energies

MDPI

Review

The Economic Feasibility of Battery Electric Trucks: A Review of the Total Cost of Ownership Estimates

Romeo Danielis [1,2,*], Arsalan Muhammad Khan Niazi [1], Mariangela Scorrano [1,2], Manuela Masutti [1,3] and Asees Muhammad Awan [1]

[1] Department of Economics, Business, Mathematics and Statistics, University of Trieste, 34127 Trieste, Italy; muhammadarsalankhan.niazi@phd.units.it (A.M.K.N.); mscorrano@units.it (M.S.); manuela.masutti@areasciencepark.it (M.M.); muhammadasees.awan@phd.units.it (A.M.A.)
[2] Interdepartmental Center "Giacomo Ciamician" for Energy, Environment, Transport, University of Trieste, 34127 Trieste, Italy
[3] Area Science Park, 34149 Trieste, Italy
* Correspondence: romeo.danielis@deams.units.it; Tel.: +39-0405587076

Abstract: This paper reviews the existing studies employing total cost of ownership (TCO) analysis to evaluate the comparative economic viability of battery electric trucks (BETs) and diesel trucks (DTs). A key finding is that until recent years, BETs have not been cost-competitive with DTs. Light-duty trucks and medium-duty trucks started to become competitive in 2021 (1) according to some estimates, whereas heavy-duty trucks might remain to be not competitive even in future decades. However, (2) TCO estimates differ across continents. (3) The combing effect of fuel prices and taxes is most likely responsible for the fact that BETs enjoy a stronger competitive position relative to DTs in Europe, Asia, and Oceania, whereas, in North America, most estimates assign them poor competitiveness, both presently and in the coming years. (4) Most studies underline that significant cost disproportions persist in the heavy-duty truck segment due to its demanding operational requirements and a lack of robust high-powered charging infrastructure. Consequently, substantial financial incentives and subsidies will be required for heavy-duty trucks to enhance their economic viability, potentially accelerating cost parity from post-2035 to the near future. This paper identifies several constraints in its TCO analysis, including limited data on residual values, variability in discount rates, depreciation costs, and a lack of longitudinal and market data for BETs.

Keywords: total cost of ownership; battery electric trucks; diesel-powered trucks; heavy-duty transportation; economic feasibility

check for updates

Academic Editor: Seung-Hoon Yoo

Received: 26 December 2024
Revised: 13 January 2025
Accepted: 17 January 2025
Published: 19 January 2025

Citation: Danielis, R.; Niazi, A.M.K.; Scorrano, M.; Masutti, M.; Awan, A.M. The Economic Feasibility of Battery Electric Trucks: A Review of the Total Cost of Ownership Estimates. *Energies* **2025**, *18*, 429. https://doi.org/10.3390/en18020429

1. Introduction

This paper provides a comprehensive examination of the economic feasibility of battery electric trucks (BETs), employing diesel trucks (DTs) as the baseline scenario. The analysis is grounded in an extensive review of economic and technical scholarly literature, as well as industrial reports, with a particular focus on total cost of ownership (TCO). The TCO methodology caters not only as an evaluative economic tool for academic research on technological competitiveness but also as a critical decision-making framework for fleet operators. Fleet operators prioritize resource optimization, cost minimization, and reductions in the environmental impact of their operations.

Typically, TCO analysis is broadly categorized into three major costs: capital costs (CAPEX), operational costs (OPEX), and residual value. CAPEX typically represents the fixed cost that is paid at the time of acquisition for the truck and the charging infrastructure. Globally, the majority of green and sustainable technologies are subject to several subsidies in terms of value-added tax (VAT), registration fee, and sales tax, which are regional sensitive and are decided autonomously. Such regional sensitivity posed a constraint for the appropriate estimation of TCO for BET and DT. CAPEX is mainly subdivided into some cost components such as the glider cost, battery cost, registration fees, and sales tax [1]. Another key determinant of TCO analysis is the operational expenses (OPEX) that are incurred cumulatively over the use life of a truck. The OPEX of trucks includes cost components such as fuel, maintenance, tolls, insurance premiums. Despite the higher CAPEX of BETs, their OPEX is estimated to be considerably lower than their conventional counterparts. Lastly, TCO analysis also considers the residual value of the vehicle, that is the revenue that can be generated from the resale of the truck. For a more formal and detailed presentation of the TCO methodology, we refer the reader to our previous papers on the topic [1,2].

Numerous studies have unwaveringly utilized the TCO estimation methodology for commercial vehicles. We selected, reviewed, and compared 25 distinct studies. The papers were selected on the basis of two main criteria: (a) reporting a TCO estimate of BETs and DTs (either in graphical or quantitative form) and (b) providing sufficient details on the assumptions made to obtain the estimate. Table 1 lists the studies considered in this paper, categorized by author, country, year of estimate, and type of truck. Due to the paucity of rigorously quantified datasets, gray literature emerged as a particularly valuable resource for deriving monetary values. From these studies, a total of 195 distinct TCO estimates were extracted.

This paper illustrates and discusses, in Section 2, the data assumptions made by the authors to estimate the TCO of BETs and DTs, both concerning the current and the future years of estimate. This section allows the reader to understand the uncertainty and the complexity involved in the application of the TCO methodology. Section 3 presents a comparative analysis of the results obtained in the selected papers. Finally, Section 4 discusses the results, highlighting the topics and issues on which more research is needed.

This paper aims to contribute to the literature, firstly, by providing an updated review and comparison of the TCO studies comparing BETs and DTs. To the best of our knowledge, no such review has been published in recent years. Such a comparison is highly needed to inform private and public decision-makers in view of the challenges lying ahead and of the rapid technological change that is taking place in the BET ecosystem. Secondly, this paper provides a detailed comparison of truck types, mission profiles, and countries. Such a comparison allows the reader to better grasp which truck market segments are likely to be more prone to electrification in the coming years and which obstacles lay ahead in the most difficult segments. The quantification of the TCO gaps between BETs and DTs might allow policymakers to calibrate their decisions and develop effective policy instruments. Last but not least, this paper indicates the topics and issues not sufficiently clarified in the existing literature in order to develop more improved and more useful applications of the TCO methodology.

Table 1. List of Selected TCO Studies.

Author		**Country**	**Years of Estimate**	**Truck Description**	**Truck Classification**
den Boer et al. (2013)	[3]	EU	2012, 2020, 2030	Distribution trucks: GVW 7.5–16 tonne. Long-haul trucks: GVW 30–40 tonne.	LDT
Lee et al. (2013)	[4]	USA	2011	Urban distribution trucks, class 4−6 (6350−11,800 kg).	LDT
Zhou (2017)	[5]	Canada	2016	Class 6 medium trucks, emergency, delivery, and dump trucks.	MDT
Kampker et al. (2018)	[6]	Germany	2020	18 tonne with long-haul application.	HDT
Yang et al. (2018)	[7]	China	2017	Urban application.	MDTs, LDT
Lebeau et al. (2019)	[8]	Brussels, Belgium	2019	Urban with delivery specifically last-mile delivery application.	LDT
Hovi et al. (2019)	[9]	Norway	2019	Distribution trucks. Light distribution trucks, heavy distribution trucks, tractors for semitrailers, waste collection vehicles, special trucks (e.g., recycling trucks).	LDT, HDT
Tanco et al. (2019)	[10]	Latin America	2019	With urban (100 km), regional (200 km), and long-haul (500 km) application.	MDT
Moll et al. (2020)	[11]	Germany	2018	Straight truck (max. GVW 18 tonne), straight truck (max. GVW 26 tonne), semi-trailer truck, straight truck with full trailer, urban application.	HDT
Alonso-Villar et al. (2022)	[12]	Iceland	2022	Delivery trucks: (GVW) 3.5–12 tonne. Regional trucks: (GVW) 12–40 tonne.	HDT
Gray et al. (2022)	[13]	Ireland	2025, 2030, 2040	Regional (GVW 40,000 kg).	HDT
Gunawan and Monaghan (2022)	[14]	Ireland	2030	Long haul, 32 tonne.	HDT
Hao et al. (2022)	[15]	China	2022	Heavy-duty trucks, mid-duty, light-duty, mini-duty trucks, and special purpose vehicles (e.g., dump trucks, specialized transporters), long, urban, and regional haul.	LDT, HDT, MDT
Noll et al. (2022)	[16]	EU (7 countries)	2021	Urban, regional, and long-haul application.	LDT, MDT, HDT
Rout et al. (2022)	[17]	UK	2021, 2050	Long-haul application, tripper trucks, waste collection trucks, forklift, and bus.	MDT

Table 1. *Cont.*

Author		**Country**	**Years of Estimate**	**Truck Description**	**Truck Classification**
Zhang et al. (2022)	[18]	China	2022	Long-haul application.	HDT
Basma and Rodríguez (2023)	[19]	EU	2030, 2040	Long-haul tractor-trailers (500, 800, 1000 km), regional heavy-duty trucks, medium-duty urban trucks, light-duty urban trucks.	HDT, MDT, LDT
Burke et al. (2023)	[20]	United States	2020, 2025, 2030, 2035, 2040	HDT—long-haul trucks, MDT—delivery trucks, HDT—short-haul trucks.	HDT, MDT, LDT
Lyu et al. (2023)	[21]	New Zealand	2022	Freight, pickup, and delivery trucks, urban application	LDT
Hu et al. (2024)	[22]	China	2023	Long haul, 49 tonne.	HDT
Jahangir Samet et al. (2024)	[23]	Finland	2025, 2035	MDT—4.5–11.7 tonne, HDT—>11.7 tonne.	HDT, MDT
Ledna et al. (2024)	[24]	USA	2025, 2035	MDT—GVW 18 metric tons. HDT—GVW: 44 metric tons. Regional and long-haul application.	HDT, MDT
Patil et al. (2024)	[25]	India	2025	Class 5 and Class 8 trucks with regional and long-haul application.	HDT, MDT
Rajagopal et al. (2024)	[26]	India	2022	7.5- tonne, 12- tonne, 25- tonne, regional and long-haul application 40- tonne trucks.	HDT
Wang et al. (2024)	[27]	UK	2023	MDT—(GVW): 18 metric tons. HDT—(GVW): 44 metric tons.	HDT, MDT

Legend: light-duty truck (LDT), medium-duty truck (MDT), and heavy-duty truck (HDT).

2. Data Assumptions

It is of paramount importance to indicate that TCO analysis substantially relies on underlying data assumptions, underscoring the critical need for a thorough understanding of the data quality and its source. This is exactly the purpose of this section.

Our initial step has been to categorize the selected papers listed in Table 1 into three groupings: light-duty trucks (LDTs), medium-duty trucks (MDTs), and heavy-duty trucks (HDTs) based on gross vehicle weight (GVW), and distance traveled, as depicted in Table 2.

Table 2. Definition of the three groupings: LDT, MDT, and HDT.

Truck Type	**GVW**	**Application**	**Daily Distance**
LDTs	<3.5 tonne	Urban	100–150 km
MDTs	3.5–12 tonne	Regional	150–200 km
HDTs	>12–44 tonne	Long-Haul	>400 km

Next, we illustrated the data assumptions and the issues regarding the cost of vehicle battery and acquisition, fuel, maintenance, fuel efficiency, insurance, taxes and incentives, infrastructure, and residual value.

2.1. Vehicle Acquisition Cost

Acquisition cost refers to the cost incurred for purchasing the truck. It does not account for the registration, value-added taxes and subsidies, or any other cost premiums associated with the purchase. Despite the beta stage existence of commercial BET in markets, the prevailing literature relies on a bottom-up approach for CAPEX estimation [16,20,27]. Such an approach offers the advantage that a plethora of estimates can be generated for varying classes of trucks and specific cost drivers for each component can be identified for the targeted cost reduction. Few authors have adopted a more case-specific approach, focusing on existing vehicle models for TCO comparisons. This latter method enhances the realism of the TCO estimates but limits the generalizability of the findings by narrowing the scope of analysis and potentially overlooking broader cost trends [6,9,17].

Figure 1 illustrates the cost assumptions presented in the reviewed papers with reference to the three different truck types for various current and future years. The figure illustrates separately the ratios of the three groupings of truck types, LDTs, MDTs, and HDTs, in a number of years. Under the year, we report the number of available estimates for that year irrespective of the country. This is the reason why we term the ratio "Average ratio of Acquisition Cost BET/DT". The following figures are similarly organized.

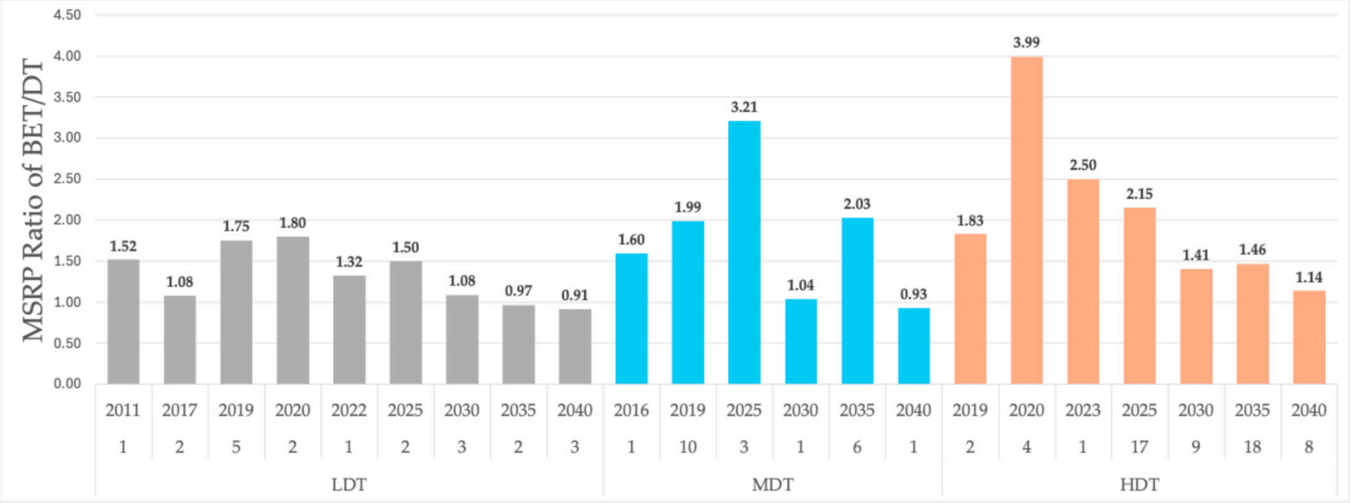

Figure 1. Ratio of the acquisition cost of BETs and DTs by year, number of estimates, and truck type.

It can be noted that BETs exhibit higher acquisition costs compared with DTs. In the past recent years, LDTs have been estimated to cost 8% to 80% more, MDTs 60% to 321% more, and HDTs from 83% to almost four times as much [26]. Relatively higher CAPEX for BETs compared with DTs is consistently observed across all regions, including China, the USA, Europe, and India. However, the prevailing literature suggests that CAPEX cost parity for BETs and DTs could be achieved by 2030 for LDTs and MDTs, with the acquisition cost differential for HDTs expected to narrow to only 14% by the early 2040s. This downward trend is strongly attributed to declining battery costs, government subsidies, and the realization of economies of scale [20,27].

2.2. Battery Cost

The acquisition cost of BETs is widely dictated by battery cost, which also presents a formidable impediment to their mass-market penetration (Figure 2). In the HDT, long-haul-BET segment, battery expenses might constitute a staggering 63% of total vehicle costs [6]. For instance, a single 1200 kWh battery required for a long-haul HDT traveling 600 km per day could incur as much as EUR 400,000, representing a substantial component of BET CAPEX.

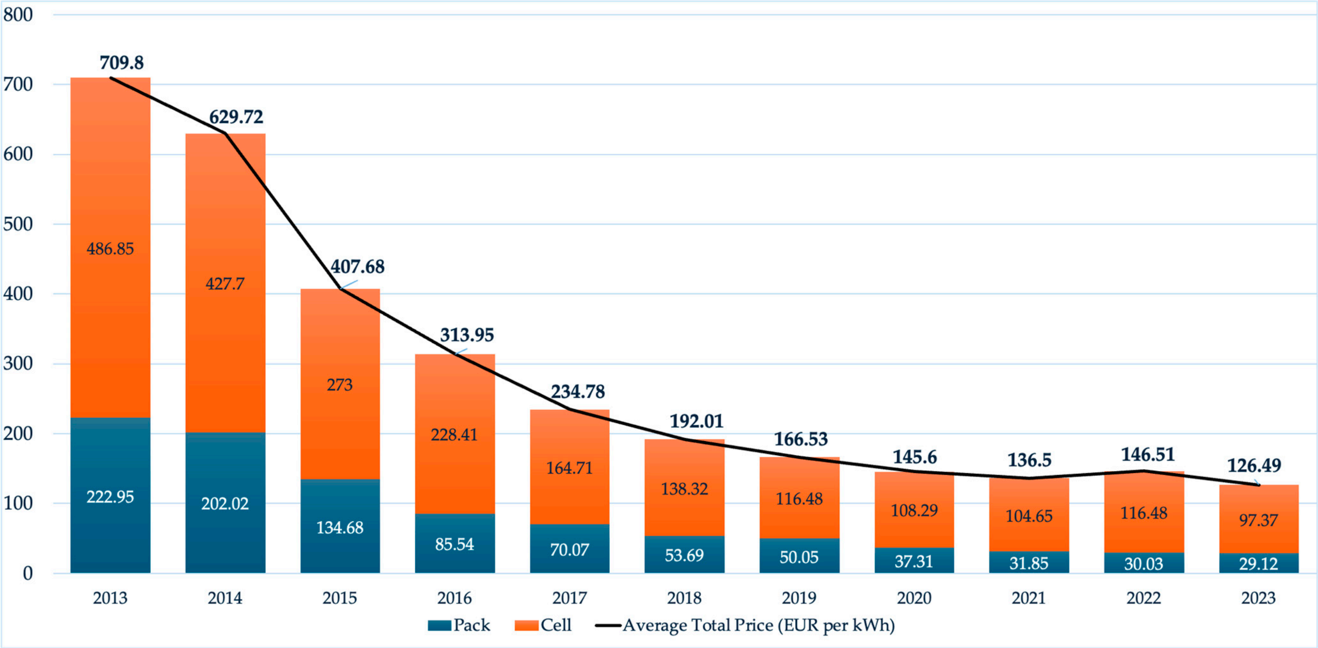

Figure 2. International battery stack cost EUR/kW.

The reviewed studies make different assumptions concerning battery costs in different countries, ranging from 100 to 496 (Figure 3). Despite these challenges, the prevailing literature remains optimistic about the downward trajectory of lithium-ion batteries driven by technological advancement and economies of scale. Ref. [10] believe that in 2030 battery cost will be below the 100 EUR/kWh threshold. These downward trends promise to bolster the economic feasibility of BETs across various vehicle classes [5,11,25]. Notably, Refs. [8,15,19] provide a nuanced TCO analysis that incorporates the residual value of batteries (deemed an essential factor by fleet owners), highlighting its potential influence on BET-TCO specifically for LDT-BETs. Most researchers overlooked this factor in TCO estimations, assuming that the vehicle's lifespan aligns with the anticipated life of the battery to circumvent the higher costs associated with battery replacement and maintenance [4]. However, efficiency varies significantly with conditions such as speed, braking, and acceleration patterns. BETs excel in urban settings where frequent stops and slower speeds due to their regenerative braking capability, while DTs are more efficient on long-haul routes with minimal braking events and stable speeds [10].

2.3. Fuel Cost

Fuel cost represents a critical determinant of OPEX, profoundly influencing the economic feasibility of various technological alternatives. In this comparative analysis, two primary energy types are considered: diesel and electricity. The economic landscape of fuel is notably region-sensitive (Figure 4). In fact, diesel fuel costs depicted high regional variability: ranging from as low as 0.83 EUR/L in Asia and 1.46 EUR/L in Oceania, followed by 1.69 EUR/L in the EU and 0.90 EUR/L in North America. In contrast, electricity prices remain relatively consistent across evaluated regions, fluctuating within a narrower band of 0.10 EUR/kWh in Oceania to 0.15 EUR/kWh in North America.

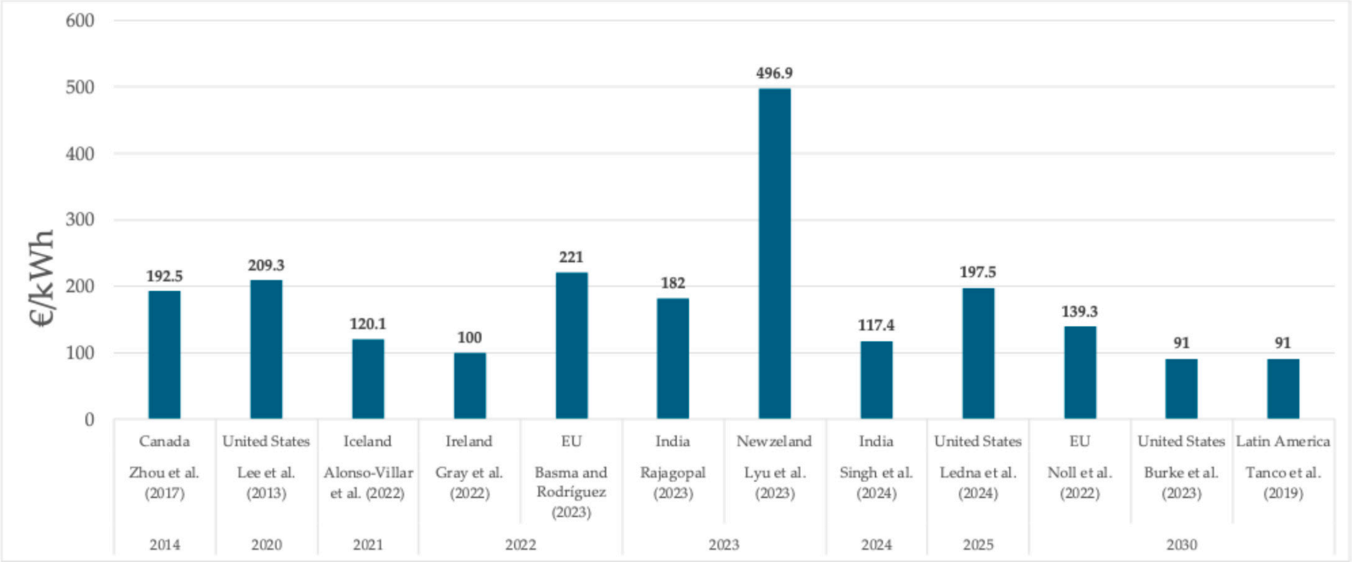

Figure 3. Battery costs by country, author, and year [4,5,10,12,13,16,19–21,24–26].

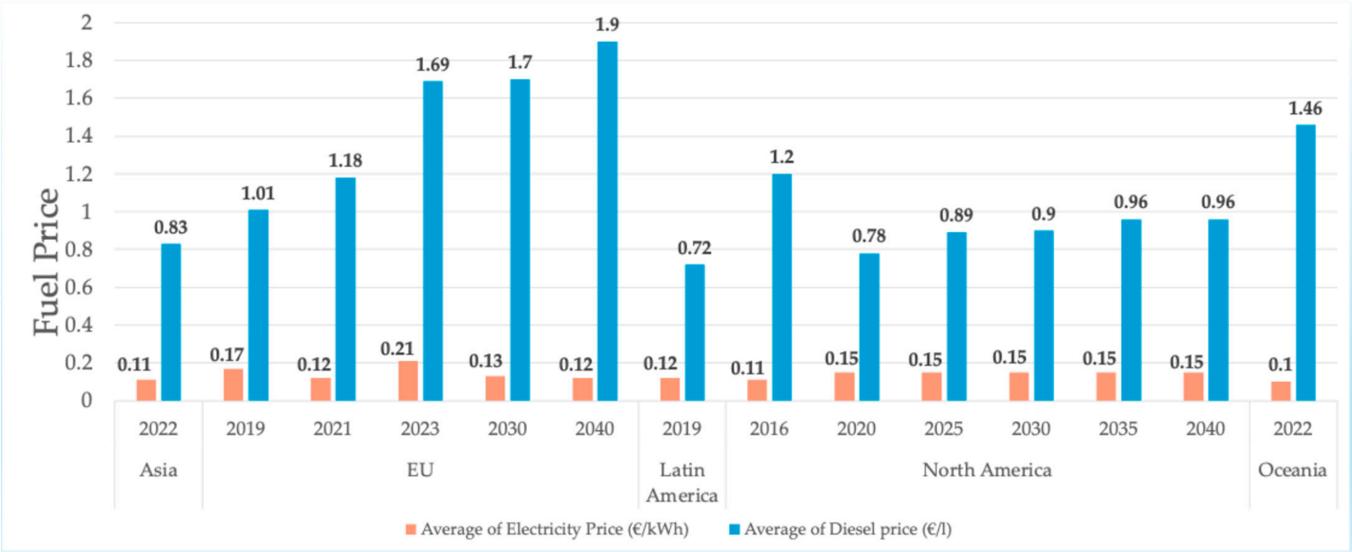

Figure 4. Fuel cost of BETs and DTs by year and continent.

A crucial determinant of electricity cost is the production pathway, with various studies exploring both grid electricity and alternative, sustainable sources like photovoltaics (PV) and wind power. Ref. [13] estimates the TCO by comparing the impact of renewable electricity generation—such as solar PV, offshore and onshore wind, and hydroelectric power—for heavy-duty electric vehicles. Ref. [23] assesses the economic viability of the BETs by specifically considering electricity generation from wind pathways. These sustainable alternatives portray a feasible, economically sound path for cost-effective electricity generation. In the case of BETs, typically commercial rates apply for charging the BETs [5,19]. Furthermore, the timings of charging the BETs can significantly impact the overall economic viability, based on the price differential between peak and off-peak rates [22].

On the contrary, diesel price volatility is largely influenced by geopolitical dynamics. Diesel prices are further influenced by government regulations targeting carbon-intensive fuels [3,17,18]. Globally, a differential tax structure on diesel—encompassing excise duties and various levies—can be observed across regions, from East Asia to the Western economies. North American nations tend to adopt a more lenient stance on fossil fuel import duties, often providing subsidies. On the contrary, the EU's vehement attitude towards carbon neutrality forces policymakers to impose intensive duties on fossil fuels for effective uptake of environmental sustainability. Within the EU, the problem of skewed duty infrastructure can be observed between member states, where excise duty ranges from 0.609 EUR/L in France to 0.379 EUR/L (in Spain) [16].

Addressing this complexity, existing literature reveals diverse methodologies for handling fuel price volatility. While some scholars apply a standardized percentage increase [20,24], others adopt a probabilistic approach to enhance the robustness of TCO evaluations [16].

2.4. Maintenance Cost

Maintenance costs represent another crucial component of operating expenses (OPEX). Beyond affecting fleet operators' purchase decisions, maintenance costs are also categorically scrutinized by private owners ultimately impacting their purchase decision for any given powertrain. However, the lack of standardized pricing mechanisms for maintenance costs results in considerable variability across truck types, as reflected in the literature. Reviewed studies address these uncertainties using sensitivity analysis, technical experiments, and industrial reports.

The prevailing consensus in the literature supports the notion that maintenance costs for BETs are substantially lower than for diesel trucks (Figure 5). This cost efficiency is largely attributed to the reduced number of mechanical components in BETs and the extended lifespan of braking systems, enabled by regenerative braking [4,26]. An analysis of average maintenance costs within the TCO framework reveals a distinct advantage for BETs over DTs, regardless of vehicle type. For BETs, the maintenance cost averages 0.13 EUR/km, markedly lower than the 0.15 EUR/km associated with diesel counterparts. Specifically, HDTs incur a maintenance cost of 0.20 EUR/km for DTs, compared with a lower 0.17 EUR/km for BETs. Similarly, for MDTs, BETs have a maintenance cost of 0.08 EUR/km, as opposed to 0.11 EUR/km for DTs. LDTs follow this trend, with BETs incurring maintenance costs of 0.06 EUR/km, while DTs require 0.08 EUR/km. However, as noted in reviewed studies—[5,9,14,15]—overall maintenance costs for both BETs and DTs are shaped by additional factors beyond vehicle type, such as mileage, payload, and operating conditions not just for BETs but also for DTs. The lack of sophisticatedly quantified figures is nuanced in the literature regarding the potential impact of hydrometeorological conditions with regard to BETs. However, refs. [12,27] identified that under such specific conditions, not just the BETs but the DTs will also be adversely affected, ultimately compromising the maintenance cost of the given powertrain. In summary, there is still a large uncertainty regarding BETs' maintenance costs. Their uptake in the market is likely to gradually clarify the many issues that are still unsettled.

2.5. Fuel Efficiency

For DTs, efficiency is commonly measured in liters per 100 km (L/100 km), whereas for BETs, it is expressed in kilowatt-hours per kilometer (kWh/km). This differentiation complicates exactly precise comparisons between the two powertrains due to the absence of a standardized testing procedure [10]. Comparing the fuel efficiency of BETs and DTs requires a consistent metric. Some studies address this challenge by employing an "efficiency ratio" (the ratio of DT energy consumption to BET energy consumption) to enhance the accuracy of TCO estimates [12,14]. Others incorporate efficiency ratios based on average speed across urban, regional, and long-haul applications [10].

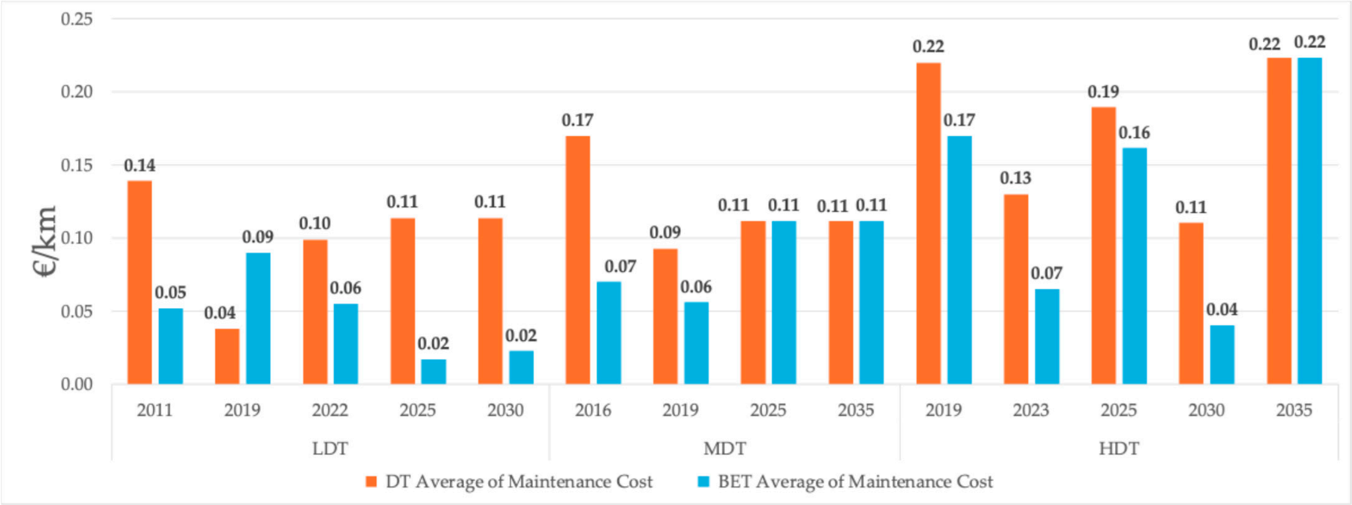

Figure 5. Average maintenance costs of BETs and DTs by year and truck type.

A recognized issue is the discrepancy between the projected range per charge by Original Equipment Manufacturers (OEMs) and actual on-road performance, especially in heavy-duty commercial applications.

In terms of energy density, lithium-ion batteries currently have a significantly lower energy density (0.36–0.87 MJ/L) compared with fossil fuels (35.8 MJ/L). However, much of the energy stored in fossil fuels is lost during combustion due to inherent inefficiencies in conventional engines [10]. Conversely, BETs leverage a more efficient drivetrain that not only minimizes energy loss but also offers greater torque.

Fuel efficiency is also influenced by various operational factors such as payload capacity, drive cycle, operating temperature, and vehicle configuration. Heavier payloads generally lead to higher fuel consumption. This impact is especially pronounced in BETs due to the additional weight of battery packs, which further increases energy demand [5]. Efficiency varies significantly with drive cycle conditions such as speed, braking, and acceleration patterns. BETs excel in urban settings with frequent stops and slower speeds due to their regenerative braking capability, while DTs are more efficient on long-haul routes with minimal braking events and stable speeds [10]. External temperature affects both BETs and DTs. This effect is even more pronounced in BETs and in some extreme cases in DTs, resulting in variations in fuel efficiency [5]. Fuel efficiency is also correlated with the design configuration of the vehicle such as aerodynamics, air drag, rolling resistance, and drivetrain efficiency [6]. Vehicle configuration is a factor that influences the fuel efficiency of both trucks similarly.

2.6. Insurance Cost

Insurance is a recurring annual expense over a truck's lifespan, mitigating risks associated with accidents, theft, or any other liability. Insurance costs are directly correlated with truck class, which is determined by gross vehicle weight and purchase cost. To simplify TCO calculations, many studies use third-party insurance cost estimates, often assuming a rate of 1.5% of the vehicle's purchase value [3]. For example, insurance costs for BETs tend to be higher than those for DTs, reflecting the CAPEX differential between the two powertrains. Some authors standardize insurance costs across truck types to facilitate comparative TCO analyses [4], while others rely on industry reports to assess BET insurance expenses [6]. Insurance premiums can also vary significantly based on motor power. Although ref. [15] highlights additional factors, such as driving behavior, terrain, and accident rates, as influential, ref. [27] suggests that BETs could incur lower insurance costs than diesel trucks due to reduced maintenance needs.

2.7. Tax and Incentive-Based Cost Analysis

The tax burden in commercial transportation can take various forms, including road tolls, import tariffs, fuel or energy taxes, and carbon emission levies. Policymaker's intervention could act as an important exogenous factor potentially affecting the overall TCO outcome [8,21]. The prevailing literature underscores the influence of contextual and regional factors on tax determination, with different countries and jurisdictions adopting unique approaches to incentivize sustainable transportation.

Value-added tax (VAT). Commercial vehicles are subject to VAT, a percentage-based tax determined on the asset's value, generally incurred at the time of purchase. Recent tax reforms in major EU countries, encouraging sustainable transportation, include tax reliefs for BETs, with China also offering a 17% consumption tax reduction based on the vehicle's acquisition cost [15]. Furthermore, several regions, such as Brussels, have introduced subsidy programs to replace conventional fleets with sustainable alternatives [8].

Toll tax. Toll taxes are generally calculated based on vehicle weight and emission class, with recent reforms offering toll exemptions or reductions for sustainable mobility options. Switzerland and Norway present compelling case studies, where BEVs are exempt from tolls, thus enhancing their economic appeal—particularly for long-haul HDTs [16].

Clean transport zones. In some large cities, such as Berlin (Umweltzone), Paris (Zone à Faibles Émissions, ZFE), and Brussels in Europe, clean transport zones are implemented—such regulatory measures can substantially impact urban transportation costs [11]. Similarly, London (Low-Emission Zones) also exempted green vehicles from congestion charges, bolstering the viability of LDTs-BETs in urban settings [3]. A TCO analysis by [11] indicates that toll taxes account for 7.45% of the total TCO for diesel-powered distribution trucks, whereas the exemption for BETs provides a notable financial advantage.

Carbon Tax. To tackle environmental challenges, several countries—including the EU, Canada, the USA, Singapore, and China—are preparing to impose mandatory carbon taxes on fossil fuels to offset emissions contributing to climate change. The prevailing literature strongly supports the narrative that imposing carbon taxes could assist alternative powertrains to reach TCO parity under optimistic scenarios, advocating for annual increases in carbon taxes to accelerate the competitiveness of BETs. Carbon taxation has a profound impact on the economic viability of DTs [7], supporting aggressive carbon pricing as a means to enhance BEV competitiveness. Tax and subsidy regulations vary widely by country, contributing to inconsistencies in their implementation. For example, ref. [21] estimates that with government-imposed carbon taxes, the TCO of BEVs could reach approximately 80% of that of DTs, achieving parity by the fifth year of ownership. Similarly, ref. [14] forecasts a carbon abatement tax rate of 80 EUR/ton CO_2 emissions by 2030, potentially incentivizing a shift to sustainable powertrains.

Import Tariffs. China's dominance in lithium-ion battery production—accounting for over 65% of global output—confers a substantial competitive edge in manipulating battery pricing mechanisms. Given the Asian dominance on lithium-ion batteries, the import tariffs on such batteries stipulate quite substantially the final purchase price of such batteries, making it essential to integrate these tariffs—directly impacting the overall reliability of the TCO metric [10]. The impact of such tariffs is even more pronounced in countries with heavy reliance on imported EV components, ultimately leading to higher taxes and import duties on BEVs than on locally manufactured conventional vehicles [25].

2.8. Infrastructure Cost

For alternative powertrains, infrastructure cost is a crucial factor, particularly given the association of implicit cost with alternative powertrains, which necessitates the requirement of a robust infrastructure concerning charging stations. The prevailing literature is faced with the question of whether to include infrastructure costs in TCO calculations, as the inclusion or exclusion of these costs significantly affects the economic viability of BETs. Diesel-powered vehicles benefit from an extensive and established refueling network, which is available in most regions, whereas BET infrastructure remains fragmented, particularly for heavy-duty long-haul applications.

The choice is dependent on the truck type and fleet size under analysis. Heavy-duty trucks (HDTs) require larger battery packs, with substantially high charging power, aiming at minimizing the extended idle times during the refueling process. While passenger EVs are supported by an extensive network of charging points, HD-BETs have limited access to compatible infrastructures. Although HD-BETs could theoretically use existing passenger EV charging stations, these stations' lower power output makes them impractical for larger battery packs, resulting in prohibitively long charging durations. Potential alternatives identified in the literature are conductive charging stations and battery swapping stations (BSSs), each with distinct approaches and costs. Conductive charging is further categorized into AC (slow charging, typically in residential settings) and DC (fast charging, suited for commercial use). Battery swapping stations (BSSs) offer a promising solution for managing energy demand through coordinated, intelligent charging of stored batteries. Countries like Switzerland and China have prioritized BSS infrastructure development to support BET adoption. One of the key benefits of BSSs is the optimized use of energy at controlled charging rates, which benefits both grid stability and battery health [25]. In terms of time efficiency, BSSs can perform battery swaps within 5–10 min, offering a competitive refueling time comparable to diesel [15]. Despite their advantages, BSS infrastructure remains scarce, leading many researchers to rely on bottom-up cost estimations. Fleet operators also face strategic decisions on whether to develop in-house charging facilities or rely on commercial charging networks. Notably, the literature does not establish a direct linear relationship between fleet size and the feasibility of in-house charging.

Light-duty BETs, on the contrary, are currently the most suitable candidates for electrification, as their charging requirements can be met with power levels below 100 kWh [13]. Such a hypothesis has also been supported by [9], who proposed a smaller transport fleet with LDTs typically covering short/urban distances that are often operated from a single terminal and can be conveniently charged overnight.

Ref. [15] similarly highlights that the electrification of short-haul HGVs (LDTs) would add an estimated demand of 4.5–7.2 MW, necessitating robust infrastructure to support the additional load. The development of fast-charging stations for HGVs represents approximately 2% of the total TCO for BETs, a cost not incurred by DTs, providing a competitive edge to the conventional powertrain. According to [11], the economic viability of HD-BETs might outweigh conventional powertrains if charged overnight, minimizing the need for high-power charging during peak hours. Robust on-site charging solutions, including reliable substations and a supportive low-voltage network, are essential to ensure operational efficiency. Ref. [27] highlights that future infrastructure investments will play a pivotal role in enabling the transition to support large-scale fleet electrification.

The literature reflects a nuanced debate regarding the inclusion of infrastructure costs in TCO analysis. These costs are generally not borne by fleet owners, but rather, the total system cost is the metric of interest to policymakers and venture capitalists. A well-developed charging network could serve as a catalyst for fleet-wise electrification, encouraging operators to transition to sustainable powertrains [13].

2.9. Residual Value

Quantifying the residual value is inherently complex and non-linear, as it depends on factors like mileage, vehicle condition, perceived brand image, and most notably, market perception of the powertrain. Residual value is primarily dictated by the depreciation rate, as vehicles lose most of their value during the initial period of ownership [6], which ultimately affects their cost. For fleet owners, the residual value represents the revenue earned at the end of a vehicle's useful life, making it a key component in the TCO metric [17]. However, predicting residual values for alternative drivetrains remains challenging due to a lack of historical data and nuance market dynamics, particularly for BETs influenced by rapid technological advancements and with many uncertainties surrounding battery lifespan and degradation. For DTs, the well-established resale market and availability of historical data enable a more standardized estimation of residual values. On the contrary, the BET resale market is still nascent because it is still awaiting retirement, complicating accurate residual value predictions. Some studies have conservatively adopted the same residual value for BETs as for DTs, applying discount rates to account for BET market maturity levels—50% for early market penetration, decreasing to 25% with small-scale production [9].

Second-life application of batteries is yet another way to maximize the residual value of BETs. Such a notion is based on the fact that batteries can be removed from trucks after reaching a certain degradation threshold level that can still be utilized in less demanding applications, e.g., stationary energy storage. Potential repurposing of such large batteries could significantly contribute to achieving the TCO parity of BETs with conventional counterparts [16]. Some studies suggest that considering a 50% residual value for batteries after eight years can lower the TCO of light-duty BETs for urban deliveries by up to 14% [8]. While many studies recognize the importance of residual value in TCO analysis, some, such as [4,5,28], chose to exclude salvage value and assumed a residual value of zero for both BETs and DTs. Another analysis maintained a skeptical view on residual value, estimating it at 20% of CAPEX with a 10% discount rate across Latin American countries [10]. Similarly, ref. [6] adopted a bottom-up approach and determined the depreciation cost to be 53.16% for BETs and 17.95% for DTs of total TCO across a time period of 4.4 years.

3. Main Results

As mentioned in the introduction, 195 distinct TCO estimates were derived from the 25 papers that qualified for our review. Having extracted the estimates from the table or the graphs (in six papers), we converted them to the same unit of monetary measurement (i.e., euro by using the following exchange rates USD/EUR = 0.91, Sterling/EUR = 1.16, CNY/EUR = 0.13, EUR/INR = 0.011, EUR/NZD = 0.55; as of October 2024) and total distance traveled in kilometers. Next, we estimated the TCO metric EUR/km for truck type, year, and country. Figure 6 presents the ratio between the TCO/km estimates for BETs and DTs. A ratio higher than one implies that BETs are not competitive with the DTs. For instance, if the ratio is equal to 1.51 (as in the case of the LDT in 2012), it means that BETs have a TCO/km that is 51% higher than that of DTs.

It can be seen that most estimates concerning the past and present years have a value above one, meaning that BETs are not cost-competitive with DTs yet. Focusing on LDTs, apart from the 2011 estimates from [4], BETs become competitive starting from the year 2021. The estimates for the years 2025, 2030, 2040 confirm their competitiveness, with values oscillating around one of the DTs. Concerning the MDT, 14 estimates available from 2021 MDT indicate that BETs have reached economic competitiveness. However, the subsequent six estimates available for the years 2022 and 2023 depict a very different picture: they indicate that they are about 50% more costly than DTs. The estimates for the years past 2025 reassign BETs' economic competitiveness with respect to DTs. As for HDTs, most estimates reach the conclusion that the BETs have and will have higher TCOs. Only 11 estimates available for the year 2030 assign, on average, an economic advantage to BETs, while 30 estimates for the years 2035 and 2040 are more pessimistic.

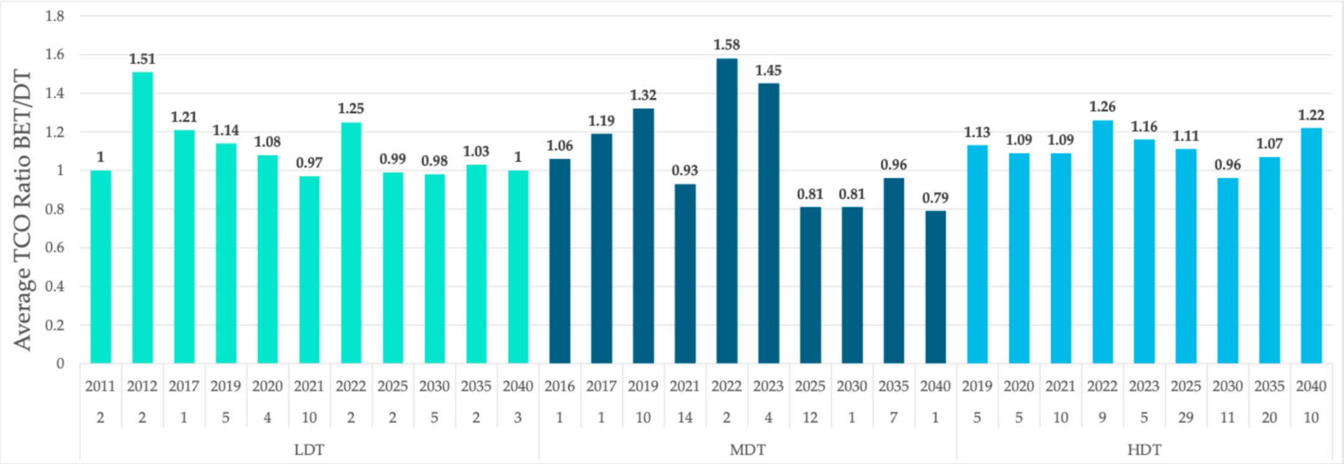

Figure 6. Average ratio of the TCO/km for BET and DT by year, number of estimates, and truck type.

Overall, it appears that size matters: LDT BETs are deemed to achieve competitiveness earlier than MDTs and HDTs, in that order. Furthermore, it seems to be an open question whether HDTs will actually achieve it or not. Time matters as well, as authors seem to agree that BETs will gain competitiveness over time, with higher levels of uncertainty in the case of HDTs.

Another interesting grouping with which to analyze TCO estimates is by country. We opted to group the countries by continent and graphically the estimates (Figures 7–9) for each truck size by using a box-and-whisker diagram to convey the estimates' heterogeneity.

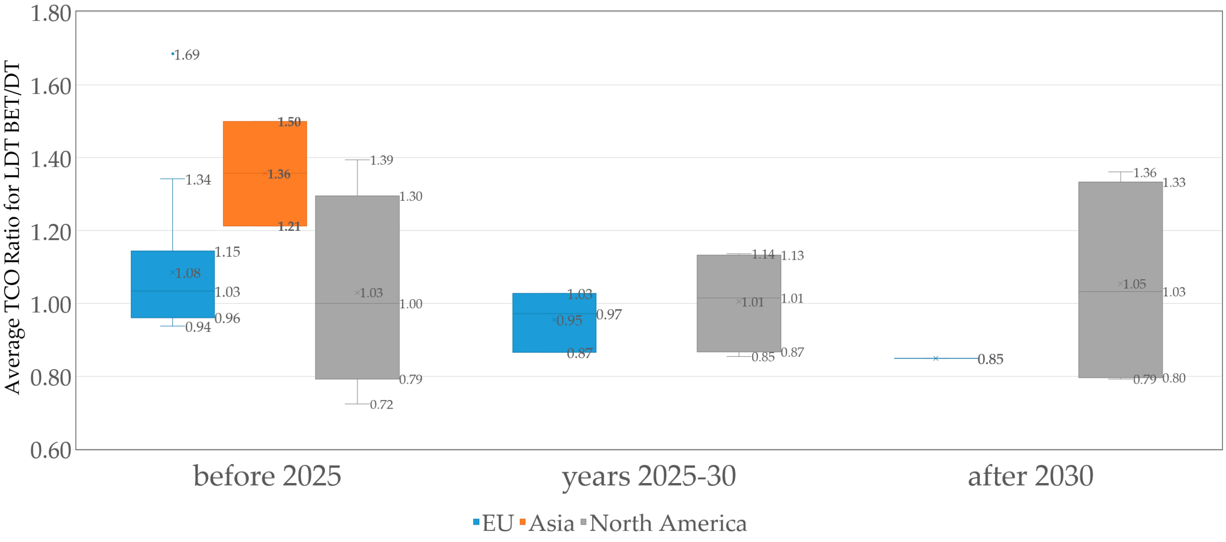

Figure 7. Ratio of TCO/km for light-duty BETs and light-duty DTs by years and continent.

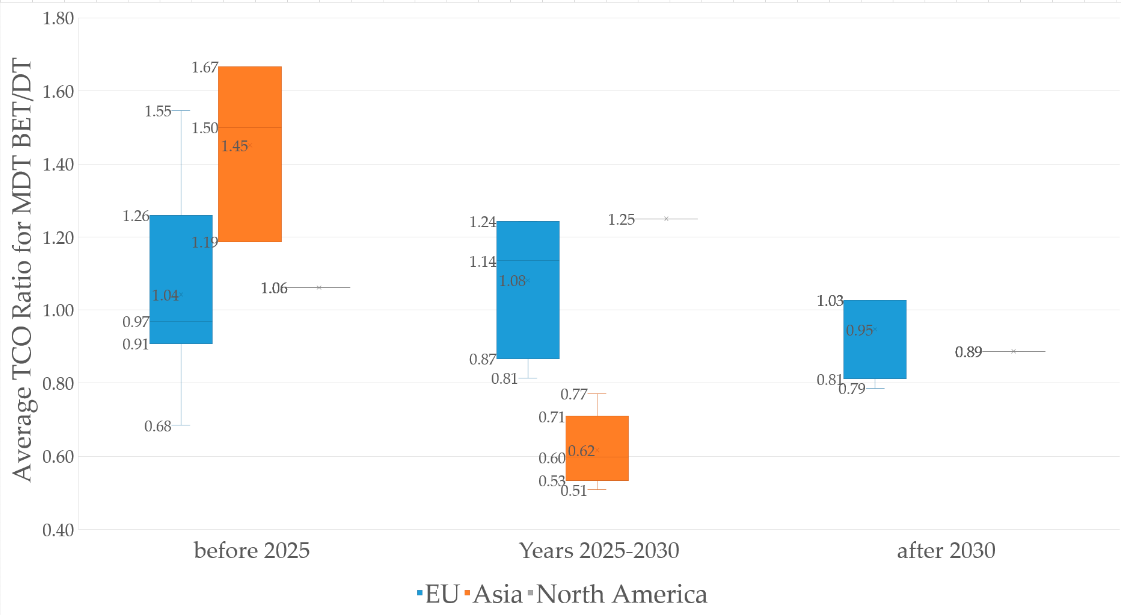

Figure 8. Ratio of TCO/km for medium-duty BETs and medium-duty DTs by years and continent.

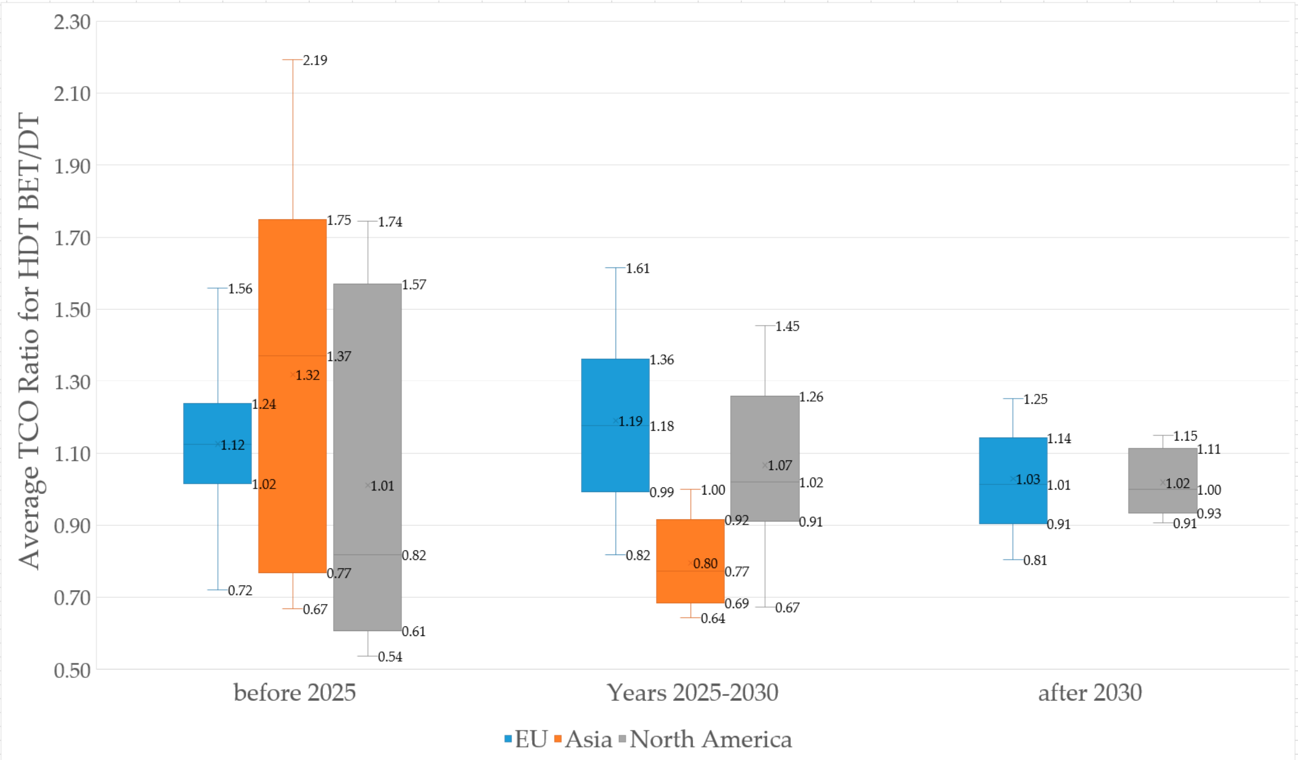

Figure 9. Ratio of TCO/km for heavy-duty BETs and heavy-duty DTs by year and continent.

Starting with LDTs, we can see that, up to the year 2025, BETs were almost cost-competitive on average both in Europe and North America but not in Asia. Both Asian and North American estimates were highly heterogeneous, with the latter ranging from 0.73 to 1.30. BETs are estimated to become more competitive in Europe after 2025, whereas the estimates remain highly heterogeneous for North America.

The estimates regarding MDTs (Figure 8) are also highly heterogeneous. Before 2025, they are estimated not to be cost-competitive, especially with regard to Asia. However, the trend is positive in the sense that their cost competitiveness is estimated to improve over time, becoming cost-competitive in Asia after 2025.

Concerning HDTs, the same remark about heterogeneity applies. Before 2025, BETs were almost cost-competitive, on average, in Europe and North America but not in Asia. Significant improvements are forecasted for Asia after 2025, however, the region is expected to face challenges in achieving competitiveness compared to Europe and North America in the coming decade.

4. Discussion

The analysis of the reviewed TCO studies revealed four important factors that could be singled out as necessitating special attention and further in-depth consideration: mission profile, single vs. fleet costing, non-monetary cost elements, and policy measures.

4.1. Mission Profile

In the commercial transportation sector, a truck's mission profile is intrinsically linked to its total cost of ownership. Numerous studies have employed annual distance traveled (ADT) and vehicle life span as proxy variables of vehicle mission profiles. However, variations in assumptions regarding ADT and vehicle lifespan among researchers have led to divergent conclusions. Scholars from Asia and North America frequently presume extended lifespans of 15–20 years, whereas in the European Union, the average period of vehicle ownership is approximately half as long. This distinction is critical, as the economic feasibility of any propulsion technology is highly sensitive to variables such as ADT, battery longevity, and payload capacity. Higher annual mileage can offset the fixed CAPEX associated with BETs but concurrently inflate TCO due to increased battery replacement costs [10,19].

The sensitivity of TCO to ADT becomes particularly pronounced in long-haul operations, where vehicles covering greater distances experience increased energy consumption, rendering them more susceptible to fluctuations in fuel or electricity costs. Such price volatility can induce significant shifts in the relative TCO of BETs and DTs, as illustrated by [5,20]. Ref. [23] demonstrated that BETs are more economically feasible in urban and regional delivery scenarios, provided battery replacements are avoided during a 10-year operational lifespan. Conversely, their cost competitiveness diminishes significantly when additional battery replacement costs are taken into the TCO equation.

The influence of ownership periods on TCO is further elucidated in several studies. The work in [20], for instance, examined MDTs under varying ownership durations, factoring in ADT and vehicle lifespan. The findings revealed that longer ownership periods (e.g., 15 years) yield lower TCO compared with shorter ownership spans, a trend observed across both BETs and DTs. These findings highlight the necessity of incorporating dynamic mission profiles into TCO analyses. Similarly, ref. [8] identified substantial financial losses for fleet operators who sell BETs in light-duty configurations within the initial couple years of ownership.

4.2. Single vs. Fleet Costing

The majority of reviewed studies did not consider the critical economic divide between single-truck owners and fleet operators. The potential interest of fleet operators is particularly critical in fostering economies of scale for BETs, as they typically operate on narrow profit margins and exhibit high sensitivity towards TCO. However, substantial uncertainties persist regarding the accurate estimation of ownership costs for both single-truck owners and fleet operators. The high upfront cost of BETs renders conventional DTs a more attractive choice for fleet operators [6]. For single-truck owners, this financial challenge is even more pronounced, as government subsidies and incentives are predominantly targeted at fleet operators and large-scale deployments. Consequently, single-truck owners are unable to fully capitalize on these financial incentives, further exacerbating their economic burden.

Fleet operators, however, leverage economies of scale, which mitigate the impact of higher upfront costs associated with BETs. Discount rates play a particularly critical role for fleet operators, as they reduce per-unit costs and enhance the economic viability of the transition to BETs [11,20]. Moreover, the payback period is a key consideration for fleet operators, with commercially acceptable ranges typically between 3 and 5 years [16,21]. According to TCO estimates, the payback period for BETs post-2030 is projected to be approximately 4–5 years [20], depending on market conditions, making BETs an attractive alternative for small and medium-sized trucks with urban and regional applications. This anticipated reduction aligns with fleet operators' expectations, fostering greater adoption of BETs in the mass market and contributing to the broader decarbonization of the transportation sector.

The electrification of heavy-duty, long-haul trucks introduces substantial complexities and uncertainties. Conventional DTs are anticipated to sustain cost competitiveness until 2035–2040, owing to their mature refueling infrastructure, lower energy costs, shorter refueling times, and the absence of battery replacement expenses. Fleet operators typically require a minimum range of 500 miles between refueling intervals with a payload capacity [20]. This range requirement imposes significant constraints on BETs due to the need for large battery stacks, which substantially elevate per-unit costs. While approximately 78% of trucking activity in the EU involves distances of 800 km or less, the elevated acquisition costs of BETs for HDTs impede their ability to offset operational savings. Conversely, LDTs and MDTs demonstrate greater potential for cost competitiveness, particularly with urban and regional applications.

Energy dependency for fleet electrification also varies by vehicle class and operational profile. Ref. [19] evaluated fleets of 10 trucks, finding that smaller models (54, 3, and 4-RD) rely entirely on depot charging, necessitating additional infrastructure investments by fleet operators. For MDTs (5-LH 500 km and 5-LH 800 km), 80% of energy needs are met through depot charging, with the remainder fulfilled by public charging stations. In contrast, HDTs (5-LH 1000 km) depend exclusively on public charging infrastructure, underscoring the critical need for widespread, high-capacity charging networks. Without robust infrastructure development, HDT fleet electrification remains highly improbable [9,13]. However, BETs in LDTs and MDTs segment operating on shorter routes offer distinct economic advantages. Ref. [9] demonstrated that own-transport operators using smaller trucks, typically operating between terminals and charging overnight, achieve superior economic viability.

The comparative cost implications of fleet-wide electrification versus single-truck charging setups remain insufficiently explored in the literature. It is desirable for future studies to investigate key factors such as refueling schedules, fleet capacity, and route frequency, as these variables have profound implications for fleet composition and operational efficiency. A holistic, fleet-wide analysis would furnish stakeholders with critical insights into the TCO of truck electrification, facilitating more informed decision-making and policy formulation.

4.3. Non-Monetary Cost Elements

Integrating non-financial considerations into TCO analyses is indispensable for presenting stakeholders with a holistic evaluation of the challenges and opportunities associated with battery-electric commercial vehicles. Non-monetary factors, such as extended waiting times at refueling stations, range anxiety, prolonged charging durations, hydrometeorological conditions, and the risk of reduced payload capacity to achieve desired ranges, are all pivotal concerns in this context. Accounting for implicit costs highlights another significant limitation in the existing TCO literature, which largely obstructs the broader penetration of BETs into the mass market. These implicit costs are often reflected in challenges such as the inconvenience of battery repowering and range anxiety.

4.4. Policy Measures

All the examined studies reached the conclusion that government intervention and policy measures are indispensable in advancing the economic viability of alternative powertrains, particularly in the commercial transportation sector. Despite escalating environmental concerns, the commercial transportation sector has shown significant resistance toward sustainable operational models, necessitating proactive governmental involvement. For instance, the EU implements substantial tax relief measures and imposes a 100% tariff on fossil fuel imports to bolster the competitiveness of BETs. In contrast, the aggressive subsidization of fossil fuels in the United States has delayed TCO parity between BETs and DTs. Government intervention via subsidies and tax incentives can be applied across various segments, though academic opinions diverge in identifying which factors should be prioritized for such incentives. Certain studies advocate for subsidies aimed at reducing the fixed costs associated with BET acquisition [3,10], while others emphasize OPEX as the primary target [8,16]. The latter approach suggests that sustained market growth is more effectively achieved through reductions in operational costs rather than through temporary purchase incentives. A consensus has emerged around the efficacy of carbon tax in enhancing the economic feasibility of zero-emission trucks. According to [21], aggressive carbon taxation could lower the TCO of BETs to approximately 80% of DTs, thereby significantly shortening the breakeven period.

The higher upfront cost of BETs, coupled with the costs of lithium-ion batteries and fast-charging infrastructure, are central to their economic feasibility, as highlighted in the current TCO analysis. Financial subsidies targeting acquisition costs can substantially alleviate the upfront financial burden of BETs, which are more than three times as expensive as their diesel counterparts [6,24]. Subsidizing acquisition costs for fleet operators, who dominate the commercial transportation sector, could catalyze widespread adoption, triggering a ripple effect. However, proportional incentives must also target independent operators to ensure inclusivity and equitable adoption.

The impact of subsidies is particularly pronounced in the HDT segment with long-haul applications. Ref. [14] emphasizes that BETs in this category can achieve cost parity with DTs only through sustained government support; otherwise, cost parity potentially can be delayed by 10–15 years. Furthermore, governmental efforts to establish robust, high-powered public charging networks are critical for reducing BET operational costs, especially in long-haul applications [22]. Strategic investment in charging infrastructure along high-traffic trucking corridors, logistics hubs, ports, and distribution centers would substantially enhance the economic feasibility of BETs.

In economically constrained regions, public–private partnerships (PPPs) offer a viable solution for developing fast-charging infrastructure. PPPs can mitigate implicit challenges such as range anxiety, improve accessibility, reduce vehicle downtime, and increase operational efficiency. Leveraging private-sector expertise and innovation ensures coordinated and effective infrastructure planning. Additionally, measures such as reduced import tariffs and toll taxes for BETs could expedite TCO parity, achieving cost competitiveness earlier than anticipated [11].

Government intervention also plays a critical role in creating a stable environment conducive to venture capital investment in zero-emission technologies. Tailored policy measures can stimulate market expansion for electric transportation, facilitating economies of scale and reducing variable costs associated with batteries and charging infrastructure [14,18]. Importantly, such policies must be context-specific and tailored to the unique requirements of different applications and regions to maximize their impact [21].

Despite the critical role of policy interventions, the prevailing TCO literature often neglects broader system-level costs and benefits associated with decarbonizing the commercial transportation sector [12]. Future studies should integrate the developmental costs of infrastructure, impacts on energy production and distribution, and potential emission reductions into TCO frameworks. For LDTs and MDTs, government policies should prioritize incentivizing the OPEX, while for HDTs, comprehensive interventions across multiple stages are imperative to address their unique challenges and accelerate the transition to sustainable transportation.

5. Conclusions

This paper reviewed the existing studies employing TCO analysis to evaluate the comparative economic viability of BETs and DTs. Over the past decade, a marked surge in techno-economic analyses of alternative powertrains has been evident in academic literature.

A key finding from this comparative TCO analysis indicates that until recent years, BETs have not been cost-competitive with DTs. LDTs and MDTs started to become competitive in 2021, according to some estimates, whereas HDTs might continue to not be competitive even in future decades. This finding is to be attributed to the high acquisition costs of BETs, especially of HDT, due to battery costs, which create substantial disparities compared with conventional counterparts. Although BETs have considerably lower operating costs than DTs, the cost disparity in CAPEX (due mostly to lithium-ion batteries) persists as a significant barrier. However, the reduced operating expenses of BETs, amortized over an ownership horizon of 3–7 years, can mitigate these disparities to a considerable extent. For MDTs and LDTs, cost parity seems to be already achieved or expected in the near future.

Another interesting finding is that TCO estimates differ across continents. The combined effect of fuel prices and taxes is most likely responsible for the fact that BETs enjoy a stronger competitive position relative to DTs in Europe, Asia, and Oceania, whereas, in North America, most estimates assign them a poor competitiveness both presently and in the coming years.

Most studies underline that significant cost disproportions persist in the HDT segment due to its demanding operational requirements and the lack of robust high-powered charging infrastructure. Consequently, substantial financial incentives and subsidies will be required for HDTs to enhance their economic viability, potentially accelerating cost parity from post-2035 to the near future. The existing literature emphasizes the critical role of government interventions, including investments in fast-charging infrastructure, policies to encourage mass-market adoption, and support for optimizing battery production chains via economies of scale. In the EU, where a substantial tariff is imposed on fossil fuel imports, BETs demonstrate significant economic competitiveness. Conversely, in the United States, where fossil fuels are minimally taxed, the cost advantage of BETs is less pronounced.

This paper identifies several constraints in TCO analysis, including limited data on residual values, variability in discount rates, and depreciation costs. The lack of longitudinal and market data for BETs in the HDT segment with long-haul applications is attributed to their niche market penetration, with existing studies predominantly relying on bottom-up simulation techniques. Labor costs, recharging inconvenience, and other implicit costs remain critical factors requiring consideration in TCO analyses. This paper has also emphasized the need to account for potential economies of scale that might be harvested when managing truck fleets instead of single trucks, as well as to incorporate infrastructural costs (e.g., charging infrastructure at the depot) in the TCO methodology. These limitations underscore the need for a more holistic understanding of the financial ramifications associated with adopting and operating BETs.

Author Contributions: Conceptualization, R.D. and M.S.; methodology, R.D., A.M.K.N. and M.S.; formal analysis, R.D. and A.M.K.N.; investigation, R.D., A.M.K.N., M.S., M.M. and A.M.A.; data curation, R.D., M.S., A.M.K.N., M.M. and A.M.A.; writing—original draft preparation, R.D., A.M.K.N., M.S. and M.M.; writing—review and editing, R.D., A.M.K.N., M.S. and M.M.; visualization, A.M.K.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating Current
ADT	Annual Distance Travelled
BETs	Battery Electric Trucks
BSS	Battery Swapping Stations
CAPEX	Capital Cost
DC	Direct Current
DTs	Diesel Trucks
GVW	Gross Vehicle Weight
HDT	Heavy-Duty Truck
HGV	Heavy Goods Vehicle
LDT	Light-Duty Truck
MDT	Medium Duty Truck
OEM	Original Equipment Manufacture
OPEX	Operational Cost
PPP	Public–Private Partnerships
PV	Photovoltaics
TCO	Total Cost of Ownership
VAT	Value-Added Tax

References

1. Danielis, R.; Scorrano, M.; Masutti, M.; Awan, A.M.; Niazi, A.M.K. The Economic Competitiveness of Hydrogen Fuel Cell-Powered Trucks: A Review of Total Cost of Ownership Estimates. *Energies* **2024**, *17*, 2509. [CrossRef]
2. Danielis, R.; Scorrano, M.; Masutti, M.; Awan, A.M.; Niazi, A.M.K. Fuel Cell Electric Buses: A Systematic Literature Review. *Energies* **2024**, *17*, 5096. [CrossRef]
3. den Boer, E.; Aarnink, S.; Kleiner, F.; Pagenkopf, J. An Overview of State-of-the-Art Technologies and Their Potential. Germany. 2013. Available online: https://cedelft.eu (accessed on 25 October 2024).
4. Lee, D.-Y.; Thomas, V.M.; Brown, M.A. Electric Urban Delivery Trucks: Energy Use, Greenhouse Gas Emissions, and Cost-Effectiveness. *Environ. Sci. Technol.* **2013**, *47*, 8022–8030. [CrossRef] [PubMed]
5. Zhou, T. Life cycle GHG emissions and lifetime costs of medium-duty diesel and battery electric trucks in Toronto, Canada. *Transp. Res. D Transp. Environ.* **2017**, *55*, 91–98. Available online: https://www.academia.edu/108041075/Life_cycle_GHG_emissions_and_lifetime_costs_of_medium_duty_diesel_and_battery_electric_trucks_in_Toronto_Canada (accessed on 25 October 2024). [CrossRef]

6. Kampker, A.; Krciskother, K.; Buning, M.K.; Gomez, J.G.D. Technological and Total Cost of Ownership Analysis of Electric Powertrain Concepts for Long-Haul Transport in Comparison to Traditional Powertrain Concepts. In Proceedings of the 2018 8th International Electric Drives Production Conference, EDPC 2018—Proceedings, Schweinfurt, Germany, 4–5 December 2018. [CrossRef]
7. Yang, L.; Hao, C.; Chai, Y. Life Cycle Assessment of Commercial Delivery Trucks: Diesel, Plug-In Electric, and Battery-Swap Electric. *Sustainability* **2018**, *10*, 4547. [CrossRef]
8. Lebeau, P.; Macharis, C.; Van Mierlo, J. How to Improve the Total Cost of Ownership of Electric Vehicles: An Analysis of the Light Commercial Vehicle Segment. *World Electr. Veh. J.* **2019**, *10*, 90. [CrossRef]
9. Hovi, I.B.; Pinchasik, D.R.; Figenbaum, E.; Thorne, R.J. Experiences from Battery-Electric Truck Users in Norway. *World Electr. Veh. J.* **2020**, *11*, 5. [CrossRef]
10. Tanco, M.; Cat, L.; Garat, S. A break-even analysis for battery electric trucks in Latin America. *J. Clean. Prod.* **2019**, *228*, 1354–1367. [CrossRef]
11. Moll, C.; Plötz, P.; Hadwich, K.; Wietschel, M. Are Battery-Electric Trucks for 24-Hour Delivery the Future of City Logistics?—A German Case Study. *World Electr. Veh. J.* **2020**, *11*, 16. [CrossRef]
12. Alonso-Villar, A.; Davíðsdóttir, B.; Stefánsson, H.; Ásgeirsson, E.I.; Kristjánsson, R. Technical, economic, and environmental feasibility of alternative fuel heavy-duty vehicles in Iceland. *J. Clean. Prod.* **2022**, *369*, 133249. [CrossRef]
13. Gray, N.; O'Shea, R.; Wall, D.; Smyth, B.; Lens, P.N.L.; Murphy, J.D. Batteries, fuel cells, or engines? A probabilistic economic and environmental assessment of electricity and electrofuels for heavy goods vehicles. *Adv. Appl. Energy* **2022**, *8*, 100110. [CrossRef]
14. Gunawan, T.A.; Monaghan, R.F.D. Techno-econo-environmental comparisons of zero-and low-emission heavy-duty trucks. *Appl. Energy* **2022**, *308*, 118327. [CrossRef]
15. Hao, X.; Ou, S.; Lin, Z.; He, X.; Bouchard, J.; Wang, H.; Li, L. Evaluating the current perceived cost of ownership for buses and trucks in China. *Energy* **2022**, *254*, 124383. [CrossRef]
16. Noll, B.; del Val, S.; Schmidt, T.S.; 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. [CrossRef]
17. 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**, *8*, e12417. [CrossRef]
18. 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. Env.* **2022**, *102*, 103152. [CrossRef]
19. Basma, H.; Rodríguez, F. A Total Cost of Ownership Comparison of Truck Decarbonization Pathways in Europe. 2023. Available online: www.theicct.org (accessed on 25 October 2024).
20. Burke, A.F.; Zhao, J.; Miller, M.R.; Sinha, A.; Fulton, L.M. 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. [CrossRef]
21. 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*, 7902. [CrossRef]
22. Hu, M.; Wu, X.; Yuan, Y.; Xu, C. Competitive Analysis of Heavy Trucks with Five Types of Fuels under Different Scenarios—A Case Study of China. *Energies* **2024**, *17*, 3936. [CrossRef]
23. Samet, M.J.; Liimatainen, H.; Pihlatie, M.; van Vliet, O.P.R. Levelized cost of driving for medium and heavy-duty battery electric trucks. *Appl. Energy* **2024**, *361*, 122976. [CrossRef]
24. Ledna, C.; Muratori, M.; Yip, A.; Jadun, P.; Hoehne, C.; Podkaminer, K. Assessing total cost of driving competitiveness of zero-emission trucks. *iScience* **2024**, *27*, 109385. [CrossRef] [PubMed]
25. Patil, A.J.; Singh, A.; Sharma, R.N.; Jarial, R.K. Assessing the cost-effectiveness of electric trucks in Indian food supply chains. *Int. J. Emerg. Electr. Power Syst.* **2024**. [CrossRef]
26. Rajagopal, D.; Gopinathan, N.; Khandekar, A.; Karali, N.; Phadke, A.; Abhyankar, N. Comparative Evaluation of Total Cost of Ownership of Battery-Electric and Diesel Trucks in India. *Transp. Res. Rec.* **2024**, *2678*, 235–247. [CrossRef]
27. Wang, Z.; Acha, S.; Bird, M.; Sunny, N.; Stettler, M.E.J.; Wu, B.; Shah, N. A total cost of ownership analysis of zero emission powertrain solutions for the heavy goods vehicle sector. *J. Clean. Prod.* **2024**, *434*, 139910. [CrossRef]
28. 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*, 284–289. [CrossRef]