future transportation

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The Cost Competitiveness of Electric Refrigerated Light Commercial Vehicles: A Total Cost of Ownership Approach

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Abstract: This article aims to investigate the economic feasibility of renewing a fleet of diesel light commercial vehicles (LCVs) with equivalent more environmentally friendly vehicles in the distribution of frozen and chilled foods. A Total Cost of Ownership (TCO) approach is proposed that includes all pertinent expenses to compare the cost competitiveness of battery electric, fuel-cell electric, and bio-diesel LCVs with respect to their conventional diesel counterparts, and to perform policy scenarios. We adopt both a private and a social perspective by also accounting for the external costs of transportation. We found that electric LCVs outperform their rivals in the city and panel LCV categories even in the absence of government subsidies while being cost competitive in box LCV segment, while FCEVs require the development of refueling infrastructure and government subsidies to compete with diesel counterparts.

Keywords: Total Cost of Ownership (TCO); Refrigerated Light Commercial Vehicle (RLCV); Fuel-Cell Electric Vehicle (FCEV); Battery Electric Vehicle (BEV)

Academic Editor: Lynnette Dray

Received: 18 October 2024
Revised: 5 January 2025
Accepted: 15 January 2025
Published: 24 January 2025

Citation: Awan, M.A.; Scorrano, M. The Cost Competitiveness of Electric Refrigerated Light Commercial Vehicles: A Total Cost of Ownership Approach. *Future Transp.* **2025**, *5*, 10. https://doi.org/10.3390/futuretransp5010010

1. Introduction

The transportation sector contributes significantly to industrial and economic growth, employing around 10 million people and accounting for about 5% of the European gross domestic product (GDP). Yet its related externalities are heavily affecting the environment and social aspects of life, making it a major contributor to habitat fragmentation, noise pollution, and air pollution [1]. A quarter of the EU's total greenhouse gas (GHG) emissions are attributed to transportation, which still relies substantially on oil and petroleum products, obtaining less than 8.7% of its energy from renewable sources [2]. Almost three quarter (71.7%) of transportation emissions come from road transport, with passenger cars as a major polluter. While accounting for less than 2% of the vehicles on the road, trucks carrying goods also play a relevant role, being responsible for 25% of climate emissions from road transport in Europe. In the absence of significant actions, GHG emissions from transportation are predicted to increase from current levels by almost 20% by 2030 and by almost 50% by 2050 (https://unfccc.int/media/521376/paris-electro-mobility-declaration.pdf, accessed on 8 September 2024). Implementing immediate and medium-term decarbonization options is thus crucial in addressing the global emission crisis and rising temperatures. Europe has set a goal to achieve climate neutrality by 2050. To meet this challenging environmental mitigation target, the EU policy specifically calls for the switch to low- and zero-emission vehicles [3]. The recent ban on the sale of new gasoline, diesel, and hybrid cars as well as LCVs from 2035 [4] goes in that direction. With the same ambition to improve air and life quality, many municipalities are setting up particularly restrictive low-emission zones in the city centers, by banning or limiting access to the most polluting vehicles.

Shifts in consumers' eating habits, population growth in cities, and the increased exportation of perishable goods increased the demand for refrigerated transport, able to maintain the quality, freshness and integrity of temperature-sensitive products, in segments such as food and beverage, pharmaceuticals, and chemicals. With a predicted worth of $113.4 billion in 2022 and a compound annual growth rate of 7.2% from 2022 to 2027, the refrigerated transport market is expected to increase rapidly and reach $160.7 billion (https://www.marketsandmarkets.com/Market-Reports/refrigerated-transport-market-779494.html, accessed on 24 September 2024). The desire for fresh and different foods to be made available all-year round and the demand for packed ready-to-eat (RTE) meals favoured the widespread usage of frozen variants of various fresh foods, making them easily accessible and cheaper. This evidence, coupled with the shift in consumer preference for home delivery services, has driven the demand for refrigerated vehicles, especially in urban areas. These vehicles—usually trucks, vans and trailers—are mainly diesel-powered and are equipped with refrigeration units that cause higher energy consumption due to the increase in the engine load, and make use of polluting refrigerants. Refrigerated LCVs, for example, emit 16x more nitrogen oxides and 40x more particulate matter per kWh of energy than conventional vehicles [5].

Due to its high environmental impact, thus, it is worth analyzing the refrigerated transport sector to investigate its potentialities to contribute to the decarbonization goals.

Refrigerated LCVs (RLCV) range in size from compact vans ideal for short-distance delivery in cities to bigger trucks built for longer distances. However, while medium and heavy-duty trucking (MDT/HDT) seem the hardest-to-abate segments, the recent literature shows that there are already feasible technologies for light commercial vehicles (LCVs) (LCV are defined as "at-least four wheels having operating capacity up to 3.5 tons" [6]. LCVs are further classified under the category N having N1, N2 and N3 sub categories. N1 category includes goods-carrying vehicles with a maximum weight of 3.5 tons or less; N2 category includes goods-carrying vehicles with a maximum weight exceeding 3.5 tons, but not more than 12 tons; N3 category includes goods-carrying vehicles with a maximum weight exceeding 12 tons) and potentialities exist especially for urban freight transport, considering the growing issues of traffic congestion, noise and air pollution. Within the European Union, there are 29.5 million vans in use; three nations account for half of this total: France (6.3 million vans), Italy (4.3 million), and Spain (3.9 million) [6]. The European Automobile Manufacturing Association (ACEA) statistics of LCVs market based on fuel types reveal that diesel engines are still dominating the market with 86.0%, followed by petrol (5.0%), electric (5.3%), hybrid-electric (2.5%) and other fuels types (1.2%) [7]. The market for refrigerated vehicles was dominated by LCVs in 2022, underscoring the importance of these vehicles for short-distance delivery of goods that are sensitive to temperature [8]. LCVs are particularly favored because of their ability to maneuver a variety of locations, from congested metropolitan streets to rural areas.

Alternatives to diesel- and petrol-fueled vehicles are already feasible from a technical point of view and can contribute to decarbonize the transport system. Electric vehicles—comprising Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs)—for example, can emit 42–61% less GHG emissions while consuming 32–54% less energy than their diesel counterparts [9,10]. Moreover, they can contribute to minimizing the noise pollution levels, which is quite a relevant factor in urban goods distribution [11]. Most European manufacturer (e.g., Audi, Volkswagen) have proactively started electrifying their product ranges. Besides cars, sales of electric LCVs (eLCVs) increased in Europe by more than 70% in 2021 [12]. The market share of eLCVs, however, is 2% globally, which is roughly four times lower than that of passenger vehicles.

Hydrogen Fuel Cell Vehicles (FCEVs) also have the potential to reduce emissions if green hydrogen is produced via electrolysis. They only emit water vapor as a byproduct when they are driven, making them almost emission-free. They greatly lower noise emissions because they are not reliant on combustion and have minimal moving parts. The initial costs of hydrogen fuel cells are, however, high because of expensive metals like platinum being used as catalysts in fuel cells. As refilling a combustion engine with gasoline, FCEVs require a few minutes for recharging, providing the same mobility as conventional vehicles, in contrast with eLCVs. The hydrogen infrastructure to fuel them is however in the early stages of implementation. In Italy, for example, there is only one operational hydrogen refueling station versus 22,700 traditional gas stations [13]. Moreover, being highly flammable, safety issues emerge in the transportation and storage of hydrogen.

Biofuels are defined as materials with a recent biological or photosynthetic origin that release sufficient energy upon combustion. Liquid biofuels that are comparable to gasoline and diesel include ethanol and fatty acid alkyl esters (FAAE, mostly methyl esters, FAME). The current petrol and diesel fuel LCVs can be powered by biofuels, without requiring significant changes. Because biofuels come from a closed carbon cycle, they are commonly thought of as carbon-neutral fuels and environmentally beneficial [14]. The consumption of biofuel in the transportation sector of the European Union amounted to 13 million tons of oil in 2015 and rose to 16 million tons in 2019. It is worth noting that biodiesel accounts for approximately 80% of this total share [15]. Furthermore, the utilization of advanced biofuel has witnessed a notable increase in recent years, surpassing 4 million tons in 2020, representing approximately 25% of the overall biofuel consumption. Biofuels are well-suited to assist the European Union in achieving its climate and energy goals. Ethanol and Ethyl Tertio Butyl Ether (ETBE) are other biodegradable fuels with reduced carbon emissions, possessing the ability to recycle carbon dioxide, and having the ability to replace conventional fuels with the existing powertrain system. In general, however, there is a lack of consensus due to the fact that biofuels compete for land and resources with food crops for both humans and other animals. Additionally, the production costs of advanced biodiesel and biomethane are substantially higher than those of fossil fuels. However, support schemes offer a premium to producers of advanced biomethane and biofuels, enabling them to offset these increased costs and compete with fossil fuels in the transportation sector.

The technical transition to low-carbon alternatives, as well as the possible effects this transformation may have on operations and working methods, are major sources of risk. However, the potential cost benefits of fleet decarbonization create substantial prospects for the sector amid a changing regulatory environment and the rising customer desire for greener transportation. Over the next five years, the global market for green logistics is expected to expand at a rate of 6% annually, whilst costs of switching to green transportation are dropping quickly. The long-term downward trend in battery prices in the LCV market segment means that the total cost per mile of eLCVs is likely to fall from 90% to 95% of that for diesel LCVs as early as 2025 [16], even though a short-term increase in battery prices has been observed due to current supply-demand constraints. Fleet operators have substantial motivation to strategically evaluate and plan for decarbonization given these benefits. However, the time and extent of this change will be influenced by three important factors: infrastructure buildup with accessibility, impact of daily operations and sale/purchase of vehicles [17].

This paper will focus on the latter aspect, since businesses typically base their decisions mostly on costs considerations. We will analyze the case study of the largest Italian frozen food company that uses RLCVs of different sizes to deliver door-to-door fresh and frozen food products through a proprietary fleet to their widespread customers. It serves customers residing both in extra urban and urban areas and has many potential customers living in the city centers. However, the recent actual banning of the conventional gasoline LCVs in the city centers of major Italian cities, i.e., Milan and Rome risk to compromise the company's growth in such areas. This reason, together with the increase in customer attention towards sustainable practices throughout the value chain, has urged the company to fulfil its demand sustainably. As a result, the company is ambitious to improve sustainable practices while minimizing their reliance on conventional practices, to attain a competitive advantage in the market. One strategy has to do with a replacement of the LCVs fleet with a sustainable one. By adopting the Total Cost of Ownership (TCO) metric, we thus compare LCVs with different sustainable propulsion systems in order to investigate the economic feasibility of this strategy. Since the TCO metric offers a comprehensive picture of all expenses related to owning and running an asset across its lifecycle, it is crucial when evaluating economic competitiveness. It allows firms to analyse options and find cost-effective solutions by considering elements like purchase price, fuel, maintenance, insurance, and depreciation [18]. TCO enhances operational efficiency, facilitates long-term financial planning, and assists in determining sustainability across fleets. Moreover, TCO takes ecological factors like energy efficiency and lower emissions into account, ensuring accurate decision-making that creates a balance between initial investment and recurring expenses for maximum efficiency [19]. Besides current private economic competitiveness, we will also compare these propulsion systems from a social point of view, hence accounting for transport externalities.

The organization of the paper is as follows. Section 2 reviews the recent literature; Section 3 outlines the methodology employed for investigating the economic competitiveness of different propulsion systems; Section 4 describes the case study and the assumptions made; Section 5 includes the results, while Section 6 concludes and discusses the practical implications.

2. Literature Review

Numerous factors influence the decision to purchase a LCV, and these factors' relative relevance can be determined using a range of methods, such as conjoint-based investigations, stated choice experiments, and multiple regression analyses. While there has been comparatively less research on LCV purchasing decisions than on electric car choices, the existing literature shows that major barriers in the adoption of eLCVs in the logistics system are driving range and purchase price, just like in the case of cars [20–23]. An overview of the literature focusing on the TCO models for different propulsion systems is presented in Table 1.

Table 1. Detailed review of literature focusing on TCO models and vehicles of different propulsion systems.

Author/Year	Case Study	Methodology	Observed Propulsion Systems	Conclusion
Contestabile et al. (2011) [24]	Urban	Private and Social TCO	BEVs, FCEVs and biofuels	FCEVs and biofuel vehicles are not market competitive while BEVs appear to be a potential alternative for low energy driving cycles (urban and low-speed) against ICEs.
Lee et al. (2013) [9]	Urban	Private and Social TCO	Diesel and BEVs	BEVs TCO is 22% less than its conventional rival. Emits 43% less GHG emissions and consumes 5–34% less enegy, but costs 1% more than diesel one.
Al-Alawi and Bradley (2013) [18]	Urban and Extra-Urban	Private TCO	Plug-in hybrid electric vehicles	PHEV has higher consumer preference and lower TCO resulting in shorter payback time and higher on-road efficiency
Wu et al. (2015) [25]	Urban	Private TCO	BEVs and Diesel	EVs cost efficiency increases with driving distance and is higher for small vehicles than large ones.
Dumortier et al. (2015) [26]	Urban and Extra-Urban	Private TCO	Gasoline, HEVs, PHEV and BEVs	BEVs, HEVs and PHEVs TCO based on fuel economy can increase consumer demand for these vehicles as compared to conventional ones.
Hagman et al. (2016) [27]	Urban and Extra-Urban	Private TCO	ICEVs, HEVs and BEVs.	Consumer-centric TCO is employed to investigate Discrepancy between purchase price and TCO of ICEVs, HEVs, and BEVs.
Bubeck et al. (2016) [28]	Urban and Extra-Urban	Private and Social TCO	PHEVs and BEV	BEVs of different categories need subsidies to be cost competitive while PHEVs are cost competitive to diesel ones in different categories.

Table 1. *Cont.*

Author/Year	Case Study	Methodology	Observed Propulsion Systems	Conclusion
Lévay et al. (2017) [22]	Urban	Private TCO	BEVs and Diesel	The relationship between fiscal incentives, TCO, net price, and sales of eight EV-ICE vehicle pairs in eight European countries.Negative relationship between TCO and sales of cars is confirmed in the European markets besides Norway. The exemption of flat taxes helps electic HD, while lump-sum taxes favours small EVs.
Vora et al. (2017) [29]	Urban	Private TCO	PHEVs	A framework incorporating fuel consumption, battery degradation models, electricity consumption and battery replacements including TCO is designed. PHEVs are economically viable in medium duty while not competitive in heavy-duty class.
Lebeau et al. (2019) [30]	Urban and Extra-Urban	Private and Social TCO	BEVs and Diesel	Fiscal incentives and kilometer-based charges for eLCVs improve TCO. Usage conditions and battery life are also crucial in making eLCVs cost competitive.
van Velzen et al. (2019) [31]	Urban and Extra-Urban	Private TCO	BEVs	TCO of EVs has been discussed from various scenarios, and does not fall much lower than to ICEs unless stimulated by tax and other policies for the long term.
Jones et al. (2020) [32]	Urban	Private TCO	FCEVs	FCEVs TCO is not economically competitive to the conventional counterpart but several market scenarios and future policies are discused.

Table 1. *Cont.*

Author/Year	Case Study	Methodology	Observed Propulsion Systems	Conclusion
Scorrano et al. (2021) [21]	Urban	Private TCO	BEVs, Petrol and Diesel	eLCVs have higher TCO than conventional counterparts but some eLCVs models in different categories are cost- competitive.
Liu et al. (2021) [33]	Extra-Urban	Private and Social TCO	BEVs and Diesel	Due to the higher initial prices BEVs can break even with ICE in 6 years. However, long-range BEVs are more favorable with policy support and economic incentives.
Lee et al. (2021) [34]	Urban	Private TCO	FCEVs	TCO of FCEV and its corelation with market share is investigated by regression curve. An optimization model of hydrogen refuelling stations is also forecasted for several years.
Wróblewski et al. (2021) [35]	Urban and Extra-Urban	Private TCO	FCEVs, EV, HEV and PHEV	Comparitive analysis of the purchase price of FCEV in relation to TCO for 3–5 years is performed. The importance of economic factors in the TCO index for the development of the market is discussed.
Hunter et al. (2021) [36]	Urban	Private TCO	diesel, diesel hybrid electric, PHEVs, CNG, BEV, and FCEV	Although more costly now, zero-emission and near-zero-emission vehicles will eventually catch up to diesel vehicles in terms of cost by utilizing developments in battery, fuel cell, and hydrogen technology.
Qasim and Csiszar (2021) [37]	Urban and Extra-Urban	Private TCO	BEVs	The TCO gap between BEVs and ICE can be bridged by incentivisation. Major issues concerning the reluctance of to adopt BEVs are also analyzed.

Table 1. *Cont.*

Author/Year	Case Study	Methodology	Observed Propulsion Systems	Conclusion
Phadke (2021) [38]	Extra-Urban	Private TCO	BEVs and Diesel	BEVs (trucks) are now poised to meet the performance demands of regional and long-haul operations. CAPEX costs and infrastructure costs are the primary barriers for BEVs. These barriers can be overcome by policy support and coordinated investment in infrastructure and manufacturing facilities.
Tanco et al. (2019) [39]	Urban and Extra-Urban	Private TCO	BEVs and Diesel	TCO analysis of battery electric trucks of different classes in Latin America is performed to calculate the break-even year. Chile and Uraguay are the first to achieve a break-even year. Initial investment is the primary barrier while fuel/electricity price is crucial for parity achievement.
Asef et al. (2022) [40]	Extra-Urban	Private TCO	HEV and Diesel	A validated model is implemented to minimize the TCO of the battery thermal management system for BEVs. Results converged the total cost of optimization for all driving cycles.
Basma (2022) [41]	Urban	Private TCO	BEVs and diesel	While last-mile delivery battery electric trucks can now achieve TCO parity with diesel trucks due to currently available purchase subsidies, otherwise it would take them until 2025–2030 to achieve economic parity. The pricing difference between BETs and diesel trucks can be closed by adjusting the battery size to the truck's daily mileage and energy requirements.

Table 1. *Cont.*

Author/Year	Case Study	Methodology	Observed Propulsion Systems	Conclusion
Rout et al. (2022) [42]	Extra-Urban	Private TCO	FCEVs, BEVs and diesel	Under baseline assumptions, several FCEVs are cost competitive to diesel counterparts while BEVs are not. Key barriers in the development of FCEVs in heavy-duty and off-road applications are also identified.
Schwab et al. (2022) [43]	Urban	Private TCO	BEV and Diesel	BEVs cost for different BEV-penetrations and charging strategies are identified. Purchase price usually drives the TCO of BEVs.
Castillo Campo and Álvarez Fernández (2023) [44]	Urban	Private TCO	Diesel, BEVs, HEVs, FCEVs and CNG	The key economic and operational factors are from the perspective of cost per kilometer, makes a certain van type more competitive than the alternatives. FCEV vehicles that use hydrogen that has been purchased and delivered to the depot are the best choice under a variety of operational and financial circumstances.
Lal et al. (2023) [45]	Urban	Private TCO	Diesel, BEVs and FCEVs	For last-mile delivery BEV is preferred over its diesel counterpart. For fleet conversion Life cycle assessment with scenario analysis is performed.
Gil Ribeiro and Silveira (2024) [19]	Urban	Private TCO	BEVs and Diesel	Cost competitiveness of BEV LCVs varies throughout Europe. It varies with market conditions, vehicle type and incentives.

The pioneering studies in TCO were conducted by [46], refs. [18,24] investigating eLCVs cost competitiveness against conventional fuels. Ref. [47] examined the cost competitiveness of various LCVs based on alternative drive technologies including CAPEX subsidies, toll, and fuel costs through TCO. Results highlight that BEVs are most promising in the light/medium duty segment. The cost competitiveness of eLCVs against the petrol/diesel counterparts from a TCO perspective was also analyzed by [21,29] which portrays that eLCVs, without government support have higher TCO per km as compared to the traditional counterparts. Several studies have focused on the optimization of life-cycle costs for the selection of alternative drive chain technologies in comparison with Internal Combustion Engines [22,47–49]. The challenges of using BEVs as LCVs comprise large charging times, material shortages, and energy densities that can lead to service and productivity shortages. Conversely, FCEV LCVs have the advantage of faster refueling, low fuel cell degradation, and sustained productivity. According to [42], hydrogen has the capability to replace BEVs in LCVs and off-road applications under specific favoring condition i.e., purchase grants and reduced price.

In urban freight transportation, BEVs tend to be cost competitive [21,32], while FCEVs need more subsidies and tax reliefs against their diesel rivals [19]. Incentives have a significant effect on TCO and are typically required to make BEVs and FCEVs cost-competitive. BEVs produce 19–43% fewer greenhouse gases and use 5–34% less energy during a drive cycle with fewer stops and a higher average speed, yet they are 1% more expensive than their diesel equivalents [9].

Several studies investigated the TCO for urban freight/deliveries while analysing different LCV models. To the best of our knowledge, none of them discusses the cost-competitiveness of sustainable fueled refrigerated LCVs while comparing its external cost with the conventional diesel LCVs. Social TCO analyses are sometimes presented, but considering only GHG emissions for different propulsion systems. Additionally, the light commercial vehicle market is anticipated to increase at the fastest rate, with a compound annual growth rate (CAGR) of more than 8.0% from 2017 to 2025. With the expansion of the fast-moving consumer goods (FMCG) and e-commerce industries, there will likely be more demand for refrigerated LCVs, which are especially useful in urban driving circumstances [50]. Thus, the contribution of this study is to analyze the TCO of RLCVs with different propulsion systems (diesel, electric, FCEV, and Biofuel LCVs) commonly used for the distribution of goods in urban and extra-urban conditions while incorporating their detailed externalities.

3. The Total Cost of Ownership Approach

Purchasing, owning, operating and disposing of a light commercial vehicle entails several monetary and non-monetary (customer complaints) as well as private (service costs) and social costs. In this paper, however, we focus only on the monetary and social/external costs of ownership. Drawing from the literature, we adopt a TCO approach to estimate and compare the cost of purchasing and operating LCVs with different propulsion systems.

3.1. The Private TCO

The TCO metric permits buyers to easily compare all costs that are related to the product during its useful life [51]. It incorporates initial costs (CAPEX), annual operating costs (*OPEX*), and the residual value at the end of useful life.

CAPEX includes all of the up-front expenditures associated with purchasing the vehicle. Besides the list price (Manufacturer's Suggested Retail Price, *MSRP*) for both the chassis and the coldbox, it includes potential Retailer Discounts (*RD*), Government Subsidies (*SUB*), Registration Cost (*RC*), and Charging Equipment (*CE*).

$$CAPEX = MSRP - RD - SUB + RC + CE$$

OPEX incorporates all the costs that are incurred during the ownership period *N*, given an annual distance travelled (*ADT*). They can be calculated for every year $n \in [1, N]$ as:

$$OPEX_n(ADT) = CT_n + INS_n + MAINT_n(ADT) + F/E_n(ADT) + E_{n,coldbox}$$

where *CT* is Circulation Tax, *INS* is Insurance Premium, *MAINT* is Annual Maintenance and Operating Costs, while F/E refers to Fuel/Electricity costs depending on the propulsion system, and $E_{n,coldbox}$ is the electricity cost to maintain the box refrigerated. F/E depends on fuel/electricity efficiency and fuel/electricity price. The former depends on many variables, such as weather, traffic, and road conditions. We took into account the share of LCV's urban or extra-urban use on the total driven distance and the weather conditions, defining F/E_n as:

$$F/E_n = \gamma \cdot (\alpha \cdot F/E_{urb,n} + (1 - \alpha) \cdot F/E_{extraurb,n})$$

where γ is a weather-adjustment factor, $F/E_{urb,n}$ and $F/E_{extraurb,n}$ the fuel/energy efficiency in urban and extra-urban roads, respectively, and α is the percentage of trips driven in urban contexts. The electricity price differs when charging occurs at the depot or at public chargers. We thus computed it as the weighted average of the electricity price paid at the company depot and that at the public charger.

The residual value (*RV*) is the resale value at the end of the ownership period and can be computed as a percentage δ of the *MSRP*:

$$RV = \delta \cdot MSRP$$

Since *CAPEX*, *OPEX* and *RV* occur at different points in time, such costs and revenues should be appropriately discounted and annualized. The annual *TCO*, hence, is computed as follows:

$$TCO = \left[CAPEX - \frac{RV}{(1+i)^N}\right] \cdot CRF + OPEX_n$$

where $CRF = \left(i\left((1+i)^N\right)/[(1+i)^N - 1\right])$ is the capital recovery factor, with i being the company's annual weighted average cost of capital.

Dividing this sum by the *ADT* in kilometers, we finally obtain the metric TCO/km, which represents the average cost per kilometer of owning a given vehicle:

$$\frac{TCO}{km} = \frac{TCO}{ADT}$$

3.2. The Society Oriented TCO

Besides private costs borne directly by transport users [52], transport generates numerous detrimental effects that affect other people but are not entirely represented in the user's cost [53]. For such reason, they hardly influence the mobility decisions of individual travelers. Ignoring such costs may result in undesirable consequences, with society bearing the uncompensated expenses [54]. Transport negative externalities include, among others, air pollution, greenhouse gas emissions, noise pollution, and land usage. Internalizing such external costs could contribute to making transport users more aware of the negative social consequences of transport, and to include these effects in their decision-making process. In this research we thus added a social perspective to the solely private TCO metric, by considering all the externalities of LCVs (€ cent/km) shown in Figure 1. They comprise accident costs, air pollution costs, climate change costs, noise costs, congestion costs, well-to-tank emission costs and habitat damage including soil and water pollution. These costs are reported in [52,55] and estimated using data from Eurostat (Road Transport Performance Data) relative to EU28 countries. These estimates were available individually for the diesel-powered, biodiesel, BEVs and FCEVs, but some values are missing in the handbook due to uncertainty in the input data. We made some assumptions to obtain the missing values. For BEVs and FCEVs, we have assumed zero tailpipe emissions [56,57]. Similarly, the air pollution costs for BEVs and FCEVs are also assumed to be zero [14,57,58]. The climate change costs for BEVs and FCEVs are assumed 90 percent lower than conventional diesel vehicle [52]. Finally, we assumed green sources of electricity for BEV LCVs charging and green hydrogen for FCEVs in our calculation.

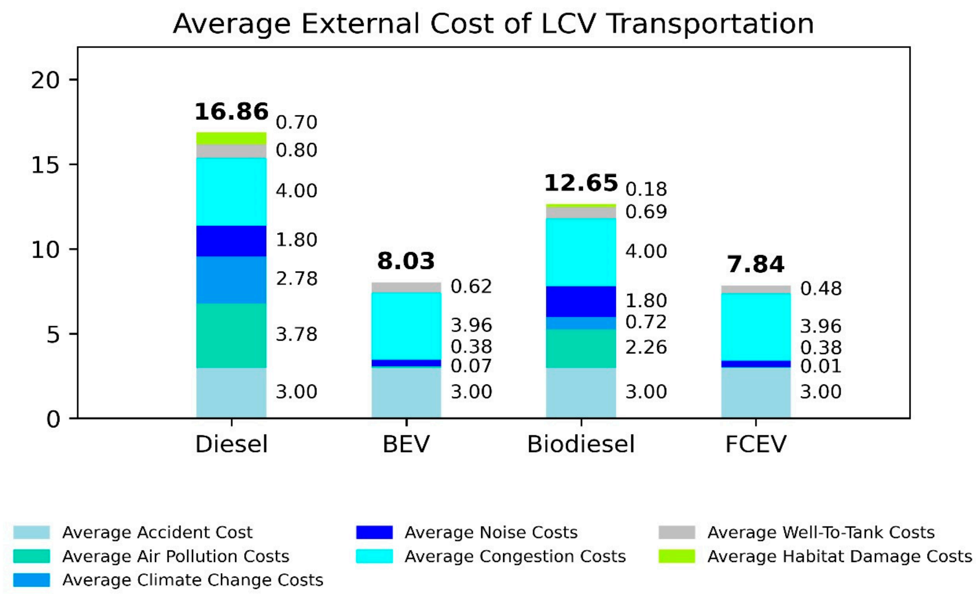

Figure 1. Average External Costs (€ cent/km) of LCV Transportation [52].

4. The Case Study

4.1. The Bofrost Case Study

Bofrost is a multinational German Food company that delivers frozen foods and ice-creams door-to-door through a proprietary fleet. The company database comprises six million customers with 246 branches globally. Bofrost holds a major share in the Italian market. From the logistics perspective, Bofrost Italia S.P.A has a gigantic transportation fleet of more than 1600 refrigerated diesel LCVs travelling 47 million km per year. Almost 90% of the current fleet comprises diesel-fueled IVECO-daily and the rest comprise diesel fueled Toyota Hilux (Figure 2).

However, the increase in customer attention towards sustainable practices throughout the value chain, as well as the stringent environmental goals posed at the European level, has urged the company to fulfil their demands sustainably. As a result, Bofrost is ambitious to improve sustainable practices while minimizing its reliance on conventional practices, to attain a competitive advantage in the market. This study was primarily motivated by the severe regulations applied in the main Italian cities, where the access to traditional gasoline-powered vehicles has been prohibited or limited in the city centres. The company's interest in investigating the economic feasibility of converting part of/its fleet with more sustainable vehicles is fostered by the fact that most of the potential customers reside inside these areas, and they are the prominent contributors to the company's sales in these regions.

Figure 2. LCVs in Bofrost Fleet.

4.2. Assumptions and Parameters

The prominent challenge encountered when trying to compare the TCO among LCVs lies in the presence of multiple LCV variants. Bofrost uses LCVs of different size and mass. We thus divided them into three categories (city, panel, and box LCVs). City LCVs are those which are designed and promoted especially for the transportation of products, and they resemble car-derived LCVs in size. Due to their small size, trading and delivery companies use them in urban areas. Panel LCVs lack rear side windows and are bigger than city LCVs but smaller than a truck or lorry. They are particularly suited for deliveries in cities since they are agile and maneuverable while yet having more cargo space than city LCVs. Box LCVs have a large, independent cargo space in the shape of a cube, separate from the cab. Delivery drivers and couriers utilize them because they value their boxy shape when transporting heavier or larger packages. Box LCVs are often only accessible through the back doors because they are raised off the ground due to their chassis placement, the cargo compartment is not compromised by wheel arch incursions.

For each category, we identified the main diesel LCVs in the Bofrost fleet, and the electric and FCEV alternatives currently available in the market and offered by the main LCV manufacturers (e.g., Iveco, Fiat, Mercedes e-Vito, Opel, Peugeot, Toyota, Citroen) Specifically, the models considered are: (i) for the BEVs, the Iveco e-Daily, the Fiat e-Scudo and e-Doblo, the Peugeot e-expert combi, the Mercedes e-Vito Panel Van, the Toyota e-Proace, the Citroen e- Space, the Renault e-Kangoo, and the Opel Vivaro-e Combi; (ii) for the diesel/biodiesel the Iveco Daily, the Toyota Hilux and the Fiat Doblo; (iii) for the FCEV the Opel e-Vivaro Hydrogen, the Renault Master and Kangoo ZE Hydrogen.

TCO is calculated based on several parameters derived from the existing literature and data sources from country-specific perspectives. Many uncertainties characterize the TCO metric. There are, for example, different versions of LCVs with different equipment and accessories, and such differences might affect their economic competitiveness. To overcome this issue, we selected the base variant for the vehicles to guarantee comparability among different models. Another uncertainty regards the actual purchase price paid by an operator. It may differ from the MSRP because of location- and season-specific retail discounts, or for subsidies. Our simplifying assumption for all models and all propulsion systems is that the purchase price is equal to the MSRP (VAT excluded). The headquarter of Bofrost lies in San Vito al Tagliamento, in the Friuli Venezia Giulia Region in Italy, so the current country-specific incentives and subsidies are adopted in calculation. In Italy, national purchase subsidies amount to €12,000 for the box electric and FCEV, and €8000 for panel electric and FCEV, and €4000 for city electric and FCEV (https://ecobonus.mise.gov.it/ecobonus, accessed on 21 September 2024). These subsidies can be availed with scrapping at the end of useful life. For biofuel fueled LCV, the subsidies for box, panel and city categories are €3000, €2500 and €1500, respectively. No subsidies and extra charges are considered for diesel-fueled LCVs.

Cost of the cold box and their respective energy costs are separately identified for small and large LCVs.

As for the OPEX costs, regarding the maintenance and operations costs, diesel and biodiesel LCVs have higher maintenance costs, due to the majority of moving parts but their spare parts are less expensive than their rivals. BEV spare parts are moderately priced but frequent battery maintenance is crucial. In contrast, FCEV spare parts are highly expensive with much lower maintenance costs and routine.

We used the Italian average fuel and electricity prices in 2024. These values are kept constant over the vehicles' lifetime. Bofrost warehouses exist throughout Italy, so most of the charging for the eLCVs will be at the branch (80%), and the rest (20%) at the public charging stations. The electricity price at the depot is set at 0.21 €/kWh, while that at the public charging stations at 0.45 €/kWh. We did not consider the conversion of the full fleet as this would pose additional expenses of electric infrastructural upgrading on the company management which is estimated to be up to 300,000 euros per company branch. The current capacity of electric infrastructure supports 3–4 charging stations at each branch. For FCEVs we considered the price of green hydrogen in our analysis. We did not include the infrastructure costs for hydrogen and eLCVs and assumed their availability at refueling/charging station.

As for the fuel efficiency, while for the diesel LCVs we relied on real time data from the Bofrost database, for eLCVs (https://ev-database.org/, accessed on 21 September 2024) and FCEVs we based our analysis on fuel consumption data (in urban and extra-urban-conditions) provided by manufacturers. Bofrost operations extend throughout Italy, so we assumed 60% of the trips to be in urban areas and 40% in extra-urban areas. Moreover, based on the evidence we gathered from previous literature [58] and social media data, we considered for eLCVs a 30% decrease in energy efficiency when driving at very high (in summer) or very low (in winter) temperatures. This entails an adjustment γ in the electricity consumption of 1.15 (no adjustment, i.e., $\gamma = 1$, is needed for diesel LCVs).

Another source of uncertainty has to do with resale prices, particularly those pertaining to eLCVs and FCEVs. Due to the immaturity of their market, in fact, no data are available from the second-hand market. In line with the company's and industry standards, we considered a useful life of 8 years (with no battery substitution costs for eLCVs), and a low residual value (15%) at the end of the ownership period. Based on the existing literature, most of the manufacturers guarantee battery useful life of 8 years or 160 thousand km, hence sustaining our assumption [59]. We assumed an annual distance travelled of 30,000 km. Bofrost has 225 working days (excluding 104 weekend days and 8 Italian festival vacations), thus the average daily distance travelled is 130 km.

While using the parameters described, the formulated baseline scenario for this research includes:

5. Results

5.1. The Baseline Scenario

Table 2 reports the TCO estimates for the baseline scenario for the three LCV categories (city, panel, and box) and for the four different propulsion systems (diesel, biodiesel, electric, and FCEV), considering only private costs and then adding social costs.

Table 2. Private and Social TCO/km per Propulsion System for Refrigerated LCVs.

	Box LCV				Panel LCV				City LCV			
	Diesel	Bio Diesel	BEV	FCEV	Diesel	Bio Diesel	BEV	FCEV	Diesel	Bio Diesel	BEV	FCEV
MSRP (€)	49,255	49,255	96,300	152,300	46,848	46,848	55,965	135,600	33,120	33,120	47,850	59,000
Annualized Capex (€)	6202	6202	11,082	17,891	6201	6201	6592	16,232	4407	4407	5528	6744
Annual Opex (€)	10,050	10,521	5402	10,443	10,085	10,568	4976	9830	6375	6541	7426	7810
Annualized Resale Value (€)	241	181	603	2353	362	361	832	2261	302	299	672	875
Annualized TCO (€)	16,011	16,543	15,882	25,982	15,924	16,408	10,736	23,801	10,480	10,649	12,282	13,680
TCO/km (€)	0.534	0.551	0.53	0.866	0.531	0.547	0.358	0.793	0.356	0.355	0.323	0.456
Overall TCO (Private + Social) TCO/km (€)	0.702	0.677	0.61	0.944	0.699	0.627	0.438	0.871	0.524	0.481	0.403	0.534

The findings indicate that BEV LCVs offer significant advantages in terms of the environment and economy. While looking at the MSRP, diesel and biodiesel offer lower initial costs because of the low development cost and the already attained maturity level. Current MSRPs for the BEVs are double (Box €96,300 and Panel €55,965) and for FCEVs (Box €152,300 and Panel €135,600) they almost tripled when compared to the diesel and biodiesel counterparts (Box €49,255; Panel €46,848; and City €33,120). BEVs, on the other side, present the lowest annual operating costs. Overall, the TCO/km of the BEV in box LCVs is €0.53, for diesel €0.534, for biodiesel €0.55, and for FCEV €0.87. In the panel and city segments BEVs are already cost-competitive (€0.36, €0.32) because of their current market expansion offering a variety of vehicles based on battery power and mileage capacity, confirming the results in the recent literature [21,44]. Biodiesel also emerges as a prospective remedy to bridge the gap for LCVs, given its ability to deliver satisfactory outcomes across all the dimensions under consideration. The FCEV alternative is the least cost-competitive. The two primary reasons for the FCEV's higher cost are fuel cost and MSRP. Currently, fuel cells are the more expensive option due to their high upfront expenses. However, future cost advantages over combustion engines and battery-electric vehicles may result from increased production efficiency and lower fuel prices. Concentration on applications with a broader scope and long-range solutions are desirable.

Regarding the social TCO, it plays a pivotal role in the decision-making process of acquiring green fuel LCVs. Transport users only consider a portion of the social costs when making decisions, leading to sub-optimal outcomes, since the market does not incentivize them to consider external costs. Recalling Table 1, social TCO/km has the ability to change strategic decisions while acquiring LCVs of different propulsion systems. When considering not only private costs, but also transport externalities, BEVs result in the less expensive alternative in each LCV category, confirming its competitiveness both from an economic and an environmental prospect. Due to the restricted distance capability of existing battery technology, however, their operation could be restricted, thus so far their widespread adoption is expected to be primarily feasible for urban delivery trucks.

5.2. Sensitivity Analysis

The TCO metric is inherently vehicle-, region- and individual-specific. Country and regional specificities in terms of regulatory and financial policies (with incentivizing subsidies or disincentivizing taxes) or individual characteristics (driving style, travelling and charging habits/needs, vehicle use intensity measured by the average annual distance travelled) might affect the results. For this reason, we performed a sensitivity analysis to explore the impact of changes in the model parameters.

We start with assessing the impact of ADT on the economic competitiveness of the proposed alternatives. Our results show that for each category, variations in ADT significantly change the TCO/km. The longer the annual distance travelled, the higher the annual savings on operating expenses for the BEV against conventional ones, hence their cost-competitiveness. In the panel and city categories, BEVs result cost competitive even with very low ADT. In the box category, they become cost-competitive with ADT higher than 27,000 km. As for FCEVs, we find that they are currently not competitive to their diesel ones in all three categories even if the ADT is doubled (see Figure 3 for the Box category).

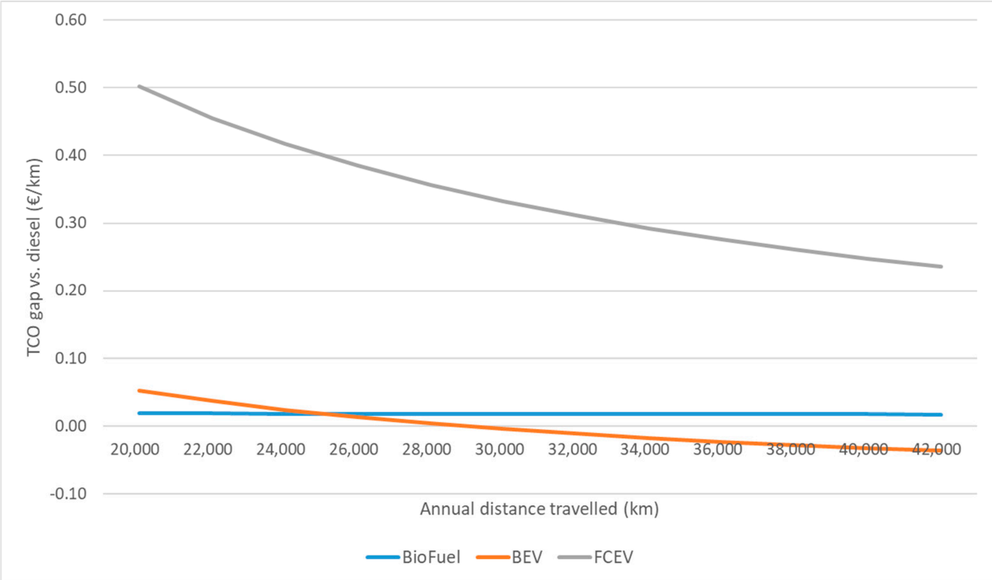

Figure 3. TCO gap vs. diesel LCVs in the box segment by varying ADT.

Generally, eLCVs hold great potential for the transportation of goods within urban areas (Figure 4). This is primarily due to their ability to operate optimally in environments characterized by low average velocities, frequent decelerations, and stops, as well as their efficient utilization of regenerative braking mechanisms. Moreover, the limitations on the range of eLCVs align more suitably with urban goods distribution, thereby enabling their predominantly home or company garage charging at the conclusion of the workday [21]. In contrast, diesel and biodiesel LCVs exhibit better fuel efficiency on the highway as compared to urban locations. FCEV offers far more driving range than its electric rivals. Master ZE hydrogen, for example, offers more than 350 km and Kangoo ZE hydrogen has best driving range offering 370 km plus, enabling its use for longer distances and less recharging time (approx. 5 to 10 min). Figure 4 shows that BEV LCVs in the box category need to travel at least 40% of the trips in urban areas to be cost-competitive with respect to the diesel counterpart, while the gap is always negative for the pane and city BEV LCVs.

Policies also play a relevant role. LCVs are subject to a multitude of regulatory (command-and-control) and fiscal policies, particularly in the context of urban areas. These policies are applied in both large and medium-sized cities, particularly those with a historical center characterized by narrow streets. Typical measures include regulations on the time of access for delivery LCVs, restrictions based on vehicle type, policies related to loading and unloading, fiscal measures, and the encouragement of urban transhipment and consolidation centers [60]. Because of zero emissions, FCEVs and BEV LCVs have unlimited access to the limited traffic zones (LTZ). To enhance the effectiveness of the measure regarding vehicle replacement, the city of Milan and the Lombardy Region offer subsidies. Specifically, the latter provides financial assistance for the procurement of alternative-fuel LCVs. The amount of subsidy varies depending on the propulsion system employed (with the highest incentive awarded to eLCVs) as well as the vehicle's mass. The incentives range from €6,000 for smaller eLCVs (weighing up to 1.49 tonnes) to €10,000. Rome charges very high annual fees to access the LTZ ranging from €392 to €2032, depending on fuel and engine technology [61]. Milan imposes a daily fee, which can range from €3 to €5, for individuals to enter the restricted areas known as "Area C", which is the central area of the city. Conversely, Florence charges a fixed fee of €5 per day. It is worth noting that all cities in Italy waive access fees for eLCVs [62]. Our results show that the introduction of subsidies has sufficiently improved the threshold purchase price and TCO for FCEV and eLCVs in all categories. Besides decreasing the financial requirements, these subsidies made the city (Renault e-kangoo, Fiat e-doblo) and panel eLCVs (Peugeot e-expert combi, Fiat e-Scudo, Mercedes e-Vito, Toyota E-Proace, Citroen E- Space tourer, Opel Vivaro-e Combi) even more effective than the diesel ones even at low ADT. However, in the box category, IVECO e-daily is also cost competitive with its diesel counterpart. Contrary, due to the high MSRP of the FCEVs, more subsidies and financial incentives are required to make them cost-competitive with their rivals in the box, panel and city segments. For FCEV, the incentives and subsidies in the transalpine countries (Italy, Germany and Austria) are estimated at up to 16,000 euros [63]. From the user's perspective, the decision to choose a zero-emission vehicle for their upcoming purchase is not immediately obvious. In France, national hydrogen projects can be funded by the ADEME, the Agency for the Environment and Energy Control, with a maximum contribution of €16,000 toward the purchase of a hydrogen vehicle within the global hydrogen supply, vehicle, and use context. In our case, without subsidies panel and city eLCVs are still cost-competitive to diesel LCVs due to the development of charging infrastructure and minimum operating costs. The sensitivity analysis shows that the eLCVs are cost-competitive to the diesel counterparts in the absence of existing subsidies in city and panel segments. However, FCEV box LCVs require a subsidy of €36,000 to be cost competitive under the baseline scenario because of their higher MSRP. Panel and city FCEV LCVs requires a threshold subsidy of €26,000 and €15,590 respectively to be cost competitive to their diesel counterparts.

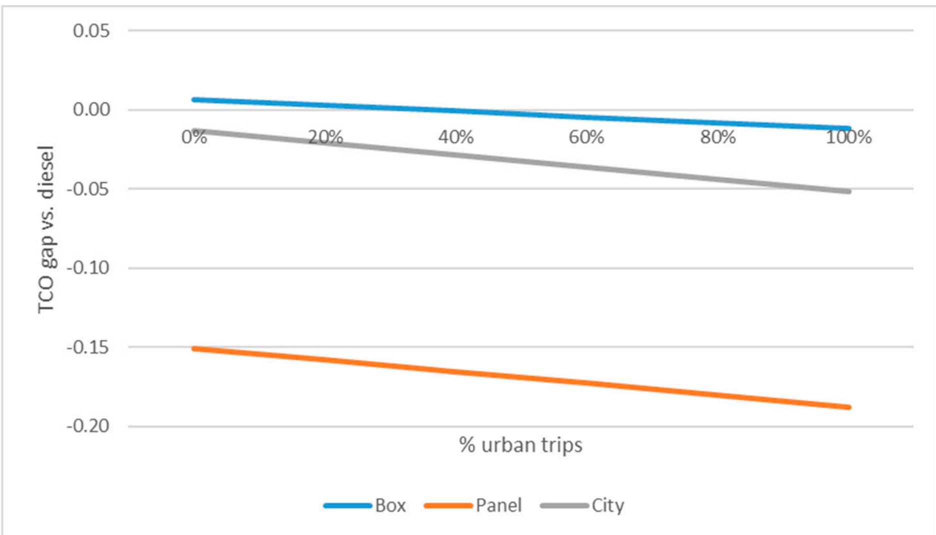

Figure 4. BEV TCO gap vs. diesel LCVs by varying the share of urban trips.

When considering the impact of electricity/fuel price on the economic competitiveness of LCVs, we found that with an electricity price up to 0.23 €/kWh eLCVs are cost-competitive to the diesel in box, panel and city categories, while in box and panel category, hydrogen is not diesel competitive if the price falls to 3 €/kg under the baseline scenario. The results vary for the city LCVs where the hydrogen is partially competitive at the price of 3 €/kg against the diesel. The possibility to charge at the depot at lower electricity prices affects the cost competitiveness of BEV LCVs. Figure 5 shows that in the box segment, the company needs to charge at least 72% of the times at the depot to make BEV LCVs cost-competitive with their diesel rivals, while in the city segment a lower share (20%) is required.

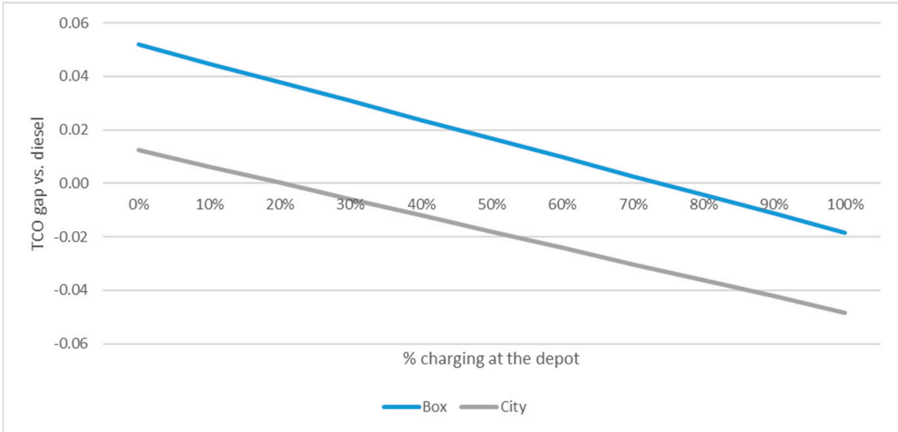

Figure 5. BEV TCO gap vs. diesel LCVs by varying the share of charging at the depot.

6. Discussion and Conclusions

In conclusion, we have investigated the economic feasibility of different alternatives to the conventional LCVs fleet of Bofrost. Besides private TCO, we also presented a social TCO to enhance the resilience of the proposed model in selecting sustainable fuel LCVs. Our case study proves that, under the baseline assumptions, BEVs are already cost-competitive with respect to the other propulsion systems, while FCEVs are not. BEV LCVs currently outperform its rivals followed by diesel, biodiesel and FCEV subsequently. Lower external and operational costs of BEVs are the primary factors making it a viable sustainable alternative. Based on the nature of Bofrost operations, BEVs are the most suited option besides their range constraints and higher MSRP. Through sensitivity analysis, it is also confirmed that even in the absence of government subsidies, panel and city BEVs are still cost-competitive with their diesel counterparts. For biodiesel, the higher price of fuel and associated external costs are the fundamental factors that affect its cost-competitiveness against its rivals. Moreover, the FCEVs lag its cost competitiveness in all LCV categories due to initial costs and the absence of hydrogen refueling infrastructure. Sensitivity analysis also confirmed that even doubling the parameters (subsidies/financial assistance, ADT) for FCEVs still makes it non-competitive to the diesel LCVs. However, the FCEV possesses the advantage of the lowest external costs due to zero tailpipe emissions.

Large corporations are progressively transitioning from pilot-scale programs to replacing considerable numbers of vehicles in their fleets with electric LCVs. UPS ordered 10,000 eLCVs from UK startup Arrival; British Gas ordered 1000 Vivaro-eLCVs from Vauxhall; and Amazon ordered 1800 eLCVs from Mercedes [64]. This reflects the belief that TCO considerations already work in favor of eLCVs in certain situations. Conversely, EV sales have increased significantly over the past few years due to widespread interest in the electrification of LCVs and passenger automobiles. Yet percentage of EVs on the road still makes up a very small portion. If we proved that eLCVs are already cost-competitive with respect to their diesel equivalents, the lower driving range might affect the daily companies' operations, requiring increased charging time and workers stops. A rethinking of the company's logistics planning and control is then required. Bofrost Italia has recently purchased several BEV LCVs (Toyota e-Proace) and they are monitoring the real-time performance of these LCVs subjected to the nature of their operations, but due to lack of sufficient data they are still hesitant to make their final decision. Bofrost is also willing to invest in the charging infrastructure for its refrigerated LCVs. Different energy companies has already given their bids for developing the infrastructure offering to install 33 charging stations at €75,000. However, the present electric system has a maximum output capacity between 80–90 KW which can support a maximum of 4 eLCVs charging at the same time. The upgrading of the electric system at Bofrost warehouses (branches) needs to be above 100 KW for installing the charging station at maximum number which is a huge investment including the cost of power increase and connection, cost of upgrading the existing cabins to medium voltage, cost of panels adoptions and electrical lines, and finally the cost of supplying and installing the charging stations. When considering the renewal of the entire fleet, these costs should be properly taken into account.

Low-carbon hydrogen is anticipated to be a dependable dispatchable and backup power source, contributing significantly to the decarbonization of vital industries, transportation, and power generation. Its widespread adoption, however, is beset by substantial investment obstacles. Initially, the direct expenses associated with manufacturing FCEVs are one facet of financial issues. Refueling stations also demand an investment, which is one of the several direct expenditures. The cost of producing low-carbon hydrogen is currently two to three times greater than that of fossil fuels. Hence, it is imperative to increase output and lower costs in order to facilitate the widespread adoption of low-carbon hydrogen. To do this, new markets for low-carbon and renewable hydrogen must be opened, and specialized infrastructure for hydrogen must be developed. The European Hydrogen Bank, which would provide renewable hydrogen producers with subsidies in the form of a set premium per unit of hydrogen produced, has been proposed by the European Commission. A competitive auction mechanism will be used to decide the premium's value. In addition to minimizing the expenses required to meet the EU's hydrogen production targets, this process will assist in identifying and filling the financial gap required to scale up hydrogen production. For ten years following the start of production, a set premium of between EUR 1.7 and EUR 2.5 per kg of H_2 produced is anticipated as a result of the subsidy in the initial auctions [65]. However, the program's proposed budget is still insufficient to enable the large-scale production of green hydrogen. But as hydrogen production technology advances and might eventually support higher volumes, the value of subsidies given in successive auctions is anticipated to decline. Lastly, the European Hydrogen Bank will exclusively fund green hydrogen (renewable energy sources are used for eletrolysis to produce hydrogen), rather blue hydrogen (produced from natural gas mixed with hot steam as catalyst which may result in certain emissions if not captured properly) projects in accordance with the plan.

Many countries have declared long-term plans and goals for the development of hydrogen energy. Hydrogen Europe and ACEA voiced concerns with the EU Council's lack of ambition in setting deployment targets for electricity and hydrogen refueling stations in road transportation. According to recent statements made by a number of automakers, assuming the necessary framework and infrastructure for refueling are in place, there should be about 50,000 heavy-duty hydrogen-powered vehicles operating in Europe by the end of the decade [66]. The first-ever transnational initiative, the North Adriatic Hydrogen Valley (NAHV), has been created with assistance from the Clean Hydrogen Partnership and the Horizon Europe program. The whole renewable hydrogen value chain is covered by the 17 pilot projects that make up the NAHV. The objective is to expedite the shift to renewable energy in industries like transportation and industry by establishing a competitive market for green hydrogen. The Clean Hydrogen Partnership contributed 25 million euros to the project, and it was given the Horizon Europe Seal of Excellence. Towards decarbonization and sustainable innovation, the NAHV is a major step toward the goals of the European Green Deal. The project serves as a paradigm for upcoming projects in

Europe and beyond due to its collaborative and cross-border nature. According to estimates made by the US Department of Energy and the National Renewable Energy Laboratory regarding the market adoption of FCEVs [67], 320–570 hydrogen refueling stations would be required to support the adoption of 90,000–200,000 FCEVs in the early adoption stage, and 1500–3300 stations will be required in the midterm to support 1.8 million–4.5 million FCEVs. 7800–21,000 stations will be required by 2050 to accommodate the demand for hydrogen refueling of 23 million–61 million FCEVs.

By 2026, 36 additional hydrogen refueling stations will be built around Italy thanks to financing that the government plans to provide up to €103.5 million [68]. The Ministry of Infrastructure and Transport has approved 36 projects that span the entire nation, from Bolzano in the extreme northeast to Taranto and Catanzaro in the south, Aosta in the northwest, and Rome, Milan, and Tuscany in the middle.

The production and application of biofuels in transportation are encouraged by the policies and goals of numerous governments [69–71]. The global production of ethanol increased from 49.675 billion L in 2007 to 111.026 billion L in 2019 (the production decreased to 99.972 billion L in 2020 due to COVID impact and increased to 103.379 billion L in 2021) [72]. This increase was primarily driven by the use of sugarcane ethanol in flex-fuel vehicles in Brazil and the United States. The world's output of FAME was 43 billion L in 2018 and is expected to reach 57 billion L by the end of 2024, with the European Union and Indonesia being the two main producers [73]. The yearly production of biofuel is expected to increase to 902 billion L by 2050 [74]. Even though the amount of biofuel produced today is insufficient to fully replace fossil fuels with the environmentally friendly alternative, as more and more nations enact laws requiring the blending of biofuels with petrofuels, it is conceivable that the amount of new CO_2 added to the atmosphere will be significantly decreased.

This study focused on the economic competitiveness of more sustainable alternatives to the current diesel LCVs for the refrigeration market segment, disregarding other crucial elements in the company's decision-making, such as preferences, brand loyalty, vehicles' technical characteristics, and accessibility of infrastructure for charging and refuelling. We analyzed the case study of one of the major Italian companies delivering frozen food. Most of the assumptions in the calculation of the TCO metric are, thus, company-specific and consider the Italian-specific policies. Our results, hence, might not be valid for companies operating in different countries or in other segments.

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

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be available upon request from the corresponding author.

Acknowledgments: The authors gratefully thank Bofrost Italy for their support in the data collection.

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

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