA framework: a proposed approach

In Fig. 6, an idea of the rationale for adopting a possible standardized methodology is presented, highlighting the importance of aligning the economic assessments with the specific delivery mission of the fleet operator and the corresponding truck configuration. The proposed methodology is intended to apply to all freight heavy-duty vehicles and across all powertrain technologies. While current EU regulations classify only zero-emission vehicles (ZEVs) as such BEV, FCEV and H2-ICEV, because CO_2 emissions in the transport sector are evaluated solely at the tailpipe, the framework remains fully compatible with other technologies. Hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and conventional vehicles powered by alternative fuels such as advanced biofuels or e-fuels can also be consistently evaluated within this approach. The methodology is therefore deliberately designed to offer broad applicability beyond ZEVs alone.

The foundation of TEA is built on defining the delivery mission, which may involve urban, regional, or long-haul operations. Key inputs to this process include:

- **Truck lifespan** (in kilometers and years): The total distance covered influences cost calculations through discount rates, while the

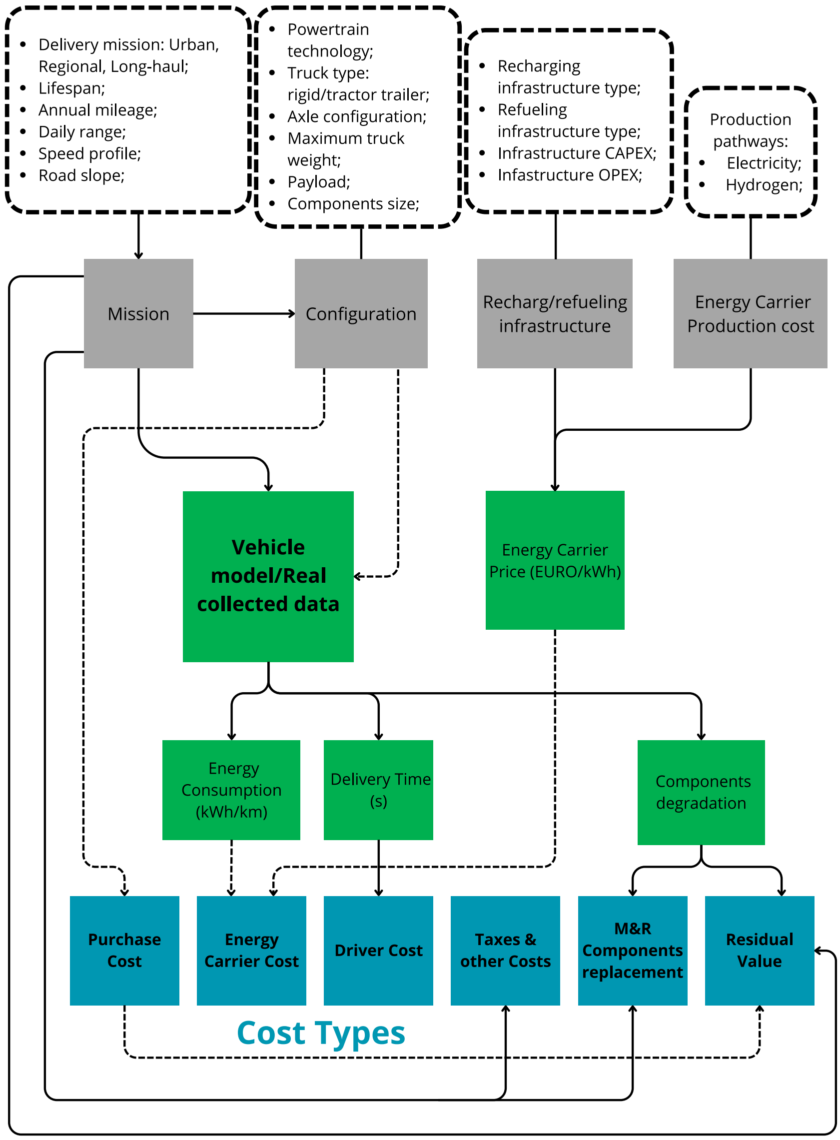

Fig. 6. Framework of a standardized methodology for the techno-economic assessment of freight road transport, incorporating mission profiles, vehicle configurations, infrastructure costs, and energy carrier production pathways to evaluate cost components and overall cost.

operational years affect costs such as taxes, insurance, highway tolls, and residual value.

- **Annual mileage and daily range**: These parameters directly determine the size of critical components such as the battery pack, fuel cell, electric motor, and hydrogen tanks, thereby significantly influencing the purchase cost.
- **Speed profiles and road slopes**: These factors impact energy consumption, and overall vehicle performance. For example, when comparing a ZEV to an ICEV truck, it is important to assess the energy demand based on the specific mission, considering factors such as road slopes, traffic conditions, and the truck's available range. Energy consumption can fluctuate depending on road and speed profiles. Furthermore, it is necessary to evaluate whether the truck will require recharging during the mission due to insufficient range. In such cases, an eco-routing strategy should be developed to take into account the infrastructure availability along the route, accounting for factors like recharging costs, delivery schedules, or both.
- **External operational factors, including traffic conditions and ambient temperature**: Traffic conditions along the route may affect both delivery time and the vehicle's energy consumption for the specific mission. In addition, external factors such as ambient temperature can influence the available range of ZEVs as well as the degradation of key components. For example, temperature is one of the main drivers of battery degradation, as shown in previous research [76].

Following the definition of the mission, attention shifts to the specific truck configuration. As shown in the upper part of Fig. 6, mission characteristics influence the following key truck attributes:

- **Powertrain technology** (e.g., BEV, FCEV).
- **Truck type** (e.g., tractor-trailer, rigid truck).
- **Axle configuration and number of axles**, which determine maximum weight and payload capacity.
- **Component sizing**, adapted to mission demands, which has a direct impact on the purchase cost. This is one of the most critical cost categories in the economic evaluation, as it depends on the size of major components such as the battery pack or fuel cell.

These mission and configuration inputs are essential for estimating energy consumption, delivery time, and component degradation (e.g., battery capacity fade, fuel cell durability). If detailed real-world data is unavailable, a vehicle simulation model tailored to the specific truck and mission should be developed to obtain accurate energy consumption values. This integrated approach enables a mission-specific and robust TEA framework. One possible approach is to follow the rationale adopted in prior works by the authors, which integrate a robust and comprehensive simulation model to assess energy consumption, vehicle range, and a possible recharging strategy [66,77].

In these studies, the simulation model combines a distance-based, backward-facing approach with a detailed driver model. The driver model features a tactical layer that anticipates upcoming stops, enabling proactive braking. It also incorporates acceleration limits influenced by both behavioral and operational factors, including the power and torque constraints of the truck's powertrain components. This model is designed to simulate distance-based operational drive cycles, defined by a time profile of vehicle speed and road grade as functions of traveled distance, and allows for the inclusion of full stops of predetermined duration. It enables the assessment of, among other important parameters, energy consumption, delivery time, and the available range of trucks.

Additionally, the delivery time, as an output of the vehicle simulation model, directly influences the driver cost, a significant cost type discussed in the results section. A previous study [77] comparing DWPT (Dynamic Wireless Power Transfer) and BEV with conventional trucks introduced a cost type called the 'time penalty cost.' This model evaluates the difference in delivery times between a ZEV and a conventional truck throughout the simulation model, factoring in mandatory EU rest stops. It assumes that the fleet operator must deliver the same amount of goods annually, and that the extended delivery time for a ZEV truck impacts the feasibility of the mission compared to a conventional truck. This results in an increased need to purchase a proportionate number of ZEV trucks to compensate for the capacity provided by conventional trucks, as well as hire additional drivers, proportionate to the number of ZEVs in the fleet.

Another crucial output of the vehicle model is the data on component degradation, which allows for more accurate estimation of component replacements, thereby impacting the maintenance and repair costs. Furthermore, linking the residual value of alternative trucks to the remaining life of key components enhances the reliability of residual value estimations. A recent TEA study [78] integrated a battery degradation model with the vehicle simulation framework to account for capacity fade over the truck's operational life. This approach enables the assessment of potential battery replacement needs, increased reliance on public charging infrastructure due to range reduction over time, and provides a method to estimate the battery's residual value based on its remaining capacity and expected lifespan when the truck lifespan is reached.

An additional benefit of integrating a detailed simulation model into the TEA framework is the ability to evaluate multiple component configurations and identify the optimal sizing for a given mission. In practice, numerous combinations of powertrain components can be explored, for example, different H_2-ICE engine sizes paired with various conventional driveline options, multiple hydrogen storage capacities, a range of battery pack sizes for BEVs, or different fuel cell stack sizes for FCEVs. This comprehensive assessment enables the identification of the most cost-effective and mission-appropriate configuration, ensuring not only the selection of the optimal technology but also the right-sizing of components for that technology. Such an approach is highly valuable for fleet operators, who must tailor vehicle specifications to their operational profiles and infrastructure constraints, and for OEMs, who can leverage these insights to propose optimized truck configurations for specific customer missions.

Finally, the simulation model also enables eco-routing, allowing the prediction of when and where a truck must refuel or recharge along a mission. This functionality makes it possible to evaluate alternative routing and infrastructure options, assessing their technical feasibility as well as their economic performance.

Turning to the infrastructure aspect, its impact of recharging/refueling infrastructure on the energy carrier price is also crucial. Fig. 6 illustrates how specific infrastructure types and their associated costs, including operational expenditures (OPEX), should be integrated into the analysis. Developing a cost model that considers both energy carrier production costs and infrastructure requirements ensures a reliable estimation of energy carrier prices for the fleet operator. For example, CAPEX increases with the size of the infrastructure, although not linearly. As shown in a study [79], the cost per kilogram of hydrogen delivered decreases as the size of the Hydrogen Refueling Station (HRS) increases, due to economies of scale. A similar trend is observed for electric recharging points: higher charging power results in higher absolute CAPEX [56]. Therefore, knowing the specific size and typology of the recharging/refueling infrastructure is essential, as it leads to significantly different investment levels for the infrastructure owner.

Furthermore, two main categories of recharging/refueling infrastructure must be distinguished in the cost model: private and public. These differ in their financial expectations and should therefore be modeled using different internal rates of return (IRR). Private infrastructure, typically owned by fleet operators or logistics companies, often targets lower IRRs, reflecting limited profit expectations. In contrast, public infrastructure, generally developed by commercial operators, demands higher IRRs to justify the investment risk. This distinction directly impacts the unit cost of the energy carrier, depending on the infrastructure type utilized, as also highlighted in [77].

Therefore, the TEA model should also account for the proportion of energy carrier consumed during the daily mission, distinguishing whether it belongs to a private or public infrastructure, as well as the size of the infrastructure, since these factors may result in different energy carrier prices. This differentiation further emphasizes the importance of accurately estimating energy consumption, which increases the need for real-world driving data or detailed vehicle simulation outputs. These data are crucial for determining the energy demand and available range for a given mission in a TEA, especially since, as previously discussed, the energy carrier cost is one of the most impactful cost categories in a TEA.

Given the complexity and variability of these factors, it is important to emphasize the need for extensive sensitivity analyses, particularly for key hotspots identified in the assessment. For instance, one key hotspot could be the geographical differences in energy costs, which are influenced by varying production costs across regions. Data from sources like EUROSTAT for electricity [69] and the European Hydrogen Observatory for hydrogen [80] reveal significant variations in energy prices depending on the country. Another critical factor is the cost of drivers, which can vary dramatically between countries. Numerous reports by the Comité National Routier highlight these differences, such as those published for France, Italy, Poland, and Spain [81–84], illustrating how driver costs differ notably between Poland and Germany. By considering a range of values rather than relying on a single estimate, we aim to provide a more nuanced comparison of alternative technologies. This approach ensures a comprehensive and robust evaluation, offering fleet operators and policymakers a clearer understanding of the potential technologies. By exploring a range of values rather than a single estimate, we aim to provide a more nuanced comparison of alternative technologies. This approach ensures a holistic and robust evaluation framework, offering fleet operators and policymakers a comprehensive understanding of the technologies under consideration.

5. Conclusions

This study provides a comprehensive overview of key findings from several studies on the TEA of the freight transport sector. By examining the assumptions underpinning these studies, we gain insights into how they affect final TCO outcomes.

A significant finding is the notable growth in interest in TEAs, as indicated by the rise in related publications over the past three years

(Section 3.1.1). This trend aligns with global efforts to decarbonize transport in accordance with the Paris Agreement. Geographically, most studies focus on Europe, driven by the European Commission's emphasis on full electrification of heavy-duty vehicles through BEV, FCEV, and H2-ICE technologies. The US and other regions are also contributing, illustrating a worldwide commitment to decarbonizing road freight transport.

TCO results vary significantly across studies due to differences in assumptions (Sections 3.2.8 and 4, also depicted in Fig. 4). One critical variable is the truck configuration and its mission profile, as energy consumption fluctuates based on use case (e.g., regional distribution vs. long-haul freight), and payload has a considerable impact on this consumption. These variations highlight the need for more detailed analyses, especially in studies that do not specify mission profiles or truck configurations.

Energy carrier costs, particularly for BEVs and FCEVs, also heavily influence TCO calculations, as highlighted in Fig. 5. Uncertainties surrounding these costs (e.g., electricity for recharging or hydrogen for refueling) play a substantial role in the final results. Many studies estimate hydrogen production costs but overlook additional expenses, such as transportation to refueling stations or markups at the pump (Section 3.2.4). Likewise, electricity cost estimates often omit the infrastructure needed for fast charging at public stations, complicating direct comparisons between vehicle technologies.

Truck purchase costs also vary significantly based on design and mission profile. For example, the cost of a BEV or FCEV truck for a 300 km range differs from one intended for 800 km (Sections 3.2.7 and 3.2.8). Limited mass production further amplifies this variability, significantly impacting final TCO results.

Driver costs are another overlooked yet highly influential factor in TCO analyses (Section 3.2.5). Many studies assume equal driver costs across technologies, overlooking potential differences in delivery times due to range limitations. In fact, depending on infrastructure and vehicle design, BEVs, FCEVs, and H2-ICE trucks may incur higher operational costs or reduced revenue from frequent recharging or refueling stops. Additionally, there may be variations in salaries due to the need for more training or higher risks associated with new technologies, even if there are no published data about it right now. Therefore, a rigorous assessment of driver costs would enable fairer comparisons among technologies.

The residual value of alternative trucks, often estimated due to the underdeveloped second-hand market, impacts TCO. More accurate residual value estimations could be achieved by focusing on the remaining lifespan of key components such as batteries, fuel cells, hydrogen engines, and tanks. This approach would help minimize reliance on assumptions and improve comparability between different technologies.

In summary, the reviewed literature points to several areas that could benefit from further clarity and standardization. These include the need for studies to specify truck configurations and mission profiles rather than generalizing heavy-duty vehicles. Furthermore, key aspects to be addressed are the uncertainties around energy carrier costs, and the variability in purchase and residual values. Addressing these aspects could help to establish a more consistent framework for evaluating advanced trucks, ultimately providing clear insights into their potential for decarbonizing road freight transport.

The outcomes of this study point to a clear path for future research on advanced truck technologies. Key recommendations include:

- **Specify truck configuration**: Clearly define truck configurations based on fleet operator needs, driving range, VECTO group (for Europe), vehicle class (for the US), and payload to determine the final TCO.
- **Purchase cost**: Through the better specification of the truck configuration and the specific fleet operator needs related to the truck operations, the purchase cost may be estimated consider a right-sizing of the main components that lead the purchase cost (e.g., battery pack, fuel cell, hydrogen tank, etc.).
- **Energy carrier cost**: This should be divided into two parts:
  1. *Truck energy consumption*: Collected from real-world scenarios or simulated using reliable models that account for the speed profiles and slope of the specific path chosen (e.g., similar to VECTO software for Europe).
  2. *Energy carrier price*: Consider uncertainties in electricity and hydrogen costs, including infrastructure and markup at the pump/recharging station, while differentiating between private and public infrastructure.
- **Driver cost**: Driver cost should be considered while also accounting for potential variations in delivery time associated with alternative technologies compared to conventional diesel. This includes the impact of recharging or refueling times, which can affect delivery schedules. Additionally, there may be different salaries for drivers operating ZEVs due to the use of new technology vehicles such as risks, recharging/refueling procedures, and the need for more training.
- **Residual value**: The residual value of key components (e.g., batteries, fuel cells, hydrogen engines) should be estimated to reduce assumptions and improve the accuracy of TCO results. This can be achieved by incorporating empirical data, or empirical models to simulate the components over their lifespan on capacity fade and the performance degradation of the main components of alternative technologies.

CRediT authorship contribution statement

Trentalessandro Costantino: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xavier Guichet:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology. **Ezio Spessa:** Writing – review & editing, Validation, Supervision, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was funded by European Union's Horizon research and innovation program under grant number 101096028 (EMPOWER Horizon Europe Research and Innovation Action).

Appendix A. Supplementary data

A table containing the relevant articles and key data, such as region, vehicle type, year of publication, truck lifetime, and powertrain type, can be accessed at the following link:

Supplementary data to this article can be found online at doi:10.1016/j.apenergy.2026.127883.

Data availability

No data was used for the research described in the article.

References

[1] De Schryver AM, Brakkee KW, Goedkoop MJ, Huijbregts MAJ. Characterization factors for global warming in life cycle assessment based on damages to humans and ecosystems. Environ Sci Technol 2009;43(6):1689–95, pMID: 19368158. https://doi.org/10.1021/es800456m

[2] Rocque RJ, Beaudoin C, Ndjaboue R, Cameron L, Poirier-Bergeron L, Poulin-Rheault RA, Fallon C, Tricco AC, Witteman HO. Health effects of climate change: an overview of systematic reviews. BMJ Open 2021. https://doi.org/10.1136/bmjopen-2020-046333

[3] Thomas C, Cameron A, Green R, et al. Extinction risk from climate change. Nature 2024. https://doi.org/10.1038/nature02121
[4] Luyten A, Winkler MS, Ammann P, Dietler D. Health impact studies of climate change adaptation and mitigation measures – a scoping review. The Journal of Climate Change and Health 2023;9:100186. https://doi.org/10.1016/j.joclim.2022.100186. https://www.sciencedirect.com/science/article/pii/S266727822200075X.
[5] IPPC. Climate change 2023: synthesis report. Contribution of working groups i, II and III to the sixth assessment report of the intergovernmental panel on climate change. IPCC 2023. https://doi.org/10.59327/IPCC/AR6-9789291691647
[6] Ritchie H. Cars, planes, trains: where do $co2$ emissions from transport come from? Our World in Data; 2020. https://ourworldindata.org/co2-emissions-from-transport.
[7] IEA. World energy outlook 2023. Tech. rep., IEA; 2023. https://www.iea.org/reports/world-energy-outlook-2023.
[8] IEA. Energy technology perspectives 2020. IEA; 2020. https://www.iea.org/reports/energy-technology-perspectives-2020.
[9] International Transport Forum. Itf transport outlook 2023; 2023. https://doi.org/10.1787/b6cc9ad5-en. https://www.itf-oecd.org/sites/default/files/docs/itf-transport-outlook-2023-launch.pdf [Accessed: 4 07 2025].
[10] IRENA. Decarbonising hard-to-abate sectors with renewables: perspectives for the g7. Tech. rep., International Renewable Energy Agency (IRENA); 2024.
[11] Regulation (EU) 2021/1119 of the european parliament and of the council of 30 June 2021 establishing the framework for achieving climate neutrality and amending regulations (EC) no 401/2009 and (EU) 2018/1999 ('european climate law'). Official Journal, 2021. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1119.
[12] Environmental statement 2022. Publication office of the european union; 2022. https://www.eea.europa.eu/publications/environmental-statement-report-2022.
[13] United Nations Economic Commission for Europe (UNECE), World Forum for Harmonization of Vehicle Regulations (WP.29). Special resolution no. 1 concerning the common definitions of vehicle categories, masses and dimensions (s.r.1), ECE/TRANS/WP.29/1045 (English PDF), adopted 22 June 2005 by the Executive Committee (AC.3) of the 1998 Agreement, 2005. https://unece.org/DAM/trans/doc/2005/wp29/TRANS-WP29-1045e.pdf.
[14] European Parliament and the Council of the European Union. Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 on CO_2 emission performance standards for new heavy-duty vehicles and amending Regulations (EC) No 595/2009 and (EU) 2018/956 and Council Directive 96/53/EC, Official Journal of the European Union, L 198; 2023. p. 202. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02019R1242-20240701 [Accessed 4 2025].
[15] Heavy-duty vehicles: council signs off on stricter co2 emission standards; May 2024. https://www.consilium.europa.eu/en/press/press-releases/2024/05/13/heavy-duty-vehicles-council-signs-off-on-stricter-co2-emission-standards/.
[16] European vehicle market statistics. Pocketbook 2023/24. Tech. rep., International Council on Clean Transportation Europe; 2023. https://theicct.org/wp-content/uploads/2024/01/Pocketbook_202324_Web.pdf.
[17] Ellram L. Total cost of ownership: an analysis approach for purchasing. International Journal of Physical Distribution & Logistics Management 1995;25:4–23. https://doi.org/10.1108/09600039510099928
[18] Ellram LM, Total cost of ownership. In: Hahn D, Kaufmann L, editors. Handbuch industrielles beschaffungsmanagement: internationale konzepte — innovative instrumente — aktuelle praxisbeispiele. Wiesbaden: Gabler Verlag; 2002. p. 659–71. https://doi.org/10.1007/978-3-663-01582-6_34
[19] Parkhi S. Total cost of ownership (TCO); 2014. https://www.researchgate.net/publication/273892848_Total_Cost_of_Ownership_TCO.
[20] Rout C, Li H, Dupont V, Wadud Z. A comparative total cost of ownership analysis of heavy duty on-road and off-road vehicles powered by hydrogen, electricity, and diesel. Heliyon 2022. https://doi.org/10.1016/j.heliyon.2022.e12417
[21] Offer GJ, Howey D, Contestabile M, Clague R, Brandon NP. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy Policy 2010;38(1):24–9. https://doi.org/10.1016/j.enpol.2009.08.040
[22] De Wolf D, Smeers Y. Comparison of battery electric vehicles and fuel cell vehicles. World Electr Veh J 2023;14(9):262, copyright - ©2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/). Notwithstanding the ProQuest Terms and Conditions, you may use this content in accordance with the terms of the License; Ultimo aggiornamento - 2024-11-06; SubjectsTermNotLitGenreText - United States–US; Germany; United Kingdom–UK; China; France; Europe; Economic. https://www.proquest.com/scholarly-journals/comparison-battery-electric-vehicles-fuel-cell/docview/2869647729/se-2.
[23] Burke AF, Zhao J, Fulton LM. Projections of the costs of light-duty battery-electric and fuel cell vehicles (2020–2040) and related economic issues. Res Transp Econ 2024;105:101440. https://doi.org/10.1016/j.retrec.2024.101440. https://www.sciencedirect.com/science/article/pii/S0739885924000350.
[24] Tsakiris A. Analysis of hydrogen fuel cell and battery efficiency world sustainable energy days 2019. Young energy researchers conference; Conference date [27 February 2019] Through [01 March 2019] (2019).
[25] Yanfei L, Shigeru K. Economic competitiveness and environmental implications of hydrogen energy and fuel cell electric vehicles in asean countries: the current and future scenarios. Energy Policy 2021;148:111980. https://doi.org/10.1016/j.enpol.2020.111980. https://www.sciencedirect.com/science/article/pii/S0301421520306911.
[26] Commission regulation (EU) 2017/2400 of 12 December 2017 implementing regulation (EC) no 595/2009 of the european parliament and of the council as regards the determination of the co2 emissions and fuel consumption of heavy-duty vehicles and amending directive 2007/46/EC of the european parliament and of the council and commission regulation (EU) no 582/2011, Official Journal, 2017. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R2400.
[27] Greenhouse gas emissions standards and fuel efficiency standards for medium- and heavy-duty engines and vehicles, Federal Register, 2011. https://www.govinfo.gov/content/pkg/FR-2011-09-15/pdf/2011-20740.pdf.
[28] Basma H, Rodriguez F. A total cost of ownership comparison of truck decarbonization pathways in Europe. Tech. rep., ICCT; 2023. https://theicct.org/publication/total-cost-ownership-trucks-europe-nov23/.
[29] Alonso-Villar A, Davíðsdóttir B, Stefánsson H, Ásgeirsson EI, Kristjánsson R. Technical, economic, and environmental feasibility of alternative fuel heavy-duty vehicles in Iceland. J Clean Prod 2022;369:133249. https://doi.org/10.1016/j.jclepro.2022.133249. https://www.sciencedirect.com/science/article/pii/S0959652622028360.
[30] Huin X, Di Loreto M, Bideaux E, Benzaoui H. Total cost of ownership optimization of a plug-in hybrid electric truck operating on a regional haul cycle. Ifac-pap 2021;54(10):284–9, 6th IFAC Conference on Engine Powertrain Control, Simulation and Modeling E-COSM 2021. doi:https://doi.org/10.1016/j.ifacol.2021.10.177. https://www.sciencedirect.com/science/article/pii/S2405896321015792.
[31] Noll B, del Val S, Schmidt TS, Steffen B. Analyzing the competitiveness of low-carbon drive-technologies in road-freight: a total cost of ownership analysis in Europe. Appl Energy 2022;306:118079. https://doi.org/10.1016/j.apenergy.2021.118079. https://www.sciencedirect.com/science/article/pii/S0306261921013659.
[32] Zhang X, Lin Z, Crawford C, Li S. Techno-economic comparison of electrification for heavy-duty trucks in China by 2040. Transp Res D Transp Environ 2022;102:103152. https://doi.org/10.1016/j.trd.2021.103152. https://www.sciencedirect.com/science/article/pii/S1361920921004478.
[33] Ravigné E, Da Costa P. Economic and environmental performances of natural gas for heavy trucks: a case study on the French automotive industry supply chain. Energy Policy 2021;149:112019. https://doi.org/10.1016/j.enpol.2020.112019. https://www.sciencedirect.com/science/article/pii/S0301421520307308.
[34] Magnino A, Marocco P, Saarikoski A, Ihonen J, Rautanen M, Gandiglio M. Total cost of ownership analysis for hydrogen and battery powertrains: a comparative study in Finnish heavy-duty transport. J Energy Storage 2024;99:113215. https://doi.org/10.1016/j.est.2024.113215. https://www.sciencedirect.com/science/article/pii/S2352152X24028019.
[35] Yuntian Z, Hui H. China's efforts to decarbonize road transport: decent, but not sufficient. The International Council of Clean Transportation Blog; 2022. https://theicct.org/china-ev-efforts-mar22/.
[36] Environmental Protection Agency. Greenhouse gas emissions standards for heavy-duty vehicles—phase 3. In: Federal register, rules and regulations; 2024. https://www.govinfo.gov/content/pkg/FR-2024-04-22/pdf/2024-06809.pdf.
[37] Xu F, Crawford C, Feng Y, Lin Z, Li S. Environment-economic analysis of diesel, hybrid electric, plug-in hybrid electric trucks in China. Transp Res D Transp Environ 2023;117:103661. https://doi.org/10.1016/j.trd.2023.103661. https://www.sciencedirect.com/science/article/pii/S1361920923000585.
[38] Burke S. Technology, sustainability, and marketing of battery electric and hydrogen fuel cellmedium-duty and heavy-dutytrucks and buses in 2020-2040. Tech. rep., National Centre for Sustainable Transportation; 2020.
[39] Burke AF, Zhao J, Miller MR, Sinha A, Fulton LM. Projections of the costs of medium- and heavy-duty battery-electric and fuel cell vehicles (2020-2040) and related economic issues. Energy Sustain Dev 2023;77:101343. https://doi.org/10.1016/j.esd.2023.101343. https://www.sciencedirect.com/science/article/pii/S0973082623002004.
[40] Burnham A, Gohlke D, Rush L, Stephens T, Zhou Y, Delucchi MA, Birky A, Hunter C, Lin Z, Ou S, Xie F, Proctor C, Wiryadinata S, Liu N, Boloor M. Comprehensive total cost of ownership quantification for vehicles with different size classes and powertrains. Tech. Rep. ANL/ESD-21/4, Argonne National Lab. (ANL), Argonne, IL (United States); Apr 2021. https://doi.org/10.2172/1780970. https://www.osti.gov/biblio/1780970.
[41] Earl T, Mathieu L, Cornelis S, Kenny S, Ambel CC, Nix JC. Analysis of long haul battery electric trucks in EU marketplace and technology, economic, environmental, and policy perspectives. 8th Commercial Vehicle Workshop 2018:22. https://api.semanticscholar.org/CorpusID:195801767.
[42] Gunawan TA, Monaghan RFD. Techno-econo-environmental comparisons of zero- and low-emission heavy-duty trucks. Appl Energy 2022;308:118327. https://doi.org/10.1016/j.apenergy.2021.118327. https://www.sciencedirect.com/science/article/pii/S0306261921015816.
[43] Vijayagopal R, Rousseau A. Electric truck economic feasibility analysis. World Electr Veh J 2021;12(2). https://doi.org/10.3390/wevj12020075. https://www.mdpi.com/2032-6653/12/2/75.
[44] Sacchi R, Bauer C, Cox BL. Does size matter? The influence of size, load factor, range autonomy, and application type on the life cycle assessment of current and future medium- and heavy-duty vehicles. Environ Sci Technol 2021;55(8):5224–35, pMID: 33735568. https://doi.org/10.1021/acs.est.0c07773
[45] Hanesch S, Schöpp F, Göllner-Völker L, Schebek L. Life cycle assessment of an emerging overhead line hybrid truck in short-haul pilot operation. J Clean Prod 2022;338:130600. https://doi.org/10.1016/j.jclepro.2022.130600. https://www.sciencedirect.com/science/article/pii/S0959652622002414.

[46] van den Oever AEM, Costa D, Messagie M. Prospective life cycle assessment of alternatively fueled heavy-duty trucks. Appl Energy 2023;336:120834. https://doi.org/10.1016/j.apenergy.2023.120834. https://www.sciencedirect.com/science/article/pii/S0306261923001988.

[47] Basma R. Fuel cell electric tractor-trailers: technology overview and fuel economy. Tech. rep., ICCT; 2022. https://theicct.org/wp-content/uploads/2022/07/fuel-cell-tractor-trailer-tech-fuel-1-jul22.pdf.

[48] Delgado OF, Rodriguez F, Muncrief R. Fuel efficiency technology in european heavy-duty vehicles: baseline and potential for the 2020–2030 time frame. Tech. rep., ICCT; 2017.

[49] Dunn J, Kendall A, Slattery M. Electric vehicle lithium-ion battery recycled content standards for the us – targets, costs, and environmental impacts. Resour Conserv Recycl 2022;185:106488. https://doi.org/10.1016/j.resconrec.2022.106488. https://www.sciencedirect.com/science/article/pii/S0921344922003317.

[50] Liu N, Xie F, Lin Z. Evaluating national hydrogen refueling infrastructure requirement and economic competitiveness of fuel cell electric long-haul trucks. Mitig Adapt Strateg Glob Change 2020.

[51] Estrada Poggio A, Balest J, Zubaryeva A, Sparber W. Monitored data and social perceptions analysis of battery electric and hydrogen fuelled buses in urban and suburban areas. J Energy Storage 2023;72:108411. https://doi.org/10.1016/j.est.2023.108411. https://www.sciencedirect.com/science/article/pii/S2352152X2301808X.

[52] Schloter L. Empirical analysis of the depreciation of electric vehicles compared to gasoline vehicles. Transp Policy 2022;126:268–79. https://doi.org/10.1016/j.tranpol.2022.07.021. https://www.sciencedirect.com/science/article/pii/S0967070X22002074.

[53] Schneider J, Teichert O, Zähringer M, Balke G, Lienkamp M. The novel megawatt charging system standard: impact on battery size and cell requirements for battery-electric long-haul trucks. eTransportation 2023;17:100253. https://doi.org/10.1016/j.etran.2023.100253. https://www.sciencedirect.com/science/article/pii/S2590116823000280.

[54] Sharpe B, Basma B. A meta-study of purchase costs for zero-emission trucks. Tech. rep., ICCT; 2022. https://theicct.org/publication/purchase-cost-ze-trucks-feb22.

[55] Kuhn. E-Truck virtual teardown study; Jun 2021. https://theicct.org/wp-content/uploads/2022/01/Final-Report-eTruck-Virtual-Teardown-Public-Version.pdf.

[56] Basma H. Total cost of ownership for tractor-trailers in europe: battery electric versus diesel. Tech. rep., ICCT; 2019. https://theicct.org/publication/total-cost-of-ownership-for-tractor-trailers-in-europe-battery-electric-versus-diesel/.

[57] Basma H, Zhou Y, Rodriguez F. Fuel-cell hydrogen long-haul trucks in europe: a total cost of ownership analysis. Tech. rep., ICCT; 2022. https://theicct.org/wp-content/uploads/2022/09/eu-hvs-fuels-evs-fuel-cell-hdvs-europe-sep22.pdf.

[58] Burke A, Miller M, Sinha A, Fulton L. Evaluation of the economics of Battery-Electric and fuel cell trucks and buses: methods, issues, and results. Aug 2022. https://escholarship.org/uc/item/1g89p8dn.

[59] Mareev I, Becker J, Sauer DU. Battery dimensioning and life cycle costs analysis for a heavy-duty truck considering the requirements of long-haul transportation. Energies 2018;11(1). https://doi.org/10.3390/en11010055. https://www.mdpi.com/1996-1073/11/1/55.

[60] Proposal for a regulation of the european parliament and of the council on type-approval of motor vehicles and engines and of systems, components and separate technical units intended for such vehicles, with respect to their emissions and battery durability (EURO 7) and repealing regulations (EC) no 715/2007 and (EC) no 595/2009, Official Journal, 2022. https://eur-lex.europa.eu/resource.html?uri=cellar:9a25dc0b-60db-11ed-92ed-01aa75ed71a1.0001.02/DOC_1&format=PDF.

[61] Lyu Z, Pons D, Zhang Y. Emissions and total cost of ownership for diesel and battery electric freight pickup and delivery trucks in new zealand: implications for transition. Sustainability 2023;15(10). https://doi.org/10.3390/su15107902. https://www.mdpi.com/2071-1050/15/10/7902.

[62] UNECE. Unece to develop battery durability requirements for electric heavy-duty vehicles. Tech. rep., UNECE; 2023. https://unece.org/sustainable-development/press/unece-develop-battery-durability-requirements-electric-heavy-duty.

[63] ICF. Comparison of medium and heavy duty technologies in California. Tech. rep., ICF; 2019. https://caletc.com/wp-content/uploads/2024/04/ICF-Truck-Report_Final_December-2019.pdf.

[64] Hunter C, Penev M, Reznicek E, Lustbader J, Birky A, Zhang C. Spatial and temporal analysis of the total cost of ownership for class 8 tractors and class 4 parcel delivery trucks. Sep 2021. https://doi.org/10.2172/1821615. https://www.osti.gov/biblio/1821615.

[65] Hall D, Lutsey N. Estimating the infrastructure needs and costs for the launch of zero-emission trucks. Tech. rep., ICCT; 2019. https://theicct.org/wp-content/uploads/2021/06/ICCT_EV_HDVs_Infrastructure_20190809.pdf.

[66] Costantino T, Miretti F, Spessa E. Improving the feasibility of electrified heavy-duty truck fleets with dynamic wireless power transfer; 2023. https://doi.org/10.4271/2023-24-0161

[67] European Commission, D.-G. for Mobility, Transport, Essen H, Fiorello D, El Beyrouty K, Bieler C, Wijngaarden L, Schroten A, Parolin R, Brambilla M, Sutter D, Maffii S, Fermi F. Handbook on the external costs of transport – version 2019 – 1.1. Publications Office; 2020. https://doi.org/10.2832/51388

[68] Burnham A. Afleet: assess the impacts of conventional and alternative fuel vehicles; Jan 2021. https://www.osti.gov/biblio/1813438.

[69] Eurostat. Electricity prices for non-household consumers - bi-annual data (from 2007 onwards). https://ec.europa.eu/eurostat/databrowser/product/page/nrg_pc_205.

[70] Tanco M, Cat L, Garat S. A break-even analysis for battery electric trucks in latin america. J Clean Prod 2019;228:1354–67. https://doi.org/10.1016/j.jclepro.2019.04.168. https://www.sciencedirect.com/science/article/pii/S0959652619312478.

[71] Alessia M, Sathvika A, Pierre-Louis R, Felipe R. Race to zero: european heavy duty vehicle market development quarterly (january – march 2024). Tech. rep., ICCT; 2024. https://theicct.org/publication/race-to-zero-eu-hdv-market-development-q1-2024-june24/.

[72] Regulation (EU) 2019/1242 of the european parliament and of the council of 20 June 2019 setting co2 emission performance standards for new heavy-duty vehicles and amending regulations (EC) no 595/2009 and (EU) 2018/956 of the european parliament and of the council and council directive 96/53/EC, Official Journal, 2019. https://eur-lex.europa.eu/eli/reg/2019/1242.

[73] IEA. Global EV outlook 2024. Tech. rep., International Energy Agency; 2024. https://www.iea.org/reports/global-ev-outlook-2024.

[74] Cheng Q, Zhang R, Shi Z, Lin J. Review of common hydrogen storage tanks and current manufacturing methods for aluminium alloy tank liners. International Journal of Lightweight Materials and Manufacture 2024;7(2):269–84. https://doi.org/10.1016/j.ijlmm.2023.08.002. https://www.sciencedirect.com/science/article/pii/S2588840423000434.

[75] Fontaras G, Grigoratos T, Savvidis D, Anagnostopoulos K, Luz R, Rexeis M, Hausberger S. An experimental evaluation of the methodology proposed for the monitoring and certification of co2 emissions from heavy-duty vehicles in Europe. Energy 2016. https://doi.org/10.1016/j.energy.2016.02.076

[76] Petit M, Prada E, Sauvant-Moynot V. Development of an empirical aging model for li-ion batteries and application to assess the impact of vehicle-to-grid strategies on battery lifetime. Appl Energy 2016;172:398–407. https://doi.org/10.1016/j.apenergy.2016.03.119

[77] Costantino T, Miretti F, Spessa E. Assessing the viability of dynamic wireless power transfer in long-haul freight transport: a techno-economic analysis from fleet operators' standpoint. Appl Energy 2025;379:124839. https://doi.org/10.1016/j.apenergy.2024.124839. https://www.sciencedirect.com/science/article/pii/S0306261924022220.

[78] Costantino T, Acquarone M, Miretti F, Spessa E. Comprehensive techno-economic analysis of battery-electric trucks: evaluating battery aging impact for regional delivery missions. In: WCX SAE world congress experience. Detroit, Michigan, USA: SAE International; 2025. p. 11, paper No. 2025-01-8591. https://doi.org/10.4271/2025-01-8591

[79] Apostolou D, Xydis G. A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. Renew Sustain Energy Rev 2019;113:109292. https://doi.org/10.1016/j.rser.2019.109292. https://www.sciencedirect.com/science/article/pii/S1364032119305003.

[80] European Hydrogen Observatory. Cost of hydrogen production; 2024. https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/production-trade-and-cost/cost-hydrogen-production [Accessed 8 April 2025].

[81] Comité national routier. Enquête longue distance. Tech. rep., Comité National Routier; 2022. https://www.cnr.fr/enquete-cnr-longue-distance-2022.

[82] Comité national routier. The Italian road freight transport sector. Tech. rep., Comité National Routier; 2021. https://www.cnr.fr/en/italian-road-freight-transport-sector-2021.

[83] Comité national routier. The Polish road freight transport sector. Tech. rep., Comité National Routier; 2019. https://www.cnr.fr/en/polish-road-freight-transport-sector-2019.

[84] Comité national routier. The spanish road freight transport sector. Tech. rep., Comité National Routier; 2020. https://www.cnr.fr/en/spanish-road-freight-transport-sector-2020.