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Master’s Degree in Mechanical Engineering

Master’s Degree Thesis

A TCO assessment of battery-electric trucks in the European market

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Abstract

The urgent need to curb greenhouse gas emissions from heavy-duty vehicles (HDVs) in Europe necessitates a transition toward zero-emission technologies. The goal of this study is to determine if zero-emission HDVs, in particular tractor-trailers, are economically feasible by thoroughly examining all factors related to total cost of ownership (TCO).

HDVs continue to contribute significantly to CO2 emissions despite international efforts; in the EU, they account for about 25% of emissions from road transport. According to the most recent provisional agreement between the European Parliament and the Council on CO2 emission standards for HDVs, manufacturers will have to cut emissions by 45% by 2030, 65% by 2035, and 90% by 2040, relative to 2019 levels in order to achieve climate neutrality by 2050.

Promising alternatives include a range of zero-emission technologies, such as electric road systems, fuel-cell electric trucks, and battery-electric trucks. Recent years have seen a sharp increase in the sales of electric commercial vehicles, fueled by demand growth and incentive programs. Large-scale adoption of these alternative technologies is hampered by ongoing doubts about their economic feasibility. By assessing the TCO of zero-emission HDVs, this study seeks to overcome these ambiguities.

TCO analysis takes into account variables like energy prices, governmental regulations, and operating costs in addition to the original purchase price. The TCO model employed in this study encompasses various factors, including fixed costs (purchase cost, incentives, registration tax, and residual value) and operational costs (maintenance costs, energy costs, road tolls, and ownership tax). Our study stands out from others due to its thorough methodology, which also offers a more sophisticated understanding of the economic effects of zero-emission HDVs. In addition, the countries chosen for examination comply with the Trans-European Transport Network (TEN-T) standards, guaranteeing thorough coverage and giving precedence to the nations with the greatest quantity of electric cars and charging stations. This broad spectrum of nations sets our study apart and enables a more thorough evaluation of economic viability.

Analysis reveals that all countries—aside from Greece—are expected to see zero-emission tractor-trailers reach price parity with diesel trucks by 2030. Notably, significant incentives are provided for battery electric trucks by nations like Sweden, the Netherlands, and France, which hastens the achievement of cost parity. On the other hand, Hungary, Greece, Spain, and Italy are not as good at offering these kinds of incentives. To achieve TCO parity, government policies—in particular, toll reductions and subsidies—appear to be essential catalysts. Policymakers and stakeholders can create focused policies to encourage the adoption of zero-emission HDVs and so contribute to a more sustainable transport sector in Europe by utilizing the findings from this study.

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Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BET	Batteries-electric truck
BEV	Battery Electric Vehicle
Capex	Capital Expenditure
DMC	direct manufacturing cost
FCET	fuel-cell electric trucks
GHG	greenhouse gas
HDV	heavy-duty vehicle
ICM	Indirect cost multiplier
NPV	Net present value
Opex	Operating Expenditure
TCO	Total cost of ownership
TEN-T	Trans-European Transport Network
VAT	value-added tax
VKT	Vehicle kilometers traveled
ZE-HDV	zero-emission heavy-duty vehicles

1. Introduction

Significant progress has been made in the last ten years in expanding our knowledge of the sustainability shift and its possible directions. Due to the road transport sector's large impact on environmental deterioration and the difficulties and high costs associated with mitigating it, scientists have focused a great deal of attention on it (Parviziomran and Bergqvist 2023a). In 2018, a quarter of the world's total CO2 emissions from fuel combustion originated from the transport sector, with road transport accounting for 74% of this share.

In addition to contributing to global greenhouse gas emissions(GHG), internal combustion engine vehicles generate noise and local air pollution. These factors have a detrimental effect on public health, especially in metropolitan areas. Furthermore, reliance on foreign energy sources due to the demand for gasoline and diesel for cars can pose risks to energy security (Lévay, Drossinos, and Thiel 2017).

In the realm of passenger transport, notable progress have been taken toward achieving a zero-emission fleet. The International Energy Agency projects a 35% share of electric vehicle sales in Europe by 2030, underscoring the growing prominence of BEVs as the leading drive technology for passenger cars. However, progress in the commercial vehicle sector has been slower, with the dominant technology or technologies remaining less clear. (Noll et al. 2022a)

Regarding road freight, the fact that more than 95% of the world's road freight vehicles run on fossil fuels suggests that less than 5% of this segment run on electricity, underscoring the difficulty of moving away from the current carbon-intensive system (Noll et al. 2022a). To reduce greenhouse gas and pollutant emissions from the transportation industry, the heavy-duty vehicle category must become less carbon-intensive. About 25% of the CO2 emissions from road transport in the EU are caused by HDVs (European environment agency, 2022).

There exists a widespread global commitment to promote the market penetration of electric heavy-duty trucks. On January 18, 2024, the most recent provisional agreement between the European Parliament and the Council on CO2 emission standards for heavy-duty vehicles was reached. According to this agreement, manufacturers will have to cut emissions by 45% by 2030, 65% by 2035, and 90% by 2040, relative to 2019 levels, in order to achieve climate neutrality by 2050. (European Parliament and Council 2024)

Embracing electro-mobility offers a promising solution to address the adverse externalities linked with the usage of internal combustion engine HDVs. In this case, a range of zero-emission technologies are available that can drastically lower the GHG emissions from trucks over their whole lifecycle. Batteries-electric trucks (BETs), fuel-cell electric trucks (FCETs), and trucks driven by electric road systems are all considered zero-emission heavy-duty vehicles (ZE-HDV).

Both battery electric and hydrogen fuel-cell trucks are zero-emission propulsion systems, offering substantial greenhouse gas emission reductions compared to diesel trucks over their lifecycle.

Given their comparable environmental benefits, the adoption of these technologies in the long-haul sector is anticipated to be influenced primarily by their economic viability (Basma, Zhou, and Rodríguez 2022a).

Obstacles hindering the broad adoption of Battery Electric Vehicles in Heavy-Duty Vehicle contexts encompass concerns related to energy density, compounded weight, material scarcities, and prolonged recharging durations, all of which can detrimentally affect service delivery and efficiency. Conversely, Fuel Cell Electric Vehicles for HDVs offer advantages such as quicker refueling, extended range, continued operation in challenging environments, and minimal fuel cell degradation, which lithium-ion batteries lack. (Rout et al. 2022a) However, battery electric trucks enjoy significantly better fuel efficiency than hydrogen fuel-cell trucks; leading to substantially lower operating costs (Basma, Zhou, and Rodríguez 2022a).

Luckily, sales of electric trucks have increased significantly in recent years. Between 2010 and 2020, the number of electric commercial vehicles sold globally increased significantly from about 5,000 to 62,000 units, largely due to incentive programs and rising demand (Sharpe and Basma 2022a). In the third quarter of 2023, all European countries witnessed a modest increase in the sale of new zero-emission heavy-duty vehicles, totaling just over 2,800 units. Of the total heavy trucks sold during this period, only a small fraction, 610 units, were heavy electric trucks, although this figure marked a notable increase compared to previous years. Analysis of heavy truck sales by powertrain revealed that diesel vehicles dominated the market, comprising 97% of sales, followed by natural gas at 2%, and battery electric vehicles at less than 1%. These trends exhibited variation across European countries, with Germany leading in zero-emission heavy-duty vehicle sales. Moreover, the Netherlands demonstrated promising growth, with nearly 3% of all heavy trucks sold being zero-emission vehicles in the third quarter of 2023, surpassing the European average. (Mulholland et al. 2024)

Despite these promising developments, the overall sales figures for heavy-duty vehicles, particularly heavy trucks, remain relatively low, underscoring the imperative for continued exploration of the economic viability of alternative technologies (Hagman et al. 2016a) (Lévay, Drossinos, and Thiel 2017). The prevailing belief among industry experts suggests that Battery Electric Vehicles are considerably more expensive than Internal Combustion Engine Vehicles. Based on results from earlier research, it is assumed that this view prevents BEVs from being widely adopted. To assess the true cost of owning and operating a vehicle, it is essential to consider not only the initial purchase price but also operational expenses. The Total Cost of Ownership methodology has been utilized in numerous studies to compare costs across various vehicle technologies (Hagman et al. 2016a).

1.2 Aim and scope

This study aims to analyze the economic viability of adopting zero-emission heavy-duty vehicles in the European market. this study places particular emphasis on tractor-trailers, which play a pivotal role in freight transportation and logistics. Given their substantial contribution to both emissions and economic activity, tractor-trailers represent a crucial segment for transitioning towards zero-emission solutions. Tractor-trailers, also known as semi-trucks, are instrumental in the movement of goods across vast distances, serving as the backbone of supply chains. However, their reliance on conventional diesel engines makes them significant contributors to greenhouse gas emissions and air pollution. Consequently, transitioning tractor-trailers to zero-emission alternatives presents a unique set of challenges and opportunities, requiring a subtle understanding of the economic and technological considerations involved. Through exploring into the specific challenges and opportunities associated with tractor-trailer operations, this research aims to provide targeted insights into the feasibility and implications of adopting zero-emission technologies in this key sector.

By employing a Total Cost of Ownership analysis, the research seeks to compare the costs and benefits of battery electric trucks, and conventional diesel trucks. Furthermore, the study explores the impact of various factors, such as incentives, energy prices, and policy interventions, on the TCO parity between different vehicle technologies. Ultimately, the findings aim to provide insights for policymakers, industry stakeholders, and fleet operators to make informed decisions regarding the adoption of ZE-HDVs, thereby contributing to the transition towards a sustainable and low-carbon transportation sector.

To gain a thorough grasp of the true costs associated with owning and operating a car is imperative in order to eliminate doubts regarding the viability of diesel fuel alternative technologies. It is imperative to take into account things other than the initial cost of purchasing. Total cost of ownership is a purchasing method and philosophy that attempts to understand the true costs associated with purchasing a certain good or service from a given source, according to (Ellram 1995). Furthermore, based on (Hagman et al. 2016b) the purchase price of the majority of capital items does not accurately reflect all of the expenses associated with using and owning them. The TCO approach has been extensively used in numerous studies to compare the costs of various car technologies (Noll et al. 2022b), (Rout et al. 2022b), (Geromel, Kristinn, and Magnússon 2022a).

To ensure a comprehensive analysis, it is essential to define the scope of countries included in this study for examining the Total Cost of Ownership of zero-emission heavy-duty vehicles. This selection process will enable a focused evaluation of the economic and environmental implications within the specified regions. The nations were chosen by the Trans-European Transport Network. The Trans-European Transport Network program of the European Union is a strategic framework designed to create a unified, effective, and superior transport infrastructure throughout the EU. Its goals include encouraging multimodal transportation, boosting environmental sustainability and safety, improving connectivity, guaranteeing access to jobs and services, and stimulating economic growth. Inland waterways, short sea transport routes, railroads, and highways linking metropolitan hubs, ports, airports, and terminals are all covered by the policy (European Commission 2023a). Trans-European Transport Network countries are presented in Table 1.

To provide complete coverage and give priority to the countries with the highest number of electric vehicles and charging stations, we implemented particular selection criteria across the board for TEN-T nations. The target countries of our study are presented in Table 2.

Corridor Name	Countries Included
Baltic–Adriatic Corridor	Poland–Czechia/Slovakia–Austria–Italy
North Sea-Baltic Corridor	Finland–Estonia–Latvia–Lithuania–Poland–Germany–Netherlands/Belgium
Mediterranean Corridor	Spain–France–Italy–Slovenia–Croatia–Hungary
Orient/East–Med Corridor	Germany–Czech Republic–Slovakia–Hungary–Romania–Bulgaria–Greece–Cyprus
Scandinavian–Mediterranean Corridor	Finland–Sweden–Denmark–Germany–Austria–Italy
Rhine–Alpine Corridor	Netherlands/Belgium–Germany–Switzerland–Italy
Atlantic Corridor	Portugal–Spain–France
North Sea–Mediterranean Corridor	Ireland–UK–Netherlands–Belgium–Luxembourg–France
Rhine–Danube Corridor	Germany–Austria–Slovakia–Hungary–Romania–Czechia–Slovakia

Table 1 Trans-European Transport Network (TEN-T).

country	Number of charging points
Netherlands	144151
Germany	124967
France	109291
Italy	39155
Sweden	31807
Spain	29227
Finland	9902
Poland	5069
Greece	3233
Hungary	3256

Table 2 Target countries.

1.3 Literature Review

Total Cost of Ownership is a notion that represents an approach to understanding the total costs associated with purchasing products or services from a particular source. TCO serves as a guiding principle as well as a useful tool for purchases. It comprises determining the important cost elements associated with important purchases. The company should concentrate on major cost items related to pre-transaction processes (from idea conception/order requisition to order placement), transactional phases (from order placement to receipt), and post-transaction flows (from receipt to final disposal by the firm or consumer) in order to identify critical cost elements (Ellram 1993). Delucchi and Lipman used this theory in electric vehicles for the first time in 2001. They created a thorough model that compared the lifecycle costs, energy consumption, and initial cost of an electric car to a vehicle with a comparable gasoline internal combustion engine (Delucchi and Lipman 2001). Roosen et al. conducted a review of TCO models published before 2015, in which models were mostly customer-oriented and concentrated on features like lower operating costs, government subsidies, energy efficiency, and incentives (Roosen, Marneffe, and Vereeck 2015). All of these elements work together to lessen the premium that comes with buying an electric car. Interestingly, they discovered that a large percentage (one-third) of the studies they looked at only focused on purchase and gasoline expenses, ignoring other crucial cost components. Of the 44 research examined, charging infrastructure and residual value were taken into account in just four and eight studies, respectively.

A recurring finding from the recent TCO research is that, in the absence of state or federal policy support, electric vehicles are typically more expensive than conventional vehicles. This finding holds true even when data sources and methodology differ. It is anticipated that, given continued support, cost parity for electric vehicles may be reached shortly. It is important to remember that a large number of these previous studies were limited to a restricted range of Battery Electric Vehicle (BEV) classes, such as sedans and small cars with short- to mid-range electric driving ranges. The lack of readily available data is the cause of this restriction (Hagman et al. 2016a), (Lévay, Drossinos, and Thiel 2017). Studies comparing the total cost of ownership for commercial vehicles are relatively new. Compared to conventional combustion engines, a number of studies have focused on optimizing the lifecycle costs of particular alternative drive technology designs (Fries, Lehmeyer, and Lienkamp 2017). Some studies have explored the cost benefits of a mix of drive technologies often within a specific region (Kleiner and Friedrich 2017b). Globally, private consultancies, international bodies, and energy businesses carry out extensive TCO assessment studies using a variety of approaches and metrics. For example, the University Of California Davis Institute Of Transport Studies emphasizes that, in order to maintain cost competitiveness with diesel, battery costs must be less than \$100/kWh; however, their research does not account for infrastructure costs or taxes (Burke and Sinha 2020a). Meanwhile, research conducted by the National Renewable Energy Laboratory in the USA thoroughly assesses the total cost of ownership for six different truck powertrain technologies and shows that battery electric powertrains are preferable in applications with shorter ranges (Hunter et al. 2021).

There is a lack of research on battery electric trucks in the European Union. The International Council on Clean Transportation (ICCT), which carried out an extensive TCO assessment across multiple EU member states, pioneered this field. Basma et al. proposes and quantifies legislative measures to improve TCO parity within five EU countries, shedding light on the unique constraints that BET technologies face in each nation(Basma, Saboori, and Rodríguez 2021a). However, other studies focus on individual nations, such as (Geromel, Kristinn, and Magnússon 2022b) which examines life cycle emissions and total cost of ownership for heavy-duty powertrains in Iceland, and (Parviziomran and Bergqvist 2023a) and (Alonso-Villar et al. 2022) undertaking similar studies for heavy-duty trucks in Sweden.

Significant numbers of studies consider two main categories namely fixed cost and operating cost in the calculation of the TCO model of the ZE-HDVs (Basma and Rodríguez 2021), (Basma, Zhou, and Rodríguez 2022b), (Basma, Saboori, and Rodríguez 2021b), (Basma et al. 2023a) in a relatively same approach with the equivalent names of CAPEX and OPEX (Rout et al. 2022b), (Parviziomran and Bergqvist 2023b). However, there are some other studies (Geromel, Kristinn, and Magnússon 2022a) in which they categorize the TCO elements into different categories: initial cost, operation cost, ownership cost, and end-of-life cost. Truck fixed costs include the vehicle purchase cost, incentives, interests on loans, registration, and ownership taxes, annual fees for road use, residual value, and all expenses independent of the vehicle's kilometers driven. On the other hand, Operational expenses are costs directly related to the vehicle kilometers traveled, including fuel costs, maintenance costs, and road tolls (Basma, Saboori, and Rodríguez 2021b). There are other parameters that can be studied such as labor cost considered in (Geromel, Kristinn, and Magnússon 2022a), (Basma et al. 2023a), (Noll et al. 2022], and insurance cost investigated in (Geromel, Kristinn, and Magnússon 2022a), (Rout et al. 2022b), (Basma et al. 2023a). The estimations derived from these studies are specific to particular cases and cannot be universally applied or generalized.

At the outset, it's crucial to acknowledge that another important consideration is the incorporation of net present value(NPV). By accounting for the time value of money, the inclusion of net present value in the TCO calculation provides a more thorough and precise evaluation of long-term costs. While some studies do not incorporate net present value in their calculations (Shenoy 2021), (Burke and Sinha 2020a), (Lévay, Drossinos, and Thiel 2017), (Mao et al. 2021) a majority of research includes it as a means of enhancing the precision of TCO evaluation, exemplifying (Basma, Saboori, and Rodríguez 2021a), (Noll et al. 2022a), (Rout et al. 2022a), (Liu et al. 2021), (Wu, Inderbitzin, and Bening 2015). This disparity complicates cross-study comparisons and has a substantial impact on their findings.

Many of the research in the literature focus only on specific nations and ignores the larger range of nations. Furthermore, many of these studies overlook additional total cost of ownership indicators in favor of concentrating only on a few. This study differs from others in that it takes a comprehensive approach, including a broad range of European nations, and attempts to build a TCO model that takes into account all relevant elements. As an illustration, we carefully account for energy and infrastructure expenditures, and we consider the various tax regimes in other nations. To offer a comprehensive assessment, our study includes both fixed costs and operating costs. The fixed costs include purchase costs, incentives, registration tax, and residual value. The operating costs include maintenance costs, energy costs, road tolls, and ownership tax.

1.4 Contribution

This study makes several significant contributions to the existing literature on the economic viability and environmental implications of adopting zero-emission heavy-duty vehicles in the European market. It also provides a comprehensive synthesis of existing knowledge on Total Cost of Ownership analysis in the context of ZE-HDVs. Reviewing previous studies establishes a foundation for understanding the economic factors influencing the adoption of ZE-HDVs and identifies gaps in the literature.

Furthermore, this study develops an original TCO model adapted to evaluate the economic feasibility of ZE-HDVs compared to conventional diesel trucks. This model incorporates various factors, including purchase cost, incentives, operational expenses, and policy interventions, to provide a comprehensive assessment of the economic implications of adopting ZE-HDVs. Through empirical analysis, the research investigates the TCO parity between battery electric trucks and diesel trucks in selected European countries. It explores the impact of factors such as incentives, energy prices, and policy interventions on TCO parity, providing valuable insights for policymakers, industry stakeholders, and fleet operators.

To guide our study, we present the following primary research question:

- What are the key components and factors contributing to the TCO for BETs and diesel trucks in Europe?
- How does the TCO of BETs compare to that of diesel trucks in the European market?
- What are the primary challenges faced by BETs in achieving cost parity with diesel trucks in terms of TCO?
- How do policy interventions, such as incentives and toll exemption, affect the economic viability of adopting ZE-HDVs?

By addressing these primary research questions, this study aims to advance our understanding of the economic considerations and policy implications associated with the adoption of ZE-HDVs in the European market. It provides valuable insights for policymakers, industry stakeholders, and researchers striving to promote sustainable transportation solutions and mitigate environmental impacts.

1.5 Case Definition

Our study focuses on the total cost of ownership analysis of heavy-duty vehicles in Europe. We have chosen to investigate the most expensive and power-intensive segment of HDVs, anticipating that it presents the greatest challenges in terms of electrification. This strategic choice is driven by the need to address factors such as battery capacity and power consumption, which are critical for achieving total cost of ownership parity. By establishing parity within this high-capacity, high-price segment, we can confidently assert our position in achieving parity with diesel counterparts across the HDV market.

The European Commission classifies automobiles used for the transportation of products into three groups: N1, N2, and N3. In this classification, N1 vehicles are used for the carriage of goods with a maximum mass not exceeding 3.5 tonnes, N2 vehicles have a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes, and N3 vehicles, which are the focus of our study, have a maximum mass exceeding 12 tonnes. This classification ensures compliance with European regulatory frameworks and market dynamics while providing clarity on the Heavy-Duty Vehicle market category we are analyzing. (European Union 2023)

As the main part of our study, we have chosen tractor-trailers as a specific case study. These tractor-trailers, which fall within the N3 category in Europe, are equivalent to the Class 8 trucks commonly used in the United States. Our examination of this critical segment aims to uncover insights into their total cost of ownership and compare them to their diesel counterparts.

The Drive-Technology Configuration Schematic in Figure 1 provides a visual representation of the key components constituting the powertrain system of a Battery Electric truck. Each element plays a crucial role in facilitating the vehicle's propulsion and energy management.

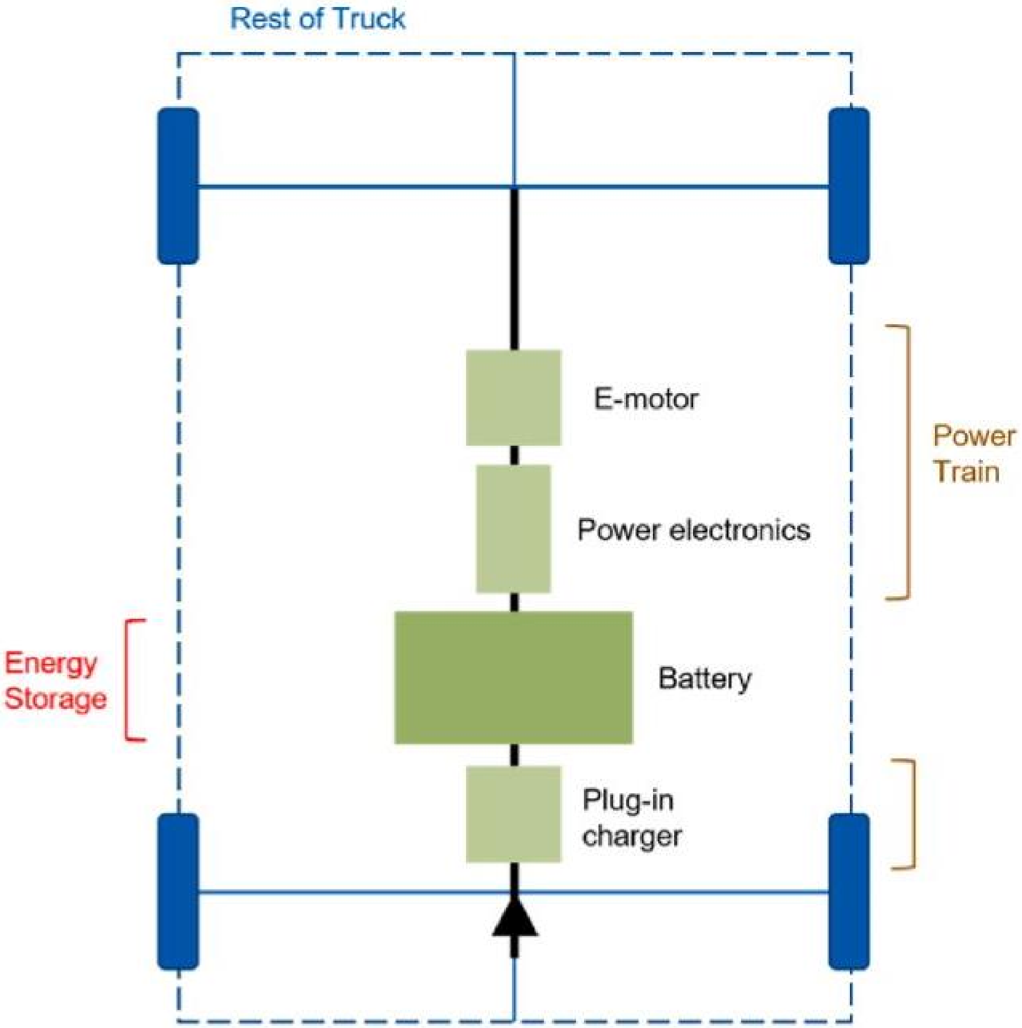

Figure 1 Drive System Configuration Diagram (Noll et al. 2022a).

Given the extensive daily mileage typical of long-haul tractor trucks under examination in our study, the inclusion of sleeper cabs is crucial to facilitate continuous operations during the day and night. As depicted in Figure 2, Day cab trucks are designed for shorter routes and do not include sleeping accommodations. Conversely, sleeper cab trucks are equipped with sleeping quarters to accommodate long-distance journeys. This allows drivers to rest during breaks or overnight stops. This distinction highlights the differing functionalities and usage scenarios between the two types of trucks.

	
Day cab tractor	Sleeper cab tractor

Figure 2 Day cab vs sleeper cab tractor (Ricardo 2021).

The considered financial horizon refers to the duration during which vehicle purchasers assess the cost of driving (€/km). This variable may change depending on various study conditions and motives. Conversely, owners of large trucks are thought to have longer time horizons than owners of lighter vehicles because of the significant upfront expenses and the expectation of high mileage (Ledna et al. 2022). This assessment considers a period of 5 years following registration which is common for HDVs as highlighted in previous studies, such as (Burke and Sinha 2020a), (Lanz et al. 2022), (Ledna et al. 2022). This study also entails all non-recoverable taxes relevant to the commercial usage of the vehicles. Notably, recoverable taxes such as value-added tax (VAT) are excluded from this analysis.

Our study relies on the segment and class of the truck, with a primary focus on its daily mileage. This factor serves as a pivotal determinant in allocating the necessary battery capacity for our trucks, accounting for the fuel consumption of existing technology. Tractor trailers serve various purposes, from urban delivery to long-haul transportation. Tractor trucks used for short-haul routes typically follow regular paths, returning to designated yards at the end of each day, and typically cover distances of no more than 180 miles daily. In contrast, long-haul tractor trucks tend to travel greater distances on a daily basis (Xie 2023). Electrification poses a significant challenge for the latter due to the extensive daily distances these vehicles must cover. Data sourced from (Wentzel 2020) reveal that 70% of trucks travel less than 500 km per day. This percentage increases to 95% for trips shorter than 660 km. This assumption aligns with (Noll et al. 2022a), which proposes a daily mileage of 600 km for long-haul trucks. Consequently, our study on long-haul applications aims to encompass these predominant usage scenarios.

Depending on the truck's application segment—which includes things like weight, range, payload, drive, and charging profiles—different power and energy needs are necessary. To address these distinctions, we reference findings from (Noll et al. 2022a), where usage profiles are modeled based on world-harmonized vehicle drive cycles to determine the total power and energy demands of the vehicle. These determinations serve as the basis for formulating detailed vehicle cost estimates. It is assumed that the car must have enough power to finish the specified drive cycle with a full load and enough energy to go the necessary daily range without requiring fuel or recharging. Notably, these findings are corroborated by results from (Basma, Beys, and Rodríguez 2021), which utilize the Simcenter Amesim commercial simulation tool to assess the performance of battery electric tractor-trailers under VECTO-like conditions, validated against a representative diesel tractor-trailer.

Concerning the battery capacity that we have assigned to our vehicle, (Xie 2023) insights indicate that by 2022, a battery electric truck with comparable technological characteristics to ours will need a capacity of 1,150 kWh in order to maintain regular operations. This number can also be obtained from (Basma, Beys, and Rodríguez 2021), taking into account a driving range of 600 km and adding in the extra battery capacity required in extremely cold or hot weather to keep the cabin at 20°C. As depicted in Figure 3, the energy efficiency of both Battery Electric Tractor-trailers and diesel tractor-trailers shows significant improvement each year, advancing at an approximate annual rate of 2%-3% (Xie 2023), (Basma, Beys, and Rodríguez 2021). This enhancement in efficiency primarily stems from advancements in aerodynamics, rolling resistance, and lightweight design, collectively referred to as the road load, across both diesel and battery-electric tractor-trailers. Furthermore, as highlighted in (Xie 2023), it is crucial to account for the potential reduction in battery pack size resulting from these efficiency improvements, which allows for achieving the same level of performance and range.

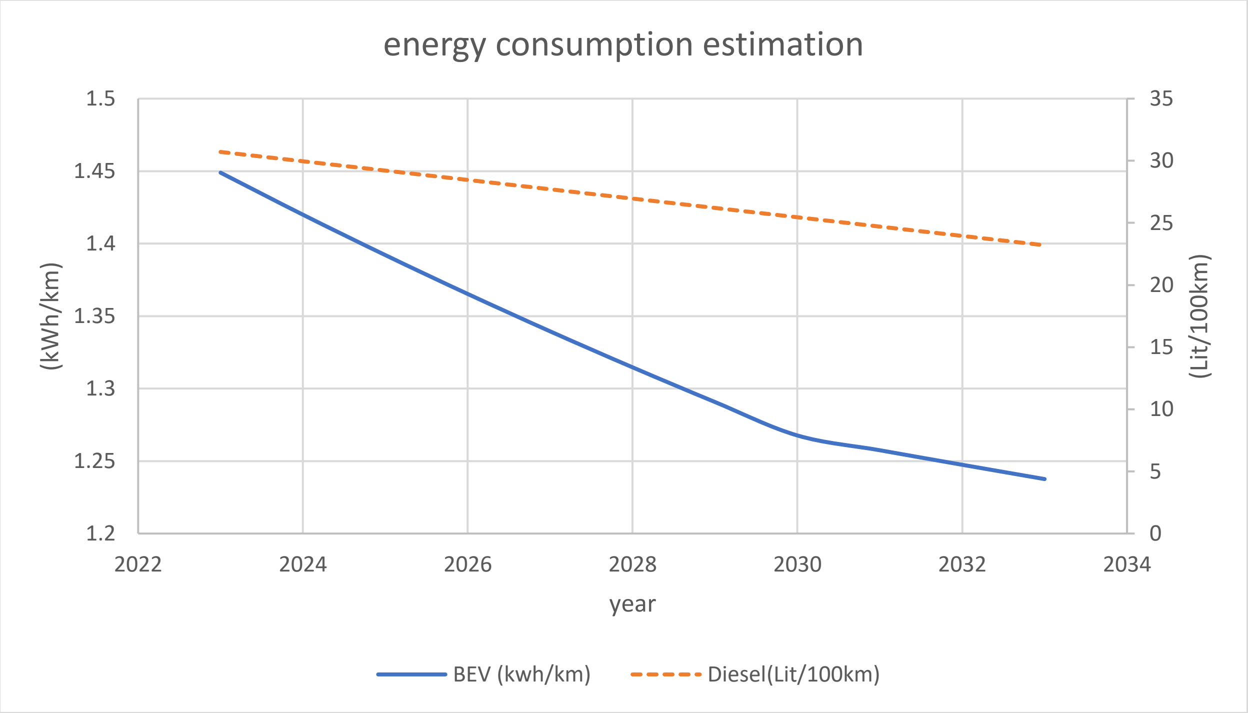

Figure 3 Energy consumption estimation for BETs and Diesel trucks through time.

Table 3 summarizes the technical specifications of the analyzed tractor-trailers. The diesel vehicle is configured to match the typical technical characteristics of existing tractor-trailers, while the battery-electric vehicle is designed to match the performance of the diesel counterpart, with its battery sized for a 600 km range. It is important to note that the 600 km driving range serves as a fixed target for all truck models from 2023 to 2033.

Parameter	**value**
Gross vehicle weight	40 tones
Maximum payload	22.5–27.3 tones
Axle configuration	4×2
Powertrain rated power(kW)	350
Range single charge	600km
class	Class N3, sleeper cab (class 8 in USA)
Average truck daily distance	158000 km/year

Table 3 Technical specifications for Diesel and BEV.

To calculate the operational cost of a truck it is essential to consider vehicle kilometers traveled (VKT) for tractor-trailers. These Data stratified by age, are sourced from (Meszler et al. 2018). These data rely on The EU TRACCS database (EU Transport and Climate Change Statistics), providing supplementary data from regulatory agencies of EU member states to delineate various transport statistics, including VKT and vehicle population categorized by type and age, for vehicles up to 30 years old. Within the dataset, VKT information is available for different sizes of tractor-trailers, ranging from 14 tonnes to 60 tonnes gross combined weight (GCW). However, according to (Meszler et al. 2018), the data utilized encompassed the weight ranges of 34-40 tonnes and 40-50 tonnes, which collectively cover the 40-tonne segment analyzed in this study. Additionally, adjustments are made to these data, illustrated in Figure 4, to ensure their suitability for long-haul trucks.

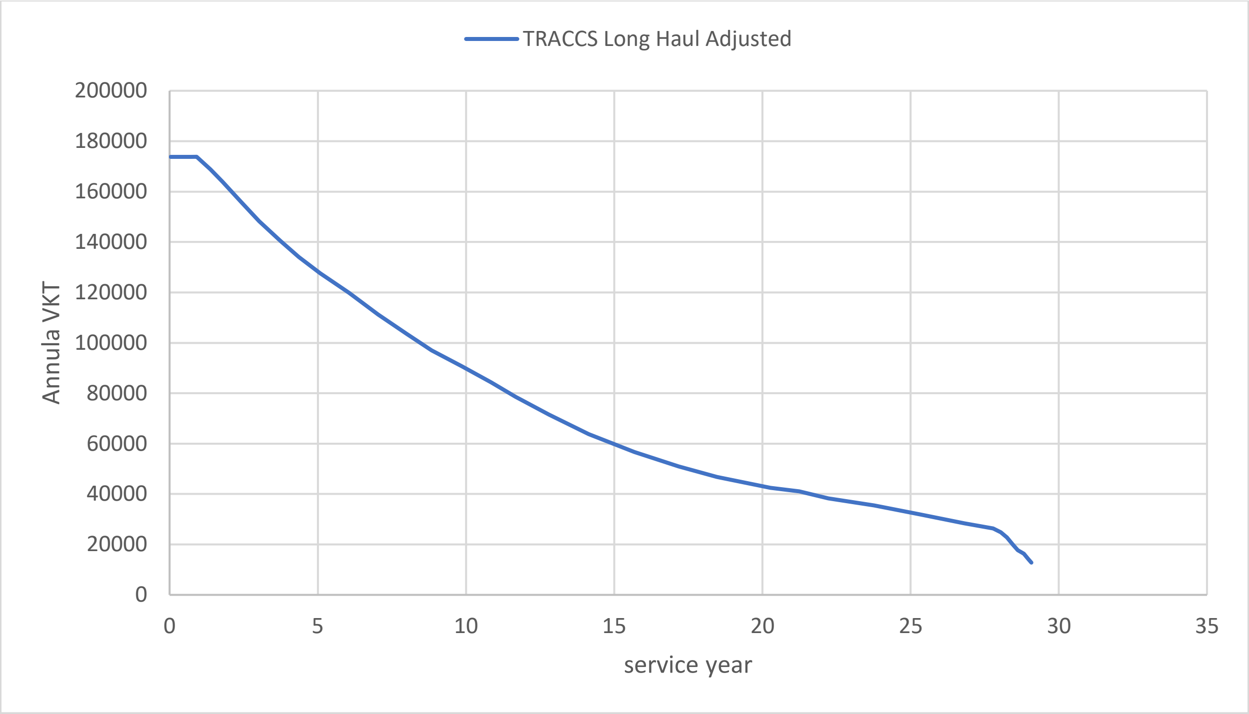

Figure 4 Annual vehicle kilometers traveled (VKT) for tractor-trailers.

2. Methodology

This section provides a comprehensive overview of the methodology employed in this study to investigate the Total Cost of Ownership for vehicles. The TCO analysis evaluates the overall expenditure required for purchasing and maintaining a vehicle over its lifespan, typically measured in Euros and standardized based on the vehicle's total mileage. The chosen methodology encompasses various components, including the research design, data collection, variables and measurements, procedure, data analysis, validity and reliability considerations, limitations, and assumptions. Through a systematic approach, this study aims to shed light on the factors influencing TCO across different contexts, offering valuable insights for decision-making in the transportation sector.

2.1 TCO Model

The foundation of our analysis is the Total Cost of Ownership model, which offers a thorough framework for assessing the viability of zero-emission heavy-duty vehicles on the European market. The two primary cost categories in the TCO model are fixed costs and operating costs. A variety of expenses that are incurred upfront or do not change over time are included in fixed costs. These consist of the purchase cost (C_p), incentives (C_I), registration tax (C_{Tr}), and residual value (C_R). These elements are critical in establishing the necessary initial outlay of funds as well as the possible returns throughout the course of the vehicle's life. Conversely, operational expenditures include ongoing costs related to the upkeep and operation of vehicles. These consist of maintenance costs (C_M), energy expenses (C_E), road tolls (C_R), and ownership tax (C_{To}). The daily operations and overall profitability of zero-emission HDVs are directly impacted by these aspects. Our study aims to offer a thorough knowledge of the economic ramifications connected with the adoption of zero-emission HDVs in the European market by methodically analyzing both fixed and operational costs within the TCO model. The proposed conceptual TCO model is presented in Figure 5.

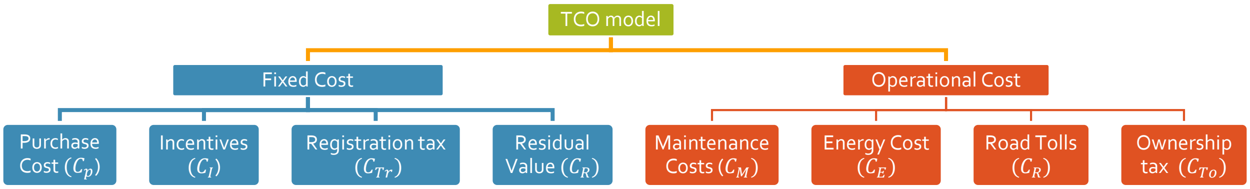

Figure 5 Proposed conceptual TCO model.

The Total Cost of Ownership is computed by summing the initial costs and the present value of the operating costs over the vehicle's lifespan. The formula for TCO calculation is represented in equation (2.1).

$$TCO = initial\ cost + \sum_{n=1}^{5} \frac{Operational\ cost}{(1+r)^n} \tag{2.1}$$

Where:

- r represents the discount rate, in this study 9.5%.
- n denotes the year of operation, in this study 5.
- $Initital\ cost = Purchase\ cost - Inventive + Registration\ tax$
- $Operational\ cost = Maintenance\ xost + Energy\ cost + Toll\ cost + Ownership\ tax$

The initial cost is paid upon purchase of the vehicle, and the operational cost represents the annual operation cost. When expanding the formula for a 5-year period, considering that the residual value is determined and subtracted from the TCO value at the end of year number 5, we arrive at the equation (2.2):

$$TCO = Initial\ cost + \frac{operating\ cost}{(1+r)} + \frac{operating\ cost}{(1+r)^2} + \frac{operating\ cost}{(1+r)^3} + \frac{operating\ cost}{(1+r)^4} + \frac{operating\ cost}{(1+r)^5} - \frac{Residual\ value}{(1+r)^5} \tag{2.2}$$

2.1.1 Fixed Cost

Fixed costs constitute the cornerstone of the TCO framework for heavy-duty vehicles. These costs are essentially constant over the course of the car's life and are essential in determining if it is financially feasible. One significant component of fixed costs is the Purchase Cost, which encompasses the initial investment needed to buy the vehicle, covering its base price along with any optional features or accessories. The other component of fixed cost is financial subsidies or discounts provided by governmental or industry-issued incentives. They are used to encourage the adoption of environmentally friendly automobiles, thereby easing the burden of their purchase. Another component of fixed costs is registration taxes charged by the government. The customer is obliged to pay that at the time of purchasing the car. Finally, the Residual Value of the vehicle, representing its estimated worth at the end of its useful life, is a crucial consideration for assessing the long-term economic implications of vehicle ownership.

2.1.1.1 Purchase cost

Based on the vehicle specifications we have chosen for our case study, a tractor-trailer with a sleeper cab, we have carefully considered a number of factors such as power, weight, axle configuration, and daily distance traveled which were explained in the 1.5 Case Definition.

Based on these factors and an efficiency estimate derived from the engine's present state of technology, we have calculated the necessary battery capacity needed by the truck to fulfill its operational needs. A better grasp of the cost structure is achieved by dissecting the truck pricing into its four primary components: the glider, battery, powertrain, and auxiliary components. Key parts of the powertrain unit sometimes referred to as the E-driveline, are the electric motor, gearbox, and inverter. We have used the ICT estimating approach to estimate the powertrain's cost, with a starting price of 42 €/kW for 2023 (Xie 2023). Figure 6 illustrates the price curve for the powertrain cost over time.

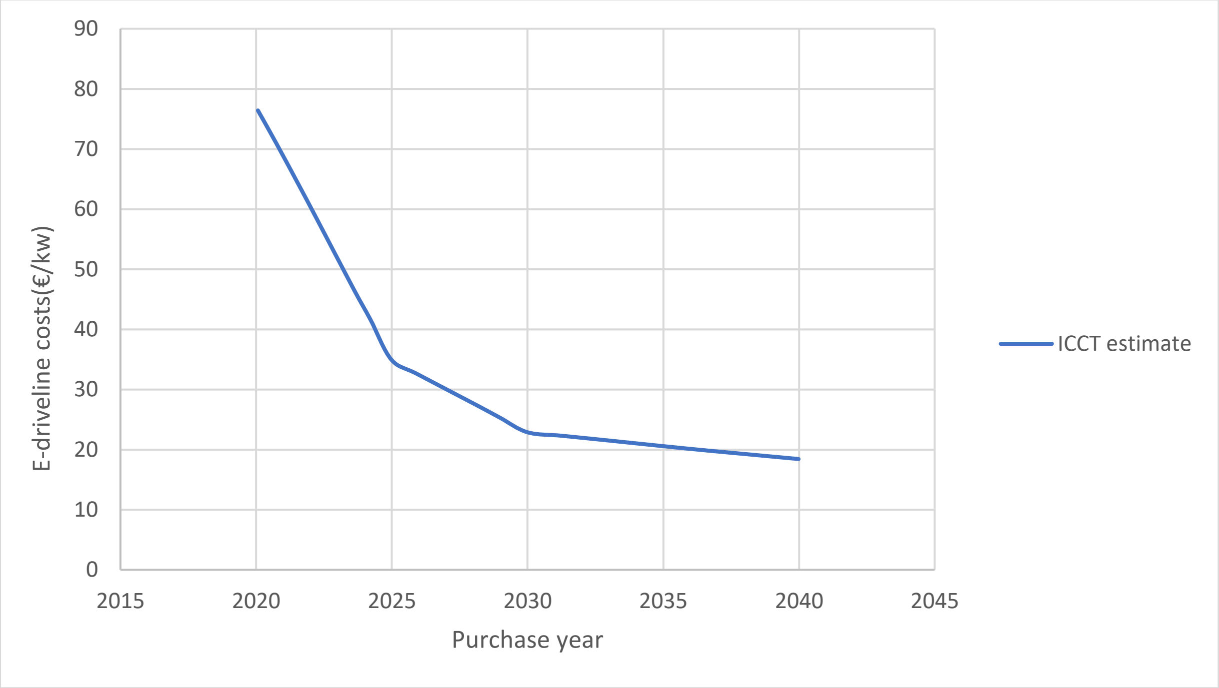

Figure 6 Estimates for manufacturing cost of electric drive systems.

Auxiliary components also play a significant role in the overall functioning of the truck and its acquisition cost, including the electronic steering pump and air brake compressor system, among others. Using research by authors like (Ricardo 2021), (Xie 2023), and (Sharpe and Basma 2022b), among others, we have created an exhaustive list of these parts and their associated costs in (€/kW). Table 4 presents auxiliary components and their costs. As stated in (Sharpe and Basma 2022b), the cost of the high-voltage system and the battery thermal management system varies based on the nominal power of the electric motor.

We have used Parviziomran's analysis from 2023 to estimate the cost of the glider, which includes the cab and chassis, and have found that it will cost approximately 38,000€ and it is regarded as a constant expense, given that technological advancements are unlikely to significantly impact its price further (Parviziomran and Bergqvist 2023a).

Component	cost (€/kW)	power (KW)
High voltage distribution	27	350
Electric air brake compressor system	1498	6
Electric steering pump	300	9
PTC heater	74	10
Air conditioning unit	70	10
Thermal management	20	350
Onboard charger	70	44

Table 4 Auxiliary components price.

Determining the price of the battery, given its status as the most expensive component of the truck, necessitates accurate calculation. Furthermore, the projection of its price must be approached with precision, as any variation significantly affects the TCO. The battery cost directly influences various aspects of the TCO, making it critical to ensure accurate estimations and projections to provide a robust foundation for decision-making processes.

It is expected that battery prices will continue to fall in the near future, following a notable decline in recent years. Since the heavy-duty industry produces battery packs on a far smaller scale than passenger automobiles, the current pricing difference between the two types of battery packs is thought to be a passing trend. This cost difference should quickly close in the upcoming years as the manufacturing of electric trucks and buses picks up speed (Fedor Unterlohner 2021).

Two cathode chemistries frequently used for lithium-ion batteries in electric vehicles are NMC (Nickel Manganese Cobalt) and LFP (Lithium iron phosphate). LFP batteries have become increasingly popular in the Chinese commercial vehicle industry. According to industry trends, this switch to LFP chemistry, which is renowned for being cost-effective, is anticipated to soon reach the USA and Europe (Oktavia Catsaros 2023). However, it has been difficult to determine the primary battery chemistry for ZE-HDVs due to the unique nature of the technology. Because of this, many study publications do not differentiate between different battery chemistries in terms of cost (Xie 2023). Even while NMC and LFP chemistries are both reasonably priced, it is crucial to remember that an NMC cell's pricing may differ from an equal LFP cell at any given time from any particular source (Brotherton 2021). Meanwhile, worth mentioning that, to provide longer ranges and higher energy density, long-haul truck batteries will need to be upgraded, to higher-performance cell chemistries. This could result in increased expenses for raw materials, which would affect battery pricing generally. Some literature suggests that a markup factor of approximately 40% can be applied to accommodate this anticipated cost premium (Fedor Unterlohner 2021).

To establish a comprehensive understanding of battery price dynamics, it is critical to recognize the wide range of sources and production techniques that influence the battery market. The price range might vary greatly because different manufacturers operate in different nations and produce batteries with unique chemistries. We have consulted the report from the International Council on Clean Transportation (ICCT) to navigate this complexity and guarantee accuracy. ICCT utilizes the data from primary research conducted by reputable organizations such as (Ricardo 2021) and secondary research from various sources including (Burnham et al. 2021), (Hunter et al.

2021),(Burke and Sinha 2020a), (Phadke et al. 2021),(Noll et al. 2022a), and (Slowik et al. 2023) to generate a battery price cost curve which is demonstrated in Figure 7. The ICCT uses these sources, which serve as the basis for our analysis, to give a thorough understanding of battery pricing trends from 2020 to 2040.

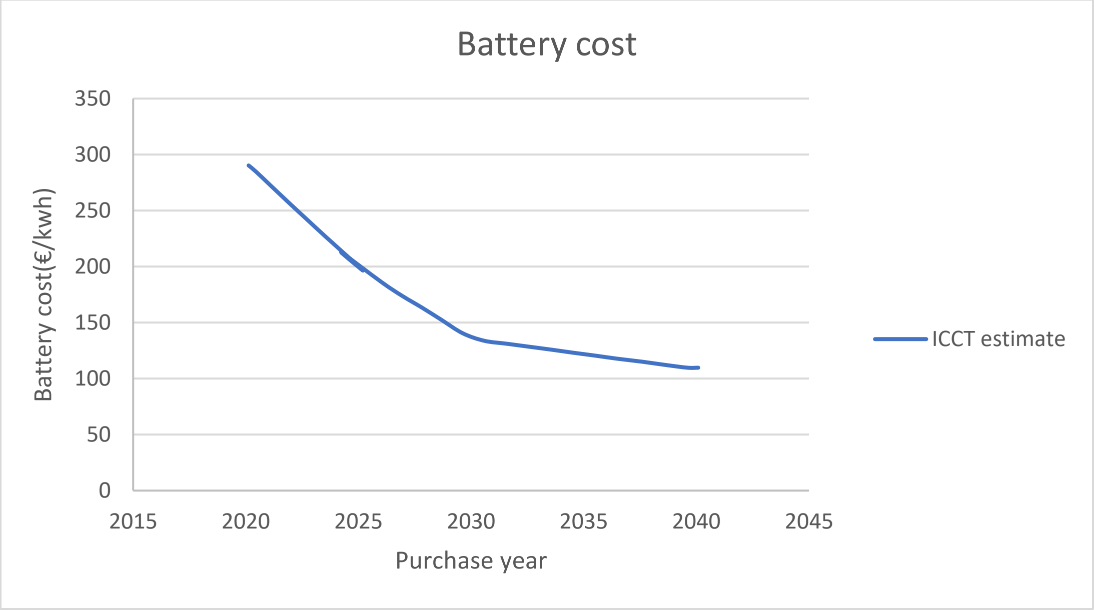

Figure 7 Battery price cost curve.

The cost curve provided in Figure 7 illustrates the drop in battery prices, which may be attributed to numerous major reasons driving this decreasing trend. These variables are consistent with the tactics frequently used to lower the price of batteries for electric vehicles. For instance, developments in enhanced cathode chemistry have reduced the requirement for precious elements like cobalt, which has lowered production costs. Improvements in energy density have been made possible by simultaneous advancements in battery cell design, allowing for the storage of more energy in battery cells with the same mass or volume. Increased efficiency and lower costs per unit of energy are the results of this rise in energy density. Moreover, continuous improvements in battery pack construction and assembly techniques have resulted in reduced production costs and increased energy density. Manufacturers can maximize storage capacity and reduce production costs by optimizing the arrangement and packing of battery cells within packs. Economies of scale have also become relevant, as the amount of batteries produced for electric vehicles has expanded over time. The learning curve effect, which occurs when manufacturing process efficiencies are established, causes higher production volumes to result in reduced costs per unit. Costs have decreased even more as a result of process improvements and technological developments made possible by the expertise and information gained in battery manufacture. Together, these elements have contributed to the general decline in battery prices that have been seen over time, lowering the cost of electric vehicles and hastening the shift to more environmentally friendly modes of transportation (Berckmans et al. 2017),(Lutsey and Nicholas 2019).

It's crucial to remember that determining any type of vehicle purchase price requires accounting for both direct and indirect costs. These indirect costs include a variety of items, including charges for marketing and distribution, overhead, dealers, and research and development. In order to approximate the truck's retail price, these costs are added in by applying indirect cost multipliers (ICMs) to the truck's direct manufacturing cost (DMC) (Basma, Zhou, and Rodríguez 2022a). Notably, according to (Mao et al. 2021) and (Xie 2023), indirect cost multipliers related to BETs were quoted at 0.425 in 2020 and 0.27 in 2023.

Based on studies by (Noll et al. 2022a) and (Xie 2023), we have estimated the price for the diesel truck counterpart to be roughly 150000€. Furthermore, we project a 6%–8% growth in diesel truck prices over the next ten years, taking into account developments in emissions control systems, road load technologies, and diesel engine technology. Research by (Meszler et al. 2018) and (Xie 2023) supports this estimate.

Taking into account the assumptions established for determining the purchase prices of both Battery Electric Trucks and their Diesel counterparts, we have derived purchase cost curves for each. These curves are depicted in Figure 8. As illustrated in the graph, the price of BETs exhibits a downward trend over time. This reduction in price can be attributed to the decreasing cost of batteries and the diminishing value of the indirect cost multiplier. Conversely, the price of Diesel trucks shows an upward trajectory, which can be attributed to advancements in emissions control systems and road load technologies, as mentioned previously.

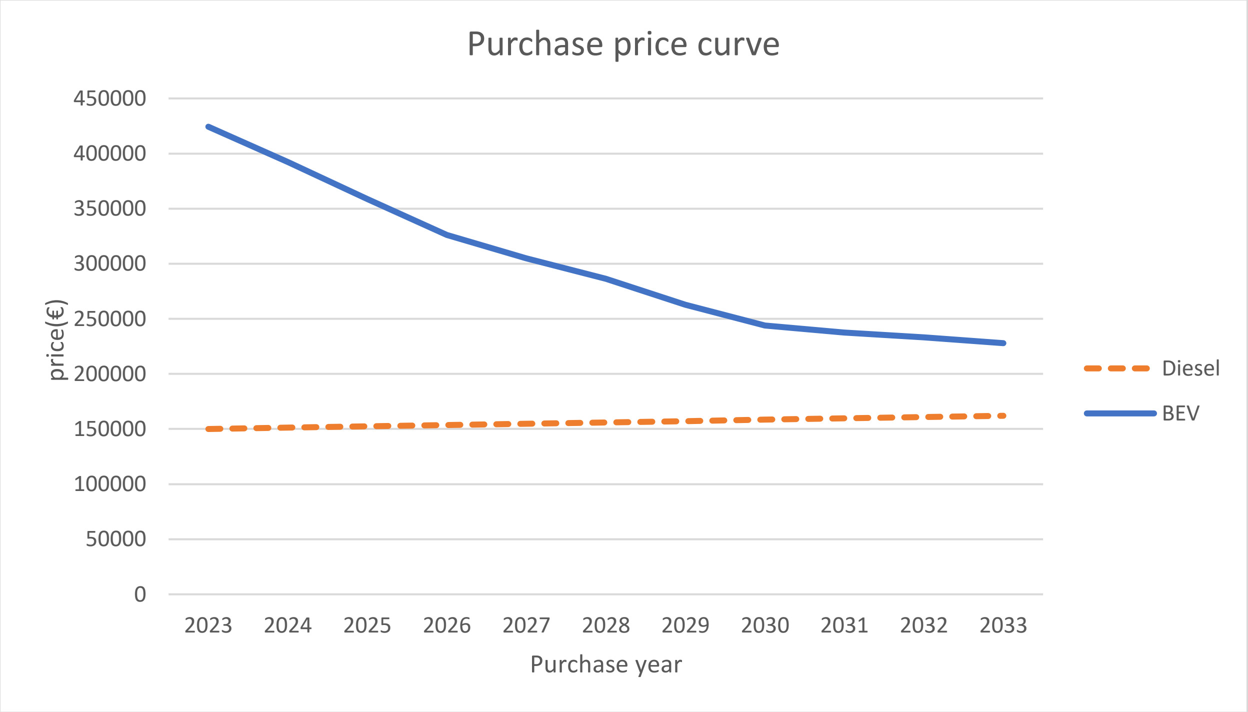

Figure 8 Purchase price curve of BETs and Diesel trucks.

2.1.1.2 Incentives

Internal combustion engine vehicles produce noise and local air pollution, especially in metropolitan areas, in addition to contributing to global greenhouse gas emissions. These factors have a negative impact on human health. Furthermore, depending too much on petrol and diesel for automobile-related requirements might lead to a dependency on imported energy sources, which presents problems for energy security. Acknowledging these problems, national and municipal governments across the globe have put in place a number of initiatives to encourage the use of electric vehicles (Lévay, Drossinos, and Thiel 2017). Financial incentives are frequently used in the early phases to encourage the uptake of zero-emission vehicles, as their purchase costs are usually greater than those of internal combustion engines (Rout et al. 2022a). The capital expenditure subsidy is one such incentive that seeks to lower vehicle costs and indicate the government's preference for zero-emission drive technologies. Moreover, these incentives are primarily accessible for passenger cars and light vans, with limited availability for commercial trucks (Noll et al. 2022a). However, the magnitude of the incentive and the clarity of the repaying procedure are crucial to the effectiveness of CAPEX subsidies, especially for fleet owners and other interested parties.

The amount of subsidies for an HDVs initial purchase price varies greatly between nations based on things like their application, weight, and drive technology. For example, Germany provides €40,000 in subsidies, whereas Italy offers €20,000. Subsidies in France pay for 40% of the purchase price, with a cap of €50,000. In a similar vein, Poland and the Netherlands provide subsidies up to a maximum of €50,000 and €45,000, respectively, based on the price differential with internal combustion engine vehicles. Other nations that offer fixed subsidies are Finland and Spain, which offer €40,000 and €15,000, respectively. Now, Hungary and Greece do not provide any subsidies; Sweden provides a subsidy equal to twenty percent of the buying cost. The subsidy data presented above have been collected from (Noll et al. 2022a) and (European Automobile Manufacturers' Association (ACEA) 2022), and (European Automobile Manufacturers' Association(ACEA) 2023) reflecting the various strategies used by different nations to encourage the use of HDVs and emphasizes the significance of examining and contrasting subsidy statistics across geographical areas. The purchase premiums offered by public authorities are listed in Table 5.

Country	Subsidy Data
Italy	€20,000
Germany	€40,000
France	40% of acquisition cost; max €50,000
Netherlands	40% of price difference with ICE-D
Poland	30% of price difference with ICE-D; max €45,000
Spain	€15,000
Finland	€40000
Sweden	20% of acquisition cost
Hungary	0
Greece	0

Table 5 Purchase premium across Europe.

2.1.1.3 Registration taxes

Vehicle taxes are essential for both bringing in money for the government and influencing car ownership trends. Ownership taxes and registration taxes are the two primary categories into which they are usually divided. Ownership taxes are yearly levies paid by car owners, whereas registration taxes are one-time charges assessed at the time of purchase (Basma et al. 2022).

There are several different reasons for registration taxes. First and foremost, they provide governments with a source of income that they may use to finance transportation projects, public services, and infrastructure improvements. Furthermore, registration levies are frequently employed as regulatory instruments to affect car ownership and usage patterns. They could be set up, for example, to discourage the spread of outdated, high-emission cars or to promote the purchase of ecologically appropriate automobiles. Countries' registration taxes vary greatly from one another, owing to differences in economic conditions, legal frameworks, and taxing strategies. Certain nations, like Greece and Italy, charge high registration costs, while other nations, like Spain and the Netherlands, do not charge any registration taxes at all. The information shown here, which comes from (PricewaterhouseCoopers(pwc) 2022), (European Automobile Manufacturers' Association(ACEA) 2022), and (Basma, Saboori, and Rodríguez 2021a), demonstrates the various ways that registration taxes are handled throughout Europe. For instance, registration taxes of €1500 are levied in Italy and Greece, whereas no taxes are levied in Spain or the Netherlands. Similar to Spain and the Netherlands, Finland and Sweden do not impose registration taxes, while Germany, France, and Hungary do charge a modest registration cost. Table 6 displays the registration taxes that were previously discussed.

Country	Registration (€)
Italy	1500
Spain	0
Germany	0
France	800
Netherland	0
Poland	290
Finland	0
Greece	1500
Hungary	1035
Sweden	0

Table 6 Registration and ownership taxes.

2.1.1.4 Residual value

Battery-electric heavy-duty trucks have an end-of-life cost that includes both the cost of scrapping and the resale value, with the former being highly uncertain. When a BEHV's ownership time ends, it might be difficult to determine its resale value, and in certain situations, there might even be associated scrapping expenses.

The majority of the field's literature supports estimating the terminal value by utilizing depreciation as a point of reference. This method is dependent on the rate of depreciation of the vehicle, which is affected by various factors like the number of kilometers driven and the duration of ownership.

As such, this depreciation rate controls the gap between the scrapping cost and the resale value (Geromel, Kristinn, and Magnússon 2022b).

Diverse estimates of residual values have been proposed by various studies. For example, during the course of a five-year ownership term,(Basma, Saboori, and Rodríguez 2021a) recommend a residual value of 30% for the base glider and powertrain and 15% for the battery. Over a 5-year period, (Geromel, Kristinn, and Magnússon 2022b) suggest different percentages: 50% for short-term ownership and 100% for long-term ownership. With a longer ownership duration of ten years, (Rout et al. 2022a) offer a breakdown of 30% for the basic glider, 25% for the engine, and 20% for the battery. According to (Basma et al. 2023b), over five years, 35% should go towards the basic glider and powertrain, and 43% towards the battery. Over a ten-year ownership period, (Parviziomran and Bergqvist 2023a) suggest a residual value of 20% for the complete truck. (Noll et al. 2022a) provide varying percentages throughout a 7-year ownership period based on the type of truck: 25% for urban trucks, 11% for regional trucks, and 18% for long-haul trucks. (Burke and Sinha 2020a) recommend a five-year residual value of 15% for the battery and 50% for the basic glider and powertrain. The residual values discussed above are presented in Table 7.

In accordance with (Basma, Saboori, and Rodríguez 2021a) recommendations, we have adopted a residual value of 30% for the base glider and powertrain, and 15% for the battery for this study. This decision is justified by the fact that, according to numerous studies in the literature, it offers a fair calculation that takes into account elements like ownership duration, car components, and depreciation rates.

Residual value estimation in the percentage of the corresponding part price	**Period of ownership**	**study**
Base glider and powertrain: 30%, Battery 15%	5 years	(Basma and Rodríguez 2021)
for short run:50% and for a long run:100%	5 years	(Geromel, Kristinn, and Magnússon 2022a)
Base glide: 30%, Powertrain: 25%, Battery: 20%	10 years	(Rout et al. 2022b)
Base glider and powertrain: 35%, battery: 43.	5 years	(Basma et al. 2023a)
The whole truck: 20%	10 years	(Parviziomran and Bergqvist 2023b)
The whole truck: 25%, 11%,18% for urban, regional, and long haul truck category	7 years	(Noll et al. 2022b)
Base glider and powertrain: 50%, Battery 15%	5 years	(Burke and Sinha 2020b)

Table 7 Residual value estimation.

2.1.2 Operational Cost

Another essential component of the total cost of ownership framework is operational costs, which include expenditures related to the routine upkeep and operation of heavy-duty vehicles. The entire

TCO is greatly impacted by these expenses, which change based on things like vehicle usage, maintenance requirements, and regulatory norms. Among the key components of operational costs, the Energy Cost stands out, covering expenses related to fuel or electricity consumption during vehicle operation.

This includes the cost of charging for electric vehicles and the cost of diesel, petrol, or alternative fuels for conventional automobiles. Another important factor is maintenance costs, which pay for regular service, repairs, and component replacements required to maintain the vehicle's longevity and best performance. Additionally, road tolls are charged for using toll roads or infrastructure facilities. Road tolls contribute to operational expenses, especially for long-haul transportation. Lastly, the Ownership Tax is a recurring levy imposed on vehicle owners. Ownership tax adds to the operational cost burden and is typically based on factors such as vehicle type, emissions, and annual mileage.

2.1.2.1 Energy cost

Diesel fuel prices include a number of expenses, including those related to the extraction of crude oil, the refining process, and the logistics of distribution, excise taxes, and value-added taxes. The information provided in Table 8 depicts the pricing of diesel fuel seen in the selected countries this study looks at up to the year 2023; it is taken from (Comité national routier 2023). To ensure the validity of the analysis, the average diesel price throughout the year 2023 was calculated.

With knowledge of the diesel price, the energy cost for diesel trucks can be determined by multiplying the diesel price by the annual mileage. Notably, VAT is included in diesel fuel prices; however, this element is typically refunded for commercial fleet operators (Basma, Zhou, and Rodríguez 2022a). Since there is a great deal of uncertainty about diesel fuel costs until 2033, we have created a number of scenarios to show possible price swings, as outlined in the subsequent results section.

Country	gross price(€)	Vat (%)	vat value(€)	price excluding vat(€)
Germany	1.6429	19	0.2649	1.378
France	1.7914	20	0.2984	1.493
Italy	1.7935	22	0.3249	1.4686
Netherlands	1.6388	21	0.2869	1.3519
Spain	1.5447	21	0.2681	1.2766
Poland	1.4277	23	0.2742	1.1535
Finland	1.9254	24	0.3754	1.55
Greece	1.6748	24	0.3264	1.3484
Hungary	1.6119	27	0.3484	1.2635
Sweden	2.0988	25	0.4187	1.6801

Table 8 Diesel price.

The cost associated with charging an electric vehicle also referred to as the energy cost, is influenced primarily by two factors: the electricity price set by utility providers and the infrastructure costs of charging stations.

The electricity price set by utility providers can vary depending on several factors, including the country of operation, the time of charging (taking into account day and night tariffs), the purpose of usage (residential or non-residential), and the annual consumption level, which ranges from bandwidth IA (less than 20 MWh per year) to IG (more than 150,000 MWh per year). Charging station infrastructure costs encompass both the initial capital investments and ongoing operational expenses. The initial capital investment represents the expenditure incurred by charging station owners to purchase equipment and install it. On the other hand, ongoing operational costs refer to expenses related to maintenance that may occur annually (Muratori, Kontou, and Eichman 2019), (Morrissey, Weldon, and O'Mahony 2016), (Basma, Saboori, and Rodríguez 2021a).

We calculate the infrastructure cost through equation (2.3) where $C_{equipment}$ represents the expense associated with the charging equipment hardware, while $C_{installation}$ denotes the cost of installing the charging equipment. $C_{O\&M}$ is the cost of operating and maintaining the charging infrastructure in year t of the project's lifespan, $E_{charging\ station}$ denotes the annual amount of energy charged at the plug in year t of the project's lifespan, i denotes the interest rate used to discount future costs and energy to a net present value and C_{el} is electricity price set by utility providers (Borlaug et al. 2020; Lanz et al. 2022).

$$Infrastructure\ cost = \frac{\left[C_{equipment} + C_{installation}\right] + \left[\sum_{t=1}^{life} \frac{C_{O\&M}}{(1+i)^t}\right]}{\sum_{t=1}^{life} \frac{E_{charging\ station}}{(1+i)^t}} + C_{el} \tag{2.3}$$

Depending on the kind of charging station taken into consideration, the estimation of equipment and installation can change. Charging stations with 350 kW and 100–150 kW capacities are the two most popular varieties. Whereas the latter functions as a quick charging station appropriate for mid-travel pauses, the former is usually utilized for destination charging.

In Table 9, we compiled the cost estimates for 2023 used (Basma, Saboori, and Rodríguez 2021b) which is aligned with (Rajon Bernard et al. 2022; Tsiropoulos, Siskos, and Capros 2022). it is determined that 20% of the daily electricity requirement should be obtained from the commercial 350-kW fast charging station, with the remaining charge obtained at the destination's overnight charging station. The overhead charges outlined in this scenario represent an average of the charges incurred between the fast 350-kW and depot 100-kW charging stations, with the former supplying 20% of the total daily energy needs, and the remaining provided by the depot 100-kW charging station.

notation	**description**	**Value in 2023**		**Value in 2033**	
	Capacity of charging station	*350kw*	*150kw-100kw*	*350kw*	*150kw-100kw*
$C_{equipment}$	Hardware costs per unit (€)	15,4700	44,647	105,974	30,779
$C_{installation}$	Installation costs per unit (€)	56,400	17,332	45478	14,161
$C_{O\&M}$	OPEX share of CAPEX	1.2 %			
t	Station service life (years)	15			
i	Internal rate of return	9.5 %			

Table 9 Infrastructure cost.

Based on the data provided in Table 9, we developed an infrastructure cost curve, as illustrated in Figure 9. This infrastructure cost is subsequently combined with the electricity price of each respective country to derive the final energy cost used in the calculation of the total cost of ownership.

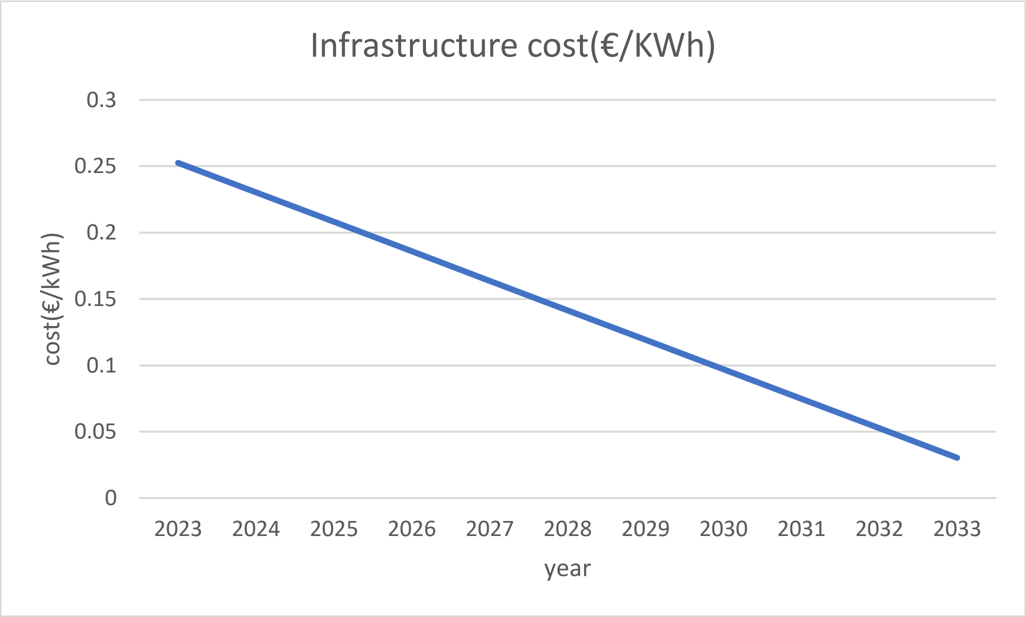

Figure 9 Infrastructure cost projection.

Electricity price data were gathered from the European Commission's public database (European Commission 2023b). Non-residential electricity prices in each country are categorized into different bandwidths based on annual consumption. Significant variations exist in the unit price of electricity across these bandwidths. Particular bandwidths of interest in this study are IB and ID based on (Basma, Saboori, and Rodríguez 2021a).

Electricity prices in the EU remained consistent between 2017 and 2021. However, a subsequent significant increase in prices occurred due to heightened global energy demand following the COVID-19 pandemic, escalating wholesale gas prices, augmented carbon pricing, and geopolitical tensions arising from Russia's actions in Ukraine. Consequently, in this study, we opted to utilize the average electricity price values from 2020 and 2021 for more reliable data, while excluding the 2022 data, which were the most recent available at the time of the analysis. Table 10 shows the electricity price in target countries in €/kWh.

country	Electricity price (€/kWh)
Germany	0.1836
Greece	0.1706
Spain	0.1266
France	0.1037
Italy	0.1718
Hungary	0.0976
Netherlands	0.1183
Poland	0.1098
Finland	0.0738
Sweden	0.0846

Table 10 Electricity price.

2.1.2.2 Maintenance Costs

Costs associated with truck maintenance and repair are crucial factors in the operation of commercial vehicles, but little research has been done in this area, especially with regard to modern engine systems and heavy-duty applications. There is not much information on the costs of these systems (Wang and Miller 2022). Because battery-electric HDVs have simpler propulsion systems and fewer moving parts than conventional vehicles, their maintenance costs are significantly cheaper. Additionally, regenerative braking and fewer oil changes are two reasons why BEVs and plug-in hybrid electric cars have less brake wear than diesel vehicles (Roosen, Marneffe, and Vereeck 2015).

The development of a complete maintenance cost model for commercial vehicles was facilitated by (Kleiner and Friedrich 2017a) using a bottom-up methodology. Along with a variety of examinations, this model takes into account 46 separately assessed components for maintenance and 24 individually assessed components for repair. It makes it possible to calculate maintenance costs specifically for various alternative powertrain technologies and car sizes. The maintenance costs are presented in Table 11, used by some studies, which may vary slightly in their values.

According to the findings of (Kleiner and Friedrich 2017a), which we utilized in our study, maintenance costs for BETs are estimated to be 33% lower compared to diesel trucks. Therefore, the maintenance cost for a diesel truck is assumed to be 18.5€ per 100 kilometers.

Maintenance cost for BETs (€/100km)	**market**	**study**
(9.7)	USA	(Alonso-Villar et al. 2022)
(8.9)	USA	(Burke and Sinha 2020)
(13.24)	Europe	(Basma, Saboori, and Rodríguez 2021)
(13.72)	Europe	(Kleiner and Friedrich 2017a)

Table 11 Maintenance cost.

2.1.2.3 Road Toll

Taxation and infrastructure charging play pivotal roles in financing the maintenance and expansion of Europe's road infrastructure network. Driven by the principles of 'user pays' and 'polluter pays' as articulated in the Treaties, the European Union (EU) issued Directive 1999/62/EC to encourage Member States to implement taxation and infrastructure pricing in an efficient and equitable manner. It also calls on Member States to address the negative impacts of air pollution, noise pollution, and traffic congestion in order to support the Paris Agreement and decarbonize road transport. Although Member States are not required to impose tolls and charges, the Directive provides certain guidelines for those nations who choose to do so. Directive 1999/62/EC outlines standardized regulations on distance-based charges (tolls) and time-based user charges (vignettes) for utilizing road infrastructure. Generally speaking, when it comes to fees, the rules governing charges on the highways and road infrastructure of the Trans-European Transport Network are more restrictive than those governing costs on other roads(European Commission 2023a).

Country	**Toll value**
France	0.26 €/km
Germany	0.187 €/km
Italy	0.18 €/km
Netherlands	0.15 €/km
Poland	0.06 €/km
Spain	0.21 €/km
Finland	0
Greece	0.26 €/km
Hungary	.49 €/km
Sweden	1250 €/year

Table 12 Road toll values for target countries.

Road-use fees are levied by certain European countries according to variables such as axle number, vehicle emission type, and distance traveled in km. These road tolls based on distance will be governed by the recently amended Eurovignette Directive. Two main sources are used to calculate the road toll values in the target nations including (Noll et al. 2022a) and (Schroten et al. 2019). It is estimated that toll roads account for 80% of the movement of heavy-duty trucks. It is worth noting that in Germany, there are no road tolls for electric cars (Basma, Saboori, and Rodríguez 2021a). Road toll values for target countries are shown in Table 12.

2.1.2.4 Ownership tax

Ownership taxes are recurrent costs that car owners pay to the government on a yearly basis. They are often referred to as vehicle or road taxes. Road infrastructure, upkeep, and other administrative costs are partially funded by these taxes. They are not to be confused with registration fees (presented in 2.1.2.4 Ownership tax), which are one-time expenses paid at the time a car is first purchased.

Ownership taxes are assessed according to the type, weight, emissions, and engine size of the vehicle. The precise amount of taxes due varies from jurisdiction to jurisdiction and may be governed by local, state, or federal laws. In general, ownership tax rates are greater for cars with bigger engines or higher emissions.

Ownership taxes included in our analysis, to be considered in the TCO calculatio, came from reliable sources including (PricewaterhouseCoopers(pwc) 2022), (European Automobile Manufacturers' Association(ACEA) 2022), and (Basma, Saboori, and Rodríguez 2021a). These figures shed light on the yearly financial responsibilities that car owners in various European nations confront. The ownership tax rates shown in Table 13 help to illustrate the overall cost of vehicle ownership in the European market by illuminating the financial burden that car owners bear.

Country	**Ownership(€/year)**
Italy	1000
Spain	850
Germany	929
France	950
Netherland	1375
Poland	1300
Finland	660
Greece	1230
Hungary	1200
Sweden	895

Table 13 Ownership taxes.

3. Results

The results chapter provides a comprehensive analysis of the Total Cost of Ownership for battery-electric trucks and diesel trucks across various dimensions and scenarios. With a focus on various elements and conditions, this chapter is designed to provide a thorough examination of the TCO composition and parity between BETs and diesel trucks.

First, the chapter carefully breaks out the costs related to both capital expenditure (CAPEX) and operating expenditure (OPEX) in order to thoroughly analyze the composition of TCO in the current year. By illustrating the percentage distribution of CAPEX and OPEX components, we gain valuable insights into the financial dynamics shaping vehicle ownership and operation. Subsequently, the analysis delves into the comparison of TCO components for BETs, providing a comparative assessment across different countries. This comparative analysis offers a detailed understanding of how varying factors, such as energy costs, Toll expense, and regulatory frameworks, influence the overall TCO of BETs in diverse geographical contexts. Furthermore, the chapter extends its examination to compare the TCO components between BETs and Diesel trucks. By comparing the costs associated with each truck type, we uncover disparities and similarities that shed light on the economic considerations driving trucks acquisition decisions.

Moving beyond static comparisons, the chapter explores the dynamic nature of TCO parity between BETs and Diesel trucks. Through scenario analysis, we assess the impact of incentives, changes in electricity and diesel prices, as well as toll exemptions for BETs on the relative TCO of both vehicle types over the years.

This chapter provides insightful information about the financial outcome of switching to electric vehicles in the commercial trucking industry by providing a thorough review of TCO analysis. Through meticulous examination and scenario-based analysis, we aim to inform decision-makers and stakeholders about the economic considerations surrounding the adoption of alternative fuel technologies in the transportation industry.

3.1 Comprehensive Analysis of TCO Composition in the Current Year

To start this section, it is important to stress how important it is to comprehend the breakdown of TCO for diesel trucks and BETs in the current year. This entails carefully analyzing the TCO, taking into account the components of operational and capital expenditures. The percentage distribution of CAPEX and OPEX is used to provide important insights into the financial dynamics affecting the ownership and operation of vehicles. This section's goal is to provide a thorough examination of TCO composition, setting the stage for additional comparative study.

The total cost of ownership outcomes for Diesel and BET trucks as our drive technologies across countries are illustrated in Figure 10. Each drive technology is distinguished by color within each country on the vertical axis, while the TCO values are depicted in €/1000 km on the horizontal axis. The competitive positioning of drive technologies is evaluated by comparing their respective

TCO values within specific countries. For potential investors in commercial vehicles, a drive technology with lower TCO values (represented by shorter bars) signifies more appealing options, whereas those with higher TCO values (illustrated by longer bars) are considered less attractive choices.

Figure 10 TCO comparison of diesel and BET trucks in 2023.

A significant result from our analysis lies in the substantial impact of OPEX parameters on the total cost of ownership for commercial vehicles. Figure 11 illustrates the breakdown of CAPEX and OPEX components for both diesel and battery electric trucks across 10 countries. OPEX parameters include energy costs, maintenance costs, toll charges, and ownership taxes, while CAPEX parameters comprise purchase prices considering incentives and registration taxes. We observe that OPEX parameters constitute a significant portion of the TCO, accounting for approximately more than half of the total expenses across all countries analyzed. This goes against the conventional approach, which is more appropriate for passenger cars than commercial ones and focuses mostly on CAPEX subsidies to promote the adoption of BEVs. Policies that target OPEX criteria may have a greater effect on enhancing the competitiveness of commercial cars with zero emissions.

Our analysis reveals that for BETs, OPEX expenses are notably higher compared to Capex, accounting for approximately 60% of the total expenses across all countries analyzed in all countries. This indicates an opportunity for cost optimization in this area to enhance the competitiveness of electric trucks. Leveraging this insight, policymakers can implement targeted measures to reduce operational costs for BETs. Consideration of France, Netherlands, and Finland provides insight. While all three countries offer substantial subsidies for BETs, aiming to lower the TCO by targeting the CAPEX, only Finland effectively addresses OPEX by waiving toll fees. This strategic focus on reducing operational expenses results in a lower total TCO, positioning Finland as a more favorable country compared to France and the Netherlands in fostering the prevalence of green technology.

On the other hand, when it comes to diesel trucks, OPEX accounts for the bulk of costs worldwide, over 70% and even surpassing 80% in certain instances, like Hungary, Greece, and France. Tolls and diesel costs are the main drivers of this, underscoring the importance of these variables in the total cost of ownership computation for conventional combustion engine trucks.

Governments can take into account a number of tactics to encourage the use of BETs, including financial incentives to reduce the cost of electricity and infrastructural expenditures to support the fleets of electric trucks. Furthermore, like the programs put in place in Germany and Finland, exemptions or subsidies from toll rates for BETs can greatly minimize operating costs and help these nations' electric truck TCOs.

The adoption of alternative-drive vehicles in general is aided by CAPEX subsidies, but our analysis shows that in order to make EVs economically competitive, OPEX characteristics must be addressed. Policymakers may optimize the TCO for commercial fleets while promoting the shift towards sustainable transportation options by concentrating on cutting Opex and enacting tailored incentives.

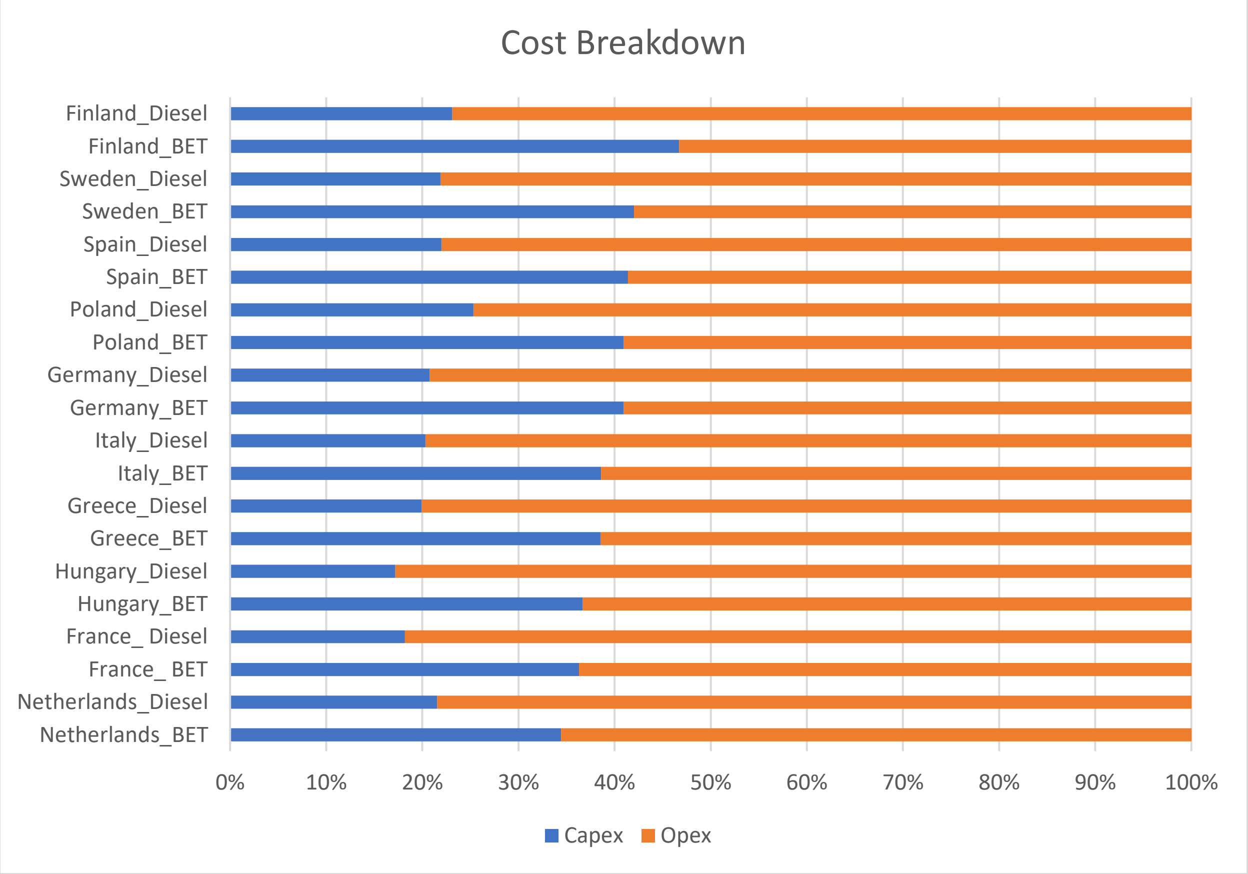

Figure 11 Cost Breakdown: CAPEX vs. OPEX for EVs and Diesel Trucks in target countries.

To better understand the composition of the Total Cost of Ownership, waterfall charts are employed to compare the various elements contributing to TCO across different parameters. These graphs provide a thorough visual depiction that enables a detailed analysis of the various elements influencing the total cost structure of BETs. We examine the finer points of TCO in this research by breaking down each element and emphasizing important findings. In the presented waterfall chart for our target countries, each component of TCO is depicted along the x-axis. They include both Operational Expenditure parameters such as energy costs, maintenance costs, toll charges, and ownership taxes, as well as Capital Expenditure parameters including purchase prices considering incentives, registration taxes, and residual value. The corresponding contribution to TCO in (€/1000km) is displayed along the y-axis. One noteworthy finding from the chart is that, of the CAPEX parameters, purchase cost and, of the OPEX parameters, energy cost have the highest values. This indicates that governments and policymakers should focus more on reducing purchase costs by increasing incentives for BETs. On the other hand, to reduce energy costs, using infrastructure cost-cutting incentives could be a successful option.

Tolls and maintenance expenses are the next biggest contributors, with notable figures. The inevitability of maintenance costs is a fundamental aspect of truck and vehicle ownership. Regardless of the vehicle type or usage, routine maintenance is an indispensable requirement to ensure optimal performance, reliability, and safety. For this reason, even while maintenance expenses could account for a sizeable amount of the total cost of ownership, they are a necessary investment in the durability and effectiveness of the fleet of vehicles.

In contrast to the inevitable cost of maintenance, governments can reduce other costs like tolls, especially when it comes to Battery Electric Trucks. Toll charges, in contrast to maintenance costs, are determined in part by government policies. One way that governments can lower the total cost of ownership of BETs is by implementing policies that eliminate or significantly lower tolls for these vehicles. In addition to addressing environmental issues, this proactive strategy promotes BET's economic viability in the transportation industry.

A closer look at the waterfall charts from Figure 12 to Figure 21 reveals that nations with well-managed toll policies—such as Germany, Finland, and to a lesser extent Sweden—have somewhat lower total cost of ownership for commercial vehicles. On the other hand, countries like Greece, Hungary, and France show a notable toll expense contribution to the total cost of ownership. These nations may implement tactics similar to those of Germany and Finland in order to lessen toll expenses and, in turn, lower the TCO for BETs operating within their borders. Governments may play a critical role in promoting the adoption of greener transportation technologies and concurrently improving the economic competitiveness of zero-emission trucks by enacting toll reduction or exemption laws.

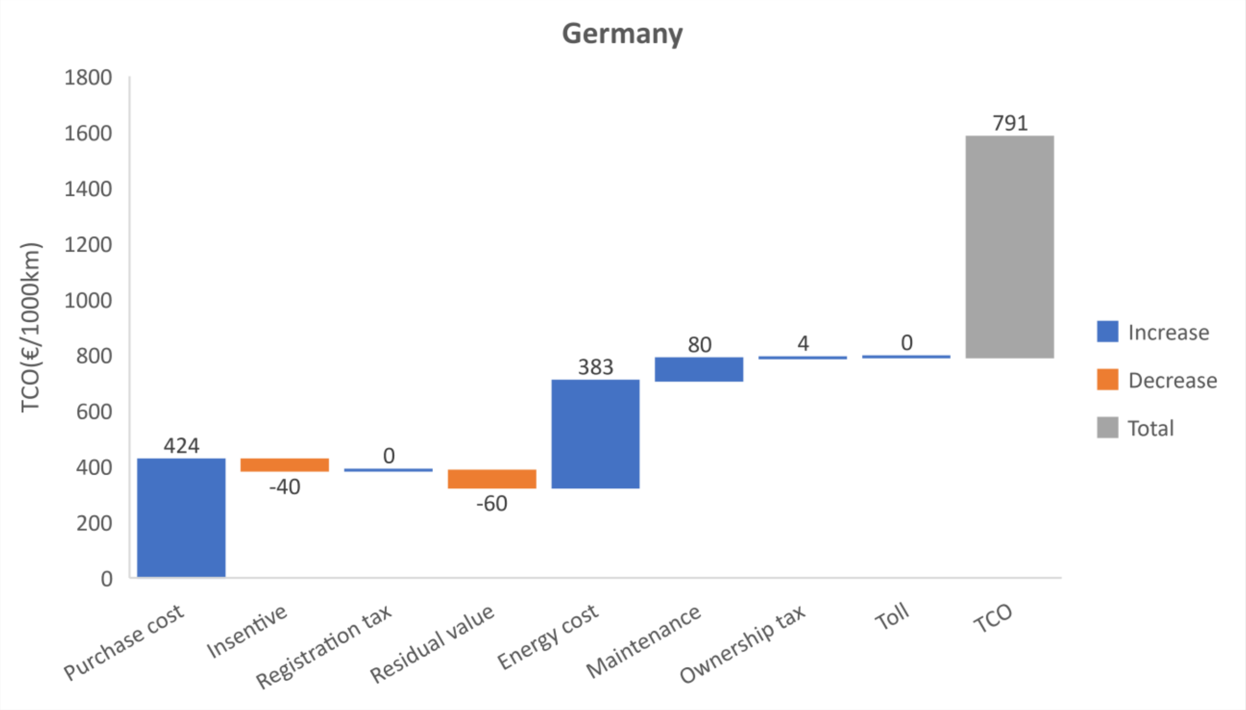

Figure 12 Comparison of TCO Components of BETs for Germany in 2023.

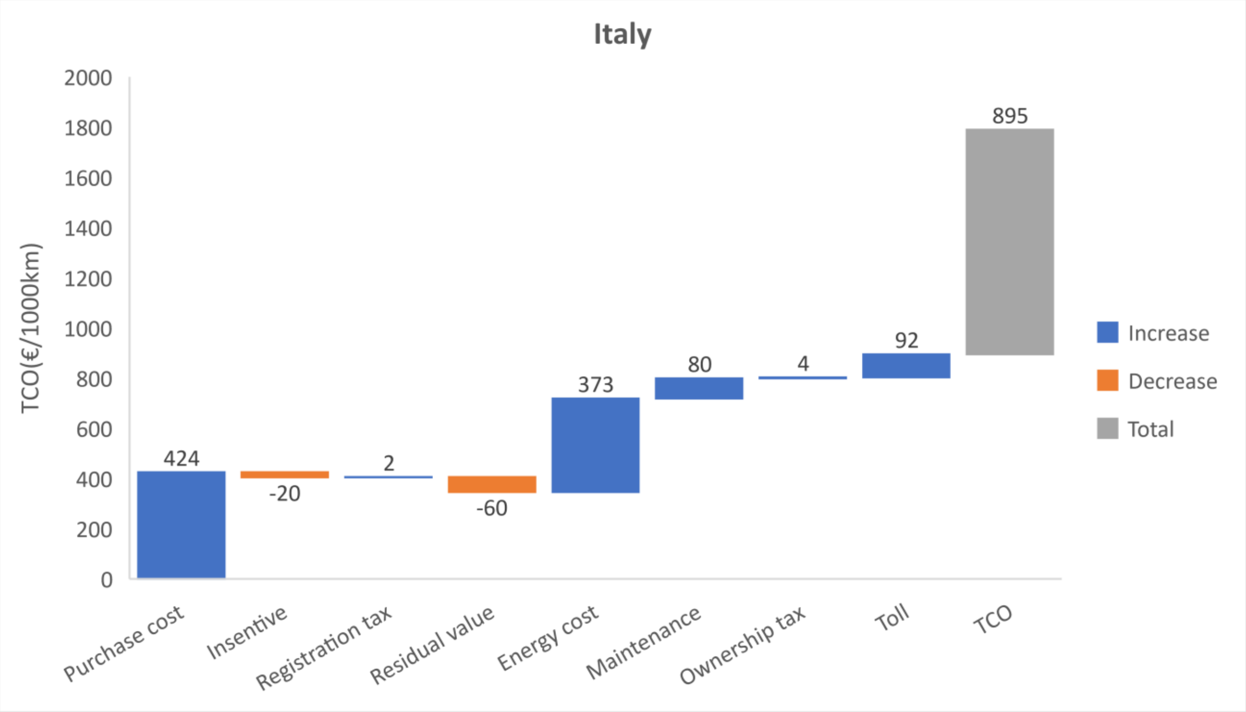

Figure 13 Comparison of TCO Components of BETs for Italy in 2023.

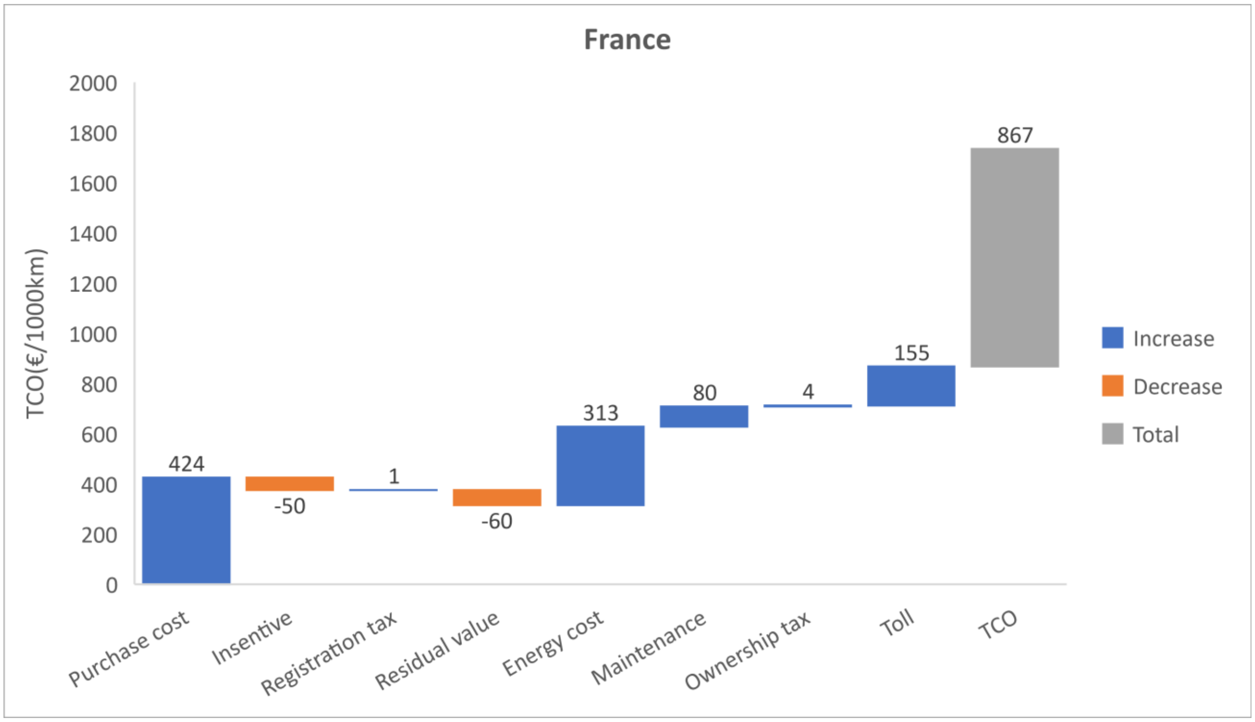

Figure 14 Comparison of TCO Components of BETs for France in 2023.

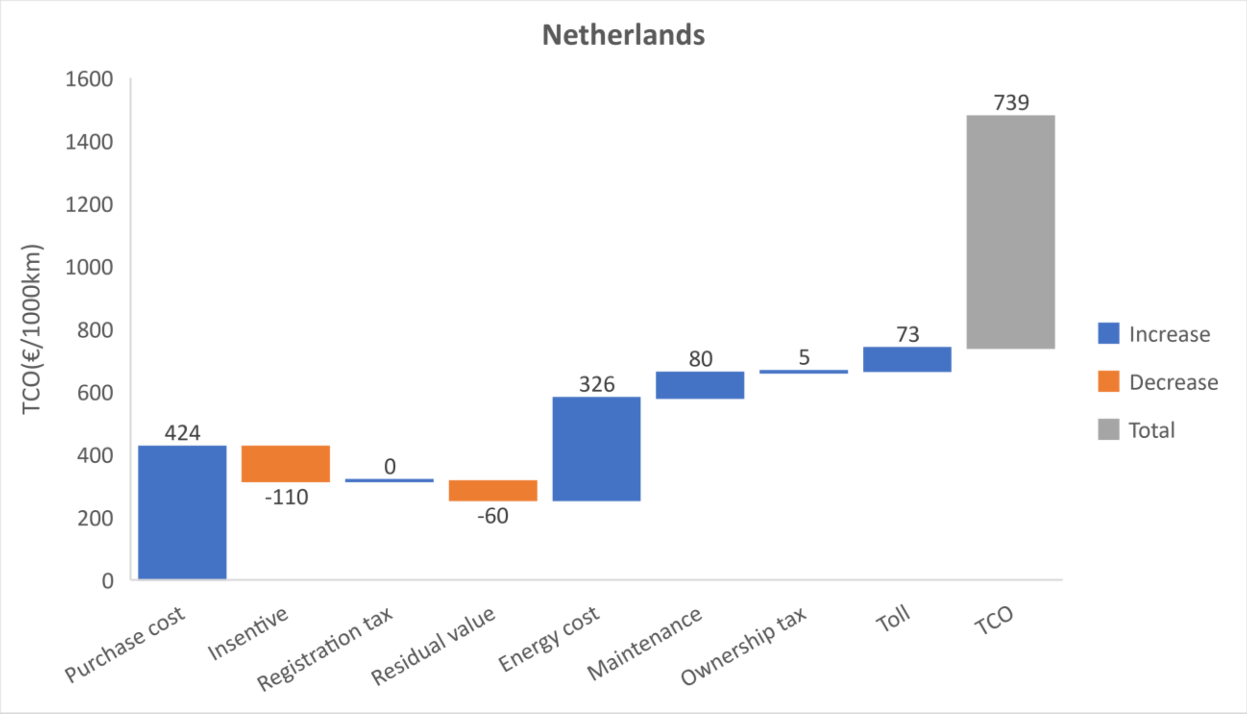

Figure 15 Comparison of TCO Components of BETs for Netherlands in 2023.

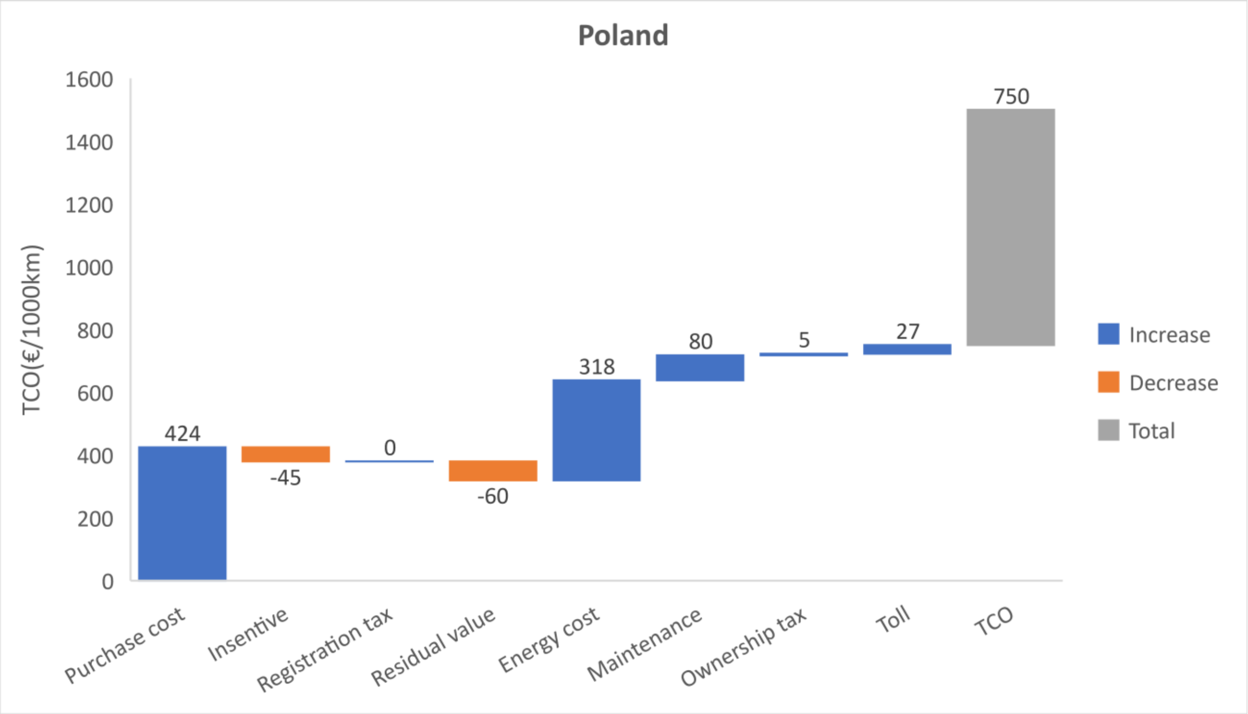

Figure 16 Comparison of TCO Components of BETs for Poland in 2023.

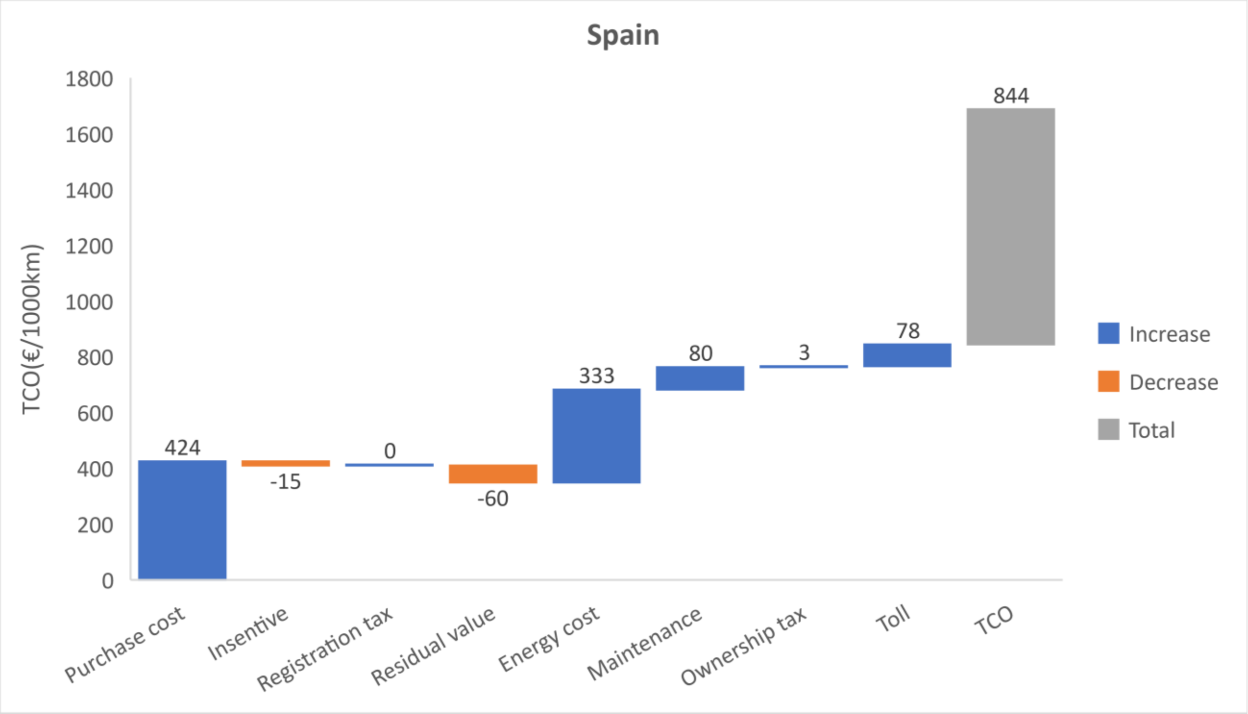

Figure 17 Comparison of TCO Components of BETs for Spain in 2023.

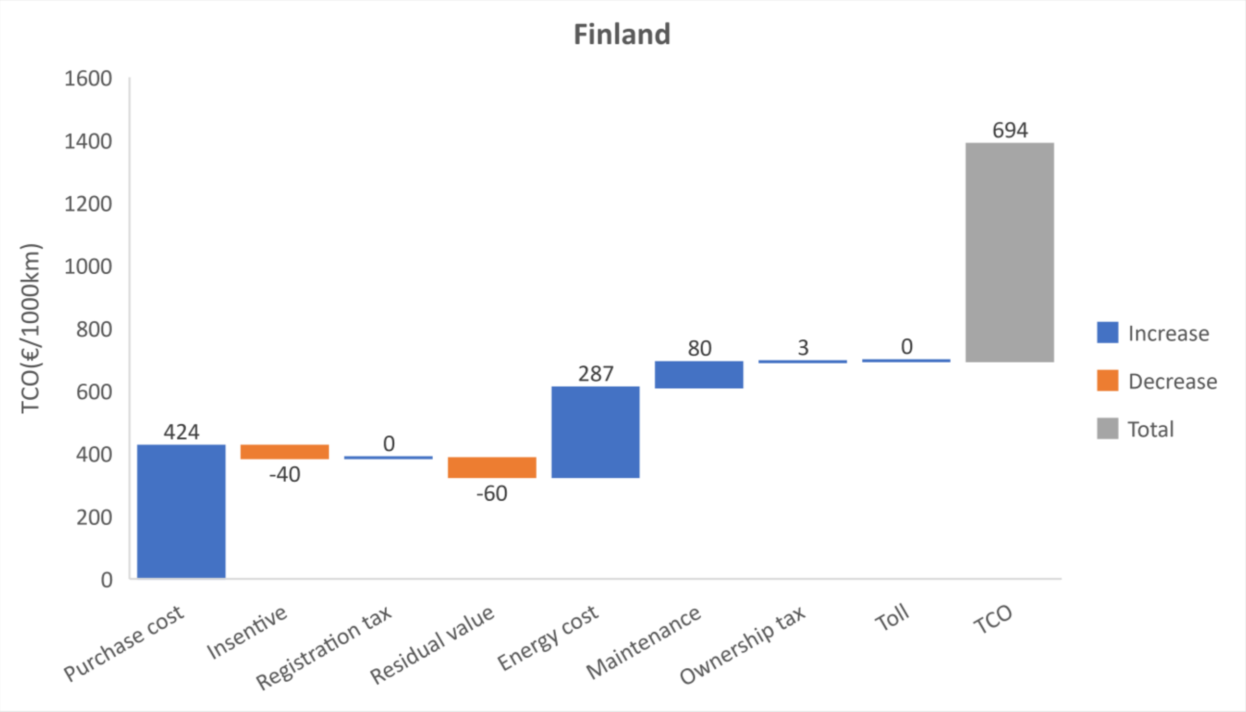

Figure 18 Comparison of TCO Components of BETs for Finland in 2023.

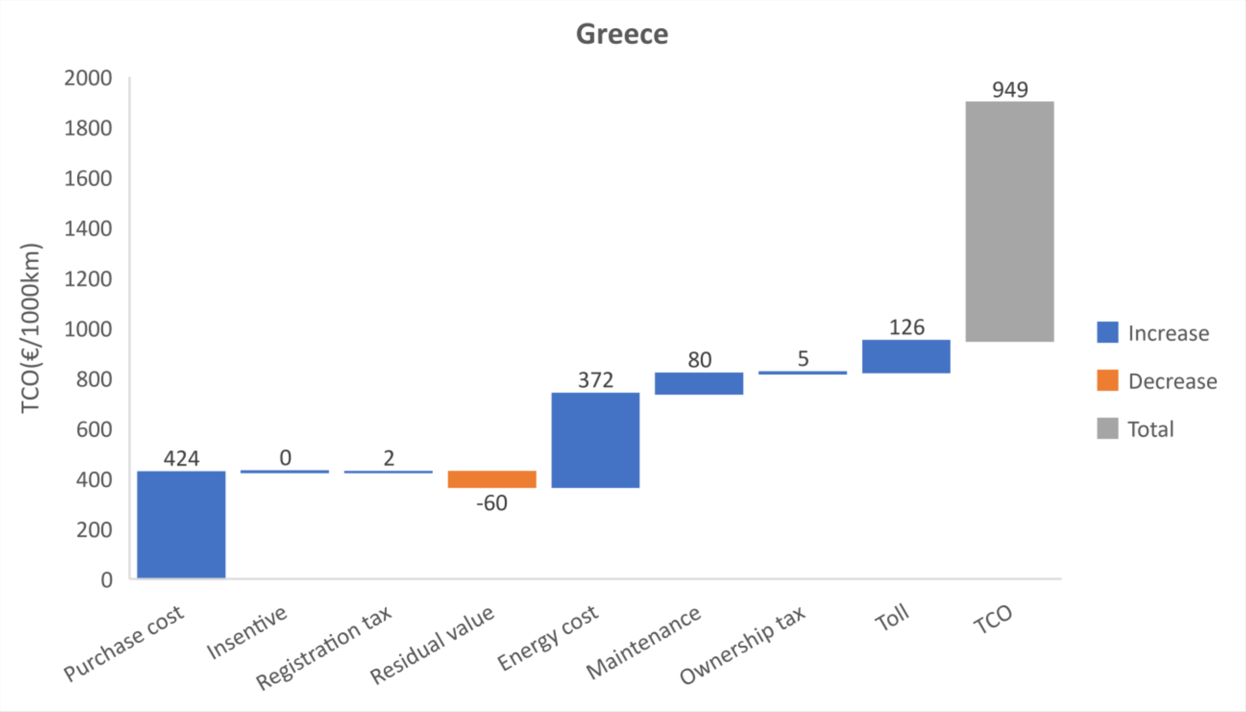

Figure 19 Comparison of TCO Components of BETS for Greece in 2023.

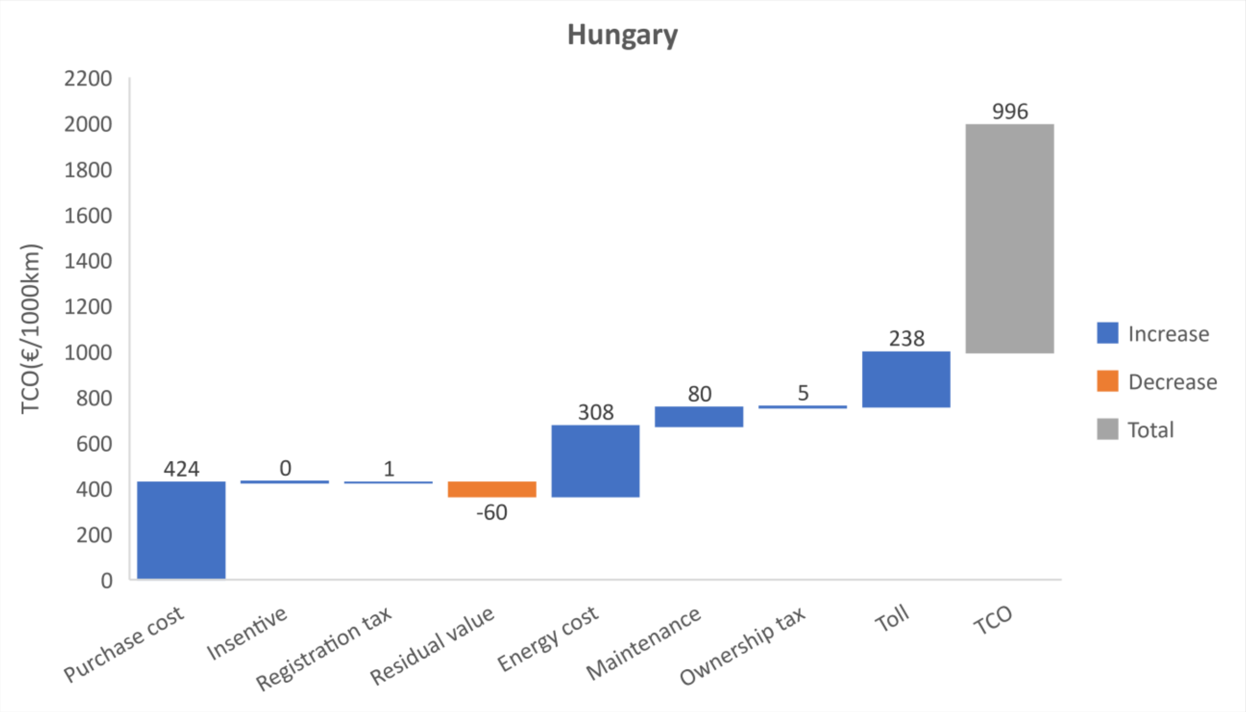

Figure 20 Comparison of TCO Components of BETs for Hungary in 2023.

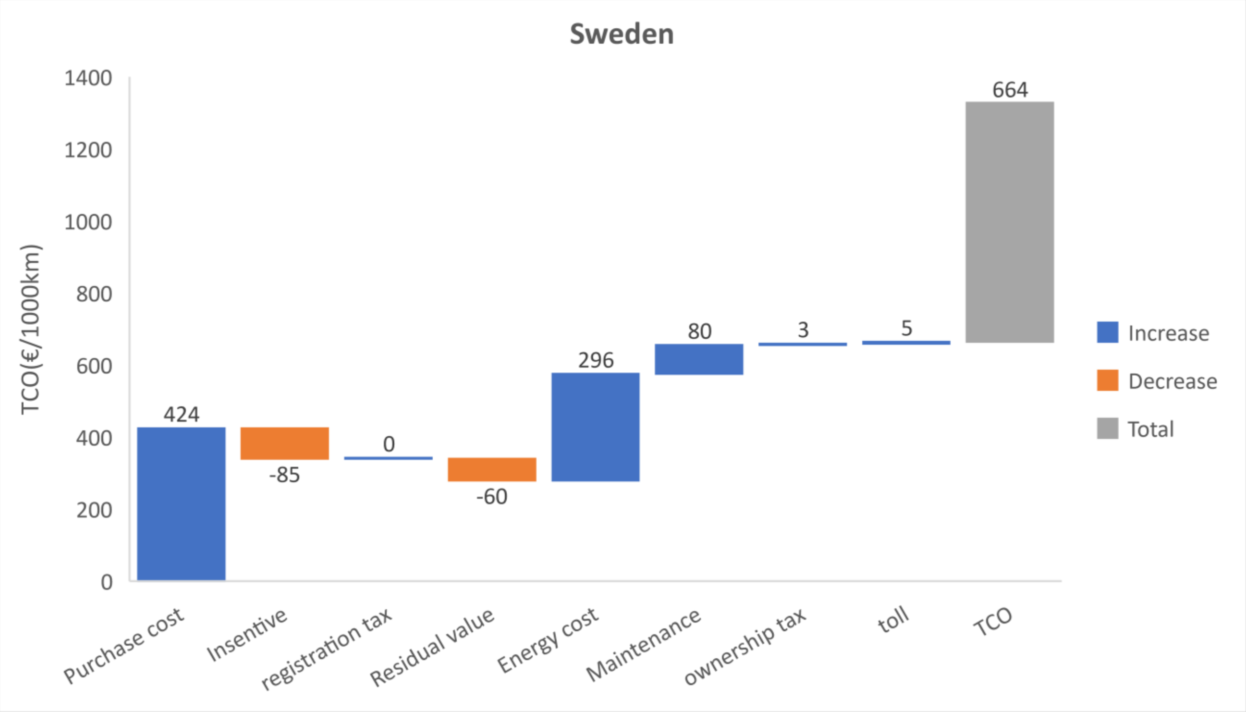

Figure 21 Comparison of TCO Components of BETs for Sweden in 2023.

This section compares the total cost of ownership components for two different drive technologies: diesel trucks and battery electric trucks. The purpose of this study, as depicted in Figure 22 to Figure 31, is to highlight the important variables that contribute to the notable TCO disparity between these two drive technologies within target countries in the present year.

First of all, it's clear that diesel trucks have lower purchase costs than BETs at current year 2023, and the latter are not eligible for any subsidies. The purchase cost of BETs is significantly higher, almost triple compared to that of Diesel trucks, mainly due to the high price of batteries and electric powertrain components, which are considered similar across all countries, as detailed in 2.1.1.1 Purchase cost. Certain TCO parameters, such as ownership and registration taxes, are the same for both, but there are some notable differences as well.

For instance, the residual value for BETs is higher than that for Diesel trucks within the same time. This is primarily due to the higher purchase price of BETs compared to Diesel trucks, considering a 30% initial price as residual for both, along with a 15% residual value for the battery in BETs.

Furthermore, Maintenance costs for diesel trucks are notably higher than for BETs, almost 40% higher, due to the simpler propulsion systems and fewer moving parts in battery-electric HDVs compared to conventional vehicles, as detailed in 2.1.2.2 Maintenance Costs. These maintenance costs are relatively consistent across all countries.

However, energy costs vary significantly among countries. In countries like Greece, Germany, and Poland, the energy cost for BETs is much higher than the fuel cost for their Diesel counterparts. In Germany by 49%, in Poland by 47%, and in Greece by 32%. This difference is primarily due to the higher price of electricity in Germany and Greece, and the lower price of diesel in Poland. Conversely, in countries like Sweden and Finland, the energy cost for BETs is lower than the fuel cost for Diesel trucks, in Sweden by 5% and in Finland by merely 0.6%, due to the high price of diesel fuel and the low price of electricity. This situation in these two countries can result in a lower TCO for BETs and encourage customers to adopt green technology.

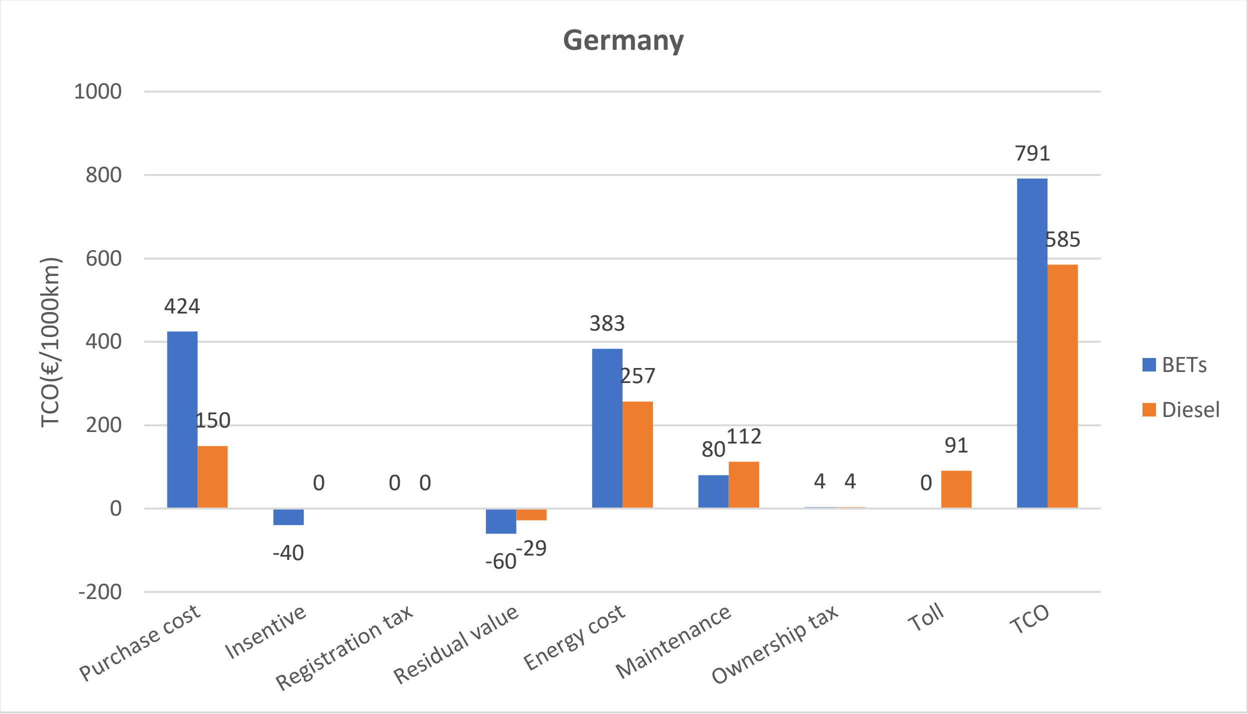

Figure 22 Comparison of the TCO for BETs and Diesel trucks in Germany in 2023.

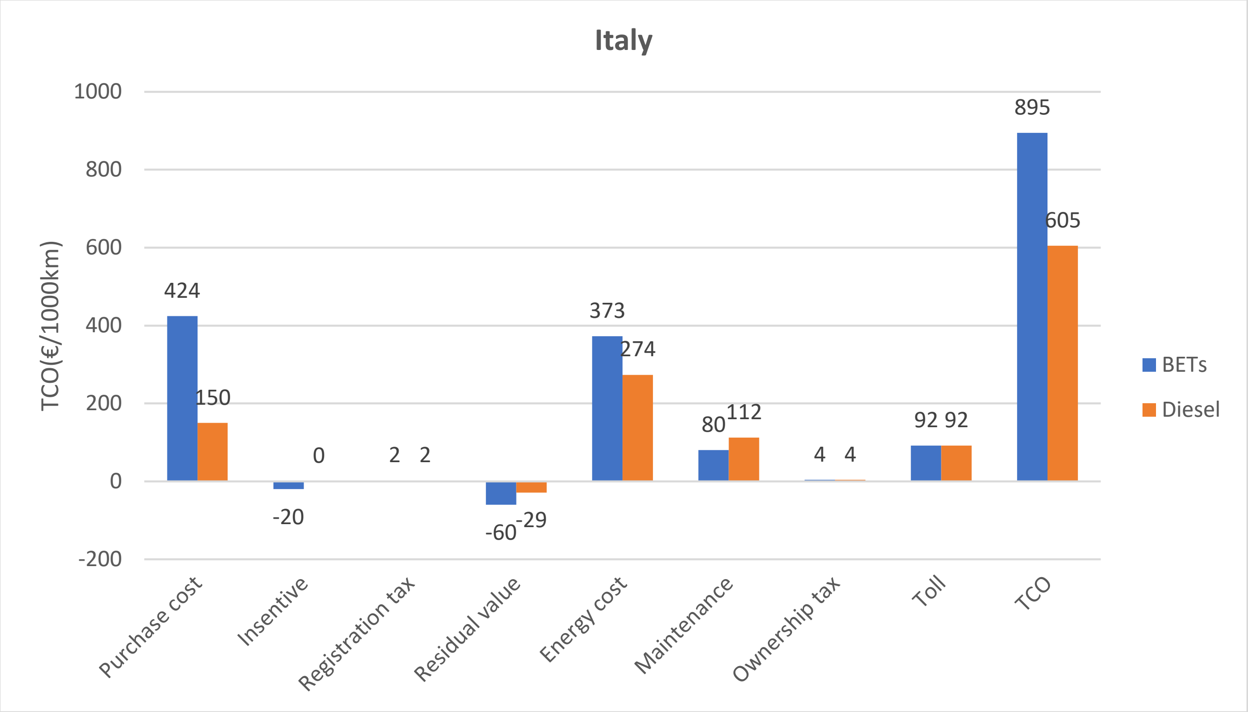

Figure 23 Comparison of the TCO for BETs and Diesel trucks in Italy in 2023

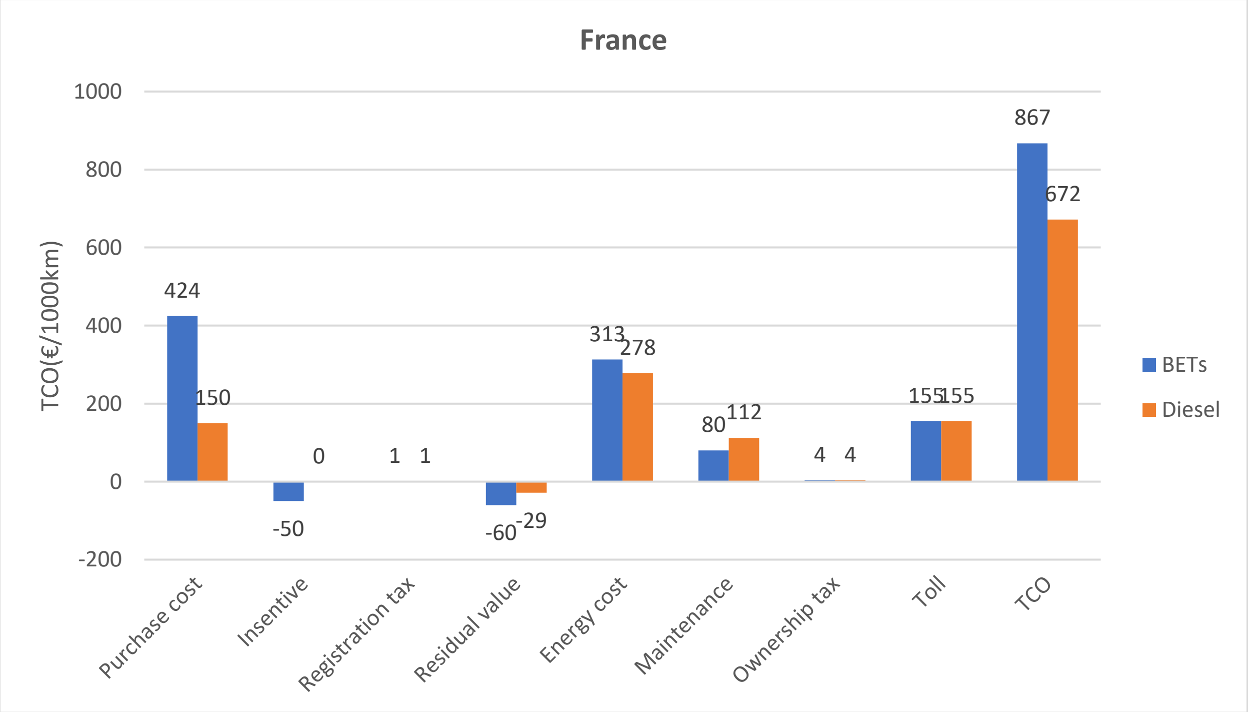

Figure 24 Comparison of the TCO for BETs and Diesel trucks in France in 2023.

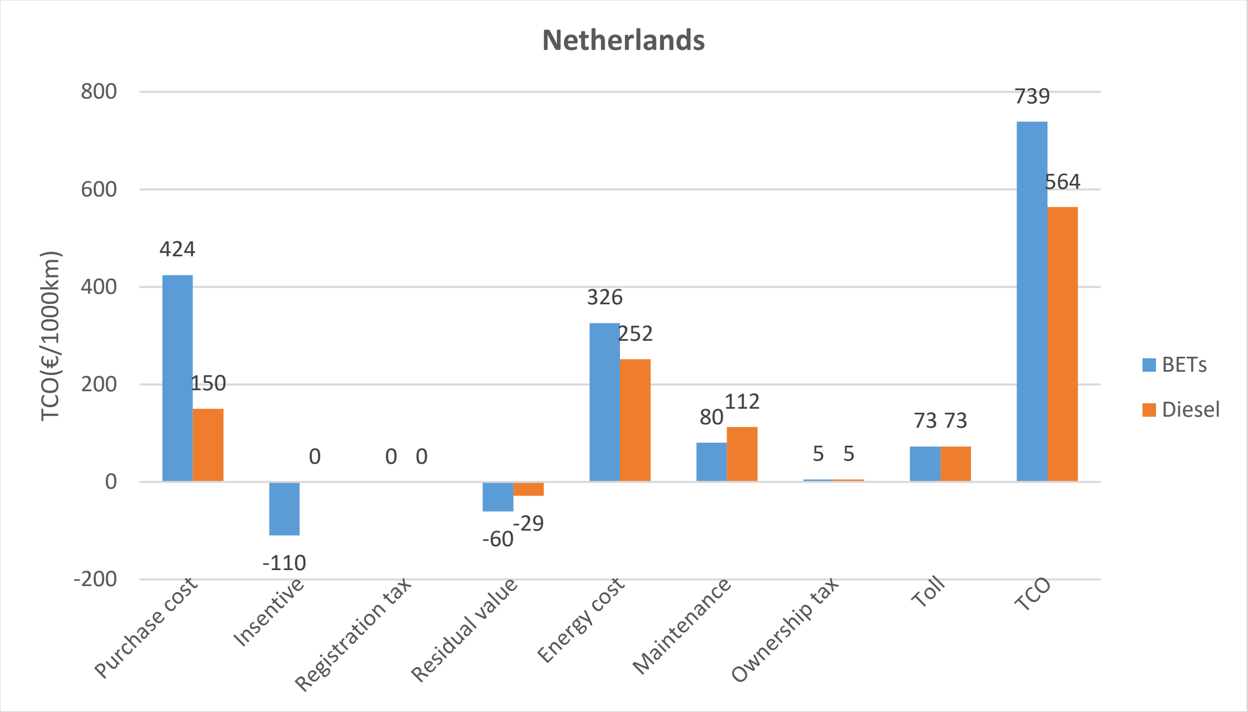

Figure 25 Comparison of the TCO for BETs and Diesel trucks in Netherlands in 2023.

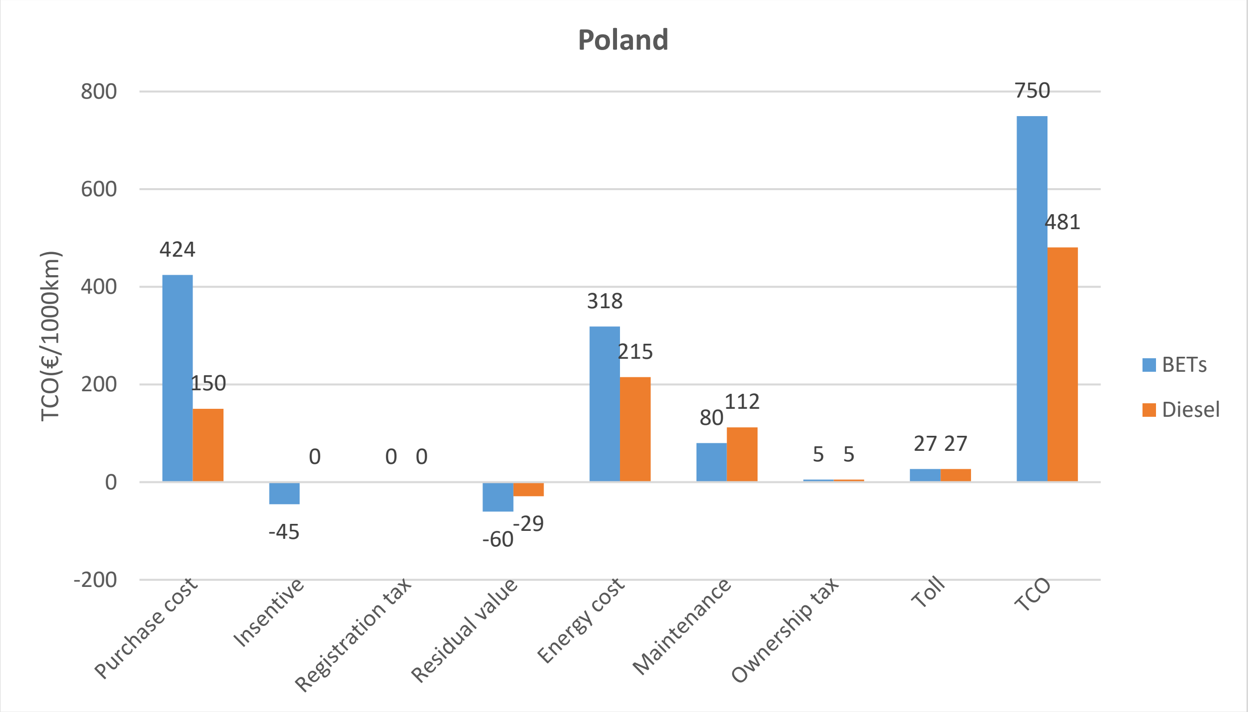

Figure 26 Comparison of the TCO for BETs and Diesel trucks in Poland in 2023.

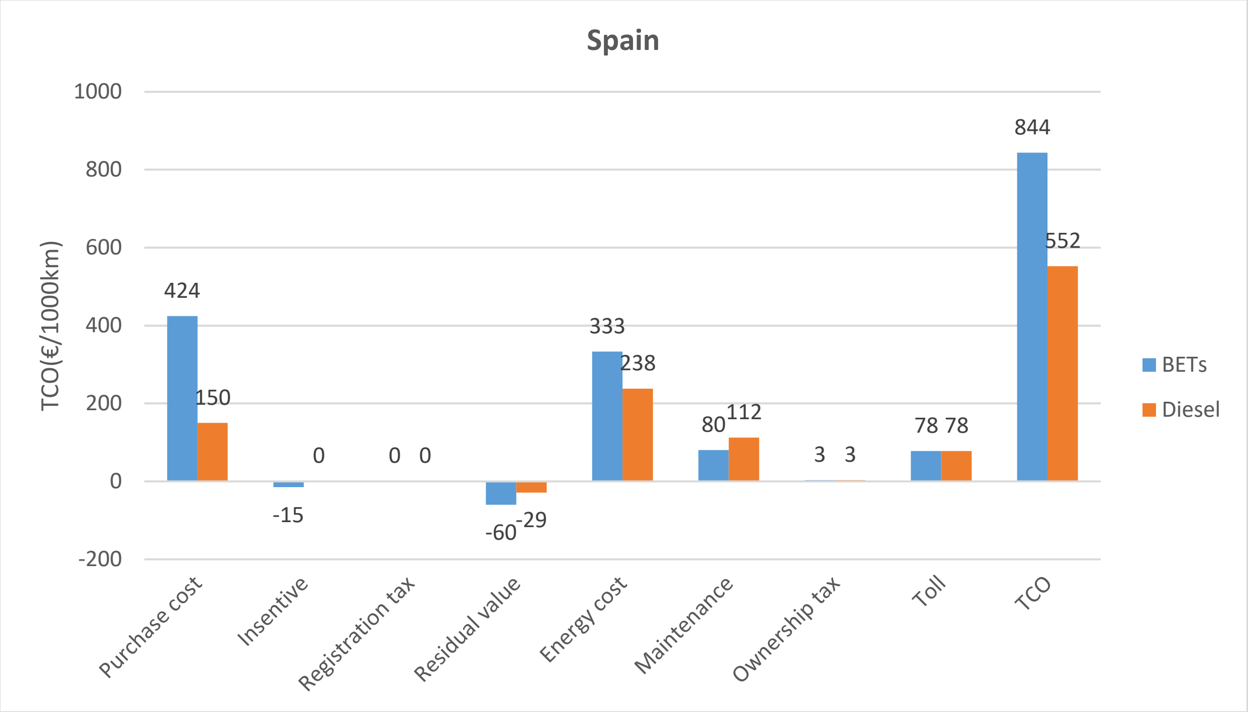

Figure 27 Comparison of the TCO for BETs and Diesel trucks in Spain in 2023.

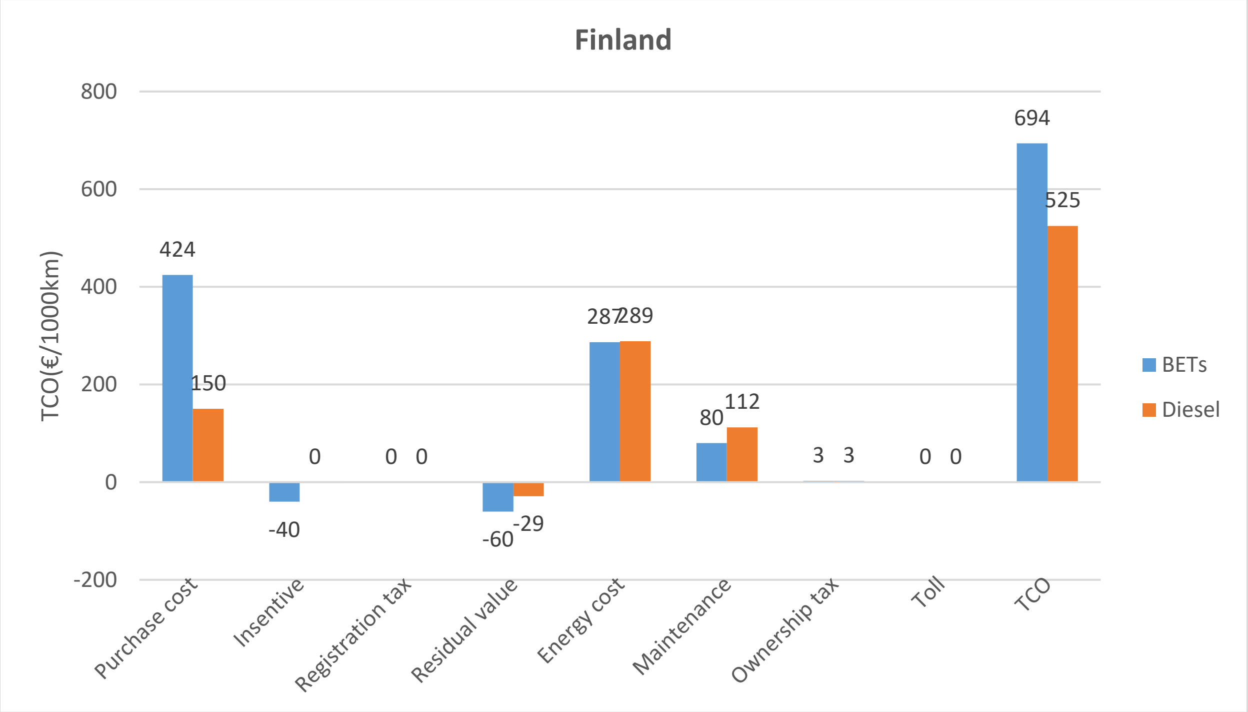

Figure 28 Comparison of the TCO for BETs and Diesel trucks in Finland in 2023.

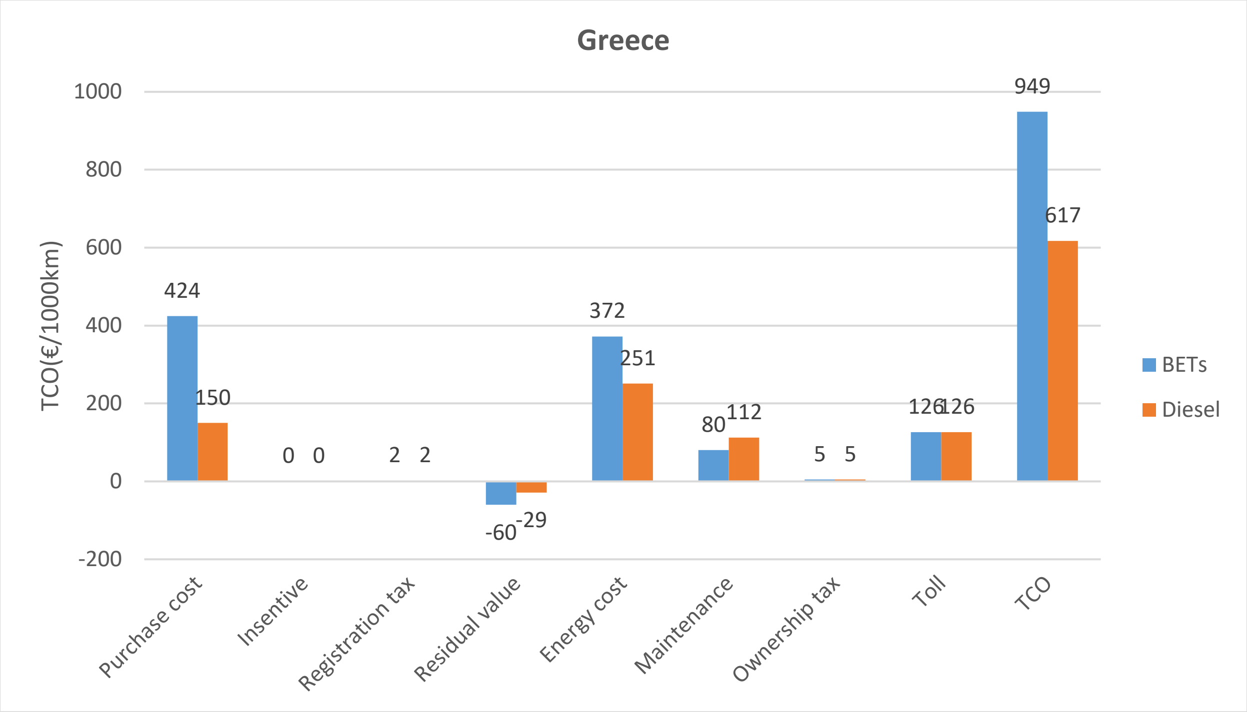

Figure 29 Comparison of the TCO for BETs and Diesel trucks in Greece in 2023.

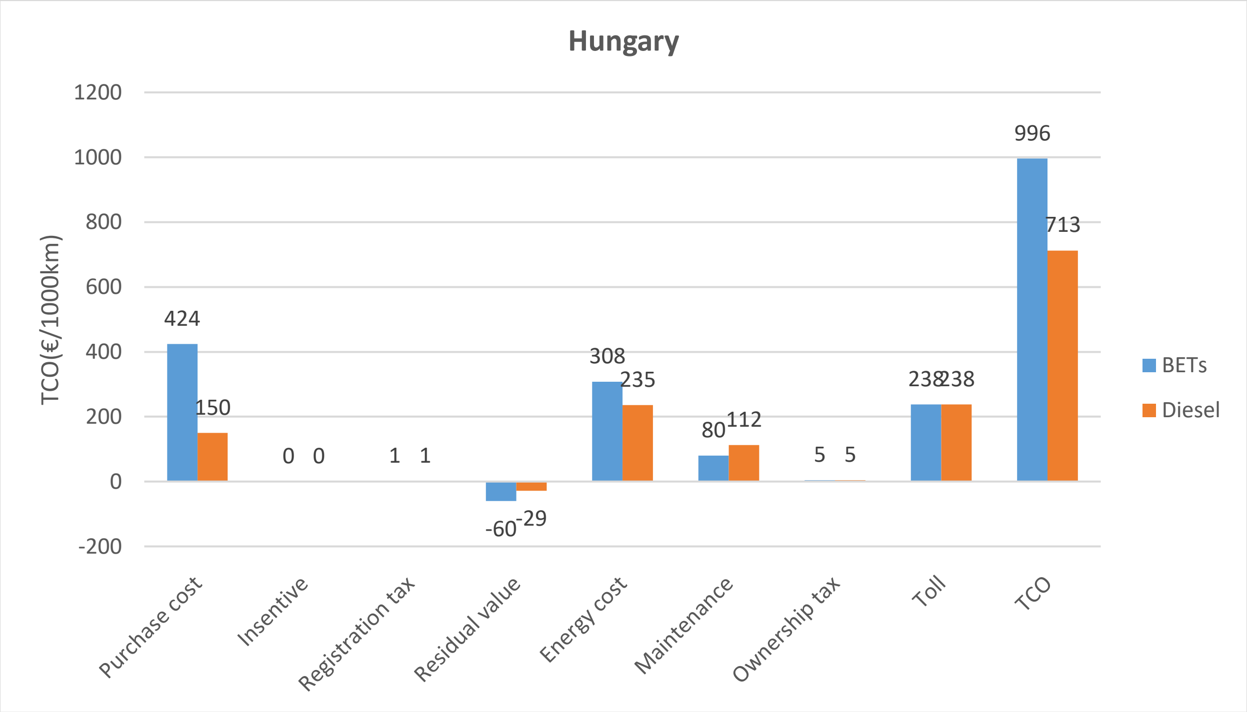

Figure 30 Comparison of the TCO for BETs and Diesel trucks in Hungary in 2023.

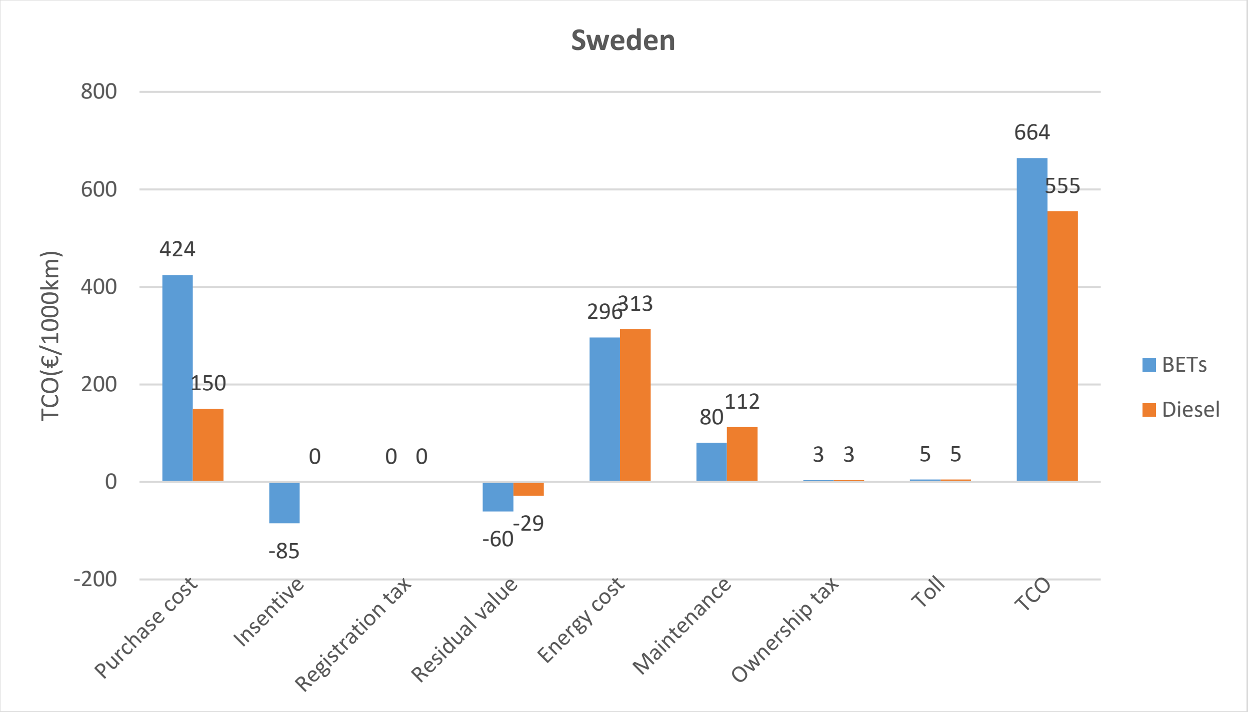

Figure 31 Comparison of the TCO for BETs and Diesel trucks in Sweden in 2023.

3.2 Dynamics of TCO Parity: Exploring Influential Factors and Scenarios

The dynamic nature of TCO parity between BETs and diesel vehicles, as well as the numerous relevant variables and circumstances taken into account, must be emphasized. It is critical to evaluate how incentives, variations in the cost of diesel and electricity, and toll exemptions for BETs affect the relative TCO of the two types of trucks over time. Here, the goal is to investigate how these variables and situations affect the economic elements that surround the transportation industry's adoption of alternative fuel technology. Using a scenario-based methodology, this analysis aims to give stakeholders and decision-makers important information on the financial effects of switching to electric trucks.

The total cost of ownership for BETs decreases in all of the nations included in this analysis. This reduction is driven by lower operating costs as a result of improved truck efficiency resulting in lower energy expenditures, as well as a decline in vehicle purchase prices linked to cheaper battery costs. Additionally, a decrease in energy overhead costs associated with the infrastructure cost has an impact on the TCO reduction for BETs. On the other hand, diesel trucks show a relatively constant total cost of ownership during this time, with a minor decline brought on by improvements in efficiency that decrease operating costs.

However, it's important to note that in this section, no government incentives for purchasing BETs are considered.

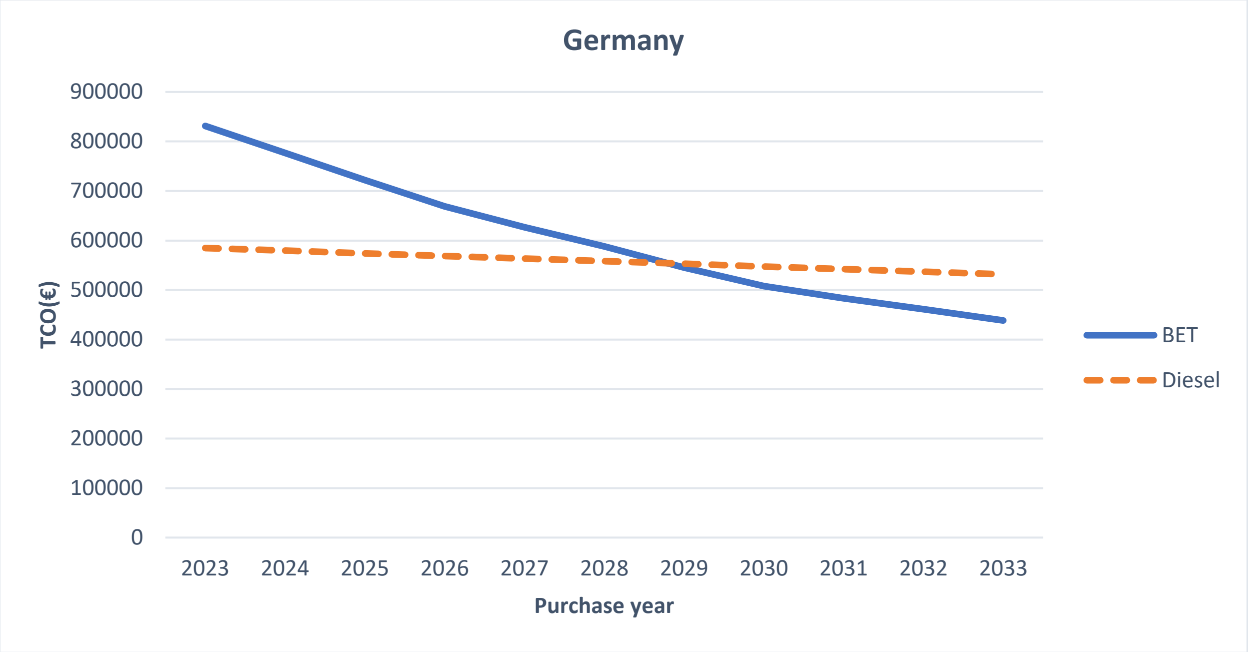

Figure 32 TCO of diesel and BETs trucks in Germany, fixed diesel fuel and electricity prices.

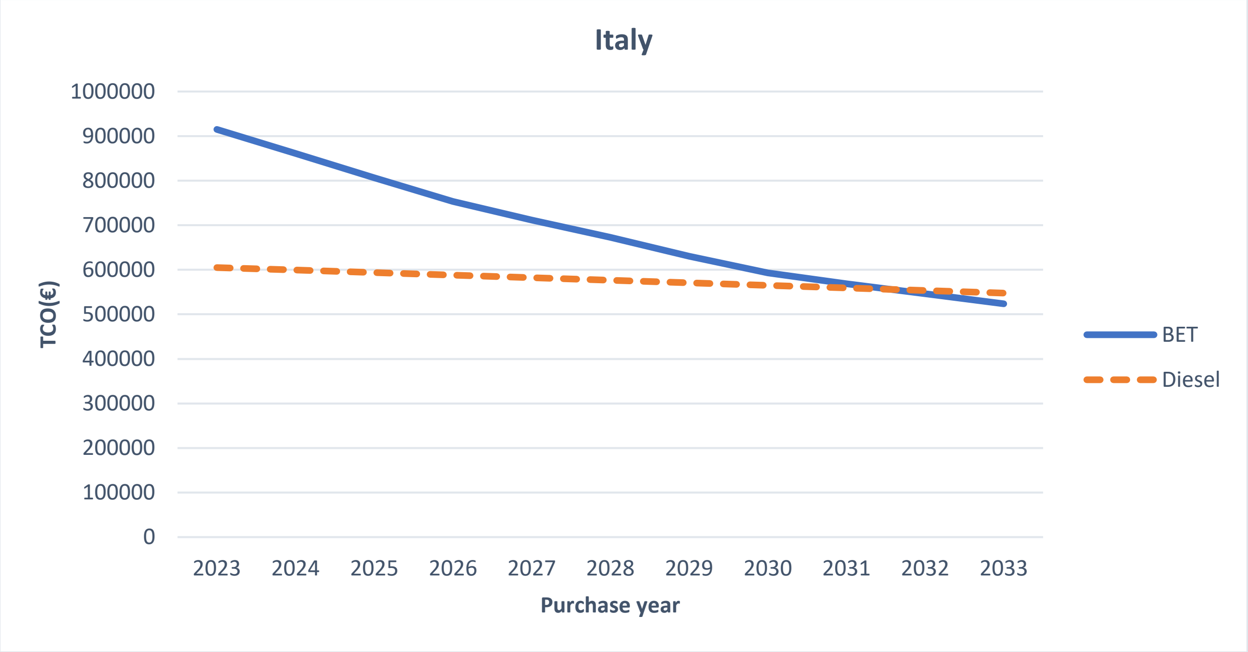

Figure 33 TCO of diesel and BETs trucks in Italy, fixed diesel fuel and electricity prices.

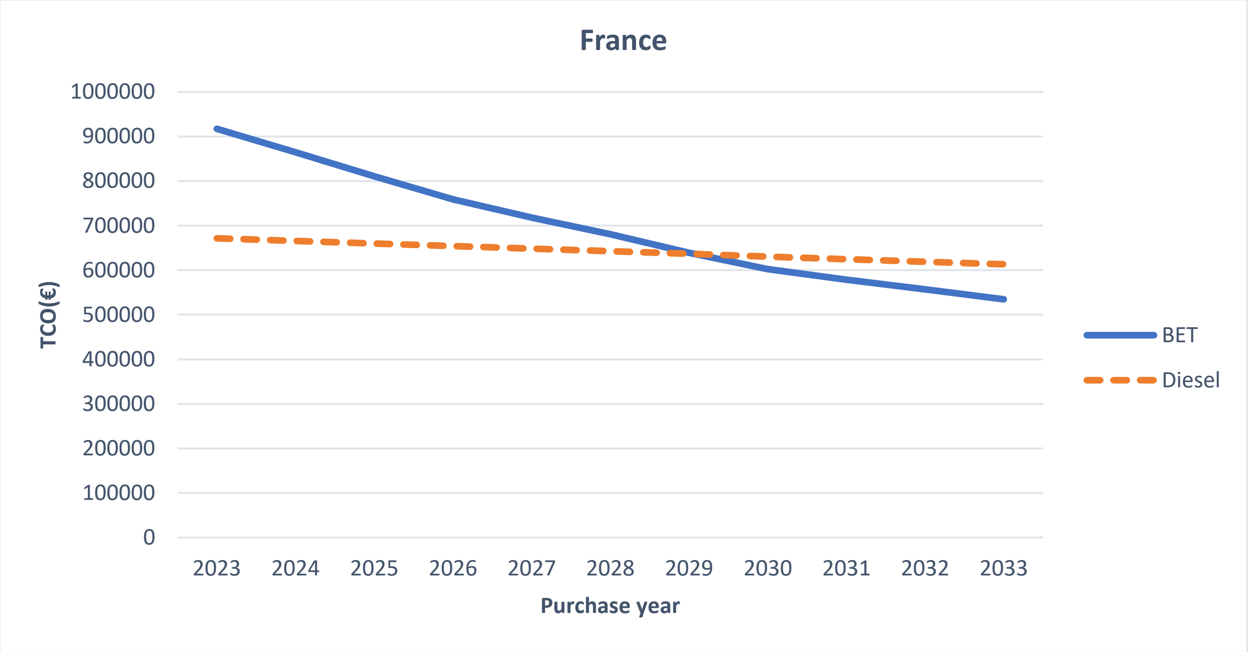

Figure 34 TCO of diesel and BETs trucks in France, fixed diesel fuel and electricity prices.

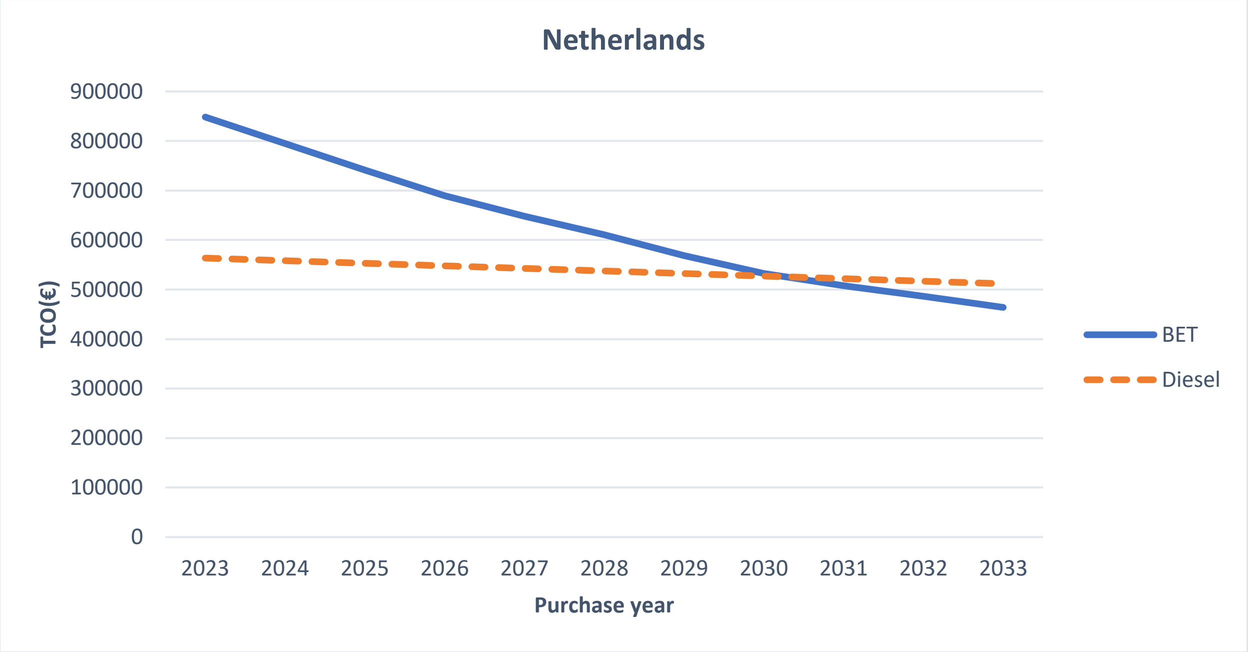

Figure 35 TCO of diesel and BETs trucks in Netherlands, fixed diesel fuel and electricity prices.

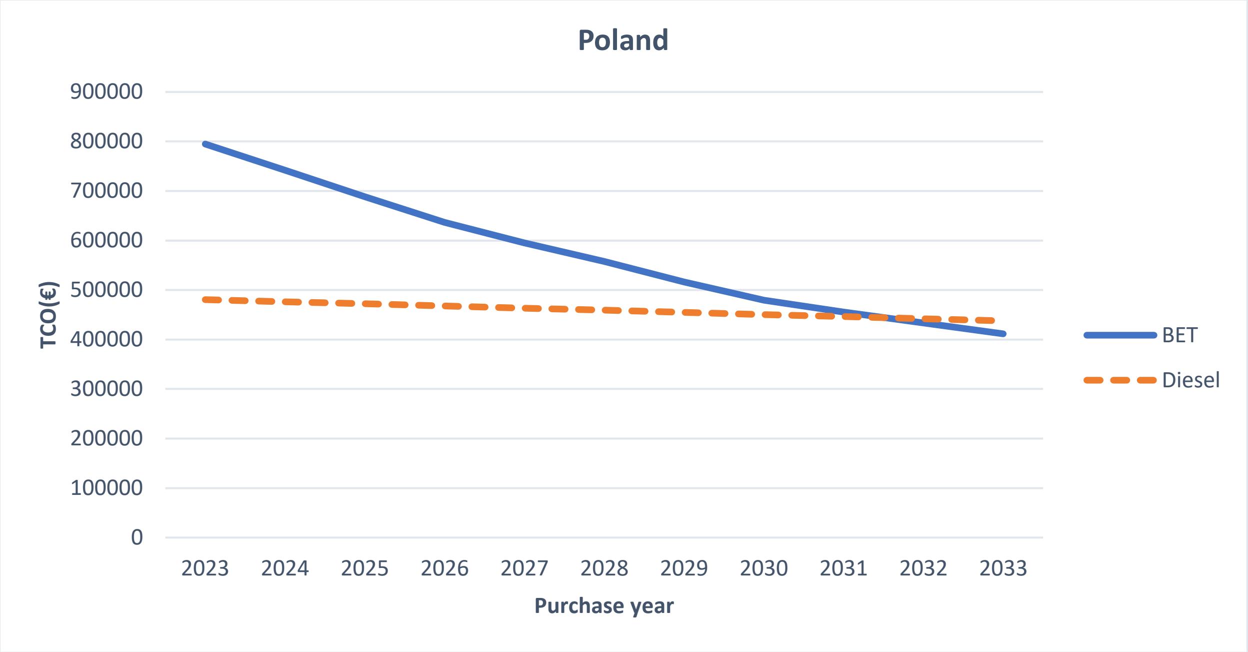

Figure 36 TCO of diesel and BETs trucks in Poland, fixed diesel fuel and electricity prices.

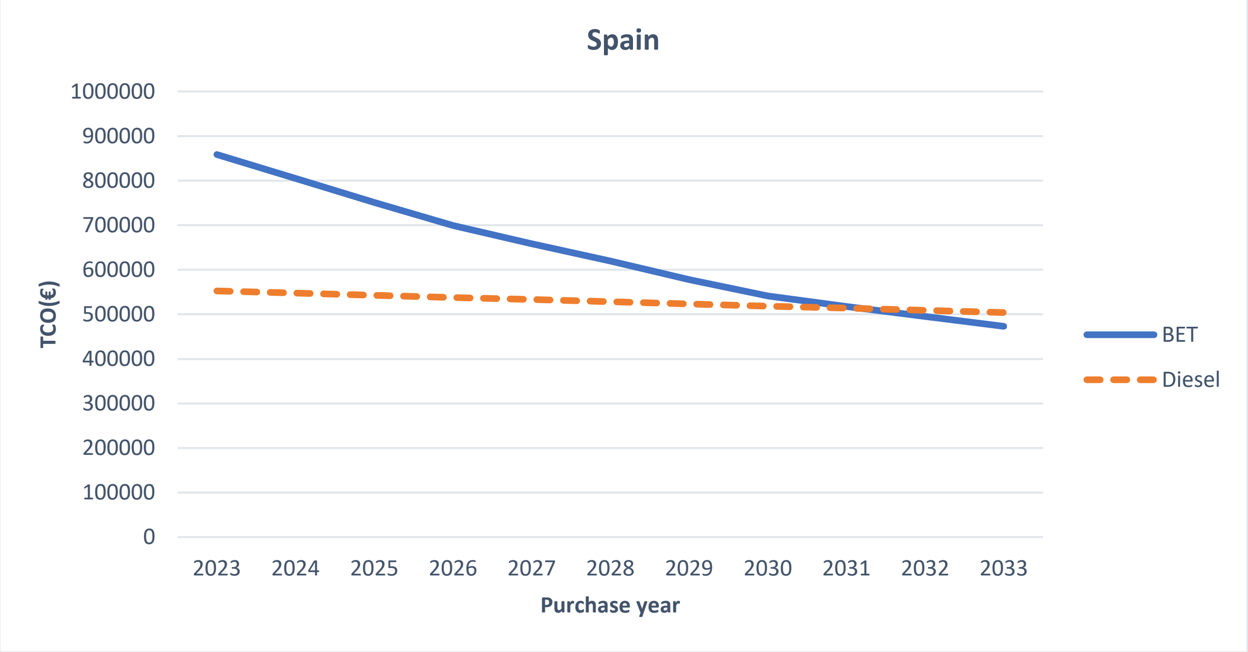

Figure 37 TCO of diesel and BETs trucks in Spain, fixed diesel fuel and electricity prices.

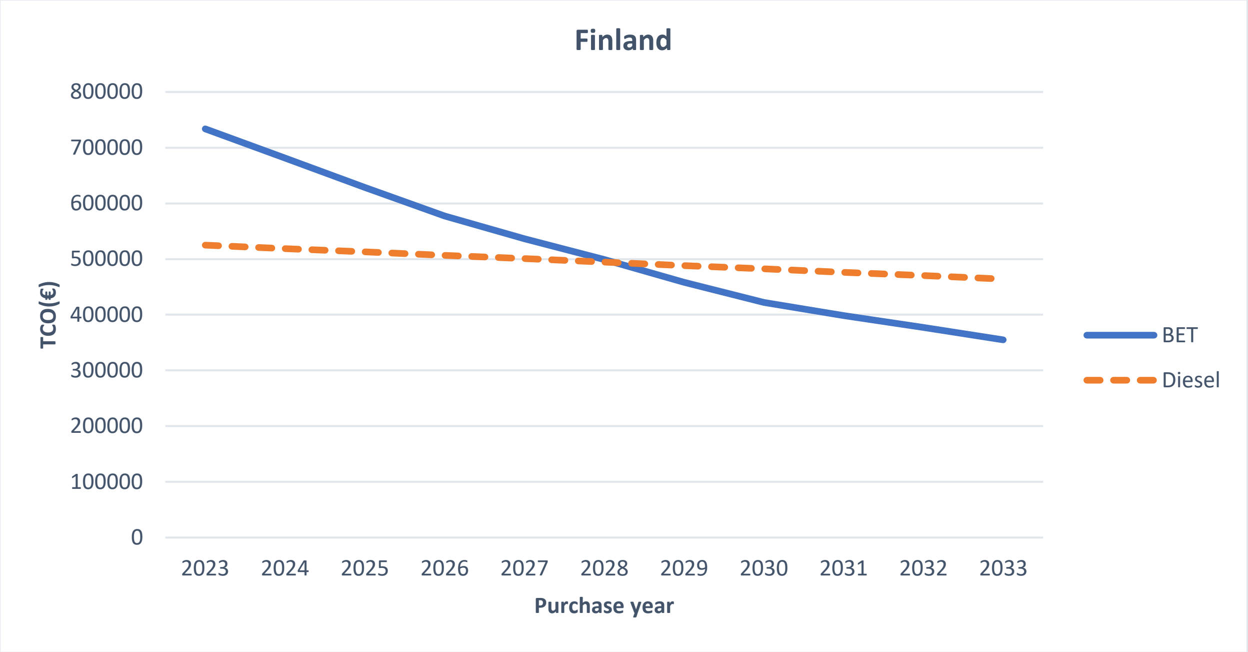

Figure 38 TCO of diesel and BETs trucks in Finland, fixed diesel fuel and electricity prices.

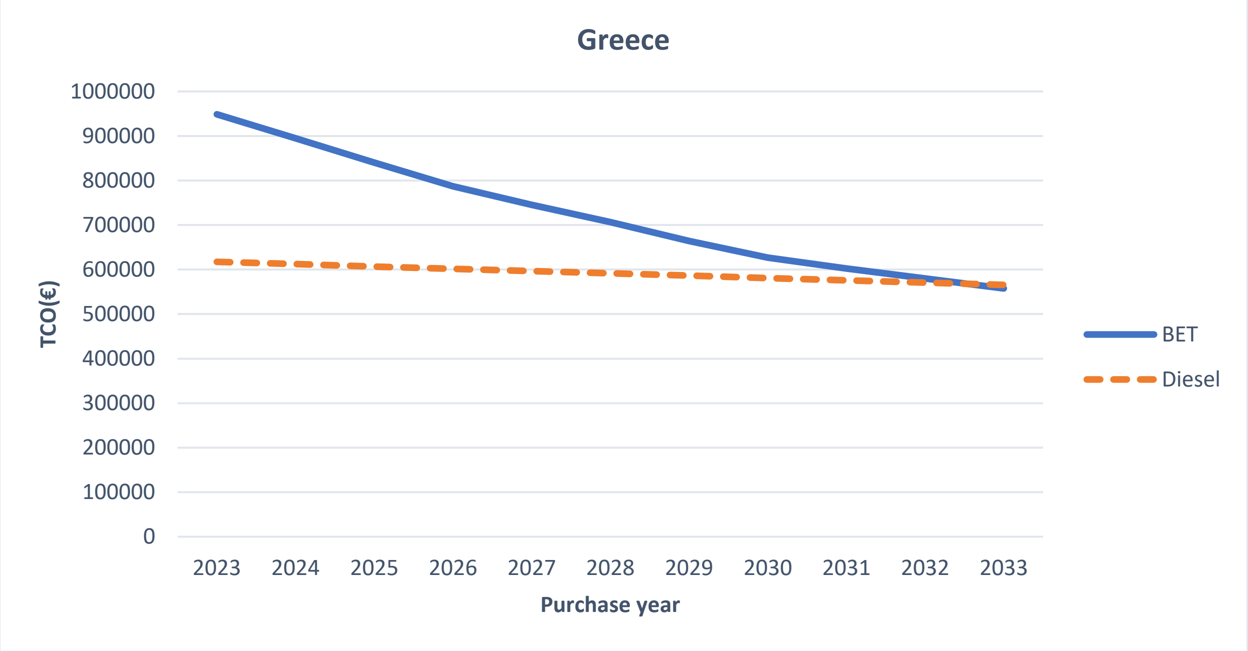

Figure 39 TCO of diesel and BETs trucks in Greece, fixed diesel fuel and electricity prices.

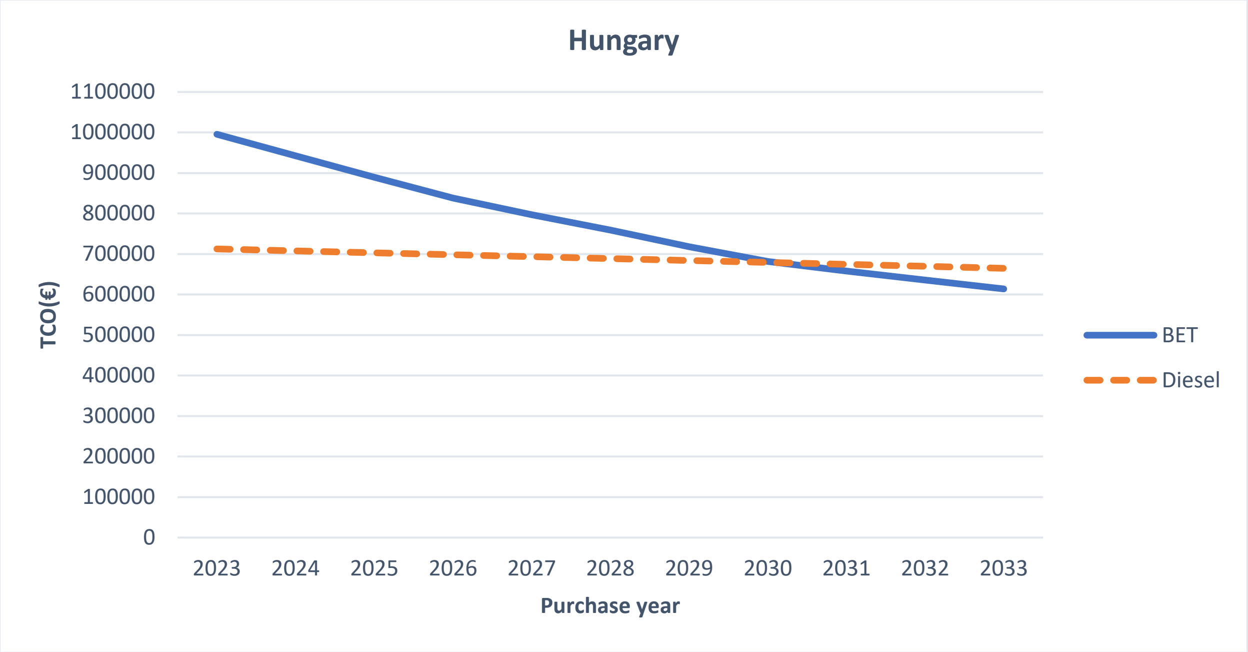

Figure 40 TCO of diesel and BETs trucks in Hungary, fixed diesel fuel and electricity prices.

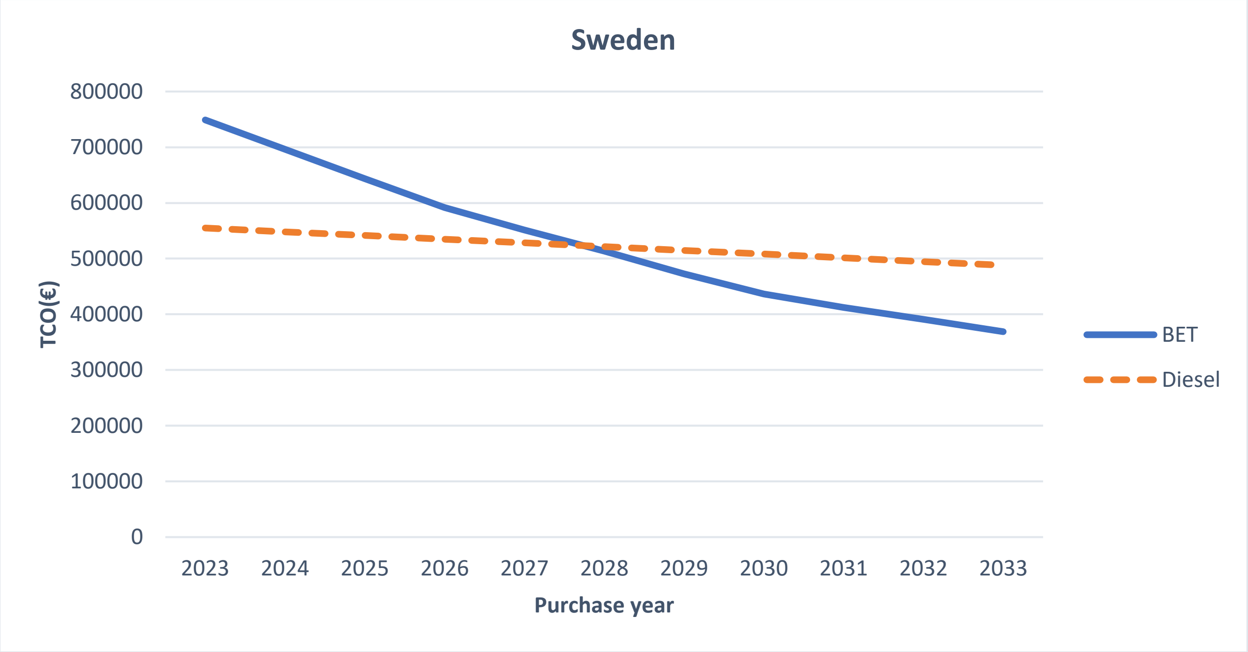

Figure 41 TCO of diesel and BETs trucks in Sweden, fixed diesel fuel and electricity prices.

Following the TCO trends of all countries, the parity year for each country is summarized in Table 14. The comparison of TCO parity years across the analyzed countries reveals notable variations in the pace of transition towards economic competitiveness between battery electric trucks and diesel vehicles. Sweden emerges as an early adopter, with TCO parity projected to be achieved by 2027, reflecting the country's strong commitment to sustainable transportation initiatives and robust infrastructure for electric vehicle adoption. Moreover, Germany, often considered a leader in automotive innovation, falls within the mid-range with a projected parity year of 2028, highlighting the importance of both policy incentives and market dynamics in shaping the transition timeline.

TCO parity without incentives	**Sweden**	**Germany**	**Finland**	**France**	**Netherland**
	2027	2028	2028	2029	2030
	Hungary	**Italy**	**Poland**	**Spain**	**Greece**
	2030	2031	2031	2031	2032

Table 14 TCO parity year without any policy intervention.

Finland and France follow closely behind, with anticipated parity years of 2028 and 2029, respectively, indicating a favorable outlook for electrification efforts in these regions. The Netherlands, renowned for its progressive stance on environmental sustainability, is poised to achieve TCO parity by 2030, underscoring the effectiveness of comprehensive policy frameworks in driving market adoption of zero-emission trucks. Hungary, Italy, and Poland exhibit similar trajectories, with parity years projected for 2030 and 2031, suggesting a gradual but steady transition towards electrification in these countries. Spain and Greece face relatively longer timelines, with parity years forecasted for 2031 and 2032, respectively, signaling the need for targeted interventions and infrastructure investments to accelerate the adoption of ZE-HDVs. These disparities underscore the need for tailored strategies and targeted interventions to accelerate the adoption of zero-emission heavy-duty vehicles across diverse socio-economic and geographical contexts. Additionally, the absence of government incentives in this analysis underscores the significance of policy frameworks in influencing the pace and trajectory of electrification within the transportation sector.

3.2.1 Effect of Incentives on TCO Parity

This section examines how government subsidies, which have the potential to greatly affect the TCO, affect the purchasing of electric trucks. The subsidies allotted for heavy-duty vehicles differ significantly between nations based on variables such as the kind of vehicle, weight, and drive technology. These subsidies successfully lower the electric trucks' initial purchase price, lowering the total TCO and bringing forward the TCO parity year, which is shown, in Table 14.

As mentioned before, different countries offer varying subsidy amounts. For instance, Germany provides €40,000 in subsidies, whereas Italy offers €20,000. Subsidies in France pay for 40% of the purchase price, with a cap of €50,000. In a similar vein, Poland and the Netherlands provide subsidies up to a maximum of €50,000 and €45,000, respectively, based on the price differential with internal combustion engine vehicles. Other nations that offer fixed subsidies are Finland and Spain, which offer €40,000 and €15,000, respectively. At the moment, Hungary and Greece do not provide any subsidies; Sweden provides a subsidy equal to twenty percent of the buying cost.

countries	**TCO parity without subsidy**	**TCO parity with subsidy**
Sweden	2027	2025
Finland	2028	2026
France	2029	2027
Netherland	2030	2028
Poland	2031	2029
Germany	2028	2027
Italy	2031	2030
Spain	2031	2030
Hungary	2030	2030
Greece	2032	2032

Table 15 the effect of incentives on TCO parity.

A comparison of government incentives for the adoption of electric trucks in the target countries shows significant differences in the subsidy arrangements and how these affect the TCO parity. When examining the years in which TCO parity is reached both with and without subsidies, it is clear that government actions are essential to accelerating the commercialization of electric trucks. According to Table 5, Sweden, Finland, France, and the Netherlands exhibit a notable decrease in the TCO parity year, demonstrating the effectiveness of large subsidies, with TCO parity decreasing by two years. The analysis further reveals that countries such as Italy, Spain, and Germany witnessed a reduction in the TCO parity year by only one year, despite offering substantial subsidies for electric truck adoption. Conversely, nations like Hungary and Greece, which currently do not offer any subsidies, exhibit delayed attainment of TCO parity, underscoring the influence of policy support on accelerating electric truck adoption.

3.2.2 Effect of Energy Price on TCO Parity

The TCO parity between BETs and diesel trucks is examined in this subsection in relation to changes in energy prices, namely in the costs of electricity and diesel fuel. We want to clarify the sensitivity of TCO to changes in energy costs and its consequences for the adoption of electric vehicles in the transportation sector by examining scenarios with different energy price patterns.

Table 16 presents different scenarios for Total Cost of Ownership parity among various countries, with each column representing a specific condition: “No Subsidy” refers to the scenario where no government subsidies are provided to incentivize electric truck adoption. "Decr. Elec -3% Ann" indicates a scenario where electricity costs decrease annually by 3%. "Incr. Diesel +3% Ann" represents a condition where diesel fuel costs increase annually by 3%. "Decr. Elec. -3% & Incr. Diesel +3% Ann." combines the previous two conditions with a simultaneous decrease in electricity costs by 3% annually and an increase in diesel fuel costs by 3% annually. And finally "Decr. Elec. & Incr. Diesel +3% Ann. & Govt. Subsidy" includes the combined effects of decreasing electricity costs, increasing diesel fuel costs, and the addition of government subsidies to promote electric truck adoption.

countries	No Subsidy	Decr. Elec -3% Ann.	Incr. Diesel +3% Ann	Decr. Elec. -3%& Incr. Diesel +3% Ann	Decr. Elec. & Incr. Diesel +3% Ann. & Govt. Subsidy
SWE	2027	2027	2026	2026	2025
GER	2028	2028	2027	2027	2026
FIN	2028	2027	2027	2026	2026
FRA	2029	2028	2028	2027	2026
NLD	2030	2029	2028	2028	2027
HUN	2030	2028	2028	2028	2028
ITA	2031	2029	2029	2028	2028
POL	2031	2030	2029	2029	2028
ESP	2031	2030	2029	2029	2028
GRC	2032	2030	2030	2029	2029

Table 16 Effect of Energy Price on TCO Parity.

Compared to the no-subsidy scenario, the TCO parity year for electric trucks is accelerated globally due to the decrease in electricity costs. Nonetheless, it can advance parity by around a year. The impact on the TCO parity shift, however, may fluctuate according to the variations in electricity prices among nations. In Sweden, for example, the TCO parity year is moved from 2027 to 2026. Likewise, the rising cost of diesel exhibits a comparable pattern, which could cause a one-year shift in TCO parity. When compared to the no subsidy scenario, this circumstance causes the TCO parity year for diesel trucks to be delayed. On the other hand, because electricity prices are rather consistent, it accelerates the year that electric trucks reach parity.

Combining a 3% annual decrease in electricity costs with a 3% annual increase in diesel fuel costs affects TCO parity differently across countries, generally favoring electric trucks and bringing the parity year forward by almost 2 years.

The addition of government subsidies, alongside decreasing electricity costs and increasing diesel fuel costs, significantly accelerates TCO parity for electric trucks, making them more competitive economically, with Sweden achieving the earliest parity year of 2025.

3.2.3 Effect of Toll Exemption on TCO Parity

The effect of toll exemptions on the TCO parity between BETs and diesel trucks is examined in this subsection. We seek to comprehend how policy interventions can affect the economic competitiveness of alternative fuel technologies and encourage their adoption in the commercial trucking industry by examining the financial ramifications of toll exemptions for electric cars.
Based on the data presented in Table 17, the effect of toll exemptions on the TCO parity between BETs and diesel trucks varies across different countries. The analysis reveals a range of years for achieving TCO parity, with some countries experiencing more significant impacts from toll exemptions than others.
The TCO parity between scenarios with and without toll exemptions is largely stable in nations like Sweden, Germany, and Finland, where toll rates for electric trucks are either nonexistent or extremely cheap. This implies that in areas where tolls for electric vehicles are already quite low, the impact of toll exemptions on TCO parity may be limited.

However, when toll exemptions are taken into account, Hungary shows a large decrease in the TCO parity year, suggesting that such governmental acts can considerably expedite the adoption of alternative fuel technology in some regions. In particular, toll exemptions advance Hungary's TCO parity by six years. In the same way, France exhibits a noteworthy advancement in TCO parity with toll exemptions, as a result of regulatory efforts that advance TCO parity by five years. Furthermore, the TCO parity with toll exemptions has significantly improved in nations like Greece and the Netherlands, underscoring the usefulness of toll-targeting policy measures in boosting the economic competitiveness of electric trucks in these markets.

	TCO parity	**TCO parity without toll**
Sweden	2027	2027
Germany	2028	2028
Finland	2028	2028
France	2029	2024
Netherland	2030	2027
Hungary	2030	2024
Italy	2031	2028
Poland	2031	2030
Spain	2031	2028
Greece	2032	2027

Table 17 Effect of Toll Exemptions on TCO Parity between BETs and Diesel Trucks

In evaluating the effectiveness of policies aimed at reducing TCO parity, a comparison was made between the influence of subsidies and toll exemptions on TCO parity. It was observed that subsidies could accelerate TCO parity by a maximum of two years, whereas toll exemptions had a more significant impact on altering TCO parity. This difference in effectiveness may be attributed to several factors. Firstly, the relatively low level of subsidies provided by governments may restrict their ability to accelerate TCO parity. Thus, there exists potential for governments to augment the magnitude of subsidies allocated for the purchase of electric tractor-trailers. Conversely, the substantial impact of toll exemptions on TCO parity suggests that high toll charges in certain countries could hinder the adoption of electric trucks. Consequently, the exemption of toll charges emerges as a more potent policy measure compared to current subsidy schemes. In summary, while subsidies play a role in advancing TCO parity, toll exemptions have demonstrated greater efficacy and may warrant increased attention from policymakers seeking to promote the adoption of electric trucks.

4. Conclusions

This study delves into the analysis of the total cost of ownership for electric tractor-trailers, compared to their diesel counterparts. It aims to construct a comprehensive TCO model to aid both customers and policymakers in making informed decisions. By reviewing previous literature on TCO models and their influence on decision-making in the purchase of electric trucks, this study lays the groundwork for a nuanced understanding of the economic implications of zero-emission heavy-duty vehicles.

The TCO model devised in this study employs a meticulous methodology, encompassing various factors such as fixed costs (purchase cost, incentives, registration tax, and residual value) and operational costs (maintenance costs, energy costs, road tolls, and ownership tax). By focusing on 10 European countries aligned with Trans-European Transport Network standards, we ensure comprehensive coverage, prioritizing nations with significant electric vehicle infrastructure.

Within the TCO analysis, we conducted both static comparisons for the current year, analyzing different components of TCO for both diesel and electric vehicles, and explored the dynamic nature of TCO parity between BETs and Diesel trucks within the target countries.

The key findings of this study can be summarized as follows:

1. Operational expenditure constitutes a significant portion of the TCO, surpassing half of the total expenses across all analyzed countries. Particularly, for BETs, OPEX expenses outweigh Capex, accounting for approximately 60% of total expenses. Conversely, diesel trucks exhibit OPEX as the primary cost component, exceeding 70% globally.
2. Through meticulous breakdowns of TCO elements, crucial insights emerged, highlighting the dominance of purchase and energy costs among Capex and OPEX parameters, respectively.
3. With consideration of government subsidies, all countries—except Greece—are projected to witness zero-emission tractor-trailers achieving price parity with diesel trucks by 2030.
4. Variations in energy costs, such as decreasing electricity prices by 3% annually and increasing diesel prices by 3% annually, could advance TCO parity by approximately one year.
5. Toll exemption emerges as a potent lever for accelerating TCO parity, outweighing the impact of subsidies. Toll exemptions exhibit a stronger influence on altering TCO parity, warranting their recommendation for policy implementation.

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