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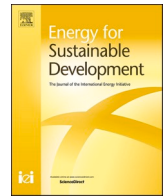
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Research trends in the total cost of ownership for electric vehicles: A systematic literature review[☆]

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ABSTRACT

Studies on the total cost of ownership (TCO) of electric vehicles (EVs) have become a crucial topic in academic research. As EVs have gained prominence globally, the volume of research on this subject has increased. However, previous review studies have not focused on examining trends in research that estimates the TCO for all types and technologies of EVs. Thus, our study aims to fill this gap by reviewing global trends and results of TCO studies on EVs. Our review employs the method of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to systematically collect and analyse 185 articles from 2011 to 2024. The contributions of our review are fourfold. Firstly, we construct a thematic research map to understand which topics are densely connected, thereby highlighting the core themes and focal points of the research field. As a result, future research should focus on reducing the TCO to accelerate EV adoption. Secondly, we show that the most extensively analysed vehicle technologies are battery electric vehicles (BEVs), while passenger cars are the most studied vehicle type. Thirdly, we differentiate the objectives of the TCO studies, identifying motivation gaps among them. We found that the primary objectives of the reviewed studies are TCO comparisons, followed by battery size and powertrain designs, policy scenario analysis, and TCO model developments. Lastly, we provide the range of TCO estimates for different types and technologies of vehicles. The average TCO for BEVs is found to be higher than that for internal combustion engine vehicles (ICEVs) across passenger cars, buses, trucks, and cargo vans. Electric motorcycles, however, buck this trend, with their average TCO being slightly lower than that of conventional motorcycles. Based on the review results, we propose several recommendations for policy implications and future studies.

Introduction

Electric vehicles (EVs) are expected to play a key role in achieving global decarbonization targets (IPCC, 2022). The transportation sector contributes to 20 % of global air pollution (WHO, 2024) and thus, the

successful adoption of EVs will be pivotal in transitioning toward more sustainable energy use in the future. EVs were initially developed in the 1830s (Moradi et al., 2022). However, they were not widely adopted as private vehicles in the early 20th century due to high cost, limited range, and low maximum velocity compared to internal combustion engine

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vehicles (ICEVs).

The contemporary era of EVs commenced in the late 20th century and they have since gained widespread acceptance. The first mass-market EV was introduced in 2010 (US Department of Energy, 2014). EV sales have experienced rapid growth, exceeding 10 million units in 2022 (IEA, 2023). Three markets dominated global sales in 2023: China led with 60 %, followed by Europe with 25 %, and the US, with 10 % (IEA, 2024). EV sales in other countries also increased, though not as rapidly as in these three countries due to several factors, including the high expenses of owning and using EVs (Alanazi, 2023), the shortage of charging stations (Metais et al., 2022), and the limited range of EVs (Steinstraeter et al., 2021).

The decision to adopt EVs is largely influenced by the total cost of ownership (TCO) (Pandiyaswargo et al., 2021). TCO is a comprehensive estimation of all costs and incentives associated with owning an asset throughout its lifetime, including the purchase price, and all other expenses required to operate and maintain the asset over a specific period (Ribeiro & Silveira, 2024). For vehicles, TCO includes both capital costs (e.g., the vehicle price and resale value) and operating costs (e.g., taxes, fuel and maintenance) (Wang et al., 2024). Additionally, factors such as route type, residential density, user demographics, and whether the vehicle is the primary or secondary mode of transportation affect TCO (Riyanto et al., 2019).

Several studies have reviewed research estimating the TCO of EVs from various perspectives. Kumar and Alok (2020) reviewed 239 studies on EVs in general and reported that TCO is one of the three most analysed topics. Graczyk et al. (2022) reviewed 25 papers on the application of open electric bus operating data (such as efficiency, routes, weather, and traffic situations) required to determine the TCO. Danielis et al. (2024a) systematically reviewed 16 publications on the TCOs of fuel cell electric buses. Meanwhile, Danielis et al. (2024b) reviewed 26 publications on the TCOs of hydrogen-powered trucks. Bhardwaj and Mostofi (2022) reviewed three studies estimating the TCOs of battery electric trucks. Roosen et al. (2015) reviewed 44 studies comparing the TCOs for various EVs and ICEVs. Kumar et al. (2023) reviewed multiple studies estimating the TCO of EVs and ICEVs in Europe, North America, South America, Asia, and Africa. Nevertheless, Kumar et al. (2023) did not conduct their review systematically, resulting in many TCO-related studies being overlooked, including those from Australia. Thus, our paper aims to fill this research gap by systematically analysing the trends in studies estimating the TCO of all types of EVs. Specifically, we aim to address the following research questions:

- Which topics are densely connected?
- Which types of vehicles and technologies are most analysed?
- What are the key objectives of the studies?
- What are the ranges of TCO estimates for different vehicle types and technologies?

The remainder of the paper is organized as follows: Section 2 discusses existing reviews of studies estimating the TCO of EVs. Section 3 outlines the methodology used to systematically select and analyse TCO studies. Section 4 presents the results of our analysis. Section 5 discusses key insights and recommendations. Finally, Section 6 concludes our review and discuss its limitations.

Literature review

The objective of a literature review is to highlight gaps in knowledge and suggest directions for future studies by analysing and assessing existing research on a particular academic topic, theme, or subject (Chigbu et al., 2023). Conducting a systematic literature review requires a structured framework to transparently report the rationale for the review, the methodologies employed, and the results obtained (Page et al., 2021). The most widely recognized method for a systematic literature review is the PRISMA (Preferred Reporting Items for

Systematic Reviews and Meta-Analyses) method, which offers strategies for data collection, search techniques and data extraction procedures (Page et al., 2021). It also advocates rigorous and transparent research practices, thereby enhancing the reliability and reproducibility of a review (Tedja et al., 2024).

Several studies have conducted reviews on EV research. Sankaran and Ranganathan (2021) reviewed the global and Indian EV markets, while Horváth et al. (2023) examined the EV market, policies, and supporting infrastructure in several Eastern European countries. Kumar and Alok (2020) conducted a systematic literature review of 239 studies related to EV adoption. The motivations for these studies can be grouped into seven categories: economic considerations, charging infrastructure availability, consumer perspectives, policies and regulations, vehicle specifications, environmental benefits, and marketing perspectives. In conclusion, the TCO of EVs is one of the most discussed topics, with 76 studies focused on it. Although TCO is an increasingly prominent topic in the EV literature, reviews specifically addressing research on the TCO of EVs remain limited as shown in Table 1.

Roosen et al. (2015) conducted a systematic literature review analysing vehicle costs. They used 12 keywords related to cost evaluation methods and impacts, including environmental impacts, resulting in 229 unique references published between 1995 and December 2013. The articles were then selected by two authors and a reviewer (in cases of uncertainty), leading to a detailed comparison of 44 articles concerning vehicle technology, evaluation methods, assumptions, private costs, and external costs. As a result, Roosen et al. (2015) analysed studies from the US (21 studies), EU countries (13), China (2), and Australia (2). They also examined six studies with a multi-country scope, including one from the U.S. and Canada and five from the EU region. The analysed vehicle technologies included ICEVs (44 studies), battery electric vehicles (BEVs) (31), hybrid electric vehicles (HEVs) (30), and plug-in hybrid electric vehicles (PHEVs) (24). However, Roosen et al. (2015) did not specify the types of vehicles (e.g., private cars and buses). Only 14 studies employed TCO, whereas the others used life cycle assessment (15), wheel-to-wheel analysis (10), and cost-benefit analysis (5). Roosen et al. (2015) concluded that the evaluation methods and data usage varied significantly, resulting in a wide range of private costs, which were between €33,016 and €66,922 for BEVs and between €19,853 and €35,420 for gasoline vehicles.

Bhardwaj and Mostofi (2022) conducted a systematic review of 53 studies on battery electric trucks covering the charging technology, the TCO, and CO₂ life cycle assessment. However, they only discussed three studies when reviewing approaches and methods for estimating the TCO and the results. Another study on the TCO of trucks was conducted by Danielis et al. (2024b). Initially, they systematically identified 198 articles related to the TCO of hydrogen-powered trucks and then conducted bibliometric analysis on these articles. After further selection, they narrowed it down to 26 articles and gray literature for the TCO

Table 1
Previous reviews on studies estimating the TCOs of vehicles.

Study	Focus	Number of Articles
Roosen et al. (2015)	A meta-analysis of studies comparing vehicle costs and their assessment methods.	44 but only 10 utilizing TCO
Bhardwaj and Mostofi (2022)	Studies related to battery electric trucks, including charging technology, TCO, and CO ₂ life cycle assessment	3 articles
Graczyk et al. (2022)	Operational data of electric buses and three open data platforms related to government, business, and citizen data.	25 articles
Kumar et al. (2023)	A comparison of the TCO of EVs and ICEVs.	Not a systematic literature review
Danielis et al. (2024a)	The TCO of fuel cell electric buses	16 articles and reports
Danielis et al. (2024b)	The TCO of hydrogen-powered trucks	26 articles and reports

review analysis. Their result showed that the TCO ranges from €0.59 to €0.94 per kilometre (km) for diesel trucks and from €0.71 to €5.12 per km for hydrogen-powered trucks, depending on the hydrogen pathways.

A systematic review by Graczyk et al. (2022) focused on electric buses for public transportation. They searched for articles on Google Scholar using six keywords related to electric buses, yielding 150 papers published between 2018 and 2021. The screening process, which concentrated on variables influencing the TCO of electric buses (such as open street maps, environmental conditions, traffic congestion, and the number of passengers), resulted in 25 articles for further analysis. While Graczyk et al. (2022) did not present a range of TCOs for electric buses, they analysed factors affecting TCO, including traffic lights' impacts on energy costs and battery degradation, ambient temperature's impact on battery degradation, and departure times related to battery charging duration. Danielis et al. (2024a) conducted a systematic review of the TCO of fuel cell electric buses. They initially obtained 283 articles and analysed them using a bibliometric approach. However, only 11 articles were eventually used for the systematic review focused on TCO analysis. Additionally, they included five reports on TCO analysis conducted by international energy agencies. The average TCO values derived from these 16 sources were €2 per km for fuel cell electric buses and €1.44 per km for diesel buses.

Kumar et al. (2023) presented TCO estimates from several studies across various continents, i.e., Europe (Germany, Italy, Norway, Turkey, and the European Union), Asia (China, Korea, and India), North America (the US.), South America (Brazil), and Africa (Ghana). Kumar et al. (2023) also discussed an inter-country study that examined the TCO for HEVs, PHEVs, BEVs, and conventional vehicles in the US, UK, and Japan. They found that the TCO of EVs varies across nations due to differences in policy.

Therefore, as a synthesis, the novelty of our systematic literature review is threefold. First, our review analyses a larger number of articles without limiting the publication year or the type of vehicle. Second, based on this larger volume of studies, we provide a more comprehensive range of TCO estimates categorized by vehicle type and technology. Additionally, our review highlights trends and research gaps in TCO, particularly concerning the types and technologies of vehicles analysed, as well as the primary objectives of the analyses. We presented a co-occurrence network and a thematic map to identify the topics that are most interconnected, thereby emphasizing the main themes and key areas of focus within the research field.

Methodology

Our systematic literature review applies the PRISMA framework as outlined in Table 2. The initial step in this framework is the identification of research questions as presented in the Introduction section. The second step involves determining specific search keywords, which are ("Total cost of ownership") AND ("Electric vehicles" OR "electric vehicle" OR "Electric motorcycle" OR "electric motorcycle" OR "Electric scooter") in the title, abstract, and keywords.

Subsequently, a comprehensive literature search was conducted on May 2, 2024, using predefined keywords and criteria. The search utilized the Scopus database, which is recognized as one of the largest and most reputable academic databases, providing extensive coverage of high-quality peer-reviewed publications worldwide (Baas et al., 2020). This choice ensures the comprehensive inclusion of significant research on the TCO of EVs, thereby enhancing the consistency and reliability of data collection. Through this search protocol, a total of 432 articles were identified for further processing.

In the fourth step, we selected articles for review based on three inclusion criteria: 1) The source type was restricted to journals, 2) the document type was restricted to articles, and 3) only English-language articles were considered. The publication years were not restricted, and articles that were not fully accessible were excluded from the analysis. Based on these criteria, a total of 239 articles were selected for

Table 2
The implementation of the PRISMA method.

PRISMA Steps	Implementations
1. Identifying the research question.	a. Which topics are densely connected? b. What are the key objectives of the studies? c. Which types of vehicles and technologies are most analysed? d. What are the ranges of TCO estimates for different vehicle types and technologies?
2. Developing inclusion and exclusion criteria.	Keywords: TITLE-ABS-KEY ("Total cost of ownership") AND ("Electric vehicles" OR "electric vehicle" OR "Electric motorcycle" OR "electric motorcycle" OR "Electric scooter")
3. Conducting a comprehensive literature search	Articles searched on Scopus database on May 2, 2024, obtained 432 articles.
4. Performing an initial screening	Applying criteria of source type (limited to Journal) AND document type (limited to Article) AND language (limited to English) reduced the search results to 239 articles.
5. Selecting studies for inclusion in the review	A review on titles, abstracts, and full texts excluded 54 articles because they were not about the TCO of EVs. 185 articles were included in the analysis.
6. Synthesising and analysing the selected articles	Data extraction and visualization.
7. Preparing the report and interpreting the results	The answer to the research questions, policy implications, and future study suggestions.

further processing.

Next, we conducted a more comprehensive screening to ensure the relevance of the articles to the TCO of EVs. The titles and abstracts of the articles were evaluated to determine if they met the inclusion criteria. This step included eligibility verification, which required a full-text review to confirm suitability for inclusion in the systematic review. As a result of this process, 54 articles were excluded, leaving 185 articles for further analysis.

The sixth step involved synthesising and analysing the selected studies. In this phase, we created a data collection template using Microsoft Excel. The data extracted from the identified articles included the year of publication, country of study, vehicle type, vehicle power-train/ technology, study objectives, and TCO values. We used Microsoft Excel to visualize, analyse, and synthesize the collected data.

We developed a database of TCO estimates from studies that reported TCO values, including our best efforts to estimate TCO values presented in graphical form. To standardise the data, we converted TCO values presented in currency or currency per mile to currency per kilometre by considering the annual kilometre travelled (AKT) and ownership period. Additionally, TCO values reported in local currencies were converted to US dollars. Using real-time exchange rate provided by Refinitiv (now LSEG Data & Analytics) through the Stockhistory function in Excel. This function was chosen for its simplicity; however, it overlooks the fact that the exchange rates at the time of the original may differs from the exchange rate used for 2024. Another limitation is that TCO values are presented in nominal term, without accounting for inflation.

We then used Bibliometrix, an open-source R tool, to perform comprehensive science mapping analyses of scholarly literature (Aria et al., 2024; Aria & Cuccurullo, 2017). Bibliometrix was selected for its reputation as an outstanding tool for creating scientific text maps. Especially, it can generate a thematic map that categorizes the most frequent keywords into four quadrants. The y-axis represents the number of themes, also known as density or development degree, while the x-axis illustrates the correlation of these themes with other topics, referred to as centrality or relevance degree. Bibliometrix takes a dataset as input, processes it, and then produces a visual map based on the provided textual information.

The last two steps are report preparation and results interpretation. Report preparation aims to answer the research questions. Thus, we analyse the results in four main areas: the co-occurrence network and thematic map, vehicle types and technologies, study objectives, and TCO

estimates. We then discuss the policy implications, research gaps, and suggestions for future studies.

Results

Fig. 1 shows the development of studies on the TCO of EVs. These studies began in 2011 with initial research conducted in Germany (Ernst et al., 2011) and the Netherlands (van Vliet et al., 2011). The number of studies on EV TCO has increased over the years, peaking in 2022 with 31 studies. Single-country studies reached 164 articles (88 %) whereas multi-country studies made up 21 articles (12 %). Multi-country studies started in 2016 with studies conducted by Jakobsson et al. (2016) in Sweden and Germany, and by Madina et al. (2016) in Spain, Germany, and the Netherlands. Recent multi-country studies were conducted by Samet et al. (2024) and Ribeiro and Silveira (2024), both focusing on various European countries.

Studies estimating the TCO of EVs have been conducted in 54 countries. Fig. 2 shows that Germany leads with 43 studies. Other countries with a significant number of studies include the US (30 studies), Italy (21), China (19), and Sweden (18). In ASEAN countries, there are a total of nine TCO studies. Singapore has four studies, Thailand has three, and Brunei Darussalam has one. Additionally, Li and Kimura (2021) covered multiple ASEAN countries, specifically Indonesia, Malaysia, and Thailand.

Co-occurrence network and thematic map

Fig. 3 depicts the results of the co-occurrence network analysis. It reveals that the top keywords are grouped into three clusters, categorized as the TCO, environmental impact, and fuel cell clusters. The largest nodes are found in the TCO cluster, which is the focus of the keywords used in the literature search. These nodes include costs, electric vehicles, cost-benefit analysis, and secondary batteries. The thickest edges connect the TCO node with the cost node and the electric vehicles node. Other nodes in the TCO cluster cover vehicle technology (e.g., battery electric vehicles and diesel engines), cost components (e.g., taxation), and charging infrastructure. Several TCO studies on electric vehicles also calculate greenhouse gas (GHG) emissions through life cycle analysis. Additionally, some studies compare BEV with fuel cell electric vehicles (FCEVs).

Fig. 4 illustrates the frequency of keyword usage over time. While the terms “total cost ownership” and “cost” have higher frequencies, the term “cost-benefit analysis” was adopted earlier and remains in use in recent years. The term “plug-in hybrid vehicles” was commonly used in

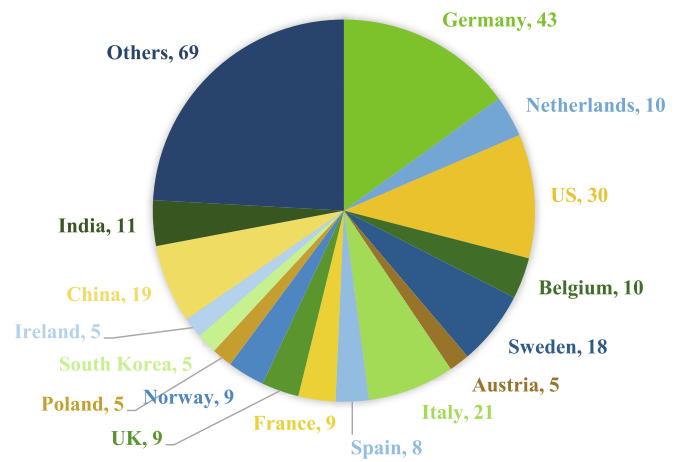


Fig. 2. TCO studies by country.

studies between 2014 and 2020; however, trending terms in subsequent years have shifted to “battery pack” and “electric buses”. The absence of keywords like “cargo vans,” and “motorcycles” in Figs. 3 and 4 suggests that studies estimating the TCO for these vehicle types are relatively limited.

Fig. 5 confirms the findings from the previous two figures, indicating that the terms “total cost ownership,” “cost,” and “electric vehicles” are motor themes and serve as primary focal points. The implication for future research is to focus on efforts to reduce the TCO to accelerate the EV adoption. In the niche themes category, topics with a high degree of development but lower relevance for TCO studies include motor vehicles, and recycling. Conversely, topics with high relevance but not yet fully developed (basic themes) include fuel cells, trucks, and cost-benefit analysis. These less intensively developed topics represent valuable opportunities for further research.

Vehicle types and technologies

The reviewed articles analysed various types of EVs, including BEVs, FCEVs, PHEVs, HEVs, extended-range electric vehicles (EREVs), and solar electric vehicles (SEVs). Additionally, ICEVs powered by diesel, gasoline, ethanol, biogas, biodiesel, liquefied natural gas (LNG), compressed natural gas (CNG), and hydrogen were examined. Table 3 shows that passenger cars were the most frequently analysed vehicle type, with 115 studies, primarily focusing on BEV technology (99 studies) and

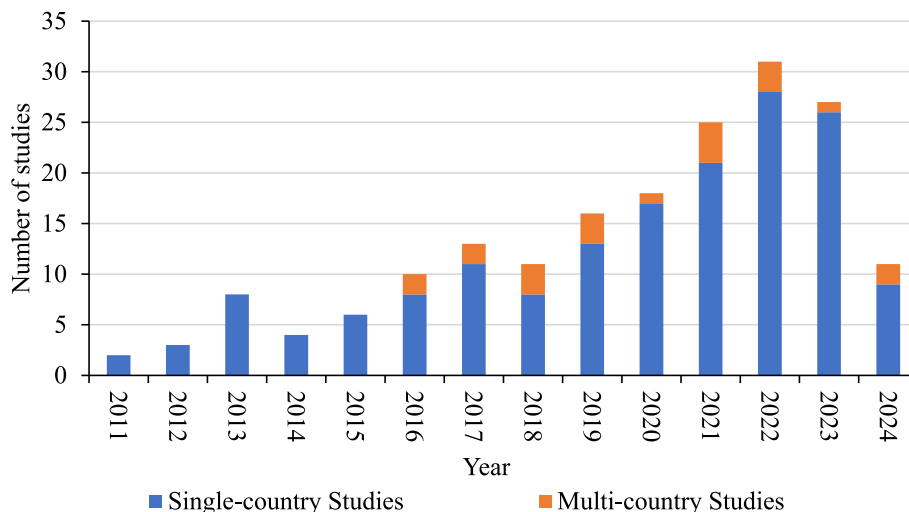


Fig. 1. Development of studies estimating the TCO of EVs.

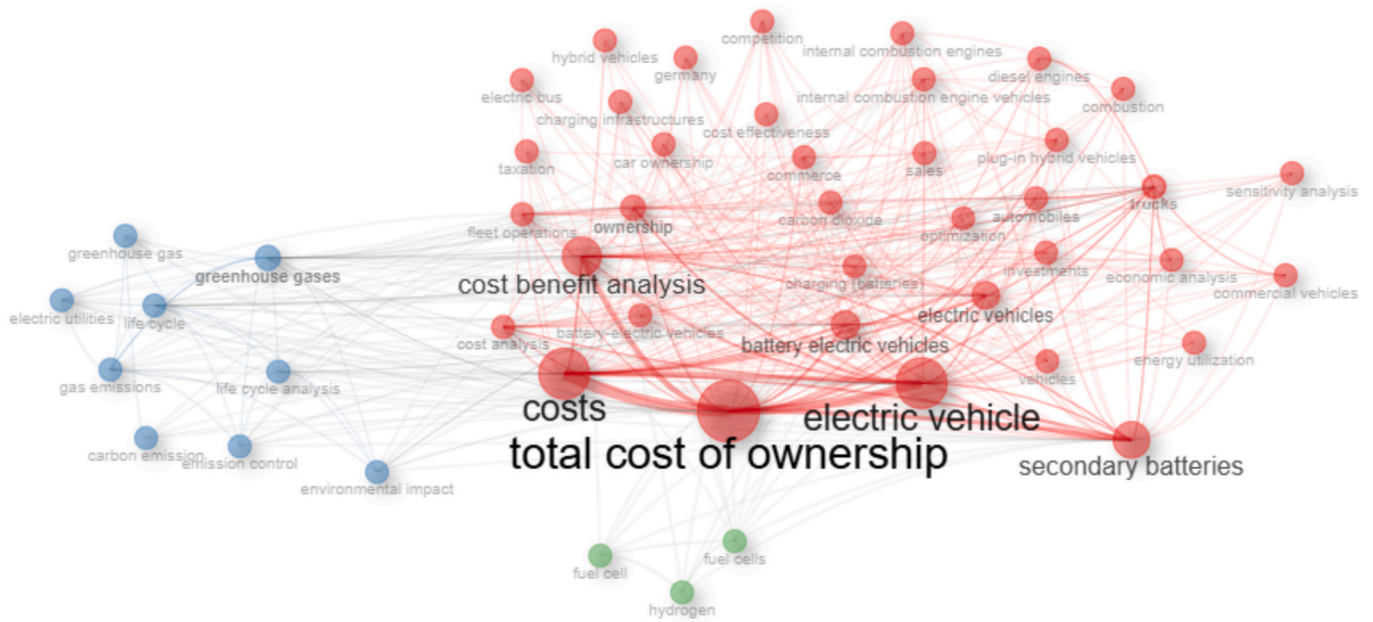


Fig. 3. Keyword co-occurrences network.

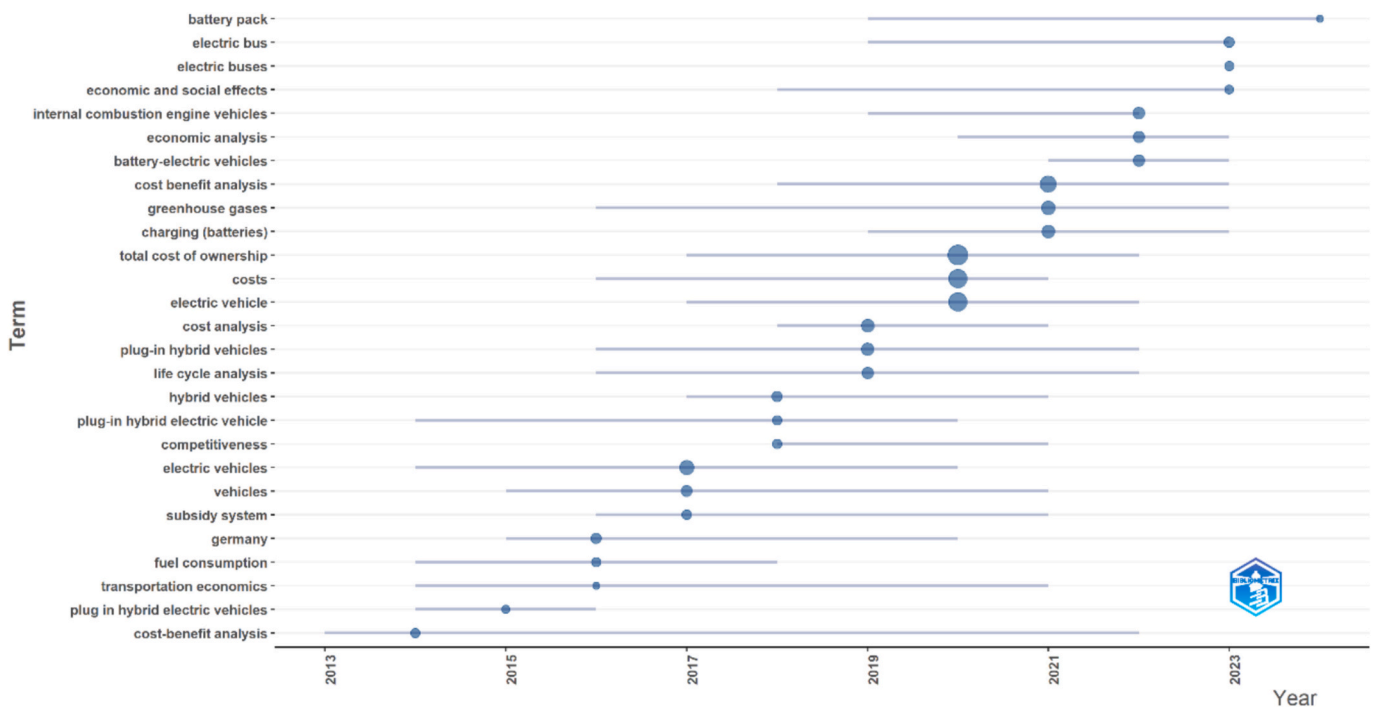


Fig. 4. Trend topics.

gasoline cars (79 studies). Trucks and buses are commonly analysed vehicle types as well, with 41 and 36 studies, respectively. Only few studies have estimated the TCOs for cargo vans (17) and motorcycles (6), particularly those based on FCEV technology.

The most analysed vehicle technology is BEVs, with a total of 155 studies, followed by gasoline and diesel vehicles, each with 94 studies. One study analysed the TCOs of three gasoline trucks, which are Ford F250, Chevrolet Silverado 2500 HD, and Dodge RAM 2500 (Gilmore & Lave, 2013). HEVs and PHEVs received moderate attention in 46 and 48 studies, respectively. Future TCO studies should focus on less researched vehicle technologies, such as EREVs (8 studies), hydrogen-powered

vehicles (3), and SEVs (1).

Study objectives

The studies reviewed have different objectives. Fig. 6 presents the distribution of research objectives from 2011 to 2024, reflecting the ongoing interest within the TCO research field. The most prevalent objective is the TCO comparison, which is the focus of 136 studies. Throughout these years, comparative TCO analysis have remained the primary research category. Other objectives include scenario analysis to forecast the number of electric vehicles (20), optimizing the battery size

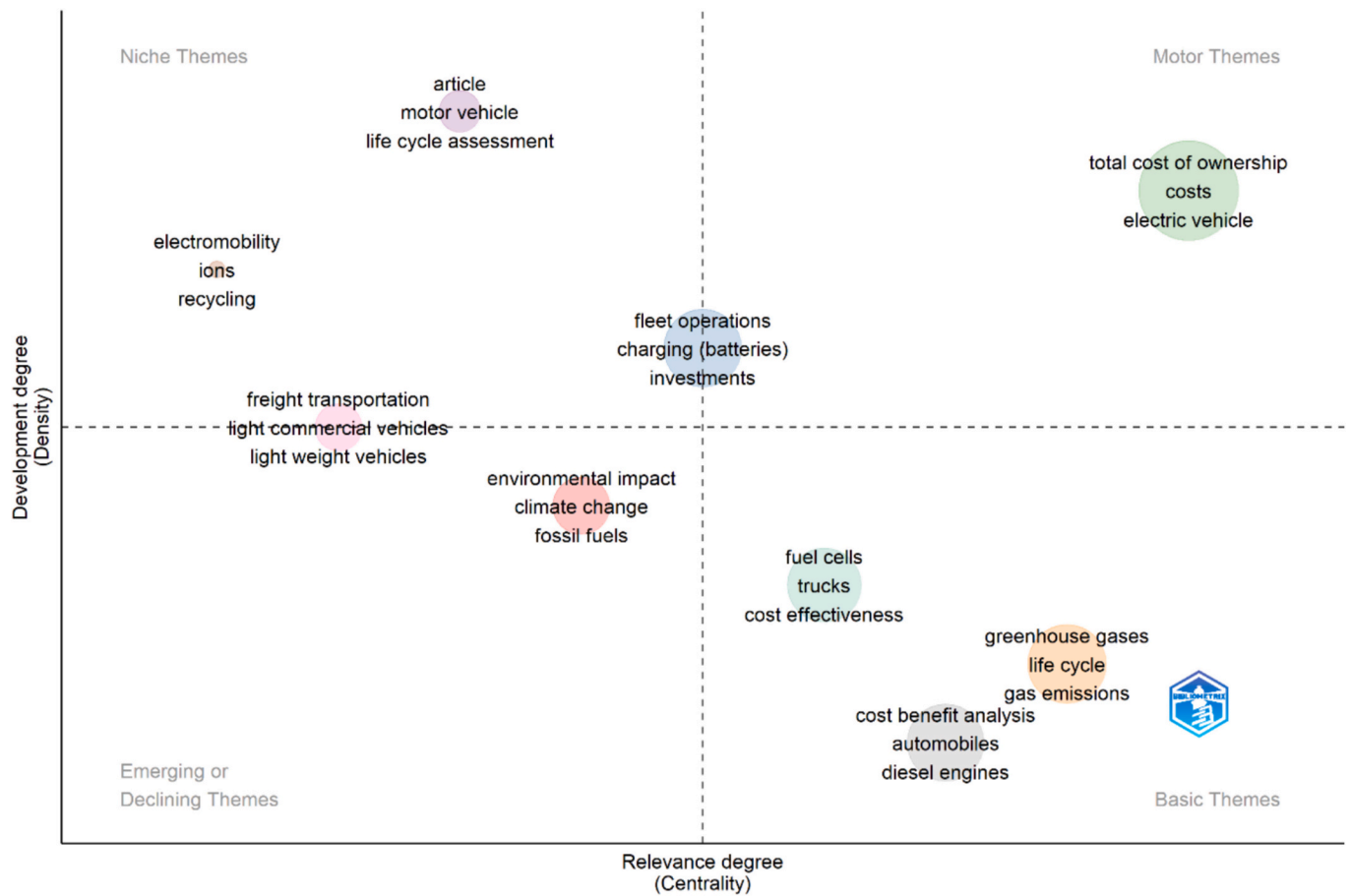


Fig. 5. Thematic map.

Table 3
Number of studies based on vehicle types and technology.

Vehicle Type & Technology	Passenger	Buses	Trucks	Cargo Vans	Motorcycles	Total
BEVs	99	29	34	14	6	155
HEVs	37	7	9	0	0	46
PHEVs	41	7	8	1	0	48
FCEVs	14	6	13	1	1	25
EREVs	6	0	1	1	0	8
SEVs	1	0	0	0	0	1
Diesel/Biodiesel	48	21	31	11	0	94
Gasoline/Bio-gasoline	79	0	1	10	4	94
Gas	10	6	6	1	0	16
Hydrogen	1	1	3	0	0	3
Total	115	36	41	17	6	

and assessing its impact on the TCO (26), designing powertrains and evaluating their effects on the TCO (11), and developing TCO models (11).

Comparative studies estimate the TCO for various types of vehicles and technologies. Table 4 shows the most frequently compared vehicle technologies. Most of these studies compare the TCOs of BEVs and diesel ICEVs, with a total of 23 studies. Following this, 21 studies compare the TCOs of BEVs and gasoline ICEVs. For instance, Shrimali (2021) compares the TCOs of various vehicle types, including passenger cars, trucks, buses, cargo vehicles, and motorcycles. In addition, Baek et al. (2021) also compare the TCOs of HEVs across different countries.

Fig. 6 illustrates a broadened research focus, with an increase in

studies on battery and powertrain design. These studies include battery design optimization, charging process improvements, and the development of charging infrastructure. Most research on battery design and charging processes aims to minimize the TCO. For example, Basma et al. (2023) optimized battery capacity and charging approaches to reduce the TCO of electricity buses. Say et al. (2024) considered charging infrastructure costs by analysing minimum and maximum charging capacities. Reinhart et al. (2023) estimated the profitability of pyrometallurgical recycling processes for various types of lithium-ion batteries from BEVs.

Additionally, TCO has been used in studies on powertrain design. Finesso et al. (2018) created several designs for power-split HEVs and analysed their TCO to identify the optimal design that reduces both the TCO and CO₂ emissions. Similarly, Verbruggen et al. (2020) examined various electric powertrain topology designs to find the one that achieves the greatest TCO reduction. Abdelouahed et al. (2024) conducted a study on the powertrain of electric buses using both forward-facing and backward-facing approaches and calculated the TCO for the project.

Studies on the TCO model involve developing, modifying, or incorporating new variables or methods into TCO estimation models. For instance, Parker et al. (2021) included the variable of spatial heterogeneity in the TCO at the neighbourhood scale. Samet et al. (2024) examined the TCOs of electric trucks and conventional trucks using a levelized cost of driving (LCOD) model. Their analysis incorporated methodological advancements such as evaluating the economic impacts of charging activities, conducting thorough assessments of operational efficiency, and exploring optimal travel distances or battery capabilities. Additionally, Danielis et al. (2018) developed a probabilistic TCO model that integrates both random and deterministic variables to assess the present and future potential of EVs in Italy.

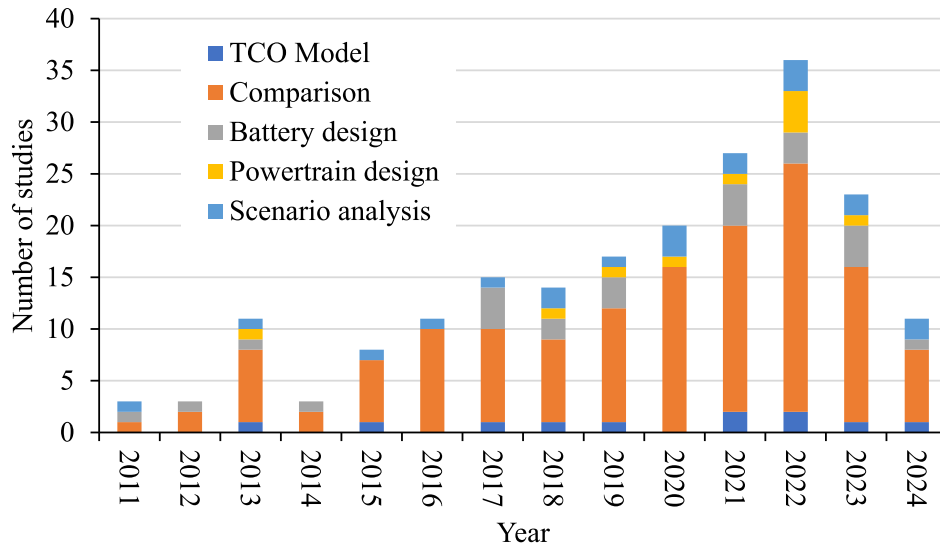


Fig. 6. Trend of TCO studies based on study objectives.

Table 4

The most frequently compared vehicle technologies.

Vehicle Technology	The most compared vehicles									Other comparisons
BEVs	✓	✓	✓	✓	✓	✓	✓	✓	✓	
HEVs				✓	✓	✓	✓	✓	✓	
PHEVs					✓	✓	✓	✓	✓	
Diesel/ Biodiesel		✓	✓			✓	✓	✓	✓	
Gasoline/ Bio-gasoline	✓		✓	✓	✓	✓	✓	✓	✓	
Gas									✓	
Number of studies	21	23	8	3	5	4	5	4	3	57

We also found 20 TCO studies that employed multiple scenarios to determine the impacts of various policy options. For example, Teng et al. (2024) studied the overall impacts of 113 policy scenarios on the adoption of heavy-duty hydrogen fuel cell electric trucks (HD-FCETs). Sadik-Zada et al. (2023) offered an in-depth analysis of the outlook for fuel-cell electric buses in German public transportation, focusing exclusively on economic considerations. They explored nine scenarios, varying fuel prices and analysis periods.

TCO estimates

Figs. 7 to 11 show the TCO range from the lowest to the highest for various vehicle types, along with the average values based on a sample size of n. In Fig. 7, BEVs and HEVs passenger cars have a wide TCO range, with their average TCO being higher than that of ICEVs powered by diesel and gasoline. EREV passenger cars have the highest average TCO compared to other passenger car types. However, it is important to note that these average TCOs are derived from the smallest sample size compared to the TCO estimates for other vehicle types.

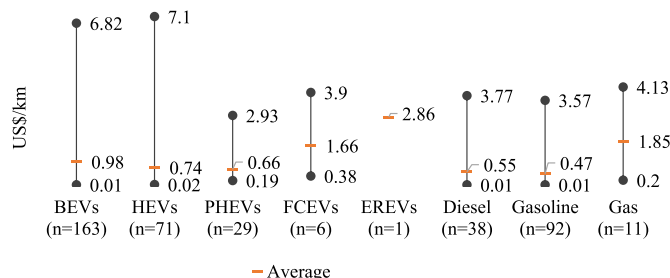


Fig. 7. The range of TCOs for passenger cars.

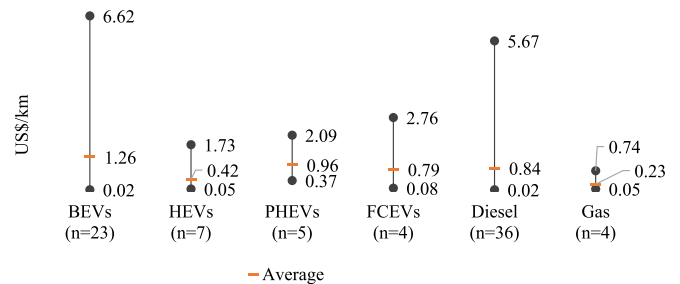


Fig. 8. The range of TCOs for buses.

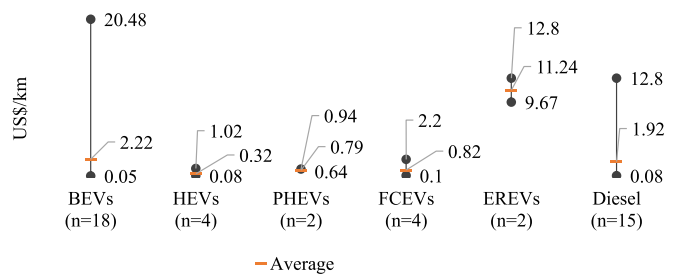


Fig. 9. The range of TCOs for trucks.

The small number of TCO estimates also results in a narrow TCO range for HEV, PHEV, FCEV, and gas-powered buses, as shown in Fig. 8. For BEV buses, the TCO range is the widest, spanning from US\$ 0.02/km to US\$ 6.62/km, with an average TCO of US\$ 1.26/km, which is the highest average TCO. This indicates a large variability in the TCO

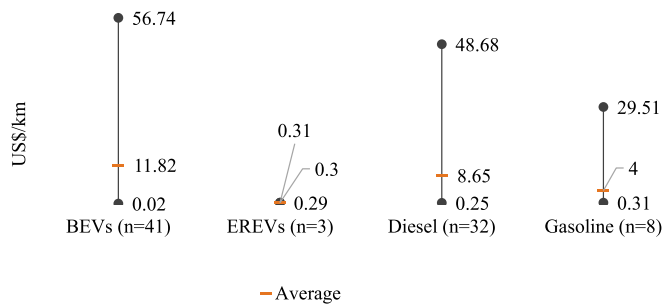


Fig. 10. The range of TCOs for cargo vans.

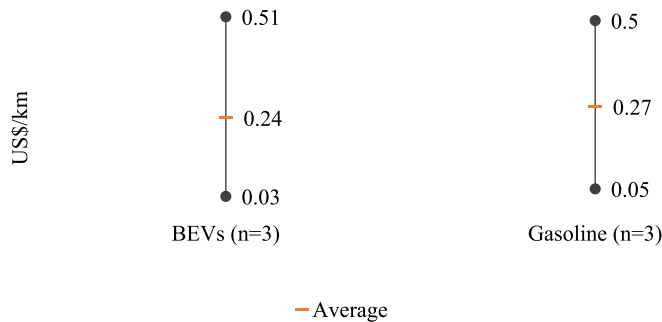


Fig. 11. The range of TCOs for motorcycles.

estimates for electric buses, likely due to differing operational and contextual factors across studies. Fig. 8 indicates that, on average, HEV and FCEV buses have the potential to be more efficient than diesel buses.

Fig. 9 shows that BEV trucks and diesel-powered trucks have a wider TCO range, likely due to differences in assumptions and data from a larger number of studies compared to trucks with other technologies. The average TCO for BEV trucks and diesel-powered trucks is quite similar, at US\$ 2.22/km and US\$ 1.92/km, respectively. EREV trucks have the highest average TCO, at US\$ 11.24/km, indicating that EREV technology for trucks is still significantly more expensive compared to diesel-powered trucks.

The TCO for BEV cargo vans is also higher compared to other cargo van technologies, as shown in Fig. 10. With a TCO range between US\$ 0.02/km and US\$ 56.74/km, the average TCO for BEV cargo vans is US\$ 11.82/km, which is significantly higher than the average TCO for diesel-powered cargo vans at US\$ 8.65/km. Among conventional cargo vans, gasoline-powered cargo vans have the lowest average TCO at US\$ 4/km.

The TCO ranges for electric and conventional motorcycles are narrow and relatively similar, as shown in Fig. 11. The average TCO for conventional motorcycles is slightly higher at US\$ 0.27/km compared to the average TCO for electric motorcycles, which is US\$ 0.24/km. This similarity in TCO values indicates that there is no significant difference in vehicle prices or in the AKT assumptions used by the three studies that analysed the TCO of motorcycles. This can be attributed to the relatively smaller variation in motorcycle prices compared to cars, buses, trucks, and cargo vans. Moreover, motorcycles have a relatively limited range compared to other vehicle types, so differences in the AKT assumptions are also not significant.

Discussions

We conclude that most of the reviewed studies focus on TCO comparisons, with the most common being between EVs and ICEVs. These comparative TCO studies evaluate and compare the economic viability, operational costs, and long-term financial implications of each vehicle type (e.g., Guo et al., 2022; Malima & Moyo, 2023; Woody et al., 2024). The objective is to provide insights into how EVs compare to ICEVs in

terms of initial purchase price, maintenance costs, fuel expenses, taxes, and financial incentives (e.g., Guo et al., 2022; Suttakul et al., 2022). These studies are essential for understanding the competitiveness of EVs and their potential for adoption in the market, which can inform policies affecting economic feasibility. Thus, the results of TCO analysis can identify necessary policies to promote the adoption of EVs, such as fiscal incentives or the development of charging infrastructure (e.g., Cheok et al., 2022; Malima & Moyo, 2023; Ribeiro & Silveira, 2024).

Studies estimating the TCO of EVs have been conducted in 54 countries, with most focusing on a single-country case. The findings of these studies reveal significant variations in the TCO of EVs across different countries. This variation can be attributed to differences in financial incentives (De Santis et al., 2022; Lévy et al., 2017; Ribeiro & Silveira, 2024), traffic density, which influences driving cycles and AKT (García et al., 2022), climate effects on energy consumption (Hasan et al., 2021), as well as fuel and electricity prices (Tanco et al., 2019), taxation systems, and other costs (Li & Kimura, 2021). Furthermore, variations in the energy mix used for electricity generation in each country lead to differences in emissions associated with EV usage (Schüller et al., 2017). Therefore, a study estimating the TCO of EVs across multiple countries could help identify the most effective policies among these nations (Held & Gerrits, 2019; Palmer et al., 2018).

The TCO across multiple countries using studies that focus on a single country cannot be fully compared. Single-country studies typically analyse different vehicle models, leading to variations in vehicle prices and energy consumption per kilometre. Moreover, each single-country study has different assumptions. Therefore, a study that compares the TCO of the same vehicle models across multiple countries would provide a more accurate basis for comparison. Nevertheless, studies comparing the TCO of vehicles across multiple countries are limited to regions such as Europe, the US, Latin America (e.g., Argentina, Brazil, Chile, Colombia, and Uruguay), ASEAN countries (e.g., Brunei Darussalam, Indonesia, Malaysia, Singapore, Thailand), and other Asian countries (e.g., China, India, South Korea). Thus, we recommend that future research expand TCO comparisons to include additional countries.

Policy interventions to make the TCO of EVs more competitive can be implemented on both EVs and ICEVs. On the EV side, policies should focus on strategies to reduce the price. On the ICEV side, governments should increase diesel and gasoline prices, including removing any subsidies for these fuels. Our review noted that the TCO of ICEVs is highly sensitive to annual mileage and fuel prices. Simultaneously, electricity tariffs for EVs should be incentivized.

One example of an effective policy to promote EV usages is the credit system for zero-emission vehicles (ZEVs), adopted by several U.S. states. In this system, vehicle manufacturers must earn production credits by producing a minimum percentage of ZEVs (10 % in 2022) and PHEVs (4.5 %) based on their average total production over the past three years (CARB, 2024). If a manufacturer does not meet these requirements, they can buy credits from others who have surplus credits, with prices negotiated between the parties. Tesla, the largest seller of credits because it focuses solely on EVs, can strategically adjust its EV prices to influence the supply and cost of these credits. The greatest benefit of ZEVs occurs when the electricity used for charging comes from renewable sources. Hope et al. (2023) highlight that using solar and wind energy to charge EVs greatly reduces harmful gas emissions, leading to cleaner air and a healthier environment. Additionally, Naik et al. (2024) emphasize that EVs play a vital role in long-term resource management, fighting climate change, and improving energy efficiency, addressing issues like GHG emissions and fossil fuel depletion.

Electric buses and trucks play a crucial role in fuel savings due to their higher annual mileage. The adoption of electric buses also has indirect effects on reducing fuel consumption from private vehicle use. As public transportation becomes more efficient, comfortable, and environmentally friendly, people are likely to prefer it over personal vehicles, ultimately reducing the number of cars on the roads and decreasing overall fuel consumption. To support the broader adoption of

electric buses, governments can implement several policies, including subsidies, tax exemptions, and other fiscal measures that lower the initial investment costs for electric buses. Additionally, green financing, such as offering low-interest rates, can serve as an attractive incentive for transportation operators to transition to electric fleets.

However, assuming that electrifying vehicles is a standalone solution for global decarbonization is a dangerous assumption. Several studies have noted the double-edged sword of the environmental impacts caused by choosing either BEVs or ICEVs. These studies typically compare their emissions, life cycle considerations, and energy efficiency. Key findings and examples of how BEVs can lower environmental impacts are summarized in Table 5. In this light, future studies should integrate TCO with environmental-social impact analyses and external cost evaluations (e.g., life cycle analysis, extended cost-benefit analysis, and triple bottom line) to provide a more holistic assessment of social, technology, and costs.

The sustainability of EVs encompasses not only their operational efficiency but also the entire lifecycle of the vehicle, from production to end-of-life disposal. Shang et al. (2024) points out that environmental

Table 5
Environmental impacts from EV usages.

Issues	Descriptions
Tailpipe emissions vs. battery production	BEVs have a significantly lower environmental impact during use compared to ICEVs, primarily due to the absence of tailpipe emissions. However, their battery production contributes substantially to emissions. The environmental benefits of BEVs are maximized in regions with low-carbon electricity grids, making them favourable for sustainable mobility (Carranza et al., 2022).
BEVs truck-drone may provide more efficient logistics for delivery systems only if the battery life is longer	A hybrid truck-drone delivery approach can reduce overall CO ₂ emissions by over 10 % compared to traditional delivery vehicles. Although truck emissions still dominate due to higher fuel consumption, drones help offset this by optimizing routes and reducing fuel usage. However, emissions from drone battery production can limit benefits in scenarios where battery life is short (Baldisseri et al., 2022).
Electrifying heavy goods vehicles (HGVs) may significantly reduce their well-to-wheel (WTW) emissions, but hydrogen fuel is also promising	Battery electric HGVs have the lowest emissions, achieving up to 50 % reductions compared to conventional diesel trucks. Hydrogen fuel cell HGVs show potential for future emissions reductions if green hydrogen is used, though current technology still results in higher emissions compared to BEVs (Gray et al., 2022). Meanwhile, BEVs generally outperform FCVs in terms of environmental impact, with a lower global warming potential. For instance, BEVs produce 0.14 kg CO ₂ /km compared to 0.17 kg CO ₂ /km for FCVs. However, FCVs have the advantage of longer driving ranges. Life cycle emissions analysis also shows that fuel supply infrastructure contributes significantly to emissions for both technologies (Bekel & Pauliuk, 2019).
Hybrid and PHEVs can reduce emission depending on the driving patterns and battery technology	Hybridization reduces emissions compared to ICEVs, with full hybrids offering the lowest WTW CO ₂ emissions. PHEVs perform better over shorter distances, while emissions improvements depend significantly on daily driving patterns and advancements in battery technology (Xu et al., 2023).

issues in producing and recycling EVs may limit emission reduction benefits, with primary constraints traced to raw material and component production, notably critical minerals. Ballinger et al. (2019) argued that the availability of these minerals is inadequate to meet global EV targets after assessing the readiness of supply chains for seven key battery components, including natural graphite, lithium, cobalt, and motor components like dysprosium, terbium, praseodymium, and neodymium. Thus, battery recycling becomes essential for the long-term sustainability of BEV programs. Recycling batteries can yield a profit margin of \$600 per ton, accounting for 13 % of the battery's total value (Breiter et al., 2023). Although recycling can offer savings of up to 20 % compared to using new materials, it may also incur a cost increase of up to 5 % (Thompson et al., 2021). With effective recycling practices, battery materials are expected to be a critical factor in the growth of EVs over time. From a policy-making perspective, the environmental advantages of EV battery recycling are also significant.

To ensure a sustainable solution, a systemic shift is required, and the following four key strategies must be adhered to. Firstly, emissions must be lowered in both vehicle production and operation by establishing a cleaner electricity mix. Secondly, all emissions from each life cycle stage must be considered because the production of EV batteries consumes substantial energy in the extraction and processing of raw materials. Thirdly, the use of BEVs in public transport, such as buses and trains, should be prioritized over individual vehicles, as they offer more significant environmental benefits due to higher passenger capacity and better energy efficiency. This is also true for logistics of goods and services. Lastly, the end-of-life disposal of batteries must be considered when assessing the environmental impact of BEVs. In summary, policies should support investments in establishing and using cleaner energy, public transit infrastructure, and the reduction of individual car ownership to achieve environmental impact reduction through the introduction of BEVs.

Conclusions

Studies on the TCO of EVs have become a crucial topic in academic research. As EVs have gained popularity worldwide, the volume of research on this topic has increased. However, studies specifically examining trends in TCO research are scarce. This study aims to fill this gap by identifying global trends in TCO research on EVs. We systematically reviewed and analysed 185 articles focused on the TCO of EVs. We employed a systematic literature review and co-occurrence network map to identify global trends. Our systematic review aims to answer the following four research questions.

The first question is which topics are densely connected? The co-occurrence network map revealed three main research topics: as the TCO, environmental impact, and fuel cell clusters. EVs and BEVs are central nodes in the network, indicating their prominent role in discussions surrounding TCO.

The second question is which types of vehicles and technologies are most analysed? The most widely analysed vehicle technologies are BEVs (155 studies), diesel/biodiesel (94 studies), and gasoline/bio-gasoline (94 studies). The most studied vehicle type is passenger cars (115 studies), particularly BEV technology (99 studies) and gasoline/bio-gasoline (79 studies). Other vehicle types analysed include trucks (41 studies), buses (36 studies), cargo vans (17 studies), and motorcycles (6 studies).

The third question is what are the key objectives of the studies? We concluded that 73 % of the analysed studies compared the TCOs of EVs and ICEVs. Our review results also highlight a notable rise in 36 studies focused on determining battery size and powertrain design to obtain optimal TCOs. This indicates a growing recognition of these components as critical to the overall performance and efficiency of EVs. Other objectives of these studies include policy scenario analysis (20 studies) and TCO model development (11 studies).

The last question is what are the ranges of TCO estimates for

different vehicle types and technologies? Generally, the TCO for BEVs has a wider range compared to other vehicle technologies. Furthermore, the average TCO for BEVs is also higher than that for ICEVs, including both diesel and gasoline, across passenger cars, buses, trucks, and cargo vans. Motorcycles are an exception, as the average TCO for electric motorcycles is slightly lower than that for conventional motorcycles. Additionally, both types of motorcycles have a low TCO range, which falls between US\$ 0.03/km and US\$ 0.51/km.

Our study has several limitations. First, restricting our review to English-language publications excluded relevant studies published in other languages, potentially reducing the comprehensiveness of our findings. Future research could address this by incorporating studies in multiple languages to capture a broader spectrum of perspectives on the TCO of EVs. Second, our focus on the TCO approach means that we only considered personal expenses during vehicle ownership. Future studies could expand this by systematically reviewing external costs through methodologies such as cost-benefit analysis, total life cycle costing, and wheel-to-wheel assessments. Additionally, we provided a range of TCO estimates but did not explore the key factors influencing these variations. To fill this gap, we recommend a meta-analysis to identify the significant factors driving differences in TCOs across the reviewed studies.

CRediT authorship contribution statement

Muhammad Indra al Irsyad: Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Ika Inayah:** Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Reninta Dewi Nugraheni:** Writing – original draft, Visualization, Software, Formal analysis. **Andante Hadi Pandyaswargo:** Writing – review & editing, Validation, Formal analysis. **Nina Konitat Supriatna:** Writing – review & editing, Project administration. **Alloysius Joko Purwanto:** Supervision, Resources, Investigation. **Arfie Ikhsan Firmansyah:** Project administration, Data curation. **V. Tri Frebrina Harisetyawan:** Visualization, Data curation. **Yohanes Gunawan:** Resources, Methodology. **I. Gusti Ngurah Agung Surya Pradipta Negara:** Resources, Data curation. **Fitria Astuti Firman:** Resources, Project administration.

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

In the preparation of this manuscript, the authors utilized ChatGPT, Copilot, and Curie (from American Journal Experts, LLC) to improve the clarity of the language. Following the use of these tools, the authors carefully reviewed and made necessary revisions to the content. The authors assume full responsibility for the content of this publication.

Declaration of competing interest

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

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