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Life cycle assessment comparison of electric and internal combustion vehicles: A review on the main challenges and opportunities

Vinicius Braga Ferreira da Costa [a,*], Leonardo Bitencourt [b], Bruno Henriques Dias [c], Tiago Soares [d], Jorge Vleberton Bessa de Andrade [a], Benedito Donizeti Bonatto [a]

[a] Institute of Electrical Systems and Energy, Federal University of Itajuba, Itajuba, MG, 37500-903, Brazil
[b] Electrical Engineering Department, Federal Fluminense University, Niterói, RJ, 24210-346, Brazil
[c] Electrical Energy Department, Federal University of Juiz de Fora, Juiz de Fora, MG, 36036-900, Brazil
[d] Centre for Power and Energy Systems, Institute of Systems and Computer Engineering, Technology and Science, Porto, Portugal

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ABSTRACT

A notable shift from an internal combustion engine vehicles (ICEVs) fleet to an electric vehicles (EVs) fleet is expected in the medium term due to increasing environmental concerns and technological breakthroughs. In this context, this paper conducts a systematic literature review on life cycle assessment (LCA) research of EVs compared to ICEVs based on highly impactful articles. Several essential aspects and characteristics were identified and discussed, such as the assumed EV types, scales, models, storage technologies, boundaries, lifetime, electricity consumption, driving cycles, combustion fuels, locations, impact assessment methods, and functional units. Furthermore, LCA results in seven environmental impact categories were gathered and evaluated in detail. The research indicates that, on average, battery electric vehicles are superior to ICEVs in terms of greenhouse gas (GHG) emissions (182.9 g $CO_{2\text{-eq}}$/km versus 258.5 g $CO_{2\text{-eq}}$/km), cumulative energy demand (3.2 MJ/km versus 4.1 MJ/km), fossil depletion (49.7 g $oil_{\text{-eq}}$/km versus 84.4 g $oil_{\text{-eq}}$/km), and photochemical oxidant formation (0.47 g $NMVOC_{\text{-eq}}$/km versus 0.61 g $NMVOC_{\text{-eq}}$/km) but are worse than ICEVs in terms of human toxicity (198.1 g 1,4-$DCB_{\text{-eq}}$/km versus 64.8 g 1,4-$DCB_{\text{-eq}}$/km), particulate matter formation (0.32 g $PM_{10\text{-eq}}$/km versus 0.26 g $PM_{10\text{-eq}}$/km), and metal depletion (69.3 g $Fe_{\text{-eq}}$/km versus 19.0 g $Fe_{\text{-eq}}$/km). Emerging technological developments are expected to tip the balance in favor of EVs further. Based on the conducted research, we propose to organize the factors that influence the vehicle life cycle into four groups: user specifications, vehicle specifications, local specifications, and multigroup specifications. Then, a set of improvement opportunities is provided for each of these groups. Therefore, the present paper can contribute to future research and be valuable for decision-makers, such as policymakers.

1. Introduction

1.1. Motivation

The world has been experiencing massive environmental issues. According to Lin et al. [1], humanity's estimated ecological footprint is currently about 1.7 "Earths", implying 70 % more resource consumption than the world can withstand sustainably. Moreover, the footprint continues to grow, which will only deepen the ecological crisis [2]. Large-scale greenhouse gas (GHG) emissions are also extremely worrying, as an increase in global temperature of 1.5 °C compared to pre-industrial levels has been reported by the Intergovernmental Panel

Abbreviations: BAU, business-as-usual; BEV, battery electric vehicle; CED, cumulative energy demand; CNG, compressed natural gas; EIO, economic input-output; EOL, end-of-life; EV, electric vehicle; FCBEV, fuel cell battery electric vehicle; FCEV, fuel cell electric vehicle; FD, fossil depletion; GHG, greenhouse gas; GREET, Greenhouse Gases Regulated Emissions and Energy Use in Transportation; HDV, heavy-duty vehicle; HEV, hybrid electric vehicle; HT, human toxicity; ICEV, internal combustion engine vehicle; IPCC, Intergovernmental Panel on Climate Change; LCA, life cycle assessment; LCIA, life cycle impact assessment; LDV, light-duty vehicle; MD, metal depletion; MDV, medium-duty vehicle; PEM, proton-exchange membrane; PHEV, plug-in hybrid electric vehicle; PMF, particulate matter formation; POF, photochemical oxidant formation; SC, Scopus; SLR, systematic literature review; SOC, state-of-charge; TRL, technology readiness level; TTW, tank-to-wheel; V2G, vehicle-to-grid; WTT, well-to-tank; WTW, well-to-wheel.

* Corresponding author.
E-mail address: vinibfc_eu@hotmail.com (V.B.F. da Costa).

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on Climate Change (IPCC) [3]. Climate change represents a massive threat to humanity and global ecosystems, requiring immediate mitigation measures [4]. In this context, the Paris Agreement, an international treaty on climate change, took place in 2016 aiming to limit global warming below 2 °C [5]. The Paris Agreement was adopted by 196 parties and is characterized as a landmark in the fight against climate change. Nonetheless, nations are required to reach their peak GHG emissions by mid-century, which is a challenging task.

Measures in several domains are necessary to mitigate such daunting environmental impacts, one of which is the automotive sector. ICEVs substantially impact the environment due to the gases and particles released by combustion and the nonrenewable characteristics of fossil fuels, among other factors. On the other hand, EVs do not involve tailpipe emissions, and they can be powered by renewable electricity generation, significantly restraining environmental impacts. Currently, ICEVs account for the majority of the global market share [6]; thus, EV penetration is limited. However, huge growth is expected in the medium term due to environmental concerns, cost increases of fossil fuels, and technological developments of EVs. In this context, assessing the environmental effects of transitioning from an ICEV-based fleet to an EV-based fleet is of utmost importance. Therefore, this paper conducts a systematic literature review on LCA research of EVs compared to ICEVs. The analysis includes the main considerations, outliers, results, statistical assessments, challenges, research gaps, and potential improvements in future research on the topic. Thus, it is valuable for the research community and decision-makers, such as policymakers.

It is important to mention that, for simplicity's sake, the nomenclature EV encompasses all types of electric vehicles in this paper, including hybrids, *i.e.*, EV encompasses battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), fuel cell electric vehicles (FCEVs), fuel cell battery electric vehicles (FCBEVs), along with advanced designs with supercapacitors.

1.2. Novelty

To ensure a thorough review, it is important to search for papers with a similar work emphasis to this article. Therefore, the following descriptors were applied to the Scopus (SC) database, which is widely used in physical sciences studies [7,8], including LCA research on EVs [9]:

Descriptors: "electric vehicle" AND "life cycle assessment" AND "review".

The descriptors must be present in the title, abstract, or keywords. The search resulted in 61 documents. However, after a screening process, it was verified that only 15 of the 61 documents were review papers dedicated to LCA research on EVs compared to ICEVs. The features of such articles are closely assessed and organized in Table 1. Two check marks mean that the article focuses significantly on the feature, one check mark means that the article focuses on the feature partially,[1] and the "x" mark means that the feature is absent. As verified, assessing multiple vehicle designs and analyzing considerations and characteristics is relatively common in the literature. Even so, the analyzed characteristics vary significantly depending on the review article. For instance, Xia et al. [10] and Onat et al. [11] do not focus on lifetime issues, even though several other characteristics are assessed. Therefore, it is beneficial to conduct a more all-encompassing analysis. It is also demonstrated that more work is required in terms of big data processing, assessing multiple impact categories, conducting numerical analysis of results, and carrying out statistical analysis, as the literature review demonstrated that such features are scarce. Notably, we could not find any article that applies software to process metadata exported from databases, which is important to improve the quality of the study.

As much as possible, this paper aims to focus on all features indicated in Table 1, providing a novel perspective on the theme and filling an important research gap. Moreover, it is noteworthy that a theme of such importance requires multiple independent studies with distinct insights, as they collaborate concurrently.

1.3. Paper structure

Section 2 describes the research methodology, whereas Section 3 presents the results and analyses. It is divided into twelve parts: 3.1. Vehicle types, classes, and models; 3.2. Storage technologies; 3.3. Infrastructure, costs, and associated challenges; 3.4. Boundaries; 3.5. Lifetime; 3.6. Electricity consumption and driving cycles; 3.7. Combustion fuels; 3.8. Location of the usage phase; 3.9. Life cycle impact assessment methods; 3.10. Additional characteristics; 3.11. Results associated with GHG emissions; 3.12. Results associated with other impact categories. Section 4 discusses key challenges and improvement opportunities identified from the research. Finally, the research limitations are presented in Section 5, followed by the conclusions in Section 6.

2. Methodology

A systematic literature review (SLR) is conducted in this paper. When compared to conventional literature reviews, SLRs have the advantage of presenting clear guidelines and methodology, preventing biased analyses, promoting research reproducibility, and allowing the processing of big data [25]. The following research question is addressed:

RQ: *What are the main considerations, outliers, results, statistical trends, challenges, research gaps, and potential improvements concerning LCA research of EVs compared to ICEVs?*

To answer the research question, the following descriptors were applied to the SC database[2]:

Descriptors: "electric vehicle" AND "life cycle assessment".

We opted for more general descriptors for a robust sample. Unrelated documents were disregarded at a later stage. The descriptors must be present in the title, abstract, or keywords, resulting in 733 documents (reference date: July/2022). A simplified workflow of the literature review is illustrated in Fig. 1. The obtained metadata were processed by R software and its open-source tool Bibliometrix, programmed and designed by Aria et al. [26], and used in dozens of publications [27]. This tool organizes information, enhancing the quality of the literature review. Given that it is impractical to analyze 733 documents thoroughly, we focused on the 100 most cited peer review articles and articles published after 2020 with more than ten citations per year (21 articles). This approach ensures that key recent articles are also included in the review. Then, we conducted a screening process to select the appropriate articles for the review, resulting in a sample of 60 highly impactful articles. Although the number of documents found by the search was substantial, we also identified related research on the topic outside the sample to complement the assessment. This approach is important since some specific subjects (*e.g.*, supercapacitor EVs) might not be present in the sample.

3. Results and analyses

The 60 selected articles were thoroughly assessed. As a result, essential characteristics are presented in Tables 2 and 3 of the supplementary material file, including the EV types, ICEV fuels, battery or fuel cell technologies, vehicle models used, boundaries, and LCA methods, among others. The information reported in such tables supports the

[1] To prevent bias and ensure a transparent analysis of the features, more information on the yellow checks is provided in Table 1 of supplementary material file.

[2] It is emphasized that the core of the analysis is conducted based on the most impatful articles, which are present in several databases (*e.g.*, Web of Science) due to the high relevance of the journals they are published.

Table 1
Comparison of this paper to review articles with a similar work emphasis.

	Article features					
Article	Big data processing [a]	Multiple impact categories	Numerical analysis of results	Multiple vehicle designs	Analysis of considerations and characteristics	Statistical analysis
Xia et al. [10]	×	×	✓	✓✓	✓✓	×
Onat et al. [11]	×	✓	✓	✓✓	✓✓	✓✓
Oda et al. [12]	×	×	✓	✓✓	×	✓✓
Xia et al. [13]	×	✓	✓	✓✓	✓✓	×
Verma et al. [14]	×	✓	✓	×	✓✓	×
Dillman et al. [15]	×	×	✓	×	✓✓	✓✓
Tintelecan et al. [16]	×	✓	✓	✓✓	✓	×
Dolganova et al. [17]	×	✓✓	✓	✓✓	✓✓	✓✓
Towoju et al. [18]	×	✓	✓	✓	×	×
Marmiroli et al. [19]	×	×	✓	✓✓	✓✓	✓✓
Garcia et al. [20]	×	✓✓	✓✓	✓✓	✓✓	×
Nealer et al. [21]	×	✓	✓	✓✓	✓	×
Nordelöf et al. [22]	×	✓✓	✓✓	✓✓	✓✓	×
Helmers et al. [23]	×	✓	✓	✓✓	✓✓	×
Hawkins et al. [24]	×	✓✓	✓✓	✓✓	✓✓	×
This paper	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓

[a] Applying software to process metadata exported from databases such as SC or Web of Science.

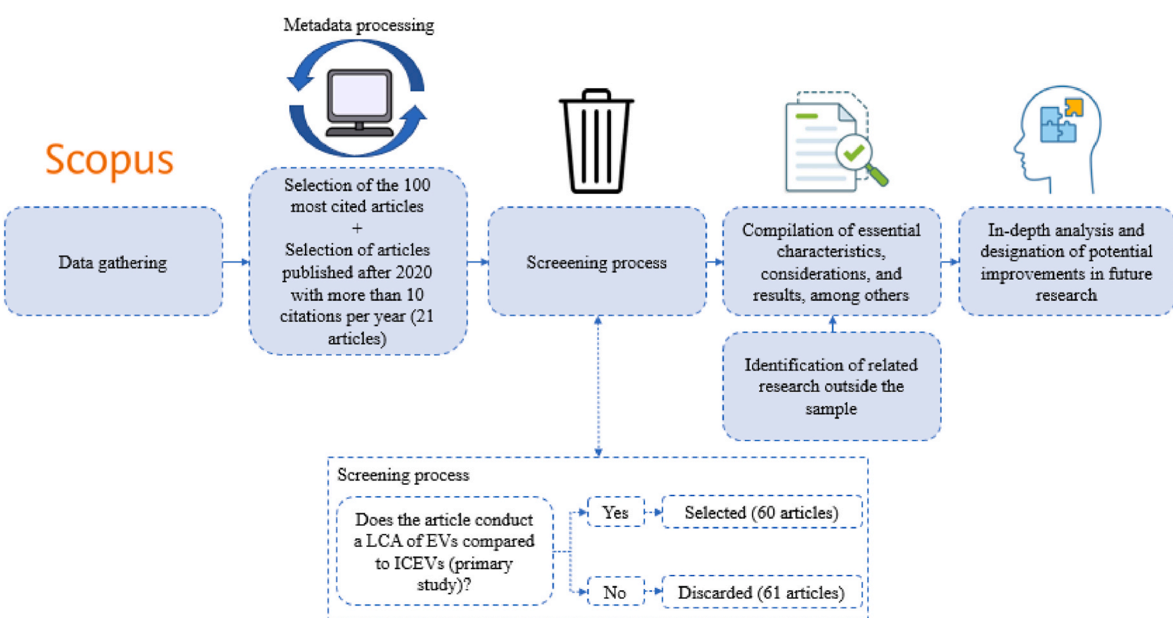

Fig. 1. Simplified workflow of the systematic literature review.

analyses performed below.

3.1. Vehicle types, classes, and models

Five EV types are assessed in the sample: battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), fuel cell electric vehicles (FCEVs), and fuel cell battery electric vehicles (FCBEVs). The number of articles that address each EV type is illustrated in Fig. 2. A substantial focus on BEVs is verified. PHEVs and HEVs are also significantly studied. On the other hand, FCEVs and FCBEVs are rarely addressed, especially FCBEVs. The environmental impacts might be profoundly different depending on the technology, but this issue is assessed more closely in Sections 3.11-3.12.

It is essential to emphasize that such technologies are on different TRLs (technology readiness levels). Given that the internal combustion engine is the main source of power in HEVs, they already became commercially available in the late 1990s through the Toyota Prius and Honda Insight models, thus with a high TRL [28]. In turn, PHEVs and BEVs became commercially available around two decades later through the Chevy Volt and the Nissan Leaf models, and have also reached a high TRL with 40 million cumulative vehicle sales in 2023 [29]. In all the cases, research and development are currently ongoing to decrease costs and increase efficiency. In a general analysis, further developments are still needed to increase the share of BEVs and PHEVs in developing countries. On the other hand, the TRL of FCEVs is relatively low, evidenced by their still incipient commercialization levels and limited associated infrastructure, in particular refueling stations.

BEVs, FCEVs, and FCBEVs are characterized as all-electric vehicles, *i.e.*, they are powered exclusively by electricity. In FCEVs, the fuel cell converts the chemical energy of a fuel (often hydrogen) and an oxidizing

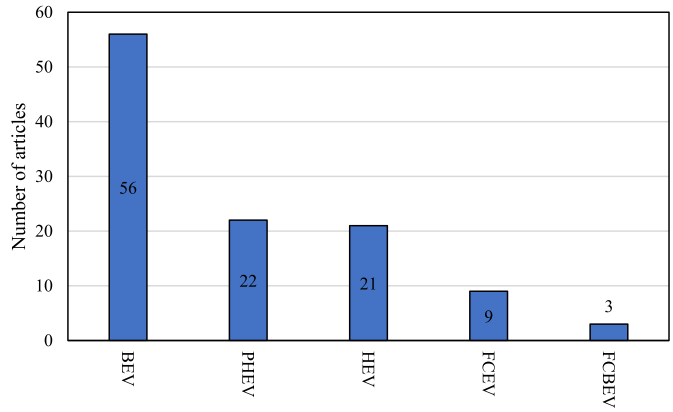

Fig. 2. Vehicle types assessed in the sample.

agent (often oxygen) into electricity to power the vehicle [30]. In turn, FCBEVs deploy both fuel cells and batteries. Typically, the fuel cell is the main power source, and the battery is used to store energy through regenerative braking. The stored energy in the battery is used when high power is required due to vehicle acceleration [31,32]. Since the fuel cell is typically the main power source in FCBEVs, their battery packs have relatively low capacity compared to BEVs.

HEVs and PHEVs are characterized as hybrids, *i.e.*, they are only partially powered by electricity. HEVs employ an internal combustion engine and an electric motor for better fuel economy and vehicle performance than conventional ICEVs. HEVs cannot be connected to external sources (*e.g.*, grid) for charging. Instead, electricity is generated through a regenerative braking scheme or by the internal combustion engine [33]. On the other hand, PHEVs can be connected to external sources for charging. Moreover, they can also charge similarly to HEVs through regenerative braking or by internal combustion engines [34]. Additionally, PHEVs run in all-electric mode until the batteries are nearly depleted (the all-electric range varies depending on the model).

The lack of studies on FCEVs and FCBEVs is justified by Faria et al. [35], as the authors suggest that fuel cell-based electric vehicles showcase economic and technical problems that need to be addressed for wider diffusion, such as hydrogen capture, storage, and distribution. Li et al. [36] corroborate the statement of Faria et al. [35] since the authors demonstrate that the cost per km of FCEVs can be roughly double the cost of BEVs without subsidies (Beijing context). Although researchers indicate that the large-scale diffusion of fuel cell-based electric vehicles is currently challenging, green hydrogen production, *i.e.*, hydrogen production from renewable electricity, has been increasing substantially, as several large-scale projects are being deployed worldwide [37]. Numerous recent papers have assessed the technical and economic feasibility of green hydrogen production, which contributes to accelerating the deployment process [38–40]. While its feasibility is very dependent on the technology, location, and technology (*e.g.*, Andrade et al. [41] report levelized costs of hydrogen ranging from 4 USD/kg to 10 USD/kg), hydrogen is seen as a very promising fuel in the near future. Therefore, LCA studies of FCEVs and FCBEVs are also essential.

It is noteworthy that hydrogen is suitable to power MDVs and HDVs since its energy density is significantly higher than that of commercial batteries. Thus, hydrogen-powered MDVs/HDVs present lower weight than battery-powered MDVs/HDVs. The difference for an 800 km range truck can be as much as 2 tons [42]. Moreover, hydrogen refueling is very quick compared to battery recharging, making hydrogen advantageous for MDVs/HDVs that run several shifts a day. However, the need to have a hydrogen production, transport, and storage infrastructure should be emphasized.

None of the articles present in the sample address supercapacitor EVs or hybrid batteries and supercapacitor EVs. The hybrid scheme can be beneficial due to the relatively high energy density of batteries and the high power density of supercapacitors. Thus, deploying both devices can assist in meeting both energy and power requirements. Supercapacitors present some advantages, such as their massive lifetime compared to batteries (hundreds of thousands of cycles [43]). Furthermore, carbon compounds used in supercapacitors are more abundant than metals used in batteries, such as lithium [44]. However, according to Faria et al. [35], batteries are currently more feasible in EV applications due to their lower energy cost. Horn et al. [44] also state that supercapacitors cannot yet compete with Li-ion batteries in the automotive market. Nevertheless, the authors present routes to improve the performance of supercapacitors, focusing on their energy density, which is a substantial bottleneck in EV applications. Such performance improvement can be achieved by increasing the cell voltage or the surface area of porous electrode materials. Material developments are expected to make supercapacitors highly important in EV applications, not replacing batteries but being implemented concurrently.

Similarly, none of the articles in the sample approach hybrid fuel cells and supercapacitor vehicles. Such a vehicle type functions analogously to the FCBEV, *i.e.*, the fuel cell is the main power source, and the supercapacitor is used to store energy through regenerative braking. In Xun et al. [31] and Zhao et al. [32], hybrid fuel cells and supercapacitor vehicles proved to be highly beneficial due to the high power density of supercapacitors, which can relieve the power required from the fuel cell in critical periods. Compared to conventional FCEVs, Zhao et al. [32] achieved 24–28 % fuel economy by applying a fuel cell and supercapacitor design. It is noteworthy, however, that Xu et al. [31] and Zhao et al. [32] focus on technical issues and not on environmental aspects.

Due to the reasons mentioned above, it is fair to state that there is a significant research gap in conducting LCA of supercapacitor electric vehicles and associated hybrids. LCA studies on the topic would be beneficial for assessing their environmental impacts and answering key research questions. For instance, LCA studies would be able to answer whether the fuel economy due to supercapacitor deployment is worthwhile from an environmental perspective.

It was found that most papers address standard passenger vehicles (51 papers in the sample – see Tables 2 and 3 in the supplementary material file), although the specific segment is not always clear. Ellingsen et al. [45] focus on quantifying the influence of the vehicle segment (from mini-cars to luxury cars) on the GHG emissions of EVs. The authors demonstrate that the vehicle segment is significantly influential (*e.g.*, 52 % difference when comparing mini-cars to luxury cars).

On the other hand, trucks are assessed in four articles, buses in three articles, and scooters in one article. While the focus on standard passenger vehicles was to be expected, more work on other vehicle classes would certainly be beneficial. Sánchez et al. [46] discuss several benefits of hybrid electric buses, battery electric buses, and fuel cell battery electric buses. However, it is demonstrated that current energy storage technologies (particularly batteries) still need some improvements to offer greater autonomy and decrease weight in large vehicle-size applications.

Although light-duty vehicles (LDVs) are analyzed more thoroughly in this paper, as there are more works related to them, it is also important to address medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs). Given the different weights of LDVs, MDVs, and HDVs, their environmental impacts per km are completely different. For instance, while LDVs are expected to imply GHG emissions of around 200 g $CO_{2\text{-}eq}$/km, as shown in Section 3.11, Sánchez et al. [46] estimated GHG emissions of about 1000 g $CO_{2\text{-}eq}$/km for battery electric buses in Madrid. However, it is noteworthy that electric buses can transport tens of people, which enhances their performance when assuming a passenger-km functional unit. Other evident differences are related to costs and infrastructure requirements. Using conventional LDVs chargers for charging MDVs and HDVs is unfeasible since the energy required for charging is much higher. Therefore, it is necessary to use chargers that can quickly deliver a large amount of energy. Naturally, charging station investors will only invest in these chargers if there is sufficient demand. This is a problem because the adoption of electric MDVs and HDVs is much lower than that of LDVs. The high cost associated with electric MDVs and HDVs makes their diffusion limited. However, there are opportunities for public investments in MDVs and HDVs and associated infrastructure, as in the case of public transportation (*e.g.*, buses), which can contribute to a greater/faster diffusion of these vehicle categories. Moreover, previous research has concluded that battery MDVs/HDVs show advantageous GHG performance compared to conventional diesel counterparts [47], favoring the diffusion of these vehicles from an energy transition standpoint.

Concerning vehicle manufacturers, several are present in the sample, as illustrated in Fig. 3. A focus on the Nissan Leaf EV (fifteen articles), Toyota Prius hybrid (twelve articles), and Volkswagen Golf (ten articles) models is clear. It was also verified that it is common to incorporate features from more than one model into the inventory of a single vehicle. For instance, the ICEV in Karabasoglu et al. [48] is modeled based on a Honda and Toyota configuration. This might be necessary due to the complexity of the inventory associated with vehicles (numerous highly technological components) or to make the comparison between ICEVs and EVs fairer (*e.g.*, matching the vehicle segment).

3.2. Storage technologies

Fig. 4 compares typical technical and economic features of the main energy storage technologies used in automotive applications. Desirable features are assigned an upward arrow, whereas undesirable features are assigned a downward arrow. It is noteworthy that such technical and economic features directly affect EV diffusion; thus, they are associated with the environmental impacts of shifting from an ICEV-based fleet to an EV-based fleet. Substantial differences are verified between the characteristics in Fig. 4, and trade-offs are inherent. Such trade-offs make the selection of the best technology challenging, especially when environmental aspects are included in the analysis.

Regarding batteries specifically, the number of articles in the sample that address each technology is illustrated in Fig. 5. A significant focus on Li-ion batteries is verified. In turn, NiMH batteries are moderately studied. Such technology was widely applied in BEV applications in the 1990s and 2000s (*e.g.*, General Motors' EV_1, which was the first BEV model to be commercialized), however, its market share has decreased due to efficiency and lifetime issues [50]. Currently, NiMH batteries are preferable in hybrids due to their relatively lower costs [51]. NiCd and lead acid batteries are seen as outdated technologies in EV applications due to significant drawbacks, such as low energy density and life cycle. Consequently, they are typically addressed in older publications [52]. Therefore, NiCd and lead acid batteries are disregarded in Fig. 4.

As discussed by Hu et al. [50], Mesbahi et al. [53], and Ding et al.

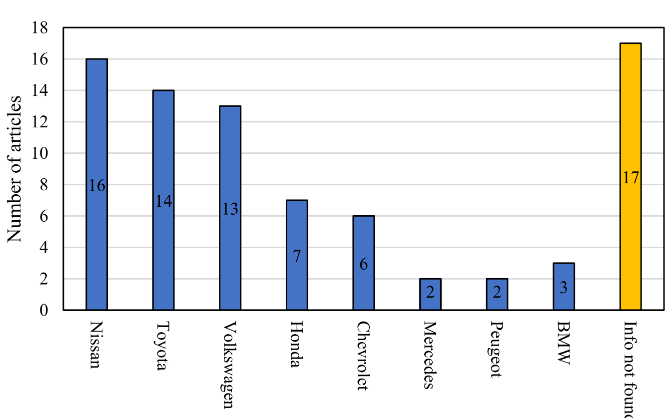

Fig. 3. Most common vehicle manufacturers present in the sample (also includes ICEVs).

[54], Li-ion batteries are regarded as the most promising battery technologies in EV applications due to their high energy density, efficiency, and lifetime. Thus, the focus on Li-ion batteries in Fig. 5 is justifiable. Nevertheless, multiple works do not clearly indicate the assumed chemistry of the Li-ion battery, which is detrimental in terms of transparency and replicability of the results. This consideration gains relevance as the environmental impacts of distinct Li-ion chemistries might be substantially different, as demonstrated by Majeau-Bettez et al. [55], who compiled detailed and accurate inventories and conducted an LCA for $LiNi_xMn_yCo_zO_2$ (NMC) and $LiFePO_4$ (LFP) batteries used in BEV applications. The authors estimate GHG emissions of NMC and LFP batteries as 1.9 kg $CO_{2\text{-eq}}$ and 1.4 kg $CO_{2\text{-eq}}$ per 50 MJ of charged and discharged energy, respectively, representing a difference of 35 %. In terms of the cradle-to-grave BEV life cycle, Hawkins et al. [56] estimate that vehicles with LFP batteries imply 6 % more GHG emissions compared to NCM batteries. Significant differences are also verified for other impact categories (freshwater ecotoxicity, terrestrial acidification, particulate matter formation, freshwater eutrophication, metal depletion, and human toxicity, with differences of up to 8 %). Even more concerning than not indicating the assumed chemistry is omitting the technology (see Tables 2 and 3 of the supplementary material file). Therefore, it is important to be more explicit about the assumed battery technology and chemistry when conducting LCA of BEVs or associated hybrids.

As with batteries in the case of BEVs, multiple works that approach FCEVs and FCBEVs do not clearly indicate the assumed fuel cell technology. Only five of twelve papers in the sample indicate that proton-exchange membrane (PEM) fuel cells are analyzed (see Tables 2 and 3 of the supplementary material file), which is the most popular technology in FCEV applications [57]. According to Vargas et al. [58], the environmental impacts of PEM FCEVs can be substantially different from those of solid-oxide FCEVs that run on bioethanol, depending on how hydrogen is produced. Hence, it is also important to be clear about the assumed fuel cell technology when conducting LCA of FCEVs or associated hybrids.

3.3. Infrastructure, costs, and associated challenges

Although this paper focuses on environmental aspects, infrastructure issues should be addressed since the efficient and wide deployment of recharging/refueling infrastructure is one of the key drivers for EV diffusion. Consequently, infrastructure plays a critical role in increasing the sustainability of the transportation sector.

According to Bitencourt et al. [59], reduced charging infrastructure is one of the main factors limiting EV adoption. In general, investors do not seek to invest in charging infrastructure in regions where EV adoption is low since charging demand is practically nonexistent. This leads to the dilemma where it is unclear which should come first, the EVs or the associated charging infrastructure. On the other hand, in regions where EV adoption is substantial, there is a concern about whether the charging infrastructure will keep up with the exponential EV growth. Naturally, decision-makers have an important role in creating means to overcome these challenges.

Regarding refueling infrastructure for FCEVs, the challenges are more pronounced since hydrogen must be produced on a large scale, transported, and stored. In addition to the challenges associated with recharging/refueling infrastructure, the increase in demand, whether electricity or hydrogen, requires additional power plants, ideally renewable to enhance the sustainability of EVs. Although significant progress has been made in the deployment of renewables, there is still a significant path to be covered.

The cost of EVs has been decreasing significantly as technology becomes more mature, making them competitive or even cheaper than ICEVs in some developed countries, *e.g.*, Denmark and Spain [60]. However, in most regions, in particular in developing countries, the acquisition cost is still relatively high and another significant bottleneck

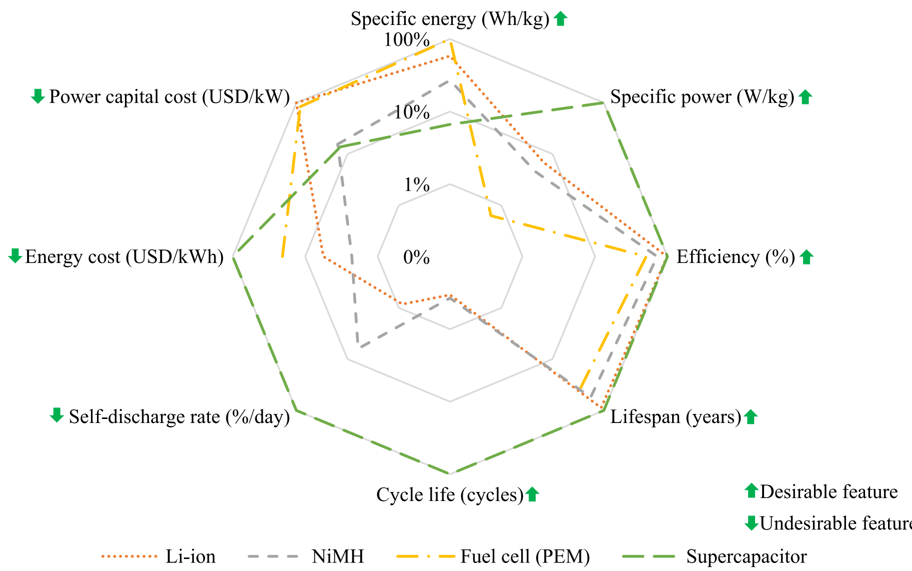

Fig. 4. Comparison of typical technical and economic features of the main energy storage technologies used in automotive applications .[31] Source: adapted from Ref. [49].

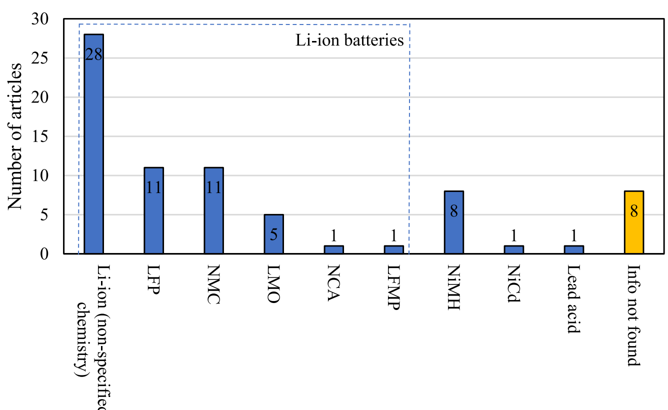

Fig. 5. Traction battery technologies assessed in the sample. LFP: $LiFePO_4$, NMC: $LiNi_xMn_yCo_zO_2$ with $x + y + z = 1$, LMO: $LiMn_2O_4$, NCA: $LiNi_xCo_yAl_zO_2$ with $x + y + z = 1$, LFMP: $LiFeMnPO_4$.

for the wide diffusion of EVs. In order to overcome the high acquisition cost in developing countries, alternative business models can be useful, such as leasing and sharing-based business models, which do not require EV users to purchase the vehicle.

3.4. Boundaries

Fig. 6 illustrates the general boundaries assumed in the LCA of vehicles. Cradle-to-gate assessments include all processes from raw material extraction to vehicle manufacturing. On the other hand, cradle-to-grave assessments include all processes up to vehicle recycling. Well-to-wheel (WTW) exclusively considers the usage phase (both fuel or electricity supply and vehicle operation). Last, well-to-tank (WTT) and tank-to-wheel (TTW) are more compressed assessments, as they only assume the fuel or electricity supply and the vehicle operation, respectively.

The boundaries assumed by the articles included in the sample are illustrated in Fig. 7. Cradle-to-gate, WTW, and cradle-to-gate + WTW assessments are relatively rarely applied. Most articles conduct cradle-to-grave assessments, *i.e.*, assume the full vehicle life cycle. However, multiple works do not detail the assumptions of the end-of-life (EOL) phase. As specified in Brückner et al. [61], Li-ion batteries can be disposed of through different means, such as pyrometallurgy recycling (thermal treatment), hydrometallurgy recycling (chemical treatment), or direct disposal in landfills. According to Kallitsis et al. [62], the environmental impacts of pyrometallurgy and hydrometallurgy recycling processes for automotive Li-ion batteries can be significantly different in multiple impact categories (*e.g.*, 24 % higher GHG emissions for the pyrometallurgy process). Similar to batteries, fuel cells can be recycled through different means [63]. In addition, other vehicle components might also be disposed of differently. Therefore, it is important to be clearer about the assumptions of the EOL phase. In turn, it was verified that cradle-to-gate assumptions are generally described satisfactorily.

The manufacturing of batteries consumes finite resources (mainly metals such as lithium), and recycling is essential to recover such resources. Oliveira et al. [64] argue that certain conditions have to be met to guarantee lithium availability in the future, such as achieving efficient and inexpensive automotive Li-ion battery recycling. In a similar context, Velázquez-Martínez et al. [65] state that, currently, there is a worrying difference between the rate of production and the rate of recycling of Li-ion batteries, *i.e.*, most batteries are directly disposed of without receiving recycling treatments. Material recovery through automotive Li-ion battery recycling is assessed by Kallitsis et al. [62], and the authors demonstrate improvements of approximately 30 %, highlighting the importance of recycling. Just as it is important to recycle batteries, fuel cells should also be recycled to prevent resource depletion (mainly platinum). According to Reverdiau et al. [66], significant progress in the recycling rate of fuel cells and the platinum load per unit of power of FCEVs is required to prevent platinum depletion in the next century. For such reasons, LCA studies with detailed EV EOL phase modeling could assist public institutions in implementing incentives (*e.g.*, economic incentives) to increase the recycling rate of automotive batteries and other EV components, thus contributing to mitigating resource depletion.

3.5. Lifetime

The assumed lifetime might vary substantially depending on the article, as illustrated in Fig. 8. It can be as low as 150,000 km and as high as 257,600 km. A mean value of 186,536 km and a standard deviation of 42,242 km were verified. Naturally, this fact is a major concern as the lifetime substantially influences LCA results. For instance, in the sensitivity analysis conducted by Cox et al. [67], the lifetime proved to be the most influential factor in the LCA results. Hollingsworth et al. [68], who

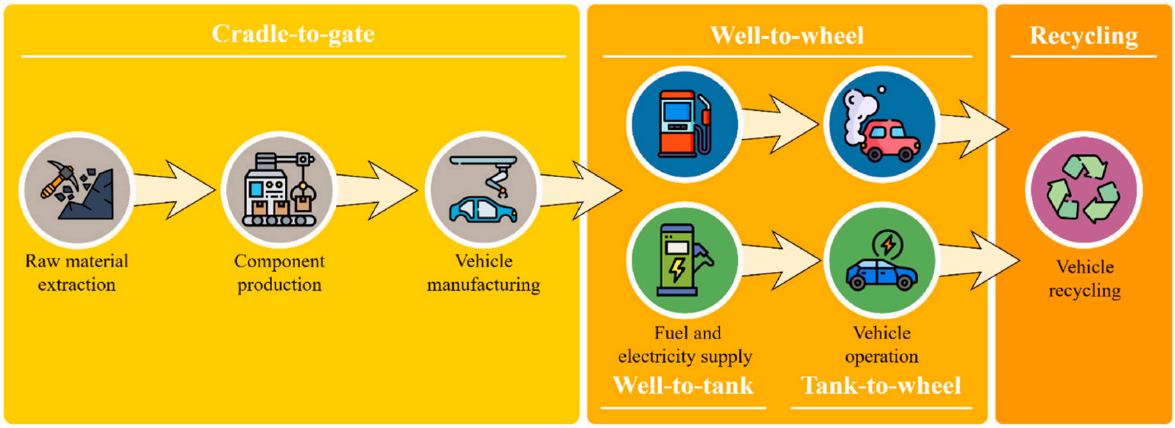

Fig. 6. General boundaries assumed in the LCA of vehicles (adapted from Ref. [13]).

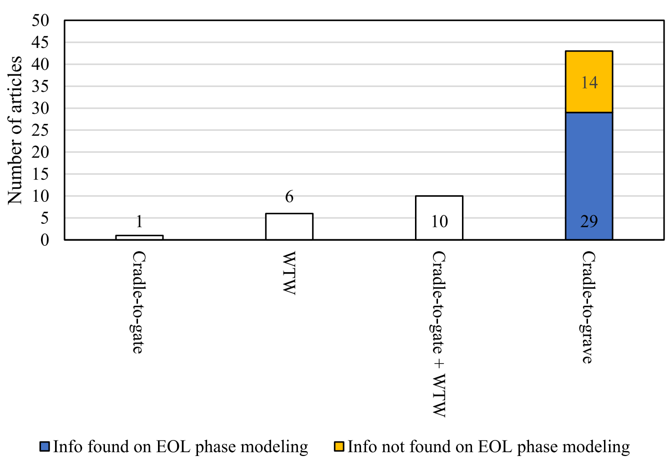

Fig. 7. Boundaries assumed in the sample.

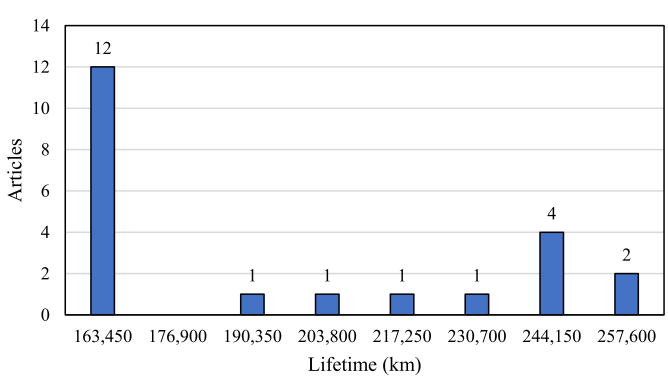

Fig. 8. Histogram of vehicle lifetime .[41]

assessed electric scooters, also demonstrated that the results are highly sensitive to scooter lifetime. Moreover, most works do not differentiate the batteries' lifetime from the other vehicle components (the batteries' lifetime is known to be significantly shorter [69]). Only nine papers clearly suggest a lower lifetime for the batteries (see Tables 2 and 3 of the supplementary material file). A mean value of 151,113 km and a standard deviation of 39,250 km were verified for the batteries, also indicating significant dispersion.

While lifetime considerations might vary substantially, most articles assume a conservative approach where the lifetime is close to or equal to 150,000 km. This is particularly true for more recent papers (see Table 3 of the supplementary material file), which might indicate an increase in consensus concerning lifetime assumptions.

Several factors influence battery lifetime in addition to its technology or chemistry, such as its state of charge (SOC), temperature, operating power, and driving conditions [48,50] and such influence is intricate [70]. This might explain the high dispersion in the assumed battery lifetime in LCA studies. It was verified that while some authors discuss SOC considerations [71], which is the most impactful factor regarding battery lifetime, the relationship lifetime × SOC is generally disregarded. Hence, battery lifetime is typically simplified in LCA studies. For instance, Qiao et al. [72] recognize that the deterioration of traction batteries is a concern in quantifying EV GHG emissions, but the authors overlook it in the conducted LCA.

As exceptions that apply capacity fade models in LCA research of EVs, we found Marques et al. [73] and Karabasoglu et al. [48]. The former concludes that such models are essential to calculate the number of batteries required throughout the vehicle life cycle. In contrast, the latter recognizes some limitations, given that the applied model is based on laboratory-tested LFP cells at room temperature, and it ignores several factors, such as temperature variation and calendar fade.

3.6. *Electricity consumption and driving cycles*

Electricity consumption is difficult to model since several factors influence it, such as vehicle design, storage technology and chemistry, auxiliary system usage (*e.g.*, air conditioning), and driving conditions. Hence, Fig. 9 shows a wide variability in the electricity consumption considered by the papers. Several driving cycles aim to standardize driving conditions through tests conducted in controlled environments (see Table 4 in the supplementary material file). Each cycle represents distinct characteristics (*e.g.*, urban or highway driving, low-speed or aggressive driving). Driving cycles ensure unbiased assessments and allow research replicability. In this context, Karabasoglu et al. [48] evaluate the influence of several driving cycles on the GHG emissions of ICEVs and EVs, demonstrating that driving cycles are substantially influential. For instance, up to 176 % GHG difference was verified on an annual basis when comparing ICEVs under the Highway Fuel Economy Test cycle and the New York City cycle (the former representing highway driving and the latter representing low-speed urban driving with

[3] The metrics are in terms of average and the axis is in logarithmic scale. The proton-exchange membrane (PEM) fuel cell is represented since it is the most applied in FCEV applications [57]. Self-discharge rate and cycle life are not applicable to fuel cells [118]; thus, they are disregarded. Li-ion batteries are not separated by chemistry due to the divergence of information on the topic. For instance, the information reported by Hu et al. [50] and Hossain et al. [119] is substantially different in terms of energy cost and cycle life.

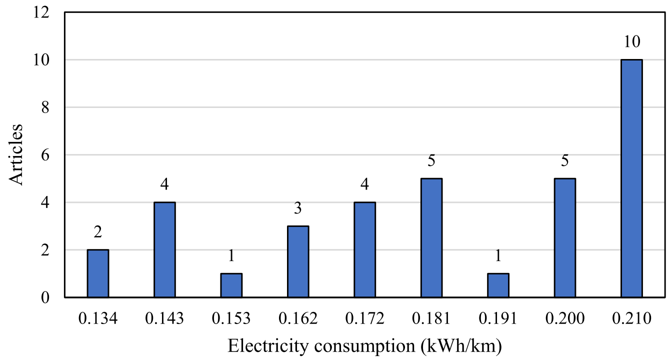

Fig. 9. Histogram of vehicle electricity consumption .[51]

frequent stops). The authors also indicate that while newer driving cycles offer an improvement in estimating real-world fuel consumption (*e.g.*, the Worldwide Harmonized Light Vehicles Test Procedure cycle introduced in 2015 [45], which combines urban, suburban, road, and highway driving), test estimates can still differ from real-world driving, favoring certain vehicle designs and powertrains over others and representing some driver habits and driving conditions better than others. For such reasons, LCA results might differ from real-world values even when considering standardized driving cycles. To overcome this issue, Rangaraju et al. [74] used real-world energy consumption data to conduct an LCA by employing a monitoring system. Such a system was officially validated by Peugeot, and test vehicles were monitored for two years. The authors demonstrate differences of about 30 % when comparing real-world consumption and the consumption of the New European Driving Cycle, as the latter fails to represent auxiliary system usage.

3.7. Combustion fuels

Fig. 10 illustrates the combustion fuels assumed in the sample. Most papers assume gasoline or diesel ICEVs. It was also verified that biofuels and compressed natural gas (CNG) ICEVs are reasonably studied. In turn, hydrogen ICEVs are hardly ever addressed. This is particularly concerning since the results obtained by Bicer et al. [75,76] indicate that hydrogen ICEVs outperform BEVs, hybrids, and other types of ICEVs in all the assessed impact categories (see Table 2 of the supplementary material file). Whereas the results obtained by Bartolozzi et al. [77] do not suggest that hydrogen ICEVs are particularly dominant, as BEVs showcased better results in multiple categories. Consequently, more LCA studies concerning hydrogen ICEVs are needed to demonstrate the real environmental potential of such vehicles. Differences in GHG emissions between combustion fuels are further assessed in Section 3.11.

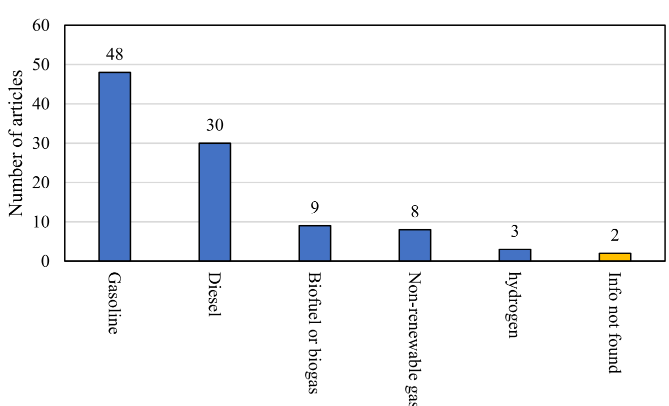

Fig. 10. Fuels assumed in the sample (ICEV).

[4] Only considers papers that address average-sized vehicles and describe the lifetime as constant.

Additionally, previous research has compared the environmental performance of flex fuel vehicles with several EV types. In particular, Elgowainy et al. [78] compared flex fuel vehicles (85 % corn ethanol blended with 15 % gasoline by volume), gasoline and diesel ICEVs, CNG vehicles, HEVs, FCEVs, BEVs, and PHEVs under current and future scenario settings, and concluded that utilizing low-carbon fuel pathways is key to improve the performance of vehicles. The consideration of biofuels, such as ethanol, is essential as they can assist the energy transition of the transport sector.

3.8. Location of the usage phase

LCA studies usually comprise multiple countries throughout the product's life cycle. Nevertheless, among high-impact publications, the usage phase is typically undertaken in Europe or the USA, as illustrated in Fig. 11. While this is beneficial on the one hand since Europe and the USA represent a large portion of the EV market share [79], studies in other regions are lacking. China is reasonably addressed, however, the number of studies is small compared to China's EV market share, which is the largest in the world [79]. Typically, the results indicate high environmental impacts for EVs in China due to its high share of non-renewables (mainly coal plants) [80,81]. Nevertheless, the Chinese electricity mix is changing since the country seeks to reach a 100 % renewable-based electricity matrix past 2060 [82]. This will tip the balance in favor of EVs in China.

In turn, studies focused on incipient countries can indirectly assist their EV diffusion. For instance, if low environmental impacts are verified for EVs in incipient countries, this can stimulate the creation of public incentive policies (*e.g.*, tax exemptions for purchasing EVs). In this context, Souza et al. [51] compare the environmental impacts of EVs and ICEVs in Brazil, which is incipient in EV diffusion but presents approximately 84 % renewable electricity generation [83], thus representing a context contrary to that of China. The results demonstrate that BEVs are very promising in terms of GHG, as they imply approximately half the impact of conventional ICEVs. BEVs also proved to be promising in terms of photochemical oxidant formation due to the absence of the combustion phase.

3.9. Life cycle impact assessment methods

Concerning the life cycle impact assessment (LCIA) method, most articles apply the ReCiPe Midpoint or CML methods (in cases where multiple impact categories are assessed) or the IPCC method (in cases where GHG emissions are the work emphasis), as illustrated in Fig. 12. That being said, we could not find information concerning the applied LCIA method in multiple articles. The analyzed impact categories are described in Tables 2 and 3 of the supplementary material file due to the large number of categories. It was verified that GHG emissions are addressed in 57 articles. The focus on GHG emissions is justifiable since it is often regarded as the most important category [4,84]. Nevertheless, quantifying multiple environmental impact categories is essential for a more all-encompassing and holistic analysis. This is particularly true since EVs might be less impactful in certain categories but more impactful in others. When that is the case, some researchers might apply weights to the impact categories to answer which vehicle type is better overall. For instance, Yu et al. [81] assumed that GHG emissions, acidification potential, eutrophication potential, photochemical ozone creation potential, and ozone depletion potential present weights of 27.5 %, 18.0 %, 9.0 %, 18.0 %, and 27.5 %, respectively (all types of vehicles). However, this approach is controversial since there is no consensus on the exact weight of impact categories. Similarly, Domingues et al. [85]

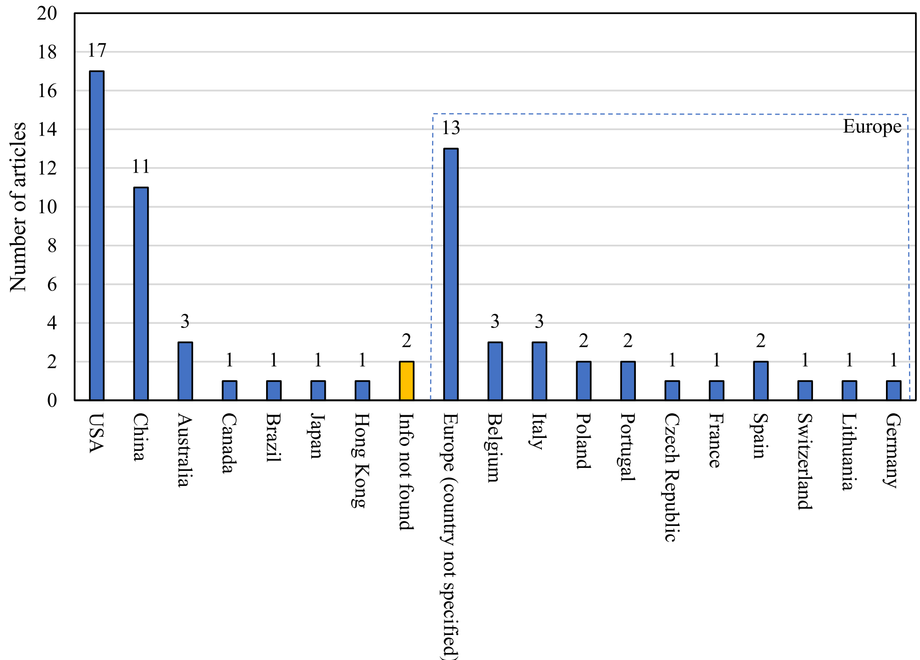

Fig. 11. Countries addressed in the sample (usage phase).

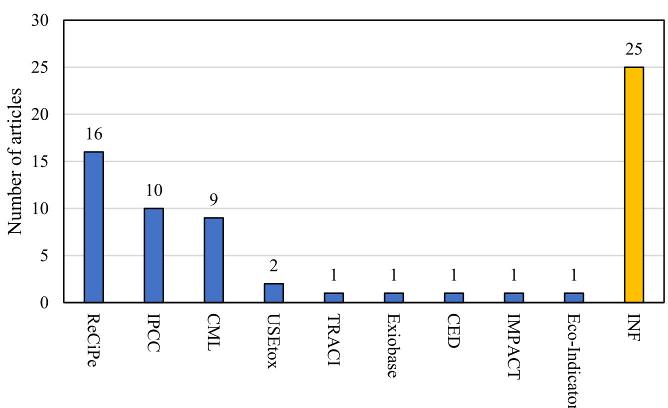

Fig. 12. Life cycle impact assessment methods applied in the sample.

applied multi-criteria decision analysis to rank vehicles; however, the results are influenced by the values selected for the model's parameters. It was also verified that some categories do not receive the necessary attention, such as water consumption, which is addressed in only three articles.

3.10. Additional characteristics

Distance-based functional units are virtually always assumed. More specifically, 1 km or mile of vehicle driven or distance traveled throughout a certain period (often one year or the vehicle's lifetime). As exceptions included in the sample, Ahmadi et al. [86] assume 1 kWh of energy storage since the authors assess a cascaded LCA, where battery packs are recovered from the EV at the end of their lifetime to be reused in a stationary application, and Sharma et al. [87] consider 1 MJ of fuel since the authors conduct a WTW LCA. Second-life battery applications extend battery lifetime and mitigate environmental impacts associated with battery production; thus, this area of research is critical. Distance-based functional units assumed in most articles are satisfactory since they are intuitive and directly linked to the purpose of transportation. However, ideally, authors should inform the driving conditions associated with the distance-based functional unit. For instance, Karabasoglu et al. [48] clearly indicate the assumed driving cycles associated with the functional unit of distance traveled throughout one year. Additional information, such as auxiliary system usage considerations, is also valuable. However, we found that this kind of information is rare in the articles.

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by Argonne National Laboratory is widely used among the articles included in the sample (27 articles). It simulates the energy use and emission outputs of several vehicles and fuel combinations, including road, air, maritime, and rail transportation [88]. Therefore, it facilitates LCA studies. Previous research criticizing the reproducibility of the GREET model was found [89], but the model is very detailed with all LCA stages and default data presented. Thus, the lack of reproducibility is linked to the lack of detailed information in the articles rather than the GREET model itself (*e.g.*, the parameters set/modified in the model should be informed by authors to allow for research reproducibility).

For foreground data, it was verified that inventories are mostly based on previously published papers or reports; however, sometimes, a primary and secondary data mix is used [56]. Lombardi et al. [90] highlight the difficulty of bringing together an inventory based on primary data, as the authors state that it is hard to retrieve detailed information from the manufacturers, and the only way to provide an exhaustive materials and weights database might be to disassemble the real vehicle. In this context, Helmers et al. [91] derive inventories from an actual disassembled vehicle, thereby implying more accurate LCA results. However, vehicle disassembling is quite rare in the literature as it requires a lot of resources. Concerning background data, the Ecoinvent database [92] prevails, as it is used in 31 articles.

Concerning the LCA approach, process-based LCA is applied in 52 articles, whereas hybrid LCA is applied in 8 articles. In a process-based LCA, one itemizes the inputs and the outputs for a given step in producing a product [93]. In contrast, hybrid LCA combines process-based

[5] Electricity consumption for driving, not manufacturing. Only considers papers that address average-sized vehicles and describe the electricity consumption as constant.

LCA with economic input-output (EIO) LCA. The latter estimates the materials and energy resources required, as well as the environmental impacts resulting from economic activities [94]. Wolfram et al. [95] compare the results of process-based and hybrid LCA, indicating that hybrid LCA can lead to 17 % higher GHG emissions for PHEVs due to the extended system boundary.

Monte Carlo simulations are conducted in fourteen articles. Such an approach is valuable due to the substantial risks associated with the environmental impacts of vehicles. By conducting Monte Carlo simulations, it is possible to assess the probability of EVs being environmentally superior to ICEVs. For instance, Abdul-Manan [96] conducted Monte Carlo simulations to assess the GHG emissions of vehicles by assigning probability distributions to the vehicles' energy consumption (miles per gallon and kWh per mile), GHG of crude oil production and gasoline refining, GHG of electricity production, and GHG of the vehicle life cycle. Data from over 200 countries are used to conduct the simulations, implying very robust results. The authors conclude that, on average, BEVs imply 43.2 % less GHG emissions than ICEVs but 15.2 % more GHG emissions than HEVs; however, substantial dispersions around the mean values are verified.

3.11. Results associated with GHG emissions

After a thorough analysis, GHG emissions from multiple articles included in the sample were gathered (more information is available in Section 4 of the supplementary material file). We focused on papers with similar boundaries, vehicle classes, and functional units. Fig. 13 presents a box plot of the results for gasoline, diesel, and CNG ICEVs, BEVs, gasoline and diesel HEVs, PHEVs, and FCEVs. Only baseline or business-as-usual (BAU) results are included in Fig. 13 to avoid bias or unrealistic findings. BAU results imply that conventional current electricity mixes are assumed instead of renewable electricity mixes or carbon-intensive electricity mixes. Additionally, hydrogen production from natural gas is considered since it is the most common method currently available. The effects of alternative electricity mixes and hydrogen production methods are further assessed separately. In total, Fig. 13 includes 126 GHG results from the articles, as detailed in Fig. 1 in the supplementary material file. Overall, BEVs were the best vehicle type, followed by diesel HEVs, PHEVs, gasoline HEVs, CNG ICEVs, diesel ICEVs, FCEVs, and gasoline ICEVs, respectively. Mean values of 182.9, 190.4, 199.1, 201.1, 213.2, 216.2, 228.8, and 258.5 g $CO_{2\text{-eq}}$/km were verified, respectively. That being said, the results show considerable dispersion; thus, there are several exceptions in the sample.

GHG emissions for alternative electricity mixes were also gathered from the sample, as illustrated in Fig. 14. Specifically concerning hydrogen, production from natural gas is assumed as the BAU scenario since it is the most common method and production from coal is assumed as the worst-case scenario. Fig. 14 is not illustrated in terms of a box plot since data for alternative electricity mixes is not as extensive as data for current electricity mixes. It is noteworthy that currently, electricity mixes are composed of both renewables and nonrenewables. That is why the BAU results are situated between the two other groups. Combining a vehicle fleet of mostly BEVs with renewable electricity generation is anticipated to lead to massive GHG emission mitigation. FCEVs are also anticipated to benefit greatly from green hydrogen production. Naturally, PHEVs are expected to benefit at a lower level since they are hybrids. For nonrenewable electricity mixes, EVs typically imply higher GHG emissions than ICEVs.

In addition to electricity mix issues, other factors are also significantly influential, such as the utility factor, *i.e.*, the percentage of the distance traveled in electric mode by a PHEV, which implied a difference of up to 50 % in Onat et al. [97], the state of the air conditioning (on/off), which resulted in a difference of up to 35 % in Zhou et al. [71],

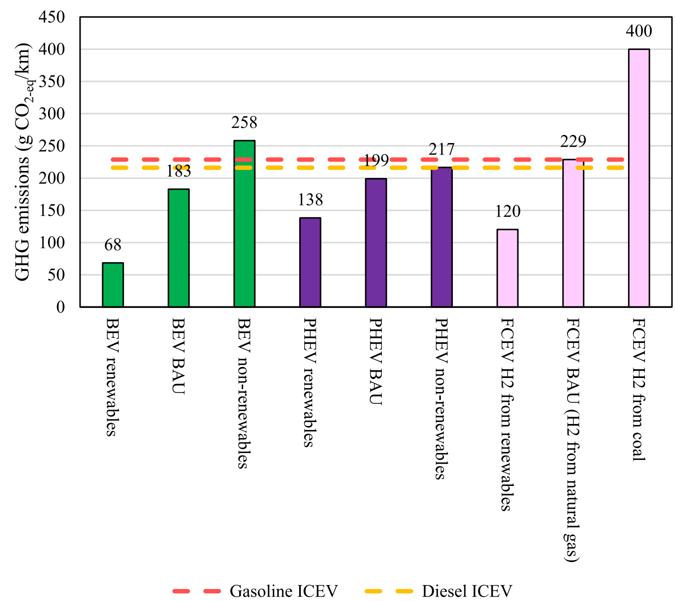

Fig. 14. Estimated influence of electricity mixes on GHG emissions. BAU: business-as-usual.

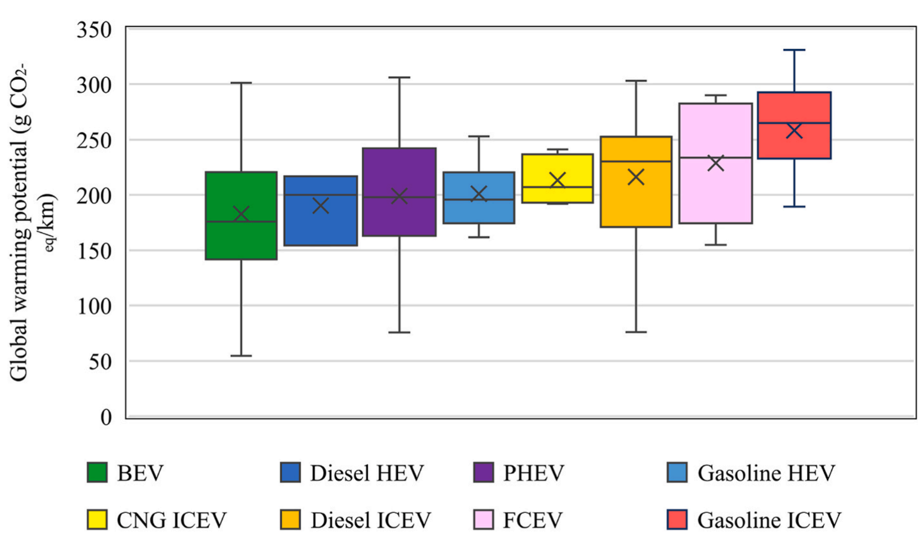

Fig. 13. Business-as-usual GHG emissions.

and the charging profile or period, which implied a difference of up to 25 % in Rangaraju et al. [74]. The several factors that influence the LCA results of vehicles highlight the importance of being clear about the considerations and inventory.

Concerning contribution analyses, we found that the assumed groups vary substantially depending on the article. Some articles breakdown the analysis into several groups, whereas others assume only major groups (*e.g.*, vehicle production, WTW, and recycling). Such differences in approach make it challenging to compare results on a more detailed level. In cases where similar groups were identified (or in cases where comparisons are suitable), we found significant discrepancies in results, such as: (*i*) drivetrain contributions of 11 %, 3 %, and 15 % in Hawkins et al. [56], Bauer et al. [98], and Messagie et al. [99], respectively, (*ii*) battery contributions of 20 % and 8 % in Hawkings et al. [56] and Bauer

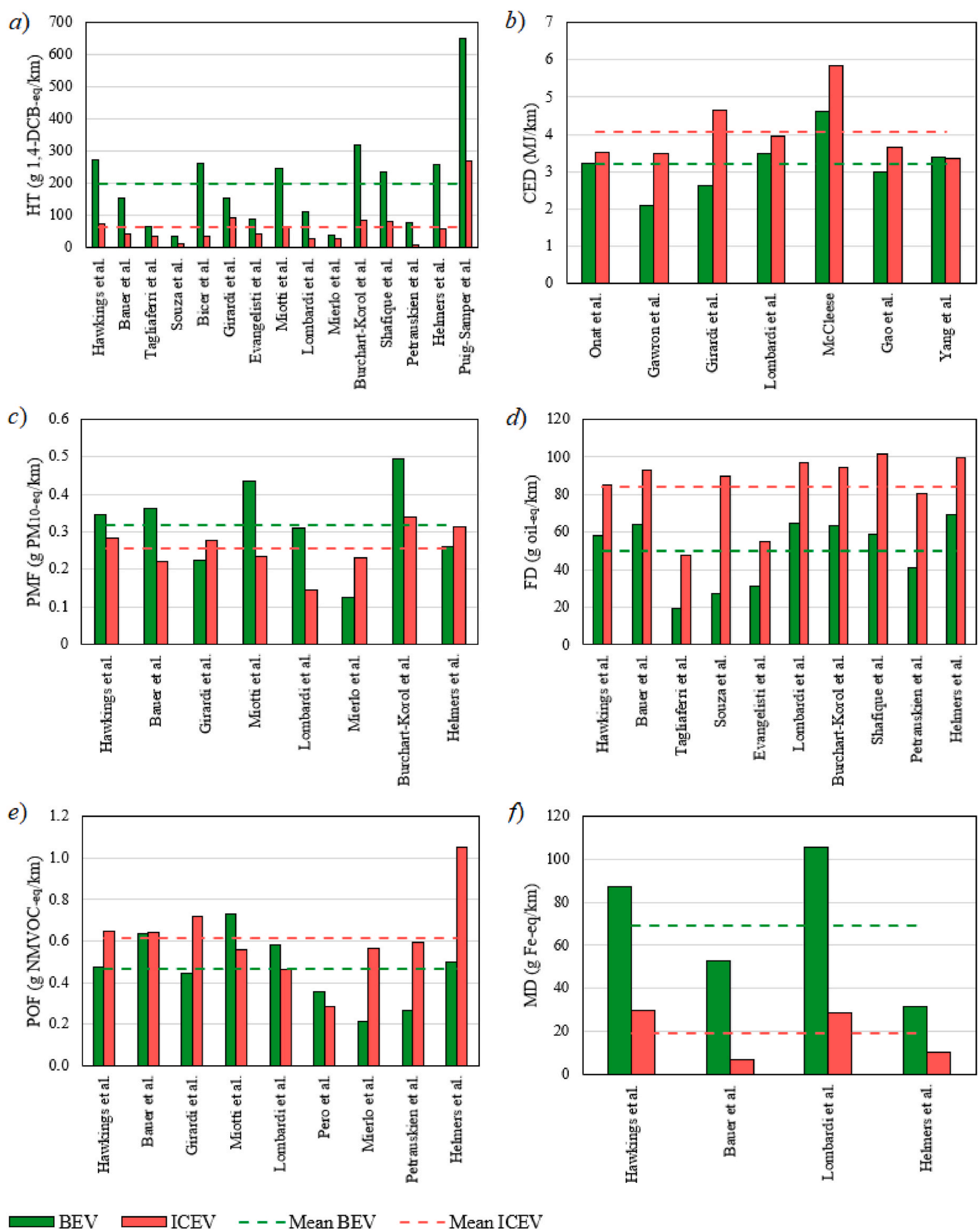

Fig. 15. Business-as-usual results for *a*) human toxicity, *b*) cumulative energy demand, *c*) particulate matter formation, *d*) fossil depletion, *e*) photochemical oxidant formation, *f*) metal depletion. References: Hawkings et al. [56], Bauer et al. [98], Onat et al. [97], Tagliaferri et al. [101], Souza et al. [51], Bicer et al. [75], Gawron et al. [102], Girardi et al. [103], Evangelisti et al. [89], Miotti et al. [104], Lombardi et al. [90], Pero et al. [105], Mierlo et al. [106], McCleese et al. [52], Burchart-Korol et al. [107], Gao et al. [108], Shafique et al. [109], Yang et al. [110], Petrauskien et al. [111], Helmers et al. [91], Puig-Samper et al. [112].

et al. [98], respectively, (*iii*) cradle-to-gate contributions of 45 % and 24 % in Hawkings et al. [56] and Bauer et al. [98], respectively, and (*iv*) WTW contributions of 53 % and 71 % in Hawkings et al. [56] and Bauer et al. [98], respectively. Therefore, for conventional electricity mixes, WTW impacts tend to be more influential than cradle-to-gate impacts.

3.12. Results associated with other impact categories

In this section, LCA results from the sample in terms of human toxicity (HT), cumulative energy demand (CED), particulate matter formation (PMF), fossil depletion (FD), photochemical oxidant formation (POF), and metal depletion (MD) are presented (see Fig. 15) and discussed. Information on why these categories were chosen is available in Section 4 of the supplementary material file. It should be acknowledged here that some environmental impact categories, such as HT, PMF, and POF depend on the region (*e.g.*, Burnham et al. [100] analyze how the region can influence environmental impacts) and the LCIA method used, as different methods might present distinct characterization factors. The modeling of such categories is very complex and subject to significant uncertainties. Thus, the idea is to provide an overview of results reported by several authors to draw valuable insights rather than determine with certainty the environmental impact of EVs and ICEVs.

The experimental outcomes are as follows:

HT: The results proved to vary substantially, ranging from 35.5 to 649.5 g 1,4-DCB$_{\text{-eq}}$/km for BEVs and 8.1–271.7 g 1,4-DCB$_{\text{-eq}}$/km for ICEVs. In all cases, ICEVs outperformed BEVs by a large margin, typically due to the additional toxic metal requirements of the latter. Mean values of 198.1 g 1,4-DCB$_{\text{-eq}}$/km and 64.8 g 1,4-DCB$_{\text{-eq}}$/km were verified.

CED: BEVs were superior to ICEVs in all cases due to the WTW phase of the latter, which requires more cumulative energy. Mean values of 3.2 MJ/km and 4.1 MJ/km were found.

PMF: ICEVs outperformed BEVs in five articles, whereas BEVs were better than ICEVs in three articles; thus, it is not very clear which vehicle type is superior overall. Mean values of 0.32 g $PM_{10\text{-eq}}$/km and 0.26 g $PM_{10\text{-eq}}$/km were obtained for BEVs and ICEVs, respectively.

FD: FD follows a similar logic to that of CED, *i.e.*, BEVs were superior to ICEVs in all articles due to the WTW phase of the latter (fossil fuel requirements). Mean values of 49.7 g oil$_{\text{-eq}}$/km and 84.4 g oil$_{\text{-eq}}$/km were verified.

POF: In this case, the results are somewhat ambiguous since BEVs were better in six articles (one of which obtained practically equal results for BEVs and ICEVs), whereas ICEVs were better in three articles. Mean values of 0.47 g NMVOC$_{\text{-eq}}$/km and 0.61 g NMVOC$_{\text{-eq}}$/km were found for BEVs and ICEVs, respectively.

MD: There is a significant research gap in the assessment of metal depletion, as only four works could be properly compared. BEVs were substantially worse than ICEVs, with mean values of 69.3 g Fe$_{\text{-eq}}$/km and 19.0 g Fe$_{\text{-eq}}$/km due to the reliance on metals of the former.

4. Challenges and improvement opportunities

Based on the conducted research, we propose to organize the factors that influence the vehicle life cycle into four groups: (*i*) user specifications, (*ii*) vehicle specifications, (*iii*) local specifications, and (*iv*) multigroup specifications, as illustrated in Fig. 16. We suggest that energy consumption per km, lifetime, EOL, and vehicle-to-grid (V2G) are examples of multigroup specifications since they depend on several factors, such as the driving pattern, battery usage, vehicle efficiency, road conditions, materials that constitute the components, recycling technologies available in the region, and willingness to provide ancillary services to the grid. Each of these groups presents associated modeling challenges. User specifications are challenging to model due to the complexity of human behavior and the infinite ways the driver can operate. Vehicle specifications are difficult to model as well, mainly due to the limited data released by manufacturers. Local specifications also present some associated challenges, such as knowing the exact emission factors of electricity generation over time. Multigroup specifications are substantially intricate, hence, they are usually oversimplified in LCA studies.

Improvement and work opportunities for each group are as follows.

4.1. User specifications

- Concerning user specifications, efforts in evaluating and modeling human behavior are needed. This is tricky since individuals with distinct personalities might act very differently. One possible approach to this might be to generate clusters with similar behavioral characteristics from a large sample of individuals. It is also noteworthy that several user specifications influence the LCA of vehicles, as exemplified in Fig. 16, thereby, this issue goes beyond only driving aspects.
- Few studies take into account the charging period of EVs, which can significantly influence LCA results since the electricity mix might notably change throughout the day [74]. Hence, it is important to approach this issue more closely in future work.

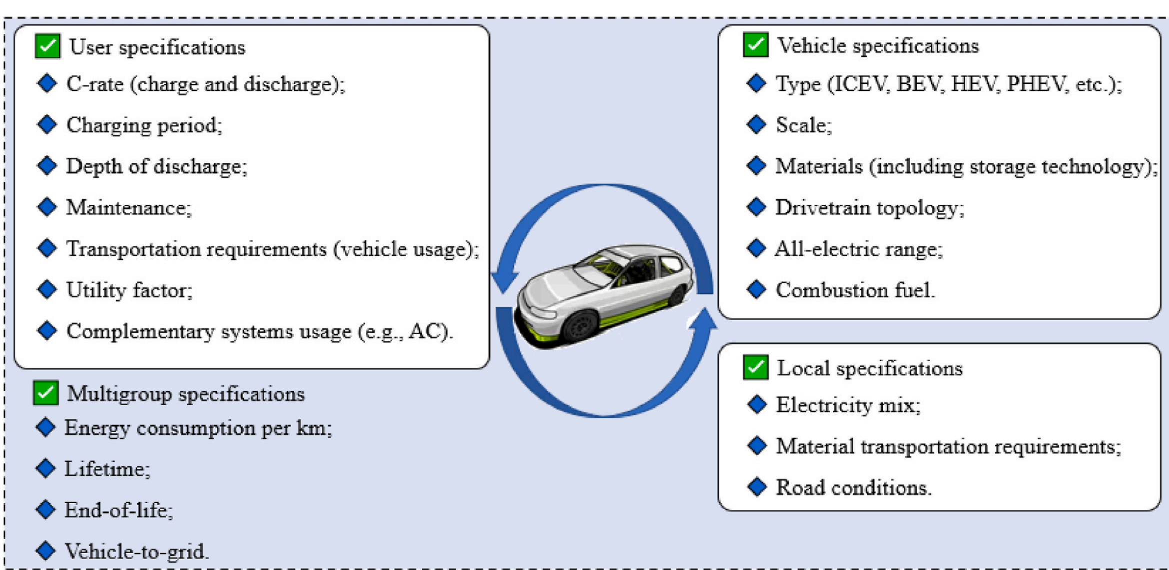

Fig. 16. Factors that influence vehicle life cycle.

4.2. Vehicle specifications

- Although not always the case, a lack of transparency was often verified in the assumed battery and fuel cell technologies for BEVs and FCEVs. Greater transparency would be valuable since LCA results are significantly sensitive to the assumed technologies.
- There is a lack of LCA research on supercapacitor EVs and associated hybrids (*e.g.*, hybrid batteries and supercapacitor vehicles or hybrid fuel cells and supercapacitor vehicles). This lack of research is explained by a low TRL. However, given that material developments are expected to make supercapacitors highly important in automotive applications [44], more work on such vehicle types would certainly be beneficial;
- There is a lack of LCA research on hydrogen ICEVs, hence, their environmental performance is not yet clear. Moreover, while biofuel ICEVs are reasonably studied, there is a wide variety of blends addressed by the authors (*e.g.*, ethanol-gasoline blends with various proportions), which impairs a proper comparison of results. More work on biofuel ICEVs would be convenient to enable a proper comparison of results concerning several fuel blends.
- Diversification of research concerning scale is important, as the vast majority of papers address standard passenger vehicles (LDVs). The market share of MDVs and HDVs (*e.g.*, trucks and buses) is expected to increase significantly with the development of storage technologies, requiring more LCA studies on the subject.

4.3. Local specifications

- Concerning the usage phase, a substantial focus on Europe and the USA was verified. China is understudied compared to its EV market share. Furthermore, greater diversification of location is important in LCA studies to stimulate EV diffusion in multiple regions.
- High-accuracy modeling of environmental impacts from the grid (*e.g.*, emission factors) over time with a high resolution is essential, given that most works assume that such impacts are constant.

4.4. Multigroup specifications

- Lack of consensus on the EVs' lifetime proved to be a special point of concern as assumptions vary substantially (from 150,000 to 257,600 km), and lifetime notably influences the LCA results. Moreover, it was verified that battery lifetime is typically oversimplified (assumed constant). Emerging advanced capacity fade models that take into account multiple factors (*e.g.*, temperature, SOC, operating power, etc.) are expected to enhance the accuracy of LCA studies.
- While several works detail the assumed driving cycle, which is important to enable research replicability, few works take into account real-world energy consumption data based on advanced measurement systems [74]. Real-world data can be substantially different from laboratory-tested data. Thus, this issue requires more attention.
- More efforts on EOL phase modeling are needed, not only for transparency in LCA research but also due to the importance of recycling in recovering finite resources used in EV manufacturing (*e.g.*, lithium and platinum). In this context, a lack of studies on metal depletion was verified; thus, it should be evaluated more frequently in future work.
- Vehicle-to-grid (V2G) technology is essential in the context of emerging power systems and smart grids, notably due to the increasing market share of EVs [25]. It allows EVs to provide energy to the grid in advantageous periods (typically high-demand periods) when they are not being driven, thereby improving several system aspects such as efficiency, power quality, and stability. Moreover, V2G can significantly reduce the environmental impacts attributed to EVs due to its ability to decrease the usage of nonrenewable dispatchable power plants. However, a substantial research gap was verified concerning the influence of V2G on the LCA of vehicles. Thus, this topic is of considerable future interest.

4.5. Additional insights

- Substantial emphasis was placed on GHG emissions, as it is an essential impact category. Nevertheless, some categories, such as water consumption, require greater attention. Furthermore, environmental categories such as acidification, eutrophication, and ecotoxicity are accounted for in several manners by the authors (acidification – terrestrial, air, or general; eutrophication and ecotoxicity – terrestrial, marine, or freshwater), making a proper comparison of results difficult.
- The applied LCIA method is not clear in multiple studies, which is worrisome due to undisclosed characterization factors; thus, greater transparency is also essential in this way.

5. Research limitations

Although the conducted research proved to be valuable as it provides novel perspectives on the theme, some research limitations are acknowledged:

The review search process was mainly conducted through an electronic database (SC) by gathering metadata on LCA research of EVs compared to ICEVs. A substantial number of articles were analyzed (121 before the screening process), including most cited articles and recent articles with high impact. That being said, it is impractical to analyze all documents gathered by the search (733 documents); thus, one research limitation is the potential exclusion of valuable articles in the screening process.

Furthermore, if used in the search process, some terms could alter the sample and potentially make it broader. However, the obtained sample is very representative of the theme since widespread terms were used (life cycle assessment and electric vehicles).

When dealing with review limitations, it is essential to address threats to validity. This paper used the threat categorization proposed by Wohlin et al. [113], which comprises four types of validity threat: conclusion, internal, construct, and external. Such threat categorization is widely recognized [114].

The first threat concerns the conclusion validity, referring to the ability to draw correct conclusions about the relationship between treatment and outcome, which in this work is related to a small sample compared to the overall number of articles published on the theme (statistical issue). The methodology used in this investigation assumes that not all existing relevant primary studies can be identified. Moreover, due to publication bias, positive results are more likely to be published than negative ones, leading to some relevant primary studies not being published. This effect is impossible to deal with and might influence the research conclusions [113]. Kitchenham [115] argues that duplicate or analogous papers by the same author must be avoided, as they can bias the results. That being said, this effect is very limited in the obtained sample since, although some authors published multiple articles, their context is typically different.

The second threat concerns internal validity, which is associated with potentially incorrect conclusions about causal relationships between treatment and results. SLRs, such as the one conducted in this paper, aim to minimize threats to internal validity by applying systematic procedures. Moreover, threats to internal validity were mitigated here by carefully selecting similar groups to compare results.

The third threat concerns the construct validity, referring to the extent to which the experiment reflects the theory. This threat was mitigated in this paper by seeking well-founded theoretical justifications for the results (*e.g.*, why a vehicle type performed better than others).

The fourth threat concerns the external validity, which is associated with the ability to generalize the results beyond the experiment setting. The external validity is related to the degree to which primary studies represent the review's focus [116,117]. This threat was mitigated by a careful screening process to select representative articles only. It is noteworthy that this SLR focused on LCA research of EVs compared to ICEVs up to July/2022. As time passes, technologies for EVs tend to mature, requiring new studies about LCA, *i.e.*, some analyses may become outdated in the medium term. Therefore, it is important to update the research in the future.

6. Conclusion

The world is withstanding substantial environmental issues, and pronounced proactive actions are required to mitigate the problem. The automotive sector is key to implementing changes as it is one of the most impactful to the environment. For such reasons, and due to remarkable technological advances, a notable shift from the conventional ICEV fleet to an EV fleet is expected to occur in the medium term. While this research indicated that EVs are yet to prove themselves in some environmental categories, they are already advantageous in others. Once electricity generation becomes mostly renewable, the environmental benefits of electric vehicles will flourish. Furthermore, other breakthroughs, such as improved energy density or increased recycling rate of batteries, are also expected to tip the balance in favor of EVs. In this context, LCA research associated with transitioning from an ICEV-based fleet to an EV-based fleet is of utmost importance. Consequently, this paper carried out a systematic literature review on the topic based on highly impactful articles, including the main considerations, outliers, results, statistical assessments, challenges, research gaps, and potential improvements in future research. Such in-depth analyses are expected to be valuable for researchers and decision-makers, presumably contributing to further research.

Concerning the qualitative research results, (*i*) some issues associated with a lack of transparency were often verified (*e.g.*, not disclosing the energy storage technology and impact assessment method); (*ii*) BEVs are by far the most analyzed EV type, but associated hybrids are also significantly studied. In turn, research concerning some EV types, such as fuel-cell-based vehicles and, most importantly, supercapacitor EVs, is lacking; (*iii*) standard-sized vehicles are virtually always addressed, but a few papers approach trucks, buses, or scooters; (*iv*) the Nissan Leaf EV, Toyota Prius hybrid, and Volkswagen Golf models are regularly addressed in LCA research, as they are very representative of standard-sized vehicles. However, it is common to incorporate features from more than one model into the inventory of a single vehicle due to data availability issues; (*v*) Li-ion batteries are by far the most assessed technologies, particularly LFP, NMC, and LMO batteries, although NiMH batteries are reasonably addressed, most notably in hybrids; (*vi*) studies usually carry out a cradle-to-grave assessment, but the end-of-life phase modeling is not always clear; (*vii*) assumptions concerning lifetime and electricity consumption vary widely (from 150,000 to 257,600 km and from 0.124 kWh/km to 0.250 kWh/km), which poses a significant influence on LCA results; (*viii*) gasoline and diesel ICEVs are highly addressed, but research on biofuel, CNG, and, most notably, hydrogen ICEVs is limited; (*ix*) the usage phase is typically undertaken in Europe or the USA, implying a lack of studies on emerging countries; (*x*) ReCiPe Midpoint, IPCC, and CML are by far the most applied impact assessment methods, although at least six other methods are applied in the sample; (*xi*) distance-based functional units are typically assumed, but, depending on the application, there are cases in which authors assume energy-based functional units; (*xii*) the GREET model is highly used, as it facilitates LCA research associated with vehicles. Although criticisms have been found concerning transparency, the issue is related to a lack of detailed information in the articles rather than the model itself since the model is very detailed with all LCA stages and default data presented; (*xiii*) process-based LCA is the preferred method, but there is also significant research on hybrid LCA, which combines process-based with economic input-output LCA, implying an extended system boundary; (*xiv*) most papers perform deterministic LCA, but risk assessment through Monte Carlo simulations is carried out with a reasonable frequency; (*xv*) substantial emphasis on the GHG emissions environmental impact category makes it possible to conduct detailed statistical assessments and comparison of results between distinct vehicle types; however, carrying out detailed statistical analysis for other categories is challenging; (*xvi*) the factors evaluated in sensitivity analyses vary substantially depending on the article, but electricity mix issues are generally considered due to the strong influence of the WTT phase on the life cycle of EVs; and (*xvii*) the groups assumed in the contribution analyses also vary substantially depending on the article, and it was found that even when the groups are similar, the results associated with contribution analyses can be substantially different.

Concerning the quantitative research results, mean values in g $CO_{2\text{-}eq}$/km of 182.9 (BEV), 190.4 (diesel HEV), 199.1 (PHEV), 201.1 (gasoline HEV), 213.2 (CNG ICEV), 216.2 (diesel ICEV), 228.8 (FCEV), and 258.5 (gasoline ICEV) were verified for GHG emissions (business-as-usual results). Therefore, BEVs already show significant benefits in terms of GHG emissions. Regarding other impact categories, on average, BEVs were superior to ICEVs in terms of cumulative energy demand (3.2 MJ/km versus 4.1 MJ/km), fossil depletion (49.7 g $oil_{\text{-}eq}$/km versus 84.4 g $oil_{\text{-}eq}$/km), and photochemical oxidant formation (0.47 g $NMVOC_{\text{-}eq}$/km versus 0.61 g $NMVOC_{\text{-}eq}$/km) but were worse than ICEVs in terms of human toxicity (198.1 g 1,4-$DCB_{\text{-}eq}$/km versus 64.8 g 1,4-$DCB_{\text{-}eq}$/km), particulate matter formation (0.32 g $PM_{10\text{-}eq}$/km versus 0.26 g $PM_{10\text{-}eq}$/km), and metal depletion (69.3 g $Fe_{\text{-}eq}$/km versus 19.0 g $Fe_{\text{-}eq}$/km). That being said, the results are substantially volatile; thus, there are several exceptions in the sample.

The research demonstrated that there is highly impactful and fundamental research concerning the LCA of vehicles, however, several improvement opportunities are clear. For such reasons, we proposed organizing the factors that influence the vehicle life cycle into four groups and suggested a series of improvement opportunities for each of them: (*i*) user specifications, (*ii*) vehicle specifications, (*iii*) local specifications, and (*iv*) multigroup specifications. While improvement opportunities are clear, the authors recognize that the theme is complex and that some points are challenging to work on. In this way, a substantial and joint effort by the scientific community is key to further developing the subject.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2024.114988.

Data availability

The data gathered from the research is available through the supplementary material file

References

[1] Lin D, Hanscom L, Murthy A, Galli A, Evans M, Neill E, Mancini MS, Martindill J, Medouar FZ, Huang S, Wackernagel M. Ecological footprint accounting for countries: updates and results of the national footprint accounts, 2012–2018. Resources 2018;7(2018):58. https://doi.org/10.3390/RESOURCES7030058. 58 7.

[2] Fanning AL, O'Neill DW, Hickel J, Roux N. The social shortfall and ecological overshoot of nations. Nat Sustain 2021;5(1 5):26–36. https://doi.org/10.1038/s41893-021-00799-z. 2021.

[3] IPCC, Global Warming of 1.5 °C —, (n.d.). https://www.ipcc.ch/sr15/(accessed August 8, 2022).

[4] O. Hoegh-Guldberg, D. Jacob, M. Taylor, T. Guillén Bolaños, M. Bindi, S. Brown, I.A. Camilloni, A. Diedhiou, R. Djalante, K. Ebi, F. Engelbrecht, J. Guiot, Y. Hijioka, S. Mehrotra, C.W. Hope, A.J. Payne, H.O. Pörtner, S.I. Seneviratne, A. Thomas, R. Warren, G. Zhou, The human imperative of stabilizing global climate change at 1.5°C, Science (1979) 365 (2019). https://doi.org/10.1126/SCIENCE.AAW6974/SUPPL_FILE/AAW6974_HOEGH-GULDBERG_SM.PDF.

[5] United Nations, The Paris Agreement | UNFCCC, (n.d.). https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed August 8, 2022).

[6] M. Manas Agrawal, IJERT-Global Perspective on Electric Vehicle 2020 Global Perspective on Electric Vehicle 2020, IJERT Journal International Journal of Engineering Research and Technology (n.d.). www.ijert.org (accessed August 8, 2022).

[7] Visser M, van Eck NJ, Waltman L. Large-scale comparison of bibliographic data sources: Scopus, Web of science, dimensions, crossref, and microsoft academic. Quantitative Science Studies 2021;2:20–41. https://doi.org/10.1162/qss_a_00112.

[8] de Doile GND, Rotella Junior P, Rocha LCS, Bolis I, Janda K, Coelho Junior LM. Hybrid wind and solar photovoltaic generation with energy storage systems: a systematic literature review and contributions to technical and economic regulations. Energies 2021;14:6521. https://doi.org/10.3390/en14206521.

[9] Alvarez-Meaza I, Zarrabeitia-Bilbao E, Rio-Belver RM, Garechana-Anacabe G. Fuel-cell electric vehicles: plotting a scientific and technological knowledge map. Sustainability 2020;12:2334. https://doi.org/10.3390/SU12062334. Page 2334 12 (2020).

[10] Xia X, Li P, Xia Z, Wu R, Cheng Y. Life cycle carbon footprint of electric vehicles in different countries: a review. Sep Purif Technol 2022;301:122063. https://doi.org/10.1016/J.SEPPUR.2022.122063.

[11] Onat NC, Kucukvar M. A systematic review on sustainability assessment of electric vehicles: knowledge gaps and future perspectives. Environ Impact Assess Rev 2022;97:106867. https://doi.org/10.1016/J.EIAR.2022.106867.

[12] Oda H, Noguchi H, Fuse M. Review of life cycle assessment for automobiles: a meta-analysis-based approach. Renew Sustain Energy Rev 2022;159:112214. https://doi.org/10.1016/J.RSER.2022.112214.

[13] Xia X, Li P. A review of the life cycle assessment of electric vehicles: considering the influence of batteries. Sci Total Environ 2022;814:152870. https://doi.org/10.1016/J.SCITOTENV.2021.152870.

[14] Verma S, Dwivedi G, Verma P. Life cycle assessment of electric vehicles in comparison to combustion engine vehicles: a review. Mater Today Proc 2022;49:217–22. https://doi.org/10.1016/J.MATPR.2021.01.666.

[15] Dillman KJ, Árnadóttir Á, Heinonen J, Czepkiewicz M, Davíðsdóttir B. Review and meta-analysis of EVs: embodied emissions and environmental breakeven. Sustainability 2020;12:9390. https://doi.org/10.3390/SU12229390. Page 9390 12 (2020.

[16] Tintelecan A, Constantinescu A, Martis C. Literature review - electric vehicles life cycle assessment, 13th International Conference ELEKTRO 2020. ELEKTRO 2020 - Proceedings 2020-May 2020. https://doi.org/10.1109/ELEKTRO49696.2020.9130289.

[17] Dolganova I, Rödl A, Bach V, Kaltschmitt M, Finkbeiner M. A review of life cycle assessment studies of electric vehicles with a focus on resource use. Resources 2020;9:32. https://doi.org/10.3390/RESOURCES9030032. , Page 32 9 (2020.

[18] Towoju OA, Ishola FA. A case for the internal combustion engine powered vehicle. Energy Rep 2020;6:315–21. https://doi.org/10.1016/J.EGYR.2019.11.082.

[19] Marmiroli B, Messagie M, Dotelli G, van Mierlo J. Electricity generation in LCA of electric vehicles: a review. Appl Sci 2018;8:1384. https://doi.org/10.3390/APP8081384. , Page 1384 8 (2018.

[20] Garcia R, Freire F. A review of fleet-based life-cycle approaches focusing on energy and environmental impacts of vehicles. Renew Sustain Energy Rev 2017;79:935–45. https://doi.org/10.1016/J.RSER.2017.05.145.

[21] Nealer R, Hendrickson TP. Review of recent lifecycle assessments of energy and greenhouse gas emissions for electric vehicles. Current Sustainable/Renewable Energy Reports 2015;2:66–73. https://doi.org/10.1007/S40518-015-0033-X/FIGURES/1.

[22] Nordelöf A, Messagie M, Tillman AM, Ljunggren Söderman M, van Mierlo J. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int J Life Cycle Assess 2014;19:1866–90. https://doi.org/10.1007/S11367-014-0788-0/TABLES/6.

[23] Helmers E, Marx P. Electric cars: technical characteristics and environmental impacts. Environ Sci Eur 2012;24:1–15. https://doi.org/10.1186/2190-4715-24-14/FIGURES/2.

[24] Hawkins TR, Gausen OM, Strømman AH. Environmental impacts of hybrid and electric vehicles-a review. Int J Life Cycle Assess 2012;17:997–1014. https://doi.org/10.1007/S11367-012-0440-9/FIGURES/5.

[25] da Costa VBF, de Doile GND, Troiano G, Dias BH, Bonatto BD, Soares T, de Freitas Filho W. Electricity markets in the context of distributed energy resources and demand response programs: main developments and challenges based on a systematic literature review. Energies 2022;15:7784. https://doi.org/10.3390/EN15207784. , Page 7784 15 (2022).

[26] Aria M, Cuccurullo C. Bibliometrix : an R-tool for comprehensive science mapping analysis. J Informetr 2017;11:959–75. https://doi.org/10.1016/j.joi.2017.08.007.

[27] Bibliometrix Organization, Publications, (n.d.). https://www.bibliometrix.org/Papers.html (accessed January 17, 2022).

[28] US Department of Energy. The history of the electric car. https://www.energy.gov/articles/history-electric-car. [Accessed 28 April 2024].

[29] IEA. Trends in electric cars. https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-cars. [Accessed 28 April 2024].

[30] Saikia K, Kakati BK, Boro B, Verma A. Current advances and applications of fuel cell technologies, Recent Advancements in Biofuels and Bioenergy Utilization 2018:303–37. https://doi.org/10.1007/978-981-13-1307-3_13/COVER.

[31] Xun Q, Liu Y, Holmberg E. A comparative study of fuel cell electric vehicles hybridization with battery or supercapacitor. SPEEDAM 2018 - proceedings: international symposium on power electronics, electrical drives, automation and motion. 2018. p. 389–94. https://doi.org/10.1109/SPEEDAM.2018.8445386.

[32] Fuel Cell Powered Vehicles Using Supercapacitors: Device Characteristics, Control Strategies, and Simulation Results, (n.d.). https://escholarship.org/uc/item/23w1m5bb (accessed August 7, 2022).

[33] US Department of Energy, Alternative Fuels Data Center: Hybrid Electric Vehicles, (n.d.). https://afdc.energy.gov/vehicles/electric_basics_hev.html (accessed August 7, 2022).

[34] US Department of Energy, Alternative Fuels Data Center: How Do Plug-In Hybrid Electric Cars Work?, (n.d.). https://afdc.energy.gov/vehicles/how-do-plug-in-hybrid-electric-cars-work (accessed August 7, 2022).

[35] Faria R, Marques P, Moura P, Freire F, Delgado J, de Almeida AT. Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles. Renew Sustain Energy Rev 2013;24:271–87. https://doi.org/10.1016/J.RSER.2013.03.063.

[36] Li J, Liang M, Cheng W, Wang S. Life cycle cost of conventional, battery electric, and fuel cell electric vehicles considering traffic and environmental policies in China. Int J Hydrogen Energy 2021;46:9553–66. https://doi.org/10.1016/J.IJHYDENE.2020.12.100.

[37] Nine Of The Largest Green Hydrogen Projects 2022, (n.d.). https://fuelcellsworks.com/news/nine-of-the-largest-green-hydrogen-projects-2022/(accessed July 27, 2022).

[38] Kopp M, Coleman D, Stiller C, Scheffer K, Aichinger J, Scheppat B. Energiepark Mainz: technical and economic analysis of the worldwide largest Power-to-Gas plant with PEM electrolysis. Int J Hydrogen Energy 2017;42:13311–20. https://doi.org/10.1016/J.IJHYDENE.2016.12.145.

[39] Zhang H, Wang L, van herle J, Maréchal F, Desideri U. Techno-economic comparison of green ammonia production processes. Appl Energy 2020;259:114135. https://doi.org/10.1016/J.APENERGY.2019.114135.

[40] Ayodele TR, Munda JL. Potential and economic viability of green hydrogen production by water electrolysis using wind energy resources in South Africa. Int J Hydrogen Energy 2019;44:17669–87. https://doi.org/10.1016/J.IJHYDENE.2019.05.077.

[41] de Andrade JVB, da Costa VBF, Bonatto BD, Áquila G, Pamplona E de O, Bhandari R. Perspective under uncertainty and risk in green hydrogen investments: a stochastic approach using Monte Carlo simulation. Int J Hydrogen Energy 2024;49:385–404. https://doi.org/10.1016/j.ijhydene.2023.08.253.

[42] Umicore. Fuel cells vs. batteries: what's the difference?. https://www.umicore.com/en/newsroom/fuel-cells-battery-difference/. [Accessed 4 May 2024].

[43] Pandolfo AG, Hollenkamp AF. Carbon properties and their role in supercapacitors. J Power Sources 2006;157:11–27. https://doi.org/10.1016/J.JPOWSOUR.2006.02.065.

[44] Horn M, MacLeod J, Liu M, Webb J, Motta N. Supercapacitors: a new source of power for electric cars? Econ Anal Policy 2019;61:93–103. https://doi.org/10.1016/J.EAP.2018.08.003.
[45] Ellingsen LAW, Singh B, Strømman AH. The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. Environ Res Lett 2016;11:054010. https://doi.org/10.1088/1748-9326/11/5/054010.
[46] García Sánchez JA, López Martínez JM, Lumbreras Martín J, Flores Holgado MN, Aguilar Morales H. Impact of Spanish electricity mix, over the period 2008–2030, on the life cycle energy consumption and GHG emissions of electric, hybrid diesel-electric, fuel cell hybrid and diesel bus of the Madrid transportation system. Energy Convers Manag 2013;74:332–43. https://doi.org/10.1016/J.ENCONMAN.2013.05.023.
[47] Liu X, Elgowainy A, Vijayagopal R, Wang M. Well-to-Wheels analysis of zero-emission plug-in battery electric vehicle technology for medium- and heavy-duty trucks. Environ Sci Technol 2021;55:538–46. https://doi.org/10.1021/acs.est.0c02931.
[48] Karabasoglu O, Michalek J. Influence of driving patterns on life cycle cost and emissions of hybrid and plug-in electric vehicle powertrains. Energy Pol 2013;60:445–61. https://doi.org/10.1016/J.ENPOL.2013.03.047.
[49] Sabihuddin S, Kiprakis AE, Mueller M. A numerical and graphical review of energy storage technologies. Energies 2015;8:172–216. https://doi.org/10.3390/EN8010172. 172-216 8 (2014).
[50] Hu X, Zou C, Zhang C, Li Y. Technological developments in batteries: a survey of principal roles, types, and management needs. IEEE Power Energy Mag 2017;15:20–31. https://doi.org/10.1109/MPE.2017.2708812.
[51] de Souza LLP, Lora EES, Palacio JCE, Rocha MH, Renó MLG, Venturini OJ. Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil. J Clean Prod 2018;203:444–68. https://doi.org/10.1016/J.JCLEPRO.2018.08.236.
[52] McCleese DL, LaPuma PT. Using Monte Carlo simulation in life cycle assessment for electric and internal combustion vehicles. Int J Life Cycle Assess 2002;7(4 7):230–6. https://doi.org/10.1007/BF02978878. 2002.
[53] Mesbahi T, Khenfri F, Rizoug N, Chaaban K, Bartholomeüs P, le Moigne P. Dynamical modeling of Li-ion batteries for electric vehicle applications based on hybrid Particle Swarm–Nelder–Mead (PSO–NM) optimization algorithm. Elec Power Syst Res 2016;131:195–204. https://doi.org/10.1016/J.EPSR.2015.10.018.
[54] Ding Y, Cano ZP, Yu A, Lu J, Chen Z. Automotive Li-ion batteries: current status and future perspectives. Electrochem Energy Rev 2019;2(1 2):1–28. https://doi.org/10.1007/S41918-018-0022-Z. 2019.
[55] Majeau-Bettez G, Hawkins TR, StrØmman AH. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. Environ Sci Technol 2011;45:4548–54. https://doi.org/10.1021/ES103607C/SUPPL_FILE/ES103607C_SI_001.PDF.
[56] Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH. Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 2013;17:53–64. https://doi.org/10.1111/J.1530-9290.2012.00532.X.
[57] Zhang B, Gong D, Wang X, Liu P, Xu S. Experimental investigation of control strategies on voltage inconsistency for proton exchange membrane fuel cells. SAE technical papers. 2021. https://doi.org/10.4271/2021-01-0736.
[58] Velandia Vargas JE, Seabra JEA. Fuel-cell technologies for private vehicles in Brazil: environmental mirage or prospective romance? A comparative life cycle assessment of PEMFC and SOFC light-duty vehicles. Sci Total Environ 2021;798:149265. https://doi.org/10.1016/J.SCITOTENV.2021.149265.
[59] Bitencourt L, Dias B, Soares T, Borba B, Quirós-Tortós J, Costa V. Understanding business models for the adoption of electric vehicles and charging stations: challenges and opportunities in Brazil. IEEE Access 2023;11:63149–66. https://doi.org/10.1109/ACCESS.2023.3287388.
[60] Costa CM, Barbosa JC, Castro H, Gonçalves R, Lanceros-Méndez S. Electric vehicles: to what extent are environmentally friendly and cost effective? – Comparative study by european countries. Renew Sustain Energy Rev 2021;151:111548. https://doi.org/10.1016/j.rser.2021.111548.
[61] Brückner L, Frank J, Elwert T. Industrial recycling of lithium-ion batteries—a critical review of metallurgical process routes. Metals 2020;10:1107. https://doi.org/10.3390/MET10081107. , Page 1107 10 (2020.
[62] Kallitsis E, Korre A, Kelsall GH. Life cycle assessment of recycling options for automotive Li-ion battery packs. J Clean Prod 2022;371:133636. https://doi.org/10.1016/J.JCLEPRO.2022.133636.
[63] Valente A, Iribarren D, Dufour J. End of life of fuel cells and hydrogen products: from technologies to strategies. Int J Hydrogen Energy 2019;44:20965–77. https://doi.org/10.1016/J.IJHYDENE.2019.01.110.
[64] Oliveira L, Messagie M, Rangaraju S, Sanfelix J, Hernandez Rivas M, van Mierlo J. Key issues of lithium-ion batteries – from resource depletion to environmental performance indicators. J Clean Prod 2015;108:354–62. https://doi.org/10.1016/J.JCLEPRO.2015.06.021.
[65] Velázquez-Martínez O, Valio J, Santasalo-Aarnio A, Reuter M, Serna-Guerrero R. A critical review of lithium-ion battery recycling processes from a circular economy perspective. Batteries 2019;5:68. https://doi.org/10.3390/BATTERIES5040068. , Page 68 5 (2019.
[66] Reverdiau G, le Duigou A, Alleau T, Aribart T, Dugast C, Priem T. Will there be enough platinum for a large deployment of fuel cell electric vehicles? Int J Hydrogen Energy 2021;46:39195–207. https://doi.org/10.1016/J.IJHYDENE.2021.09.149.
[67] Cox B, Bauer C, Mendoza Beltran A, van Vuuren DP, Mutel CL. Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. Appl Energy 2020;269:115021. https://doi.org/10.1016/J.APENERGY.2020.115021.
[68] Hollingsworth J, Copeland B, Johnson JX. Are e-scooters polluters? the environmental impacts of shared dockless electric scooters. Environ Res Lett 2019;14. https://doi.org/10.1088/1748-9326/AB2DA8.
[69] Alharbi T, Bhattacharya K, Kazerani M. Planning and operation of isolated microgrids based on repurposed electric vehicle batteries. IEEE Trans Industr Inform 2019;15:4319–31. https://doi.org/10.1109/TII.2019.2895038.
[70] Hu X, Xu L, Lin X, Pecht M. Battery lifetime prognostics. Joule 2020;4:310–46. https://doi.org/10.1016/J.JOULE.2019.11.018.
[71] Zhou B, Wu Y, Zhou B, Wang R, Ke W, Zhang S, Hao J. Real-world performance of battery electric buses and their life-cycle benefits with respect to energy consumption and carbon dioxide emissions. Energy 2016;96:603–13. https://doi.org/10.1016/J.ENERGY.2015.12.041.
[72] Qiao Q, Zhao F, Liu Z, He X, Hao H. Life cycle greenhouse gas emissions of Electric Vehicles in China: combining the vehicle cycle and fuel cycle. Energy 2019;177:222–33. https://doi.org/10.1016/j.energy.2019.04.080.
[73] Marques P, Garcia R, Kulay L, Freire F. Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade. J Clean Prod 2019;229:787–94. https://doi.org/10.1016/J.JCLEPRO.2019.05.026.
[74] Rangaraju S, de Vroey L, Messagie M, Mertens J, van Mierlo J. Impacts of electricity mix, charging profile, and driving behavior on the emissions performance of battery electric vehicles: a Belgian case study. Appl Energy 2015;148:496–505. https://doi.org/10.1016/J.APENERGY.2015.01.121.
[75] Bicer Y, Dincer I. Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. Resour Conserv Recycl 2018;132:141–57. https://doi.org/10.1016/J.RESCONREC.2018.01.036.
[76] Bicer Y, Dincer I. Comparative life cycle assessment of hydrogen, methanol and electric vehicles from well to wheel. Int J Hydrogen Energy 2017;42:3767–77. https://doi.org/10.1016/J.IJHYDENE.2016.07.252.
[77] Bartolozzi I, Rizzi F, Frey M. Comparison between hydrogen and electric vehicles by life cycle assessment: a case study in Tuscany, Italy. Appl Energy 2013;101:103–11. https://doi.org/10.1016/J.APENERGY.2012.03.021.
[78] Elgowainy A, Han J, Ward J, Joseck F, Gohlke D, Lindauer A, Ramsden T, Biddy M, Alexander M, Barnhart S, Sutherland I, Verduzco L, Wallington TJ. Current and future United States light-duty vehicle pathways: cradle-to-grave lifecycle greenhouse gas emissions and economic assessment. Environ Sci Technol 2018;52:2392–9. https://doi.org/10.1021/acs.est.7b06006.
[79] Global EV Outlook 2021 – Analysis - IEA, (n.d.). https://www.iea.org/reports/global-ev-outlook-2021 (accessed July 21, 2022).
[80] Wang D, Zamel N, Jiao K, Zhou Y, Yu S, Du Q, Yin Y. Life cycle analysis of internal combustion engine, electric and fuel cell vehicles for China. Energy 2013;59:402–12. https://doi.org/10.1016/J.ENERGY.2013.07.035.
[81] Yu A, Wei Y, Chen W, Peng N, Peng L. Life cycle environmental impacts and carbon emissions: a case study of electric and gasoline vehicles in China. Transp Res D Transp Environ 2018;65:409–20. https://doi.org/10.1016/J.TRD.2018.09.009.
[82] China's Journey to 100% Renewable Energy: Opportunities and Challenges, (n.d.). https://www.dgb.earth/carbon-offset-blog/chinas-journey-to-100-renewable-energy-opportunities-and-challenges (accessed July 14, 2022).
[83] Renewable energy in the Brazilian energy matrix: the share of solar energy reached 6.9% and wind energy, 10.9% — English, (n.d.). https://www.gov.br/en/government-of-brazil/latest-news/2022/renewable-energy (accessed July 26, 2022).
[84] Lorenzoni I, Pidgeon NF. Public views on climate change: European and USA perspectives. Climatic Change 2006;77(1 77):73–95. https://doi.org/10.1007/S10584-006-9072-Z. 2006.
[85] Domingues AR, Marques P, Garcia R, Freire F, Dias LC. Applying multi-criteria decision analysis to the life-cycle assessment of vehicles. J Clean Prod 2015;107:749–59. https://doi.org/10.1016/J.JCLEPRO.2015.05.086.
[86] Ahmadi L, Young SB, Fowler M, Fraser RA, Achachlouei MA. A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems. Int J Life Cycle Assess 2017;22:111–24. https://doi.org/10.1007/S11367-015-0959-7/FIGURES/5.
[87] Sharma A, Strezov V. Life cycle environmental and economic impact assessment of alternative transport fuels and power-train technologies. Energy 2017;133:1132–41. https://doi.org/10.1016/J.ENERGY.2017.04.160.
[88] Lark TJ, Hendricks NP, Smith A, Pates N, Spawn-Lee SA, Bougie M, Booth EG, Kucharik CJ, Gibbs HK. Environmental outcomes of the US renewable fuel standard. Proc Natl Acad Sci U S A 2022;119. https://doi.org/10.1073/PNAS.2101084119.
[89] Evangelisti S, Tagliaferri C, Brett DJL, Lettieri P. Life cycle assessment of a polymer electrolyte membrane fuel cell system for passenger vehicles. J Clean Prod 2017;142:4339–55. https://doi.org/10.1016/J.JCLEPRO.2016.11.159.
[90] Lombardi L, Tribioli L, Cozzolino R, Bella G. Comparative environmental assessment of conventional, electric, hybrid, and fuel cell powertrains based on LCA. Int J Life Cycle Assess 2017;22:1989–2006. https://doi.org/10.1007/S11367-017-1294-Y/FIGURES/10.
[91] Helmers E, Dietz J, Weiss M. Sensitivity analysis in the life-cycle assessment of electric vs. Combustion engine cars under approximate real-world conditions. Sustainability 2020;12:1241. https://doi.org/10.3390/SU12031241. , Page 1241 12 (2020).
[92] Ecoinvent, ecoinvent v3.7.1 – ecoinvent. https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-7-1/. [Accessed 4 April 2022].

[93] Approaches to LCA - Economic Input-Output Life Cycle Assessment - Carnegie Mellon University, (n.d.). http://www.eiolca.net/Method/LCAapproaches.html (accessed November 23, 2022).
[94] General Information about EIO-LCA - Economic Input-Output Life Cycle Assessment - Carnegie Mellon University, (n.d.). http://www.eiolca.net/Method/index.html (accessed November 23, 2022).
[95] Wolfram P, Wiedmann T. Electrifying Australian transport: hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity. Appl Energy 2017;206:531–40. https://doi.org/10.1016/J.APENERGY.2017.08.219.
[96] Abdul-Manan AFN. Uncertainty and differences in GHG emissions between electric and conventional gasoline vehicles with implications for transport policy making. Energy Pol 2015;87:1–7. https://doi.org/10.1016/J.ENPOL.2015.08.029.
[97] Onat NC, Kucukvar M, Tatari O. Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States. Appl Energy 2015;150:36–49. https://doi.org/10.1016/J.APENERGY.2015.04.001.
[98] Bauer C, Hofer J, Althaus HJ, del Duce A, Simons A. The environmental performance of current and future passenger vehicles: life cycle assessment based on a novel scenario analysis framework. Appl Energy 2015;157:871–83. https://doi.org/10.1016/J.APENERGY.2015.01.019.
[99] Messagie M, Boureima FS, Coosemans T, Macharis C, van Mierlo J. A range-based vehicle life cycle assessment incorporating variability in the environmental assessment of different vehicle technologies and fuels. Energies 2014;7:1467–82. https://doi.org/10.3390/EN7031467. 1467-1482 7 (2014).
[100] Burnham A, Lu Z, Wang M, Elgowainy A. Regional emissions analysis of light-duty battery electric vehicles. Atmosphere 2021;12:1482. https://doi.org/10.3390/atmos12111482.
[101] Tagliaferri C, Evangelisti S, Acconcia F, Domenech T, Ekins P, Barletta D, Lettieri P. Life cycle assessment of future electric and hybrid vehicles: a cradle-to-grave systems engineering approach. Chem Eng Res Des 2016;112:298–309. https://doi.org/10.1016/J.CHERD.2016.07.003.
[102] Gawron JH, Keoleian GA, de Kleine RD, Wallington TJ, Kim HC. Life cycle assessment of connected and automated vehicles: sensing and computing subsystem and vehicle level effects. Environ Sci Technol 2018;52:3249–56. https://doi.org/10.1021/ACS.EST.7B04576/SUPPL_FILE/ES7B04576_SI_001.PDF.
[103] Girardi P, Gargiulo A, Brambilla PC. A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study. Int J Life Cycle Assess 2015;20:1127–42. https://doi.org/10.1007/S11367-015-0903-X/TABLES/7.
[104] Miotti M, Hofer J, Bauer C. Integrated environmental and economic assessment of current and future fuel cell vehicles. Int J Life Cycle Assess 2017;22:94–110. https://doi.org/10.1007/S11367-015-0986-4/FIGURES/5.
[105] del Pero F, Delogu M, Pierini M. Life Cycle Assessment in the automotive sector: a comparative case study of Internal Combustion Engine (ICE) and electric car. Procedia Struct Integr 2018;12:521–37. https://doi.org/10.1016/J.PROSTR.2018.11.066.
[106] van Mierlo J, Messagie M, Rangaraju S. Comparative environmental assessment of alternative fueled vehicles using a life cycle assessment. Transport Res Procedia 2017;25:3435–45. https://doi.org/10.1016/J.TRPRO.2017.05.244.
[107] Burchart-Korol D, Jursova S, Fole P, Korol J, Pustejovska P, Blaut A. Environmental life cycle assessment of electric vehicles in Poland and the Czech Republic. https://doi.org/10.1016/j.jclepro.2018.08.145; 2018.
[108] Gao L, Winfield ZC. Life cycle assessment of environmental and economic impacts of advanced vehicles. Energies 2012;5:605–20. https://doi.org/10.3390/EN5030605. 605-620 5 (2012).
[109] Shafique M, Azam A, Rafiq M, Luo X. Life cycle assessment of electric vehicles and internal combustion engine vehicles: a case study of Hong Kong. Res Transport Econ 2022;91:101112. https://doi.org/10.1016/J.RETREC.2021.101112.
[110] Yang Z, Wang B, Jiao K. Life cycle assessment of fuel cell, electric and internal combustion engine vehicles under different fuel scenarios and driving mileages in China. Energy 2020;198:117365. https://doi.org/10.1016/J.ENERGY.2020.117365.
[111] Petrauskienė K, Skvarnavičiūtė M, Dvarionienė J. Comparative environmental life cycle assessment of electric and conventional vehicles in Lithuania. J Clean Prod 2020;246:119042. https://doi.org/10.1016/J.JCLEPRO.2019.119042.
[112] Puig-Samper Naranjo G, Bolonio D, Ortega MF, García-Martínez MJ. Comparative life cycle assessment of conventional, electric and hybrid passenger vehicles in Spain. J Clean Prod 2021;291:125883. https://doi.org/10.1016/J.JCLEPRO.2021.125883.
[113] Wohlin C, Runeson P, Höst M, Ohlsson MC, Regnell B, Wesslén A. Experimentation in software engineering. Springer-Verlag Berlin Heidelberg; 2012. https://doi.org/10.1007/978-3-642-29044-2/COVER.
[114] E. Figueiredo, Threats to Validity DCC/ICEx/UFMG, (n.d.). http://www.dcc.ufmg.br/~figueiredo (accessed January 18, 2023).
[115] Kitchenham B. Procedures for performing systematic reviews. https://www.researchgate.net/publication/228756057_Procedures_for_Performing_Systematic_Reviews. [Accessed 18 January 2023].
[116] Alves V, Niu N, Alves C, Valença G. Requirements engineering for software product lines: a systematic literature review. Inf Softw Technol 2010;52:806–20. https://doi.org/10.1016/J.INFSOF.2010.03.014.
[117] Vilela J, Castro J, Martins LEG, Gorschek T. Integration between requirements engineering and safety analysis: a systematic literature review. J Syst Software 2017;125:68–92. https://doi.org/10.1016/J.JSS.2016.11.031.
[118] Cano ZP, Banham D, Ye S, Hintennach A, Lu J, Fowler M, Chen Z. Batteries and fuel cells for emerging electric vehicle markets. Nat Energy 2018;3:279–89. https://doi.org/10.1038/S41560-018-0108-1.
[119] Hossain E, Faruque HMR, Sunny MSH, Mohammad N, Nawar N. A comprehensive review on energy storage systems: types, comparison, current scenario, applications, barriers, and potential solutions, policies, and future prospects. Energies 2020;13:3651. https://doi.org/10.3390/EN13143651. , Page 3651 13 (2020).