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Review Article

Environmental Impacts of Internal Combustion Engine vs Electric Vehicle: Life-Cycle Assessment Review

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Abstract: Electric vehicles (EVs) play a substantial role in future sustainability developments. However, a clear environmental impact comparison between EV types and internal combustion engine vehicles (ICEVs) are required. Therefore, a life-cycle assessment (LCA) could play an important role as an analysis tool in comparing the environmental impacts of different technologies. While several reviews on EV LCA exist, they often lack systematic literature reviews (SLR) using bibliometrics and content analysis. This article aims to find the research trend of EVs and examine the environmental impacts of different EV types in comparison with ICEVs. The results show the research trend area and provide a sound foundation for a more comprehensive environmental impact of EV by LCA. Our study indicates that locations with a significant reliance on fossil fuel electricity grids face substantial obstacles in reaping the benefits of EVs. Nonetheless, the prospective benefits of EVs are considerable. Future research has identified critical issues that must be addressed, reflecting the growing complexity of EV adoption challenges.

Keywords: Environmental impact; Electric Vehicle (EV); Life-Cycle Assessment (LCA); Sustainability; Sustainable transportation

1. Introduction

1.1. Background

The escalating ramifications of climate change have commanded international attention regarding the repercussions of fossil fuel consumption across diverse sectors. In order to alleviate greenhouse gas (GHG) emissions, the transition to more sustainable energy sources has evolved into a principal aim for many countries. Fossil fuels for power generation and transportation are responsible for 70% of worldwide GHG emissions (Duan et al., 2016). About 25% of CO_2 emissions from fossil fuel combustion are attributed to transportation (IEA, 2021). Almost 95% of worldwide transportation relies on liquid fuels derived from fossil fuels operated by internal combustion engine vehicles (ICEVs) (Leach et al., 2020). ICEVs represent the standard or conventional engine technology that is powered by fuel, such as gasoline or diesel oil. The current worldwide surge in adopting eco-friendly energy sources has increased following the Paris Agreement's implementation, which holds each country accountable for addressing climate change caused by

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the escalating global average temperature (van Soest et al., 2021). Consequently, the government has significantly invested in establishing GHG emission targets to reduce air emissions, particularly in the transportation industry.

In the transportation sector, innovative technologies such as electric vehicles (EVs) have emerged prominently to diminish reliance on fossil fuels utilisation, impacting GHG emissions reduction. EV represents the vehicle technology that is powered by electric motors. The electric motors are powered by electricity that is stored in battery packs. EV consists of several technologies, such as hybrid EV (HEV), plug-in EV (PHEV), battery EV (BEV), and fuel cell EV (FCEV).

Electric vehicle technology has emerged as a significant game-changer in the transportation industry. This technology is regarded as GHG-free, contributing to the mitigation of slow climate change, the reduction of environmental disasters, and the enhancement of public health. On a global scale, the electric vehicle (EV) market has undergone substantial development over the past decade. In 2020, the number of EVs on global roadways exceeded 10 million and has continued to increase, even during the pandemic. China has emerged as the dominant force in the EV market worldwide (IEA, 2021). In 2023, nearly 14 million new EVs were registered worldwide, increasing the total number on the road to 40 million (IEA, 2024).

Various studies have been more focused on technological advancement: braking system (Indriawati et al., 2024; Prasetya et al., 2020), gearbox system (Ataur Rahman et al., 2022), battery system (Krishna et al., 2024), and steering system (Changqing et al., 2024). They have optimised the system to support all the EV performances. In recent times, the term sustainability has emerged as a crucial paradigm in the utilisation of products (Watkins et al., 2021). The whole life cycle (LC) of products can have a substantial environmental impact, such as contributing to global warming, due to using raw materials and engaging in processes that directly harm the environment. Initially, products were developed without (less) considering the negative environmental impact and dominantly considering function, reliability, cost, quality, safety, ergonomics, and after-sales aspects. The significance of environmental impacts has expanded to include environmental considerations in product development. As a result, it is essential to assess the environmental aspects of a product throughout its entire life cycle.

Although EVs are considered an enormous contribution to reducing GHG emissions, it is important to investigate their environmental impact. The standard method to analyse the environmental impact of a product is by assessing its overall life cycle. Life-cycle assessment (LCA) has been used to evaluate the environmental impacts of all stages of EVs (Curran, 2013). The LCA examines the ecological consequences in every stage of a product's life-cycle, starting from the extraction of raw materials and their processing to production (cradle), distribution, utilisation, final disposal (grave), and recycling (Ilgin and Gupta, 2010). The chain of this analysis is also referred to as cradle-to-grave, as studied by Abraham and AbdulNour (2024) on ICEV and BEV technologies, Rashid and Pagone (2023) on HEV and PHEV technologies, while Wong et al. (2021) on BEV and FCEV technologies. Therefore, to comprehensively compare ICEVs and EVs, researchers must consider the impacts associated with fossil fuel production, electric energy, the production of automobiles and batteries, and the utilisation and disposal phases in the LCA.

1.2. State-of-the-Art of the Research

Numerous review articles on comparative LCA of EVs have been published in the last decade. The previous studies represent the most current information and findings, particularly crucial in rapidly evolving fields of LCA in EVs. In identifying the research gap within review articles, one of the criteria involves screening papers with high citation counts. This practice is advantageous for highlighting research that has made a substantial impact on the academic community. Nevertheless, the evaluation of a paper's quality and relevance remains equally essential, alongside considerations of other factors, such as content context.

Nordelöf et al. (2014) laid the groundwork by conducting a systematic literature review (SLR) that compared LCA across different types of vehicles, including ICEV, BEV, and PHEV. Their work emphasised the importance of understanding the environmental impacts across multiple vehicle types. Following this, Nealer and Hendrickson (2015) focused their literature review (LR) on the critical assumptions and inputs in LCA and policies specific to BEV. Marmiroli et al. (2018) expanded the scope of the review by exploring the impact of the electricity generation mix on LCA results for ICEV, BEV, and HEV. Their SLR provided valuable insights into how variations in energy sources influence the environmental performance of different vehicle types.

Several researchers highlighted the importance of battery-related factors in LCA. Temporelli et al. (2020) focused on the battery life-cycle, particularly for ICEV and BEV, while Dolganova et al. (2020) analysed the resource use in battery LCA, specifically for BEV. Both studies underscored the critical role of batteries in determining the sustainability of EVs, albeit with different areas of emphasis.

In 2022, research on LCA expanded further. Lai et al. (2022) employed an LR that integrated bibliometric analysis to explore a cradle-to-cradle framework for lithium-ion battery (LIB), highlighting a more holistic approach to battery sustainability. Xia and Li (2022) took a systematic approach to investigate the influence of batteries on vehicle LCA outcomes, addressing ICEV, HEV, BEV, and PHEV. Similarly, Li et al. (2022) focused on the carbon footprint of batteries, providing a detailed analysis of the emissions associated with their life cycle. Unlike the previous studies, Verma et al. (2022) incorporated the economic issue in their studies. They compared LCA and life-cycle cost (LCC) for ICEV and BEV, bridging environmental and economic considerations.

More recently, Wei et al. (2023) contributed to the literature by examining the environmental impacts of EV batteries, particularly BEV, through an LR. Their work complements earlier studies by providing updated findings on battery-related sustainability. These studies collectively represent the progressive development of LCA review for vehicles, with a growing emphasis on batteries, regional energy mixes, and the framework perspective. Each contributes unique insights, highlighting the diversity and complexity of LCA research in the transportation sector. Table 1 summarises the state-of-the-art review article on the LCA of EV.

While studies like Lai et al. (2022) have utilised bibliometric methods to provide insights into research trends and connections, most earlier works do not incorporate such analyses. Furthermore, many studies focus on specific topics without integrating bibliometric analysis to identify patterns and gaps in the broader research landscape. Hence, there is an opportunity to expand the application of bibliometric tools in LCA research to uncover underexplored areas. Addressing this gap could provide a systematic and interconnected understanding of LCA trends and enable the development of a more comprehensive and future-oriented framework. This study uniquely combines bibliometric and content analysis to systematically explore LCA research trends, uncovering patterns that previous studies often overlooked. A comprehensive review of all types of EVs and their varying environmental impacts is provided, offering significant insights and proposing a unified life cycle emission framework applicable to all EV types. To the authors' knowledge, this is one of the LCA investigations to integrate these methods, offering a comprehensive and future-oriented perspective on vehicle LCA research.

1.3. Research Objectives

This study aims to achieve several specific objectives. The study integrates bibliometric analysis to identify influential research trends in the field and content analysis to evaluate the methodologies and findings of existing LCA studies thoroughly. This dual approach allows for a more comprehensive understanding of the current state of LCA research on EVs and identifies areas requiring further investigation.

First, the study aims to identify research trends and the network in the existing literature by incorporating the main keywords. This approach highlights the critical themes and interconnections across studies and helps uncover underexplored areas.

Second, it seeks to systematically review and compare the life-cycle environmental impacts of ICEV and EV, including HEV, BEV, PHEV, and FCEV. By analysing these categories, the study intends to highlight the distinctive characteristics, advantages, framework, approach, and environmental trade-offs associated with each vehicle type.

Lastly, the research proposes a comprehensive life-cycle emission framework that can serve as a standardised model for assessing the environmental performance of all EV types. By combining bibliometric insights with content evaluations, this study aspires to provide a robust foundation for advancing LCA methodologies and guiding sustainable vehicle development in the future.

2. Methods

This study investigated the LCA research on several types of vehicles (ICEVs and EVs) to clarify whether EVs are greener than ICEVs and their environmental impact. The transition from ICEV to EV represents a critical shift in the automotive and energy sectors, driven by goals of reducing GHG emissions, improving air quality, and achieving energy sustainability. Comparing these two vehicle types allows for a detailed evaluation of their technological and environmental impacts. ICEV represents the existing technology, and EV represents future technology that would replace the ICEV, which has combustion as a cause of GHG and air emissions. The comparison highlights both vehicle types, key advantages, and limitations, offering insights into the challenges of EV adoption and areas where ICEV remains competitive. It provides a benchmark for assessing how EVs can meet or exceed the performance and utility of ICEVs. This comparative analysis contributes to the ongoing discussion about decarbonising the transport sector by identifying trade-offs between ICEV and EV.

Table 1 State-of-the-art for LCA's article review for vehicles

Authors	Year	No. of Citation	Method	Bibliometric Analysis	Content Analysis	Type of Vehicles
Nordelöf et al. (2014)	2014	348	SLR	No	Compare the LCA of the different vehicles	ICEV, BEV, PHEV
Nealer and Hendrickson (2015)	2015	44	LR	No	The critical assumptions and inputs of LCA and policy	BEV
Marmiroli et al. (2018)	2018	72	SLR	No	Electricity Generation Mix	ICEV, BEV, HEV
Temporelli et al. (2020)	2020	48	SLR	No	Batteries' life-cycle	ICEV, BEV
Dolganova et al. (2020)	2020	43	SLR	No	Resource Use in LCA Battery	BEV
Lai et al. (2022)	2022	170	LR	Yes	Cradle-to-cradle LCA framework for LIBs	BEV
Xia and Li (2022)	2022	96	SLR	No	Considering the influence of batteries	ICEV, HEV, BEV, PHEV
Verma *et al.* (2022)	2022	87	LR	No	LCA and LCC comparison of ICEV and EV	ICEV, BEV
Li et al. (2022)	2022	44	SLR	No	The LC carbon footprint of batteries	BEV
Wei et al. (2023)	2023	36	LR	No	Batteries of an electric vehicle	BEV
Present study	-	-	SLR	Yes	Compare the LCA of the different vehicles	ICEV, HEV, BEV, PHEV, FCEV

The literature review used three primary steps. In step 1, bibliometric analysis was conducted by VOSviewer based on selected papers from the Scopus search engine. VOSviewer was recognised as a user-friendly tool known for its simplicity, flexibility, and responsiveness to user needs.

VOSviewer was chosen as the bibliometric analysis tool due to its robust capabilities in visualising networks and keyword co-occurrences. Moreover, it offers excellent graphic quality. The software's ability to generate interactive maps makes it ideal for identifying key research trends and relationships clearly and comprehensibly (Van Eck and Waltman, 2010). Furthermore, VOSviewer is widely recognised for its scalability and suitability for handling large bibliometric datasets, ensuring reliability and accuracy in the analysis. However, it is limited by its reliance on predefined functions and the need to repeat analyses due to its inability to integrate data from multiple sources (Arruda et al., 2022).

In step 2, a comprehensive literature study was undertaken by gathering papers that contained specific keywords, such as life-cycle analysis, life-cycle assessment, and environmental impact in vehicles (ICEV and EV). In this step, the type of vehicles, particularly EVs, was investigated. The mapping of EV was summarised to indicate its configuration and how it works. Mapping of EV becomes a crucial step to knowing deeply the characteristics of material and energy flow within a vehicle throughout the entire life of a vehicle, especially in the operation of the vehicle. Then, works of literature on LCA were collected, categorised, reviewed, and synthesised. Initially, the basic methodology, approach, and tools of LCA were reviewed as a basic knowledge of the environmental impact of vehicles. The last step involves presenting substantial findings concerning the environmental impact of EVs.

In the LCA review, the system boundary is one of the crucial aspects of LCA. The system boundary determines processes in the whole life cycle of the relevant systems that require analysis or may be ignored for simplicity. It defines process phases that need to be included within the LCA, and their choice must be consistent with the target of the study. This review's LCA boundary includes raw material extraction, production, manufacturing, and use phase (well-to-wheel). Some of them provide an end-of-life phase (cradle-to-grave). Therefore, the discussion articles of LCA were focused on this boundary.

3. Bibliometric Analysis

Bibliometric analysis has become increasingly prominent in research (Donthu et al., 2021). Ninkov et al. (2022) presented several fundamental meanings of bibliometric concepts, including "Evaluative bibliometrics" and "Relational bibliometrics." Evaluative bibliometrics are employed to delineate the attributes of published information. Relational bibliometrics is a research methodology in which researchers examine the occurrences of shared metadata, such as authors, citations, and keywords. Recent advancements in data analysis methodologies and technologies have facilitated the processing of extensive bibliographic datasets, as well as the extraction of valuable insights. This development has substantially augmented the significance of bibliometrics in research evaluation decision-making.

The bibliometric analysis was conducted using data from the Scopus database through a systematic filtering process. Initially, 1,500 articles were identified using the keywords "electric vehicle" and "life cycle assessment." These records were refined in five stages: filtering for articles, narrowing the publication years to 2018–2023, selecting final publications in English, and focusing on studies related to environmental impact assessments. After excluding irrelevant and non-compliant records at each stage, the dataset was reduced to 321 relevant articles, which formed the basis for bibliometric visualization and analysis using VOSviewer.

The results of the bibliometric analysis were shown as a co-occurrence network among keyword and a co-occurrence network for research hotspots in recent years. Figure 1 illustrates a keyword co-occurrence network. Each node represents an entity such as an article, journal, author, institution, country, or keyword. The purpose of this figure is to illustrate the major research themes and their interconnections within the field under study. In Figure 1, the nodes represent keywords. The size of a node indicates how often the keyword occurs. The links between nodes represent the co-occurrence of keywords or when they occur together. The thickness of a link indicates how frequently the co-occurrence happens. Larger nodes indicate a higher frequency of the keyword, while thicker links indicate a higher frequency of co-occurrence between keywords. Each shade corresponds to a thematic cluster, in which the nodes and linkages within that cluster can be utilised to elucidate the coverage of themes and the relationships between the topics that are evident within that particular theme (Donthu et al., 2021).

Figure 1 shows the co-occurrence assessment and link between electric vehicle, life-cycle assessment, environmental impact, and other fields. The authors utilised the keywords from 321 articles to construct this co-occurrence network. A minimum of five keywords is required. Figure 1 illustrates the symbiotic network, which can be categorised into 4 clusters according to their correlation strength. Each cluster is represented by a distinct color. Cluster 1, denoted by the color red, comprises 78 pieces. Cluster 2, denoted by the color green, comprises 73 items. Cluster 3, denoted by the color blue, comprises 71 items. Cluster 4, denoted by the color yellow, comprises 50 items. The cluster consists of 272 items with 15027 links and a total link strength equal to 42026.

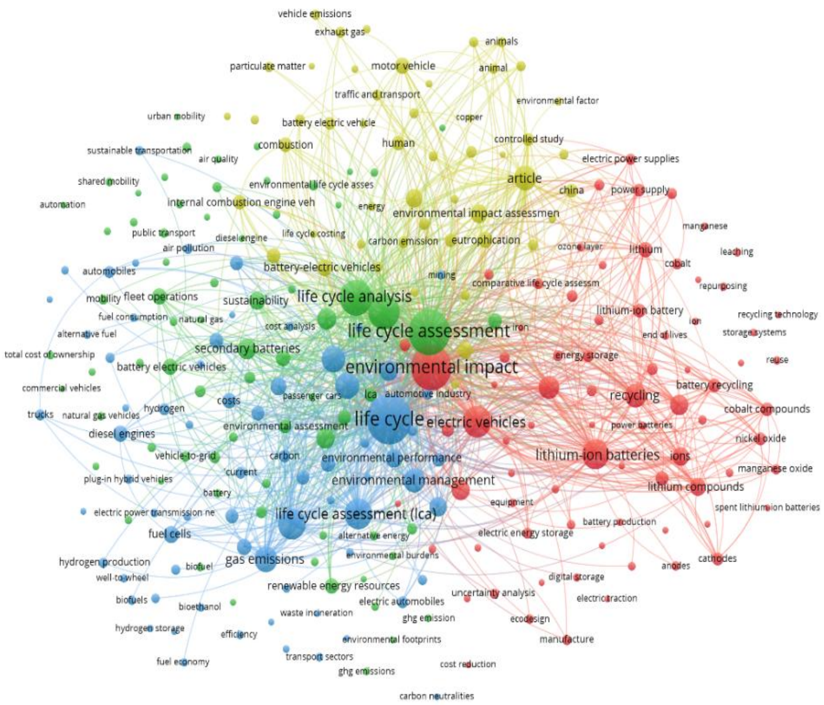
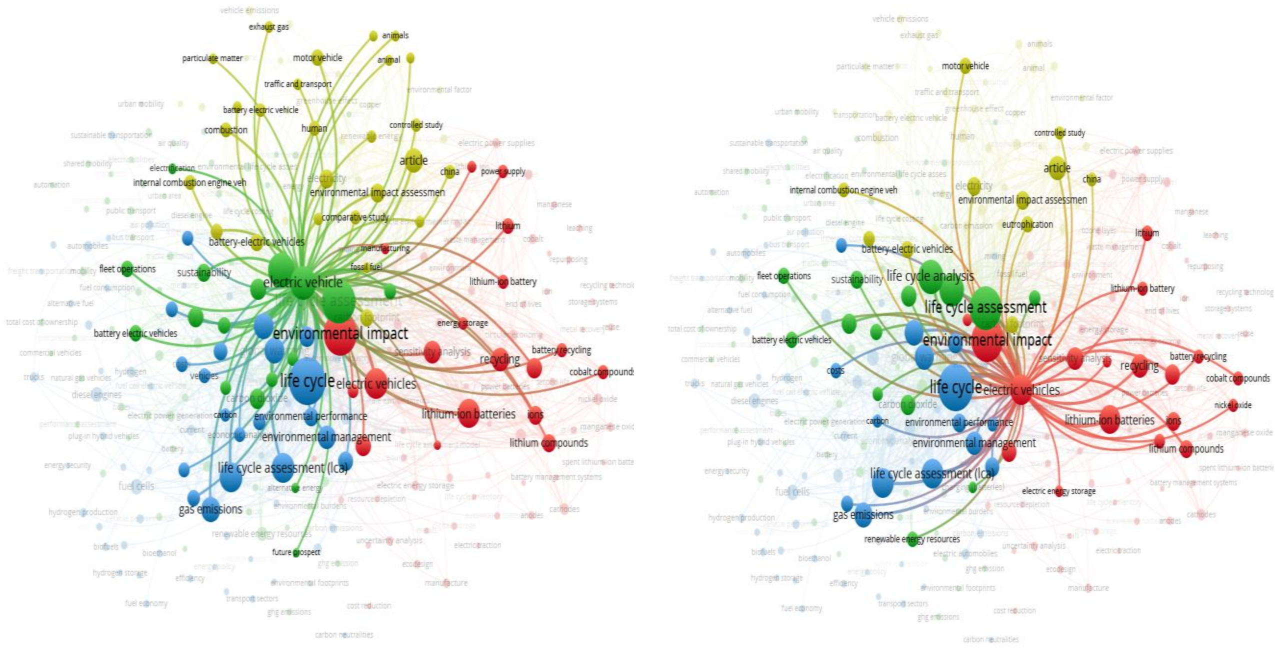


Figure 1 Co-occurrence network analysis for "electric vehicle", "life cycle assessment" and "environmental impact" words

Cluster 1 (red) relates to lithium-ion batteries, battery technologies, recycling, and manufacturing aspects, which are significant contributors to the environmental impact of EVs. The visualisation highlights the major trends in lithium-ion batteries and recycling technologies. It shows rapidly growing research on lithium-ion batteries, including their production, efficiency, environmental footprint, and recycling methods. Larger nodes, such as "life cycle assessment" and "lithium-ion batteries," indicate these are central and frequently discussed topics in the literature. Cluster 2 (green) focuses on environmental impact analysis and LCA in general, including terms like "life cycle assessment", "environmental impact", "sustainability", and "life cycle analysis". Meanwhile, cluster 3 (blue) covers topics related to broader issues, such as sustainable transportation, mobility, hydrogen, and alternative energy, relevant to emissions reduction.

Specific to the keywords "electric vehicle" and "electric vehicles", the network shows that the EV is represented by "electric vehicle" (green) and "electric vehicles" (red), as shown in Figure 2. They appeared in 118 and 97 occurrences and have total connection strengths of 1981 and 1596, respectively. Then, followed by the "life cycle" (blue) appeared in 241 occurrences, with a total connection strength of 3842, the "life cycle assessment" (green) appeared in 203 occurrences, with a total connection strength of 3134, and the "environmental impact" (red) appeared 197 occurrences, with a total connection strength of 3105. It can be understood that there are many research contents and strong correlations in the fields of electric vehicle(s), life-cycle, life-cycle assessment, and environmental impact. Furthermore, numerous studies exist concerning global warming, battery technology, gas emissions, sustainable development, and recycling electricity.



(a) (b)

Figure 2 Co-occurrence network analysis for (a) "electric vehicle" and (b) "electric vehicles" words

Based on Figure 3, the associated symbiosis network, the analysis examines the current areas of study focus based on the time frame, with brighter colours indicating more recent research in the field. In recent years, various aspects have emerged related to the life cycle of electric vehicle clusters, including battery electric vehicles, recycling, battery recycling, GHG emissions, and electricity grids. Research offers guidance for future academics.

This visualisation shows how research in LCA for EV has evolved from foundational topics (blue/green) to newer, more focused areas (yellow), such as battery technology, recycling, and framework (well-to-wheel). The yellow nodes represent cutting-edge work and provide a glimpse into the future of the field. The bibliometric clusters confirm that key areas of focus in the existing literature align with the study's objectives, such as comparing the life-cycle environmental impacts of different vehicle types and a comprehensive life-cycle emission framework.

The emergence of several nodes related to ICEV, such as "internal combustion engine vehicle," "diesel," "alternative fuel," "fuel consumption", and "diesel engine", shows that ICEV technology is still competitive with EV, not only in terms of technology performance but also environmental performance. These insights also validate the relevance of the studies comparing EV with ICEV. The clusters also highlight underexplored areas, such as integrating social and economic dimensions with environmental LCA. This reinforces the importance of addressing these gaps in future work. For example, the lack of emphasis on the impacts of economic and social issues in bibliometric clusters directly aligns with the prospective discussion, such as total cost of ownership, costs, cost analysis, human, and fuel economy. It is represented by small nodes that show the lack of discussion. In addition, regarding EV technology, the bibliometric analysis reveals a lack of focus on FCEV and a main focus on BEV. Most studies have assessed the competitiveness of BEV against ICEV in specific commercial fleet applications.

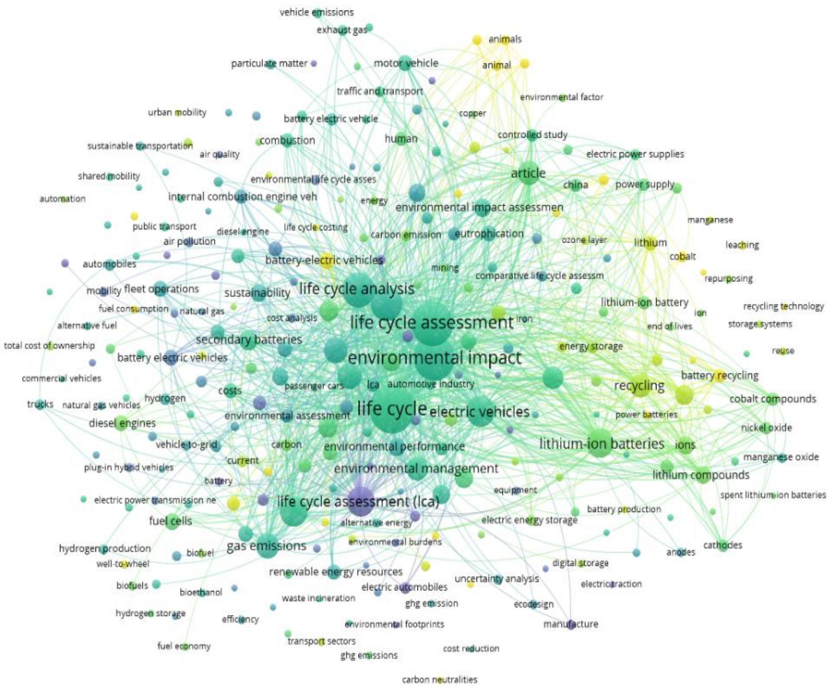


Figure 3 Co-occurrence network analysis for research hotspots in recent years

4. Classification of Electric Vehicle

4.1. Hybrid Electric Vehicle (HEV)

An HEV utilises both an electric motor (EM) and a combustion engine to power the vehicle efficiently. The motor serves as an auxiliary power source under specific operational conditions and does not necessitate recharging at a charging station, with the exception of PHEV. HEV has many application variations, categorised into mild-HEV, full-HEV, and PHEV (Das et al., 2017). In terms of the hybridisation level of HEV, micro-HEV is also classified as HEV. In Das et al. (2017), micro-HEV is categorised as ICEV due to being fully propelled by ICE during cruising. It has a similar type to mild-HEV. However, mild-HEV has a larger electric motor (EM) than micro-HEV and has electric torque assistance. To improve fuel efficiency, most automotive manufacturers have produced full-HEV. Full-HEV uses divided power flow for both the ICE and the motor. Accordingly, it can operate the vehicle independently or in combination. Full-HEV can be classified into four categories: series, parallel, series-parallel, and complex (Tran et al., 2021; Wang et al., 2018).

4.2. Battery Electric Vehicle (BEV)

A BEV is commonly called a "pure EV" of a “full battery EV”. BEV exclusively utilises a singular electric powertrain device. Batteries store energy. This car necessitates charging at dedicated charging stations utilising an electric plug-in with a specialised socket. BEVs are completely devoid of any GHG emissions and noise pollution. consequently, it exerts a beneficial influence on the environment. BEVs are relatively simple to manufacture, operate, and upkeep. However, it may contribute significantly to pollution during electricity production, battery manufacturing, and the disposal of discarded batteries (Li et al., 2017). The BEV’s performance depends entirely on its battery capacity and cooling system management. The battery's temperature is important in determining its performance and lifespan (Lyu et al., 2019). The wheels are driven by a motor powered by a battery (Un-Noor et al., 2017).

4.3. Plug-in Hybrid Electric Vehicle (PHEV)

A PHEV utilises a combustion engine in conjunction with an electric powertrain. However, it can be recharged at a dedicated charging station. An HEV typically has a lower battery capacity than other vehicles (Dižo et al., 2021). When operating on battery power, PHEVs do not release any pollutants from their exhaust; however, they produce emissions when their electricity is generated at a power plant. The PHEV is predominantly propelled by electricity and is exclusively utilised for short distances. During extended journeys, gasoline is required, but only when the battery power is ultimately used up. Although PHEVs offer a longer driving range than BEVs, they have certain drawbacks. These include a higher upfront cost than BEVs and the fact that they are not environmentally friendly due to their emissions during electricity generation. To tackle these concerns, many studies have been dedicated to analysing methods for enhancing battery performance, such as reducing charging time, analysing cooling systems, conducting tests, and determining optimal ranges. Additionally, efforts have been made to optimise the battery package by reducing its size and weight (Verma et al., 2021).

4.4. Fuel Cell Electric Vehicle (FCEV)

An FCEV or FCV has garnered significant interest because of its emission-free functioning. FCEVs, similar to BEVs, are propelled by an electric motor (EM). However, FCEVs utilise a fuel cell as their power source instead of a battery. FCEVs utilise specialised tanks to store hydrogen (H_2) for transportation. The fuel cells generate electricity, which is then directed to an EM to operate the vehicle. The car is powered by H_2, and the fuel cell turns the chemical energy stored in the H_2 gas into electrical energy to drive the EM. H_2 gas can be generated either by burning fossil fuels like natural gas or by using a process called water electrolysis. FCEVs, similar to ICEVs, possess a brief refilling duration (Un-Noor et al., 2017; Tie and Tan, 2013). Additionally, it can be used in conjunction with batteries and supercapacitors. Without a battery, this type does not affect the power system, as it is not dependent on electric charging from the grid system (Nour et al., 2020). While FCEVs are effective options for reducing GHG emissions, the hydrogen infrastructure still has certain obstacles (Ahmadi et al., 2020; Ahmadi and Kjeang, 2017). FCEVs are widely regarded as the most attractive long-term alternative for passenger vehicles. Numerous obstacles must be overcome, including durability, H_2 refueling infrastructure, and cost, before FCEVs can be widely used (de Almeida and Kruczan, 2021).

5. Life-Cycle Assessment: Environmental Impact on ICEV vs EV

5.1. Basic Methodology of LCA

Life-cycle assessment is an established and evolving technique that investigates the possible environmental impacts of a process, activity, or product (Bjørn et al., 2018; Curran, 2013). Some products are dominated by environmental impact in phase of production (Putri et al., 2023; Bianco et al., 2021), utilisation (Challa et al., 2022), and disposal (Shafique and Luo, 2022). The purpose of LCA is to analyse and quantify the material and energy flows involved in each stage of a product's life cycle and the associated emissions and waste released into the environment. Throughout the whole life cycle of a vehicle, it is essential to include design, extraction of raw materials, production, transportation/distribution, utilisation, disposal, recycling, and resource management. Nevertheless, the assessment may incorporate any combination of these phases. The process of identifying environmental influences along its whole life cycle is one that includes a lot of complexity and sophistication. Therefore, there is a need for a methodical analytical instrument or tool to assess the environmental impact of a vehicle's life cycle. LCA is an analytical tool as organised in ISO 14040.

The purpose of the LCA shall be clearly defined, including the study's context and its intended application. The scope shall be thoroughly delineated, explicitly defining the functional unit, the boundaries of the system, the methods for allocation, the categories of effect, the models utilized for LCA, and the standards governing data quality. In this step, assumptions are explicitly stated and supported with justifications. The inventory analysis process involves assessing the flow of materials and energy inside the defined system boundaries and how they interact with the environment. This is done by evaluating the inputs and outputs. Inputs involve water, raw materials, chemicals, and energy. Outputs encompass several components, such as products, co-products, air emissions, solid waste, water discharges, and emissions to land.

During the impact assessment step, the results of the inventory analysis are linked to specific impact categories, including climate change, human toxicity, acidification, ecotoxicity, ionising radiation, eutrophication, ozone depletion, respiratory inorganics, photochemical ozone formation, land use, and resource depletion. Subsequently, a comprehensive impact assessment is conducted, often encompassing three domains of safeguarding: human health, natural resources, and the natural environment (Wolf et al., 2012). Various approaches are introduced to evaluate the many potential impacts on the three domains of protection (Sala et al., 2012). Finally, during the interpretation phase, the results of the LCA are analysed in relation to the intended purpose and scope of the study. This involves assessing the comprehensiveness, sensitivity, and coherence of the outputs (Serenella et al., 2015). Accuracy and uncertainty are also considered.

To perform LCA, commercial software packages are widely used to assist in conducting life-cycle inventory and life-cycle impact assessment, including GREET, SimaPro, GaBi, Umberto, and OpenLCA. Selecting a software package for LCA is extremely vital. Every application possesses distinct characteristics that may differ in terms of database accessibility, user interface, functionality, data quality management, and modeling approaches for constructing product systems (Silva et al., 2017). The LCA output depends on methods, databases, and impact assessment models that have been developed in software packages to run LCA (Lopes Silva et al., 2019). The two prominent software packages for LCA are GaBi and SimaPro, both of which are commonly used worldwide (Herrmann and Moltesen, 2015).

5.2. LCA Model Approach

The original LCA methodology, often referred to as attributional LCA (A-LCA), is recognised globally and is used to assess the potential environmental burdens linked to a product or service. However, LCA modeling approaches were widely provided in the UNEP 2012 report on "Global Guidance Principles for Life-Cycle Assessment Databases" and are typically categorised into two types: attributional LCA (A-LCA) and consequential LCA (C-LCA) (Schaubroeck et al., 2021; Ekvall, 2019).

Several terminologies have emerged during the evolution of LCA. Brander et al. (2019) suggested that attributional and consequential elements should be merged within a single analysis. In addition, Guinée et al. (2018) found many more different approaches or modes of LCA, such as backcasting LCA (B-LCA) (Kunttu et al., 2021), decision LCA (D-LCA) (Frischknecht and Stucki, 2010), anticipatory LCA (N-LCA) (Wender et al., 2014), prospective LCA (P-LCA) (Langkau et al., 2023), scenario-based LCA (SLCA) (Rossi et al., 2023) and integrated LCA (I-LCA) (Quest et al., 2022). Environmental, social, and economic integration in LCA becomes a life-cycle sustainability assessment (LCSA) (Larsen et al., 2022). However, in general, most of the mentioned LCA approaches fall into the category of C-LCA due to their focus on change and the impact resulting from future decisions, policies, or scenarios. In contrast, A-LCA focuses more on a specific and detailed assessment of the environmental impact of a particular product or process without considering changes caused by external decisions or policies.

The selection between A-LCA and C-LCA is contingent upon the objectives of the research and the particular inquiries that require addressing. The A-LCA offers a comprehensive analysis of present environmental stresses, while the C-LCA furnishes insightful perspectives regarding the potential implications of actions or alterations on future environmental conditions stresses. Both entities play a vital role in decreasing the environmental impact and developing sustainable policies. By understanding these differences, researchers, policymakers, and LCA practitioners can choose the approach that best suits their analytical objectives, providing a static picture of environmental impacts (A-LCA) or understanding the dynamic impact of changes in the system (C-LCA).

Another approach or mode of LCA that was overlooked by Guinée et al. (2018) observation is dynamic LCA, which combines system dynamics (SD) and LCA. Combining SD with LCA needs to be done to overcome the limitations of traditional LCA and produce a more comprehensive and accurate environmental analysis. Traditional LCAs tend to be static and do not consider dynamic changes in the systems being analysed (Zhai et al., 2022; McAvoy et al., 2021). Therefore, they can capture fewer environmental, technological, and policy changes over time. By incorporating SD, a dynamic approach capable of modeling change over time, LCAs can be more realistic in evaluating long-term environmental impacts. In addition, SD enables modeling of complex cause-and-effect relationships and feedback loops that often occur in environmental and industrial systems, thus helping to identify how changes in one part of the system may affect other parts. McAvoy et al. (2021) highlighted that the combination prevents overestimating impacts when technologies change over time and underestimating impacts due to unintended consequences.

5.3. Frameworks of LCA

Due to the complex system, researchers tried to simplify the frameworks of LCA by proposing the main significant parameters. Athanasopoulou et al. (2018) proposed a well-to-wheel (WTW) framework to investigate the emission contribution of ICEV and BEV. The WTW framework encompasses the whole process of the energy flow from extraction to vehicle utilisation. They proposed an approach to evaluate the electricity and fuel consumption for BEV and ICEV, respectively. Almost similar to Zheng and Peng (2021), Athanasopoulou et al. (2018) assessed the life-cycle emission (CO_2) of EV and ICEV by considering CO_2 emissions from the overall process of energy flow. However, Zheng and Peng (2021) added the cycle of the vehicle body to the analysis. Regarding emissions and energy efficiency during the cycle of vehicle body, the process can be divided into three main phases: manufacture, maintenance, and recycling.

To comprehensively assess the environmental impact, it is important to analyse the energy consumption pattern of EVs during their operational period. Several factors influence the required energy for driving. Most studies focused on the utilisation factor that affects the LCA. Egede et al. (2015) used LCA for quantitative ecological assessment by proposing the LCA framework for EV by considering internal and external factors. Both internal and external factors were investigated as primary factors to examine the life-cycle. The external factor consists of the user, the surrounding conditions, and the infrastructure. The EV user influences the energy consumption through the driving style and charging behaviour, which leads the environmental impact (Miotti et al., 2021). A more aggressive driving style leads to a higher energy consumption (Szumska and Jurecki, 2020). The climate (ambient temperature, humidity) influences the energy consumption (Al-Wreikat et al., 2022, Skuza and Jurecki, 2022). Topography and type of road are also significant factors for energy consumption which affect speed and traction of the vehicle (Liu et al., 2017).

Ahmadi (2019) presented a comprehensive work by combining life-cycle emission and cost among EVs (HEV, PHEV, BEV, and FCEV) and compared with ICEV as the base case. The outcome of the works was indicated with the total LCC. The environmental impact is one of the aspects of consideration before it is quantified to LCC. Like other researchers, Ahmadi (2019) used mostly internal influencing factors to analyse life-cycle emission, which differs from Egede et al. (2015). An external influencing factor was assumed to be an urban environment with similar annual mileage and lifetime. In this analysis, the lifetime factor shall be the operational lifetime. EV and ICEV operational lifetimes could span different periods. In addition to that, the lifetime EV and ICEV. Therefore, both of vehicles can be assessed on equal parameters. For example, ICEV has more lifetime than EV, then EV shall be levelized to ICEV lifetime by additional treatment, i.e., refurbishment.

Similar to Li et al. (2016), Egede et al. (2015) proposed the factors that influence the energy consumption of EVs with more detailed parameters. They categorised it into six main influencing factors. The six influencing factors for investigating EV energy consumption are technology/vehicle, driver, measurement, travel type, artificial environment, and natural environment. However, Li et al. (2016) have measurement factors that affect the energy consumption of EVs. The measurement factor in EV energy consumption appears to focus on how testing and data collection methods impact the analysis of energy usage. The measurement factor emphasises the need for precise, standardised, and comprehensive methods to evaluate EV energy consumption accurately. Each aspect (engine warmup, route planning, test procedures, state of charge (SOC), and variability) plays a role in how consumption data is gathered and interpreted, ultimately influencing how well the results reflect real-world usage.

Regarding the measurement factor, Lyu et al. (2021) reviewed various measurement methods. They reviewed various measuring methods of emissions, including tunnel, laboratory, and on-road measurements. Then, the criteria were summarised by considering the vehicle operating features and road characteristics, including assessing automobile emissions at different road segments and intersections.

5.4. Significant Findings of Environmental Impacts

The environmental impact of various vehicle technologies has been extensively studied, with notable differences in outcomes based on factors such as electricity grids, manufacturing processes, and regional contexts. Girardi et al. (2015) conducted an LCA comparing EV and ICEV in Italy. Their findings revealed that the life-cycle impacts of EV were lower than ICEVs. The study highlighted the importance of a high-efficiency electricity grid in reducing the life-cycle impacts of EVs. Like previous studies, Tagliaferri et al. (2016) focused on GHG emissions during the life-cycle of BEV compared to ICEV. Their study emphasised the environmental challenges of the BEV manufacturing phase, particularly the high impact caused by the extensive use of metals in battery packs. Despite this, the life-cycle GHG emissions of BEVs were found to be lower than ICEVs, reinforcing the environmental advantages of BEVs when operational emissions are considered.

The influence of energy grids on vehicle LCA was also further explored by Athanasopoulou et al. (2018) in a European context. They found that the life-cycle CO_2 emissions of BEV were lower than those of ICEV when the electricity grid relies heavily on renewable energy and nuclear power. However, this trend reverses when the grid depends more on oil and coal, underscoring the regional variability in EV sustainability. This finding emphasises the need for cleaner energy sources to maximise the environmental benefits of BEV.

In the Czech Republic and Poland, Burchart-Korol et al. (2018) provided a comparative analysis of EV and ICEV, focusing on several environmental impact categories. Their results showed that EV generally have greater life-cycle GHG emissions than ICEVs, primarily due to the carbon-intensive electricity grids. However, they also noted that renewable electricity significantly reduces the environmental impacts of EV, highlighting the role of energy grid decarbonisation in improving their sustainability. Pipitone et al. (2021) examined environmental impacts in Europe, identifying significant challenges for BEVs. While BEVs exhibit a ~60% reduction in global warming potential compared to ICEVs, they show doubled impacts in acidification and particulate matter (PM) formation.

China is the most significant growth of EV. Yu et al. (2018) conducted a detailed LCA in South China comparing EV and ICEV, revealing that EV have greater impacts. However, their study also emphasises the potential for optimising the electricity grid and increasing battery energy density to reduce emissions significantly. Qiao et al. (2019) focused on GHG emissions in China, reporting that the life-cycle GHG emissions of EVs are 18% lower than ICEVs. Despite rapid reductions in the WTW emissions phase of EVs, challenges remain in addressing the cradle-to-gate emissions phase, which may impede EVs from fully realizing their environmental potential. Then, Qiao et al. (2020) expanded on their earlier findings by examining LCC and GHG emissions. They found that EVs have an LCC higher than ICEVs, while their life-cycle GHG emissions are lower than ICEVs. The study highlighted the potential of battery recycling and pilot projects to reduce LCC and emissions, though further advancements are needed to make these solutions viable at scale. Zheng and Peng (2021) explored the influence of energy sources on CO_2 emissions in China. Their findings indicate that BEVs exhibit higher CO_2 emissions than ICEVs in regions dominated by coal-fired power plants. However, when the carbon intensity of electricity drops below ~320 g/kWh, BEV become more environmentally favorable than ICEV. Shang et al. (2024) explored GHG emissions and air pollution in China for EV and ICEV. They found that EVs contribute to lower emissions of CO_2, volatile organic compounds (VOCs), and nitrogen oxides (NO_x) compared to ICEVs. However, they also noted that EVs result in higher emissions of $PM_{2.5}$ and SO_2, which highlights the need for advancements in grid sustainability and pollution control in EV production and operation.

In America region, Bicer and Dincer (2018) extended the comparison of ICEV to alternative fuel vehicles, including hydrogen-powered ICEV (H_2). Their study in Canada highlighted that BEV and HEV have higher human toxicity and acidification values due to manufacturing and maintenance processes. Interestingly, hydrogen-powered ICEV emerged as the most eco-friendly option, owing to their high energy density and minimal fuel consumption. Bauer et al. (2018) examined the energy and GHG emissions of BEV, HEV, and ICEV in New York, demonstrating that EV reduced GHG emissions by an impressive 73% compared to ICEV. This study underscores the importance of cleaner energy grids in amplifying the environmental advantages of EV. Ahmadi (2019) compared various vehicle technologies in the USA, including ICEV, HEV, FCEV, BEV, and PHEV, focusing on emissions and cost. Their findings revealed that FCEVs and BEVs have the most significant improvements in air quality. However, HEV demonstrated the lowest LCC, making them an economical choice. The study also highlighted increased carbon damage costs associated with the greater penetration of HEV and BEV, emphasising the need for further policy interventions. Challa et al. (2022) focused on the GHG emissions of EVs and ICEVs in the United States. They found that EVs have lower life-cycle GHG emissions than ICEVs under most conditions. The decline was attributed to the substitution of nuclear power with natural gas plants and ongoing initiatives aimed at grid decarbonisation.

Several studies explored for multiple regions. Peng et al. (2018) expanded their analysis across multiple regions, including China, the USA, Japan, Canada, and the EU, focusing on the geographic variability of GHG emissions. Their results confirm that BEVs consistently have lower GHG emissions than ICEVs, but the degree of reduction depends heavily on the carbon intensity of the regional electricity grid. The study also notes that advancements in low-carbon electricity further enhance the environmental benefits of EVs. Kawamoto et al. (2019) conducted a multi-regional analysis in Australia, China, the EU, Japan, and the USA, comparing the life-cycle CO_2 emissions of ICEV and BEV. They found that BEVs have lower life-cycle CO_2 emissions than ICEVs when powered by renewable energy or low-carbon power plants. However, when accounting for emissions from battery production, BEVs can exhibit higher life-cycle CO_2 emissions, especially when driving distances exceed 160,000 km. Franzò and Nasca (2021) analysed the life-cycle CO_2 emissions of EVs compared to ICEVs. Their study concluded that the life-cycle CO_2 of EVs are consistently lower than that of ICEVs across all scenarios. They emphasised that geographical location significantly influences CO_2 emissions due to differences in energy generation methods. Furthermore, the use phase of EVs has the most considerable impact on their CO_2 emissions, underlining the importance of sustainable energy sources for charging EVs.

In the Southeast Asia region, Veza et al. (2023) conducted their research in Indonesia, comparing the environmental impacts of BEV, HEV, PHEV, and ICEV. Their findings highlighted that EVs exhibit the lowest CO and CO_2 emissions among the studied vehicles. However, EVs were also shown to produce higher levels of NO_x, N_2O, SO_2, and PM_{10} due to the reliance on fossil fuels for electricity generation. This suggests that the environmental benefits of EVs can be amplified with cleaner electricity sources. The following tables summarise the LCA's significant findings of

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environmental impact. Error! Not a valid bookmark self-reference. shows the comparison of the LCA of ICEV and EV in various regions.

Table 2 List of LCA findings to represent the environmental impact on various vehicle technologies

Vehicle	Impact Categories	Research Location	Findings	Reference
• EV • ICEV (gasoline)	• Acidification • Climate change • Eutrophication • Human toxicity • Particulate matter • Photochemical oxidant • Primary energy Resource depletion	Italy	• LC of EV < ICEV in all the impact categories, except for eutrophication and human toxicity, because> 60 % of the electricity grid is powered by efficient CCPP. • Manufacturing of EVs and batteries has more significant impacts than ICEV for all categories due to eutrophication and human toxicity.	(Girardi et al., 2015)
• BEV • ICEV	Global warming		• BEV manufacturing phase: o Toxicity impact: The highest due to the utilisation of metals in the battery pack. LC GHG emissions of BEV < ICEV	(Tagliaferri et al., 2016)
• ICEV o Gasoline o Diesel • BEV	Global warming	Europe	• LC CO_2 of BEV < ICEV due to ↑ ratio of renewable energy/nuclear in electricity grid. LC CO_2 of BEV > ICEV due to ↑ ratio of oil and coal in electricity grid.	(Athanasopoulou et al., 2018)
• EV • ICEV	• Acidification • Eutrophication • Fossil fuel depletion • Human toxicity Particulate matter	• Czech Republic • Poland	• LC GHG emissions of EV are greater than ICEV for acidification, eutrophication, human toxicity, particulate matter formation EV with renewable electricity grid: ↓ bad impacts on the environment.	(Burchart-Korol et al., 2018)
• EV • ICEV (gasoline)	• Abiotic depletion • Acidification • Eutrophication • Global warming • Ozone depletion • Photochemical ozone	South of China	• LC of EV > ICEV for abiotic depletion • The comprehensive environmental load of the LiFePO and NCM batteries are 376% and 119% higher than ICEVs, respectively. • The optimisation of the electricity grid can reduce GWP, CO and CO_2 by 15%, 37%, and 14%, respectively. By increasing the energy density of the battery up to 100 Wh/kg, can decrease emissions by 14–20%.	(Yu et al., 2018)

Table 3 List of LCA findings to represent the environmental impact on various vehicle technologies (Cont.)

Vehicle	Impact Categories	Research Location	Findings	Reference
• ICEV • HEV • BEV	• Abiotic depletion • Acidification • Eutrophication • Global warming • Human toxicity • Ozone layer depletion • Terrestrial ecotoxicity	Canada	• BEV and HEV: higher human toxicity, terrestrial ecotoxicity, and acidification values due to manufacturing and maintenance stages. • ICEV (H_2): The most eco-friendly option due to high energy density and low fuel consumption.	(Bicer and Dincer, 2018)
• BEV • HEV • ICEV	Global warming	USA	EV reduced GHG emissions by 73% compared to ICEV.	(Bauer et al., 2018)
• BEV • PHEV • ICEV	Global warming	• China • USA • Japan • Canada • EU	• LC GHG emission of BEV < ICEV • The decrease of GHG emissions from EVs varies greatly depending on the geographical location. EVs: lower GHG emission when paired with the advancement of low carbon grid electricity.	(Peng et al., 2018)
• ICEV • HEV • FCEV • BEV • PHEV	Global warming, air pollution	USA	• Air quality: FCEV and BEV have better than ICEV (~84% reduction) • ↑ carbon damage cost due to penetration of HEVs and BEVs	(Ahmadi, 2019)

• ICEV:
  ○ Gasoline
  ○ Diesel
• BEV
	Global warming	• Australia
		• China
		• EU
		• Japan
		• USA
			• The LC CO_2 of BEV > ICEV when the LC CO_2 is added from battery production.
			• The LC CO_2 of BEV < ICEV when renewable energy and low CO_2 of power plant.
			• Additional LC CO_2 when driving distance > 160,000 km (BEV), due to battery replacement.
			LC CO_2 of ICEV < BEV when LC CO_2 for battery production is very large.
				(Kawamoto et al., 2019)

• ICEV • BEV	Global warming	China	• LC GHG emissions of EV are ~ 41.0 t CO_2eq, 18% < ICEV. The GHG emissions during the WTW phase of a BEV are reducing rapidly.	(Qiao et al., 2019)

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Table 4 List of LCA findings to represent the environmental impact on various vehicle technologies (Cont.)

Vehicle	Impact Categories	Research Location	Findings	Reference
• BEV • ICEV	Global warming	China	• The LC GHG emissions of BEV are about 29% < ICEV. Recycling is an effective method for reducing GHG emissions. However, it is not effective in reducing LCC.	(Qiao et al., 2020)
• BEV • ICEV	Global warming, air pollution	China	• The LC CO_2 of BEV > ICEV when the coal-fired power plant is still dominant LC CO_2 of BEV < ICEV when the overall average LC CO_2 by electricity grid is at least ~320 g/kWh.	(Zheng and Peng, 2021)
• ICEV • HEV • EV	Global warming	Europe	• BEV: ○ Global warming impact: ~60% ICEV ○ Acidifying impact: doubled ○ Particulate matter impact: doubled. • HEV: ○ Global warming impact: 85% to ICEV ○ Terrestrial acidification impact: similar to ICEV Particulate matter formation: similar to ICEV	(Pipitone et al., 2021)
• EV • ICEV	Global warming		• LC CO_2 of EV < ICEV in all the scenarios. • The geographical location significantly influences the amount of CO_2 emissions. The use phase has the most significant influence on the CO_2 emissions of EVs.	(Franzò and Nasca, 2021)
• EV • ICEV	Global warming	USA	• LC GHG emissions of EV < ICEV for most conditions considered. • LC GHG emissions are expected to reduce on average by 5% for EVs and 27% for ICEV in 2030 compared to 2018. LC GHG emissions of EV < ICEV due to grid decarbonisation	(Challa et al., 2022)
• EV • HEV • PHEV • ICEV	Global warming, air pollution	Indonesia	• EV: the lowest CO and CO_2 emissions. • EVs have higher NO_x, N_2O, SO_x, and PM_{10} emissions, due to fossil fuels for electricity generation.	(Veza et al., 2023)
• EV • ICEV	Global warming, air pollution	China	• EV: lower CO_2, VOCs, NO_x emissions. • EV: higher $PM_{2.5}$, SO_2 emissions.	(Shang et al., 2024)

Besides global warming potential, eutrophication and acidification significantly impact EV batteries' life-cycle. In particular, battery part production (anode) significantly impacts categories such as eutrophication and acidification (Faria et al., 2014). Eutrophication is increasing the amount of nutrients, especially nitrogen (N) and phosphorus (P), in an aquatic ecosystem, which causes the overgrowth of algae or aquatic plants. This process can occur naturally or be accelerated by human activity (Akinnawo, 2023). Waste from mining and processing battery materials can flow into the waters, carrying nutrients such as phosphate and nitrogen. This can lead to excessive algae growth in water bodies, which disrupts aquatic ecosystems. Moreover, waste disposal in battery production facilities can produce chemicals contributing to eutrophication.

Acidification is dominant in EV battery production. The production of their components, especially during mining and processing of materials such as cobalt and nickel, produces emissions such as SO_x (Zhou, 2024). Sulfidic tailings from copper and cobalt mining also significantly contribute to eutrophication (Lavigne Philippot et al., 2023). Besides, Fossil fuel power plants used to charge EVs also produce SO_x and NO_x if renewable energy is not widely used. These gases react in the atmosphere and cause acid rain.

On the other battery's part, the cathode significantly impacts abiotic depletion (Du et al., 2023; Faria et al., 2014). Abiotic Depletion is a term used to describe the reduction of non-renewable (abiotic) natural resources, such as minerals, metals, and fossil fuels, due to human activities. Abiotic depletion in EV battery manufacturing occurs due to a heavy reliance on non-renewable natural resources such as lithium, cobalt, and nickel. Abiotic resources are limited in nature. Overuse can lead to scarcity. Mining and extraction of abiotic resources often damage ecosystems, polluting soil, water, and air (Moghimi Dehkordi et al., 2024). However, Temporelli et al. (2020) show at least 16 impact categories that are commonly assessed by researchers, such as cumulated energy demand, global warming potential, abiotic depletion, ozone depletion, human toxicity, particulate matter, ionising radiation, photo oxidant formation, acidification, eutrophication, ecotoxicity, land use, water use, resource depletion, and fossils depletion.

Overall, the reviewed studies collectively highlight that EVs generally offer lower life-cycle GHG emissions and environmental impacts than ICEVs, particularly when powered by cleaner energy grids. However, challenges such as emissions from battery production and regional energy grid carbon intensity remain significant. These findings underscore the critical need for advancements in renewable energy adoption, battery technology, and recycling initiatives to fully realize the environmental benefits of EVs.

5.5. Electricity Grid in LCA for EVs

Electricity grids play a significant role in EVs' LCA because they significantly influence their overall environmental impact. The environmental footprint of an EV is primarily determined by the sources of electricity used to charge its battery. Each electricity source has an environmental impact associated with GHG emissions. Most of the carbon footprint of EV comes from this operation phase. The related GHG emissions and environmental deterioration are significantly reduced when electricity is produced using renewable sources like wind power. Conversely, if the electricity comes from fossil fuels like coal, the benefits of EV over ICEV are diminished due to high emissions from power plants.

Turconi et al. (2013) conducted a comprehensive analysis of 167 prior studies examining the LCA of GHG emissions associated with electricity generation sources, that summarised by Woo et al. (2017). Varun et al. (2009) and Guidi et al. (2023) also investigated the life-cycle emission of various power generation from numerous references. Their findings show a similar trend with different values due to locations and specific technologies. Table 5 shows GHG emissions based on power generation sources. Coal produces the highest GHG emission in fossil fuel-based energy, while natural gas produces the lowest GHG emission.

Fossil fuels have more significant emissions than non-fossil energy due to the characteristics of their production and utilisation that rely heavily on burning carbon-rich organic matter. Energy

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from coal, oil, and natural gas is obtained by burning fossil fuels, directly producing CO_2 as a by-product. This process is the leading cause of high emissions. Coal has a very high carbon content. Therefore, each kilogram of coal burned produces a large amount of CO_2. Moreover, coal has lower energy efficiency than other fuels, which means more fuel is burned to produce the same amount of energy (Graus et al., 2007). Even though oil and natural gas also produce CO_2, natural gas is relatively more efficient because it contains more hydrogen than carbon.

Carbon dioxide also contributes directly to the extraction, processing, and transporting of fossil fuels (Ankathi et al., 2022; Yeh et al., 2010). They also affect the overall value of emissions contribution. Before generating electricity, fossil fuels require various stages that produce additional emissions. Therefore, emissions from fossil fuels include direct combustion and the carbon footprint of the entire life cycle. In addition, burning fossil fuels also releases other GHG emissions, such as N_2O (Yokoyama et al., 1991). For natural gas, CH_4 is produced during extraction (Omara et al., 2018; 2016). CH_4 is a more potent GHG emission than CO_2, although it is less frequent, while N_2O is formed during combustion at high temperatures, which is also a potent GHG emission.

Table 5 Comparison of GHG emissions for fossil power plants in gCO_2eq/kWh

Power Generation Sources	Range	Type	References
		Fossil Fuel Based	
Coal	660—1,370	Without carbon capture	Malode et al. (2022), Rasheed et al. (2021), Šerešová et al. (2020), Li et al. (2020), Woo et al. (2017), Akber et al. (2017), Varun et al. (2009)
Natural Gas	350—1,000	Simple, Combined Cycle	Šerešová et al. (2020), Woo et al. (2017), Akber et al. (2017), Asdrubali et al. (2015), Varun et al. (2009)
Oil	530—890	Not Specified	Woo et al. (2017), Varun et al. (2009)
		Non-Fossil Fuel Based	
Hydropower	0.107—547	Reservoir, Run-of-River	Motuzienė et al. (2022), Šerešová et al. (2020), Mahmud et al. (2019), Woo et al. (2017), Hidrovo et al. (2017), Akber et al. (2017), Varun et al. (2009),
Wind	3—123.7	Onshore, Offshore	Xu et al. (2022), Garcia-Teruel et al. (2022), Xie et al. (2020), Woo et al. (2017), Varun et al. (2009)
Solar PV	13—250	Mono/multi crystalline	Šerešová et al. (2020), Woo et al. (2017), Varun et al. (2009)
Biomass	1—178	Not specified	Varun et al. (2009), Woo et al. (2017)
Solar Thermal	9.8—202	Parabolic trough, Tower plant	Guillén-Lambea and Carvalho (2021), Gasa et al. (2021), Varun et al. (2009)
Geothermal	15—38.2	HT single/double flash, Binary	Menberg et al. (2021), Paulillo et al. (2019)
Nuclear	3.1—64	Pressurised water reactor	Pomponi and Hart (2021); Wang et al. (2019), Woo et al. (2017), Varun et al. (2009)

On the other hand, non-fossil fuel energy has very low GHG emissions compared with fossil fuel energy, which has enormous discrepancies (Turconi et al., 2013; Varun et al., 2009). Non-fossil fuel or renewable energies, such as hydro, wind, or solar, only have emissions in the infrastructure manufacturing stage (turbines or solar panels), but have no emissions during the operating phase. Hydropower has the lowest GHG emissions.

However, biomass has slightly different characteristics from other non-fossil fuels with combustion energy. Biomass (such as wood, agricultural waste, or other organic matter) comes from

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plants that absorb CO_2 from the atmosphere during photosynthesis. When biomass is burned, the CO_2 released back into the atmosphere is the carbon previously absorbed by the plant. As a result, biomass burning is often considered carbon neutral (Zheng et al., 2022). In production, biomass can be harvested sustainably through reforestation or replanting cycles. Then, the carbon cycle can continue to repeat without increasing carbon accumulation in the atmosphere. However, biomass still reaps controversy. Based on Ahamer (2022), the findings indicated that long-term biomass utilisation leads to a significant decline in carbon stocks within litter and soil organic carbon, thereby disrupting the natural carbon cycle. These results challenge the assumption of biomass carbon neutrality, suggesting that biomass may be only "half as carbon-neutral". Furthermore, emissions arising from the biomass life cycle, such as production, transportation, and conversion into fuels, further weaken the claim of biomass energy's carbon neutrality. Nian (2016) confirmed that woody biomass is not a carbon-neutral energy source.

Geothermal plants offer an effective solution to avoid CO_2 emissions to the atmosphere (Guidi et al., 2023). Geothermal energy systems typically emit very low GHG emissions compared to fossil fuels. Most of the CO_2 released during geothermal operations comes from naturally occurring gases in the geothermal reservoir, not from the combustion of fuels. Additionally, some geothermal systems can be designed to inject CO_2 into underground reservoirs to enhance geothermal systems (Li et al., 2023; Wu and Li, 2020).

Unlike fossil fuels and biomass, nuclear energy is often considered a low-carbon energy source, as it does not produce direct CO_2 during electricity generation. However, its overall carbon footprint arises from indirect sources associated with its life cycle. Nuclear energy is a highly effective low-carbon energy source, with life-cycle emissions comparable to renewables. It is crucial in reducing GHG emissions while providing reliable energy. Nuclear power plants are capable of providing consistent and carbon-free base-load electricity. These plants do not discharge any GHG emissions during operation and require a much smaller land footprint (Suman, 2018). However, its long-term sustainability and broader environmental impacts require careful management, particularly regarding waste disposal and uranium resource dependency.

According to previous studies, the GHG emissions of EVs powered by an electricity grid are strongly influenced by the electricity grid prevalent in the country, as shown in Figure 4. In countries where low renewable energy sources (including nuclear power plants) are predominant, GHG emissions are higher than in countries with low-carbon electricity. The findings are derived from a typical BEV utilising the electricity grid from 2009, which is the average for each country listed (Ritchie and Rosado, 2024; McCarthy, 2013). Moreover, the efficiency and carbon intensity of the electric grid vary by region over time, impacting the LCA results. While EVs are currently seen as the upcoming technological shift in the transportation industry, their impact on the environment is closely tied to the specific mix of power generation methods employed in each region or country. Thus, in countries lacking an environmentally sustainable energy generation mix, there is a contention that EVs may not be highly efficient in diminishing GHG emissions, as has resulted in former studies (Santos and Smith, 2023; Shu et al., 2023).

In countries such as Australia, China, India, Indonesia, and South Africa, where power generation relies significantly on coal, the emissions from EVs can be comparable to those of ICEVs, with a value of approximately 300 gCO_2eq/km. In India, coal contributes more than 70% of the electricity mix. Based on Table 5, the GHG emissions of coal-fired power plants vary from 660 to 1,370 gCO_2eq/kWh. In contrast, countries with a high percentage of renewable energy in their grids, such as Sweden, France, Canada, Brazil, Paraguay, and Iceland, have the lowest GHG emissions for EVs, below 100 gCO_2eq/km. Hydropower dominates the electricity grid in Sweden, Canada, Brazil, Paraguay, and Iceland. Almost 100% of the electricity grid in Paraguay is powered by hydropower, and nuclear power plants dominate in France. These countries benefit from substantial investments in EVs due to the availability of renewable energy infrastructure, such as hydropower, wind, and solar energy, resulting in a cleaner energy mix and, consequently, lower emissions from EVs. The extreme comparison between India and Iceland clearly shows that the electricity grid plays a significant role in the GHG emissions of EVs. Grid electricity becomes a big challenge for countries with a low renewable energy mix to benefit from adopting EVs. Renewable energy infrastructure should be considered, not only in terms of the energy source but also in terms of the investment cost. However, the price of renewable energy, such as solar PV, wind, solar thermal, and geothermal, has declined (Osman et al., 2023). Therefore, Figure 4 emphasises the critical role of renewable energy in maximising the environmental benefits of EVs.

Andrich et al. (2013) highlighted the trade-offs among reducing carbon emissions, EV utilisation, and cost. Figure 5 outlines various scenarios related to CO_2 emissions, electricity prices, and their associated impacts on society, emphasising the importance of balancing environmental sustainability, economic feasibility, and social equity. Scenario 3 shows the ideal condition (lowest CO_2 emissions) with 100% EV and 100% renewable energy electricity. Scenario 3 features significant CO_2 savings from renewable energy, the lowest CO_2 emissions, low fossil fuel use, and high EV use. This scenario highlights the potential for substantial environmental improvements through adopting renewable energy and clean technologies, combined with policies promoting social equity. It stands out as the optimal scenario for long-term sustainability. However, renewable energy development face challenges due to the investment cost, hence the optimization is required (Saroji et al., 2022).

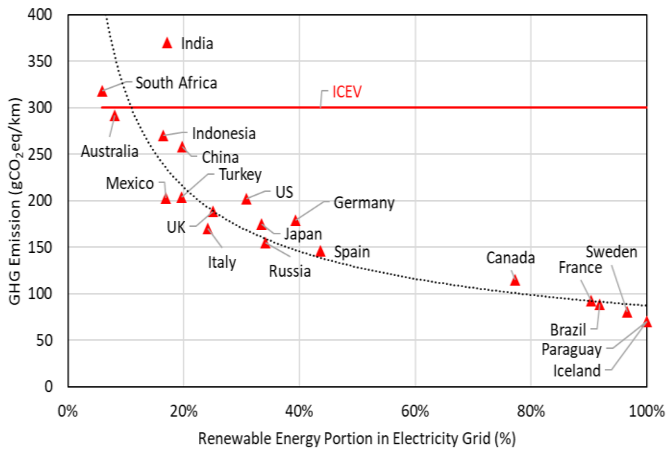

Figure 4 GHG emission of EVs in gCO_2eq/km against renewable energy portion in the electricity grid

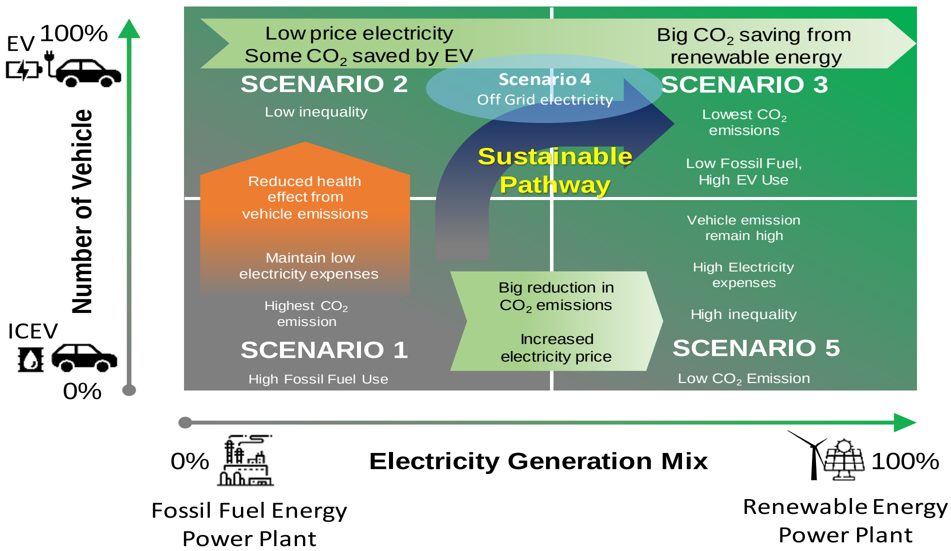

Figure 5 Energy use sustainability matrix, adapted from Andrich et al. (2013)

The impact of EV penetration was simulated by Onat et al. (2016b). It shows how abundantly EVs affect lower life-cycle CO_2 emissions as a whole in transportation systems. Onat et al. (2016b) simulated the critical role of EVs in achieving sustainable transportation by showing projected CO_2 emissions for different vehicle technologies throughout some time. Under the business-as-usual (BAU) scenario with ICEV-dominated, emissions remain high and relatively steady, underscoring the unsustainable nature of traditional fossil-fuel-dependent transportation compared to EV-dominated (HEV, PHEV, and BEV). However, the most significant impact was observed with BEV, which shows a sharp and sustained decline in emissions. This projection demonstrates that widespread adoption of BEVs and clean energy advancements is the most effective pathway to drastically reducing transportation emissions and achieving long-term climate goals.

5.7. Development and Adoption of EVs in Various Country

As discussed in the previous section, energy consumption is a significant parameter of vehicle technologies, particularly for ICEV. This factor contributes to their environmental impact and long-term viability. Although EV technology has emerged, technological advancements of ICEV are still going by improving fuel efficiency and hybrid technology to reduce emissions (Leach et al., 2020; Chung et al., 2019). Numerous studies have investigated reducing emissions by finding alternative fuels while improving engine performance (Dwinanda et al., 2021; Veza et al., 2021; 2020). The development of ICEV is also triggered by the increasing emission standards and decreasing the carbon emission quota by stringently the emission of ICEV (Zeng et al., 2024). Even though Leach (2023) showed that a modern ICEV can be a negative emission, its reliance on fossil fuel resources limits its long-term sustainability.

On the other hand, significant parameters of EVs are also involved in energy consumption, which is affected by battery capacity, charging infrastructure, and energy source. EVs represent a significant technological shift, incorporating advancements in battery technology, smart charging systems, and vehicle-to-grid (V2G) connectivity. These innovations are driving the adoption of renewable energy and reshaping energy consumption patterns.

The development and adoption of EV technology have different growth in each country, especially when compared among developed, developing, and underdeveloped countries. While EVs have excellent prospects, the adoption rate in several countries has faced challenges. In developed countries, EVs are already very established. In 2023, EV sales approached 14 million, with 95% coming from the US, Europe, and China (IEA, 2024). The adoption rate of EVs is significant, and recently, the development of EV technology has led to autonomous vehicles and also the interconnection of EVs with various other technologies called vehicle-to-everything (V2X) (Orieno et al., 2024; Yusuf et al., 2024). EV challenges in battery technology and price are important keys to this technology's ability to compete with ICEV in the future. Thus, the ability of EVs to compete can open up opportunities for price affordability for users.

Rajper and Albrecht (2020) discovered that because of their high initial cost, EVs (four-wheelers) are not a viable alternative in developing countries. On the other hand, electric two-wheelers can be advantageous because they are less expensive. Besides China being the biggest market for EVs, India and Southeast Asia are the biggest two- and three-wheeler markets worldwide. Specifically, Indonesia, Vietnam, Philippines and Thailand are the biggest markets among Southeast Asia countries, with sales of two- and three-wheelers far outnumbering sales of passenger cars (IEA, 2024). Despite having smaller markets overall, two- and three-wheelers also play a critical role for daily passenger and commercial transportation. Therefore, electrifying two- and three-wheelers is a promising lever for decarbonising mobility and improving urban air quality in developing and underdeveloped countries. Veza et al. (2022) discussed the opportunities and challenges of EVs in Malaysia and Indonesia.

In underdeveloped countries, ICEV dominates due to affordability, established fuel infrastructure, and availability. However, their environmental impact is more pronounced due to lenient regulations and older vehicle technology. Nevertheless, EV adoption presents opportunities to leap to cleaner technologies and integrate renewable energy systems. The role of government policies, international aid, and private investment may overcome barriers to EV adoption in these countries.

5.8. Proposed LCA Framework: ICEV vs EV

Based on the review of several LCA studies, it can be summarised that it is important to define precisely what kind of EVs want to be investigated. Each EV's type has different life-cycle stream components. This framework can easily investigate the life-cycle emissions of vehicles based on the EV type. While several studies have shown that the LCA comparison of ICEV and EV, the general framework for all types of vehicles has not been established. In LCA vehicle research, numerous recent studies have used the cradle-to-gate (Kim et al., 2023), cradle-to-wheel (Zhang et al., 2023), and cradle-to-grave approach (Kelly et al., 2024). Most existing studies focus on the cradle-to-grave approach, which end at disposal and overlooks opportunities for recycling and reusing materials, particularly in battery components. However, the waste of vehicles becomes a further problem. With the development of material recycling and remanufacturing, therefore the cradle-to-cradle method is attracting more attention. Specifically, the cradle-to-cradle method is a new full-life-cycle LCA method that considers reusing waste materials and remanufacturing. Despite the growing body of research on LCA for EV, there is still a notable gap in studies employing a cradle-to-cradle approach, which emphasises not only the environmental impact across the life-cycle but also the potential for resource recovery and material circularity. Figure 6 shows the life-cycle emission framework for all types of vehicles with a cradle-to-cradle approach.

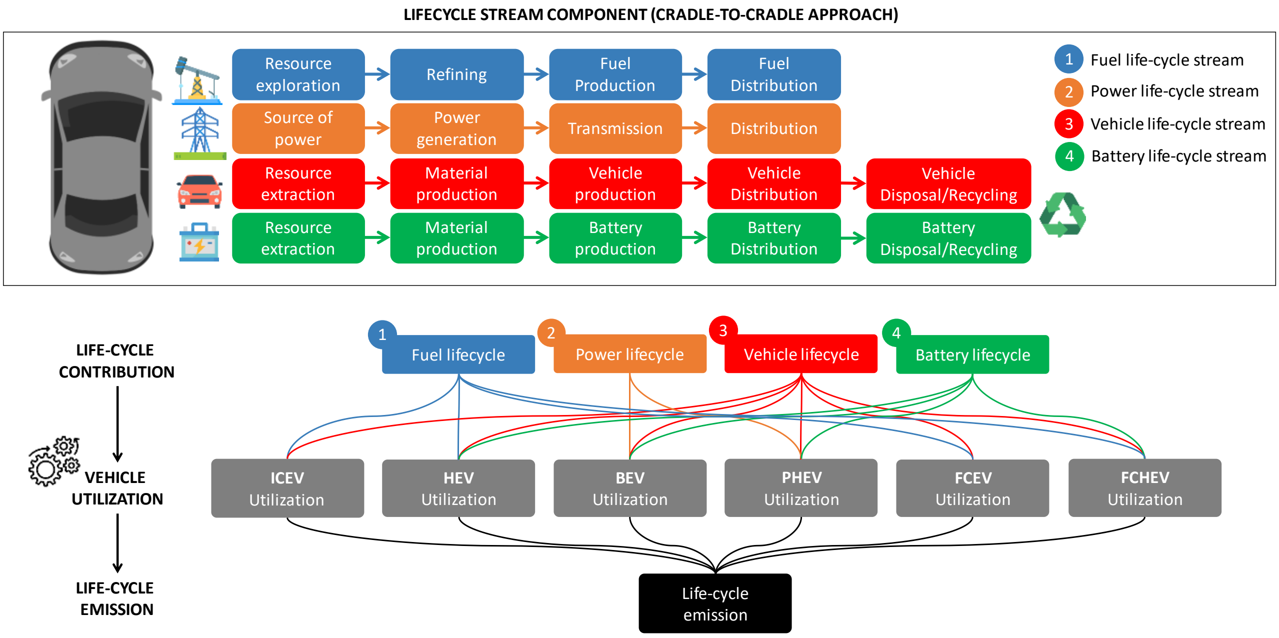

Figure 6 Life-cycle emission framework for all types of vehicles with a cradle-to-cradle approach

However, several limitations must be addressed in the LCA framework. One of the primary challenges is its reliance on available data, which can vary greatly in quality, as also noted by Finnveden (2000). For instance, data related to raw material extraction, energy consumption, and recycling processes often differ across regions and manufacturers, leading to potential variability in the results. This variability underscores a critical challenge in achieving consistent and reliable assessments. Additionally, the framework does not fully account for geographical variations in energy generation mixes, an important factor for assessing the impact of EVs. Since the carbon footprint of electricity production can vary widely depending on the energy sources used, overlooking these variations could influence the accuracy of the results. Moreover, the end-of-life phase for EV batteries introduces additional uncertainties due to the variability in recycling rates and the technological immaturity of current recycling processes. These uncertainties complicate the sustainability assessment of EVs and highlight the need for further research to understand better and improve battery recycling practices. Hence, collaborative data for data inventory is crucial.

Another limitation of the framework lies in its static analysis, which does not consider temporal factors, such as EV adoption growth, the improvements in ICEV technology, advancements in battery technology, or changes in energy policies. These factors can significantly affect the long-term applicability of the findings, particularly in a rapidly evolving industry like EV. Without incorporating these dynamics, the framework risks providing conclusions that may become outdated as technologies and policies progress. As references, Onat et al. (2016b) combined system dynamics in LCA, which then Onat et al. (2016a) incorporated uncertainty analysis in LCA frameworks.

Although the LCA framework mainly employs a cradle-to-grave approach, specific indirect effects remain excluded, which may result in an incomplete assessment of life-cycle impacts. For example, the environmental effects of infrastructure development, such as charging station networks, or the life-cycle of secondary components, including lubricants and auxiliary systems, are not fully addressed. These exclusions could underestimate the overall environmental footprint of EVs when considered within a broader context.

Lastly, the proposed LCA framework primarily focuses on environmental impacts, with limited integration of social and economic dimensions. Key aspects, such as the societal benefits of reduced urban air pollution or the economic implications of transitioning from ICEV to EV, are not explored in depth. This narrow scope limits the framework's ability to provide a holistic view of the sustainability transition.

The authors acknowledge these limitations and emphasise that the results of the LCA framework should be interpreted within these constraints. Despite its limitations, the framework is valuable for identifying broad trends and impacts. However, additional studies are necessary to address specific gaps, such as regional variations in energy mixes, dynamic modeling over time, and the inclusion of socio-economic factors to provide a more comprehensive understanding of the life-cycle impacts of EVs.

6. Conclusion and Future Works

6.1. Conclusions

The bibliometric analysis highlighted the trends of LCA research for EVs, transitioning from foundational studies on environmental impact to recent advancements in battery technology, materials, and recycling. However, ICEV is still an interesting discussion in the world of vehicles. These trends underscore the need for future research to prioritise scalable recycling technologies, resource-efficient battery designs, and context-specific LCA frameworks to support the sustainable growth of EVs. Therefore, potential topics such as social and economic aspects indicate a growing interdisciplinary focus aimed at aligning LCA research with global sustainability goals. This literature review shows that EVs have lower environmental impacts than ICEVs, particularly in terms of GHG emissions during the operational phase. However, the environmental benefits of EVs are highly dependent on the electricity grid; reliance on fossil fuel-based electricity can diminish these advantages. Conversely, the production phase of EV, particularly concerning batteries, demonstrates greater environmental impacts in comparison to ICEV owing to the utilization of rare materials and energy-intensive manufacturing processes. Nevertheless, the operational phase benefits of EVs often offset their production-related impacts. To maximise the environmental advantages of EVs, a transition to renewable energy sources or clean power plants and advancements in battery recycling technologies are critical. The shift from ICEV to EV has the potential to deliver significant environmental benefits. However, it requires a holistic approach that considers the entire life-cycle of the vehicles and the development of sustainable supporting infrastructure toward a low-emission transportation system.

6.2. Future Works

Attention must be paid to the fact that LCA for EV is a tool to evaluate a product only from one side of the viewpoint (environmental). To promote and expand the ecosystem of EV, it shall be evaluated in multiple aspects, such as economic, social, and technological. Therefore, integrating socio-economic factors, such as public health benefits and economic implications, and advancing recycling innovations will ensure a holistic understanding of EV sustainability. In addition, future research should focus on developing a comprehensive LCA framework that incorporates cradle-to-cradle methodologies to promote material circularity and resource recovery for all vehicle types. Regarding EV technology, recent studies have not widely discussed LCA for FCEV. It allows for investigation and comparison with other EVs. There is no single method for performing LCA, particularly for facing the dynamic of vehicle technology with high complexity due to multiple aspects considered. Hence, by integrating system dynamics, LCA can better account for technological advancements, shifts in energy policies, and evolving market behaviors, providing a more realistic and forward-looking assessment. This dynamic approach enables researchers and policymakers to identify long-term trends, evaluate the effectiveness of mitigation strategies, design adaptive solutions for sustainable development, and enabling actionable policy recommendations for a global transition to cleaner transportation.

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Author Contributions

Muhammad Idris: Conceptualization, Project administration, Writing – review and editing; Iwa Garniwa: Methodology, Supervision; Tri Edhi Budhi Soesilo: Methodology, Supervision; Suyud Warno Utomo: Supervision, Writing – review and editing; Muhammad Zacky Asyari: Validation, Project administration.

Conflict of Interest

The authors declare no conflicts of interest.

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