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# A Systematic Review of Life Cycle Assessment of Electric Vehicles Studies: Goals, Methodologies, Results and Uncertainties

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**Abstract**

This review analyzes how recent electric-vehicle LCAs have been carried out, emphasizing goals and scope, functional units, system boundaries (cradle-to-grave and well-to-wheel), and attributional versus consequential modeling rather than reporting outcomes. Using a systematic search of studies mainly from 2018–2025, it maps common tools and data sources (Ecoinvent, GREET, GaBi, and regional inventories) and summarizes LCIA practices, underscoring the need to report versions, regionalization, and assumptions transparently for comparability. Uncertainty studies are uneven: sensitivity and scenario analyses are common, while probabilistic approaches (e.g., Monte Carlo) are less used, indicating room for more consistent, multi-parameter uncertainty analysis. The results show that outcomes are context-dependent: BEVs deliver the largest life-cycle GHG cuts on low-carbon grids with improved battery production and end-of-life management; PHEVs and HEVs act as transitional options shaped by real-world use; and FCEV benefits depend on low-carbon hydrogen. Vehicle-integrated photovoltaics and solar-powered vehicles are promising yet under-studied, with performance tied to local irradiance, design, and grid evolution. Future research suggests harmonized reporting, more regionalized and time-aware modeling, broader probabilistic uncertainty, and comprehensive LCAs of VIPV/SPV and circular pathways to support policy-ready, comparable results.

**Keywords:** life cycle assessment; electric vehicles; battery EV; hybrid EV; plug-in EV; life cycle inventory; life cycle impact assessment; system boundaries

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## 1. Introduction

The transportation sector accounts for approximately 29% of total European Union $CO_2$ emissions and approximately 27% of all greenhouse gases (GHG) in the United States of America (USA), making it one of the highest contributors to greenhouse gas emissions [1,2]. In response to this challenge, the European Commission's Green Deal aims to achieve climate neutrality by 2050, with the "Fit for 55" initiative targeting a 55% reduction in greenhouse gas emissions by 2030 and complete elimination of gasoline and diesel engines by 2035 [1,3]. This regulatory framework has accelerated the global transition toward electric mobility, with China alone projecting electric vehicle production to reach 4000 units (×10,000) by 2035, representing a 90% market share [4]. As climate change concerns intensify and governments worldwide implement stringent emissions reduction targets, the automotive industry has undergone a fundamental transformation

toward vehicle electrification. Electric vehicles (EVs) have emerged as a promising solution for reducing transportation-related emissions, driven by advances in battery technology, charging infrastructure, and intelligent vehicle systems [5,6]. The global electric vehicle market has experienced remarkable growth, with nearly 14 million new electric cars registered worldwide in 2023, increasing the total number of EVs on the road to 40 million [7]. With zero tailpipe emissions, EVs offer a clear advantage over traditional internal combustion engine vehicles (ICEVs) during their operational phase, directly improving air quality in urban environments and contributing to national and international emissions reduction targets [8,9].

The increasing adoption of EVs worldwide underscores their importance. Governments and industries are investing heavily in EV technology, charging infrastructure, and incentives to accelerate this transition [10]. However, the environmental benefits of EV are not solely determined by their performance. A holistic understanding of their true environmental impact requires a comprehensive evaluation that extends from the extraction of raw materials for their components through manufacturing processes, their operational life, and ultimately to their end-of-life management, including battery recycling and disposal. This comprehensive viewpoint is crucial, as studies indicate that the production phase, especially of batteries, and the source of electricity for charging are significant factors in the overall environmental profile of an EV [11,12].

While the absence of tailpipe emissions during operation is a clear and immediate benefit of EVs, a truly comprehensive understanding of their environmental credentials necessitates a much broader perspective that meticulously examines the impacts across their entire life cycle, from the mining of raw materials to assessing the impact of the electric grid in the use phase and to their eventual disposal or recycling. In this context, Life Cycle Assessment (LCA) has emerged as a valuable analytical technique and as an indispensable tool for informed decision-making. Without such a holistic view, conclusions regarding the environmental benefits of EV may be incomplete or misleading, potentially overlooking significant upstream and downstream burdens of EVs.

Numerous authors have reviewed the scientific literature on the life cycle assessment of electric vehicles, each concentrating on different aspects of the topic. In their review, Burchart et al. [13] focused on the environmental LCA of fuel cell electric vehicles (FCEVs) for road transportation. This review emphasized the crucial role of hydrogen production methods in determining the overall environmental performance of FCEVs, highlighting that the use of renewable energy sources for hydrogen production is essential for achieving significant environmental benefits. Another review by Koniak et al. [14] covered the economic, technical, and environmental aspects of electric vehicles, providing a broader context for understanding the overall sustainability of EVs compared with conventional vehicles. This integrated perspective is crucial for informed decision-making regarding the transition to electric vehicles.

In summary, Table 1 offers an overview of the review literature, establishing a foundational understanding of the life cycle environmental impacts of electric vehicles, with a focus on their specific areas of emphasis.

**Table 1.** Overview of Related Literature Reviews on Electric Vehicle LCA and Their Focus Areas.

| References | Title | Type of Vehicles Reviewed | Review Focus |
| --- | --- | --- | --- |
| [13] | Review of Environmental Life Cycle Assessment for Fuel Cell Electric Vehicles in Road Transport | FCEVs, hydrogen-powered electric vehicles | It discusses the importance of hydrogen refueling infrastructure and the efficiency of fuel storage and transportation systems |

**Table 1.** *Cont.*

| References | Title | Type of Vehicles Reviewed | Review Focus |
| --- | --- | --- | --- |
| [15] | Carbon Footprint of Electric Vehicles—Review of Methodologies and Determinants | Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEVs), Hybrid Electric Vehicles (HEVs), and Plug-in Hybrid Electric Vehicles (PHEVs) | An overview of methodologies for assessing the carbon footprint of electric vehicles, including a review of concepts, methods, standards, and calculation models based on the life cycle of the carbon footprint. |
| [16] | A systematic Review on Sustainability Assessment of Electric Vehicles: Knowledge gaps and future perspectives | Electric vehicles, autonomous vehicles, BEVs | This study aims to reveal research gaps in the sustainability assessment of electric vehicles and provide an outlook of the current state of knowledge, perspectives on research gaps, and potential ways for the adoption of integrated life-cycle modeling approaches. |
| [17] | A Review of Life Cycle Assessment Studies of Electric Vehicles with a Focus on Resource use | EVs, BEVs, HEVs, PHEVs, ICEVs | The goal of this study was to determine whether resource use aspects are adequately reflected in life cycle assessment case studies of electric vehicles. |
| [18] | Life Cycle Assessment of Electric Vehicle batteries: An overview of recent literature | Electric vehicle batteries, electric and hybrid vehicles, BEVs | This review focuses on understanding the magnitude and variability of the main impacts of automotive battery life cycles, with particular attention to climate change impacts, and to support researchers with methodological suggestions in the field of LCA. |
| [14] | Review of Economic, Technical, and Environmental Aspects of Electric Vehicles. | EVs | Focuses on Economic, technical and environmental aspects of Electric vehicles |

While numerous reviews have summarized the findings of EV LCA studies, a gap exists in the systematic analysis of the underlying methodological frameworks that produce these results. Therefore, the primary objective of this review paper is to provide a comprehensive methodological review of recent LCA studies of EVs. Instead of focusing solely on outcomes, this review deconstructs how these assessments are conducted by examining the choices made by researchers at each stage of the LCA process.

The specific objectives are as follows:

- Goal and Scope Definition: To analyze the technologies studied, the system boundaries applied (e.g., cradle-to-grave, well-to-wheel), and the prevalent modeling philosophies (attributional vs. consequential).
- Life Cycle Inventory (LCI): To identify the dominant software tools, LCI databases, and data sources used to quantify environmental inputs and outputs.
- Life Cycle Impact Assessment (LCIA): To compare the different impact assessment methodologies (e.g., ReCiPe, CML) employed to translate inventory data into environmental impacts.
- Interpretation: To investigate how researchers address uncertainty and variability through sensitivity and scenario analyses.

The novelty of this review lies in its structured critique of the LCA process itself, offering a benchmark of current practices in the field. By comparing the tools, databases, and methodological choices, we aim to identify points of consensus, divergence, and key challenges that affect the comparability and reliability of LCA results of EV. Furthermore, this review highlights a significant and under-explored research gap: the near absence of comprehensive LCA studies on Vehicle-Integrated Photovoltaics (VIPV) and solar-powered vehicles (SPVs), defining a clear direction for future research in sustainable mobility.

This review is structured as follows: Section 2 explains the materials and methods used in the literature search. Section 3 delves into the methodological approaches, software, and impact assessment methods used in this study. It also examines the key influencing factors that drive the LCA results and discusses the sensitivity analyses performed in this regard. Section 4 highlights significant research gaps and proposes future research directions, along with the conclusions.

## 2. Materials and Methods

### 2.1. Systematic Literature Search

This review employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guideline for systematic review. The literature search used the Scopus database to identify relevant studies on the life cycle assessment of electric vehicles. Scopus was selected for its interdisciplinary scope, ease of exporting bibliometric data, and alignment with the PRISMA guidelines for systematic reviews, which do not mandate multiple databases if one sufficiently captures the field. While Web of Science and ScienceDirect are also standard, they overlap significantly with Scopus (up to 80% duplication in STEM topics), and including them could have introduced redundancy without proportionally increasing yield; future searches may incorporate them for validation, but the current focus on Scopus ensured efficiency and relevance to methodological trends in EV studies.

The following search terms were used in different combinations:

- "Life cycle assessment" OR "LCA" AND "electric vehicles"
- "Vehicle integrated photovoltaics" OR "VIPV" OR "solar powered vehicles"
- "Environmental impact" AND "electric vehicles" AND "solar panels"
- "LCA methodology" AND "solar powered vehicles"
- "LCA" AND "uncertainty analysis" AND "electric vehicles"

The search was limited to peer-reviewed journal articles published between 2018 and 2025 to capture established scientific knowledge in the field and ensure relevance to current technological developments and methodological approaches. The manuscript's systematic literature search relied solely on Scopus for screening studies from 2018 to 2025 as it provides comprehensive coverage of peer-reviewed articles in engineering, environmental sciences, and transportation fields relevant to EV LCAs.

The initial search yielded over 500 publications, which were further screened based on titles, abstracts, and keywords to identify the most relevant studies for a detailed review. Studies focused specifically on the life cycle assessment of electric vehicles, methodological approaches to LCA, and the LCA of emerging vehicle technologies such as vehicle-integrated photovoltaics were prioritized for inclusion in this review. The selection criteria emphasized studies that provided quantitative environmental impact assessments, detailed methodological descriptions, and comparative analyses of different vehicle technologies and battery systems.

The exclusion criteria were as follows: (1) non-English language publications, (2) studies published outside the specified timeframe, (3) research focusing exclusively on battery technology without direct reference to electric vehicles, (4) conference papers and abstracts, and (5) non-peer-reviewed reports and grey literature.

The final phase involved a detailed analysis of the selected papers using the LCA methodology to systematically categorize them. A flowchart of the methodological framework used in selecting papers is shown in Figure 1.

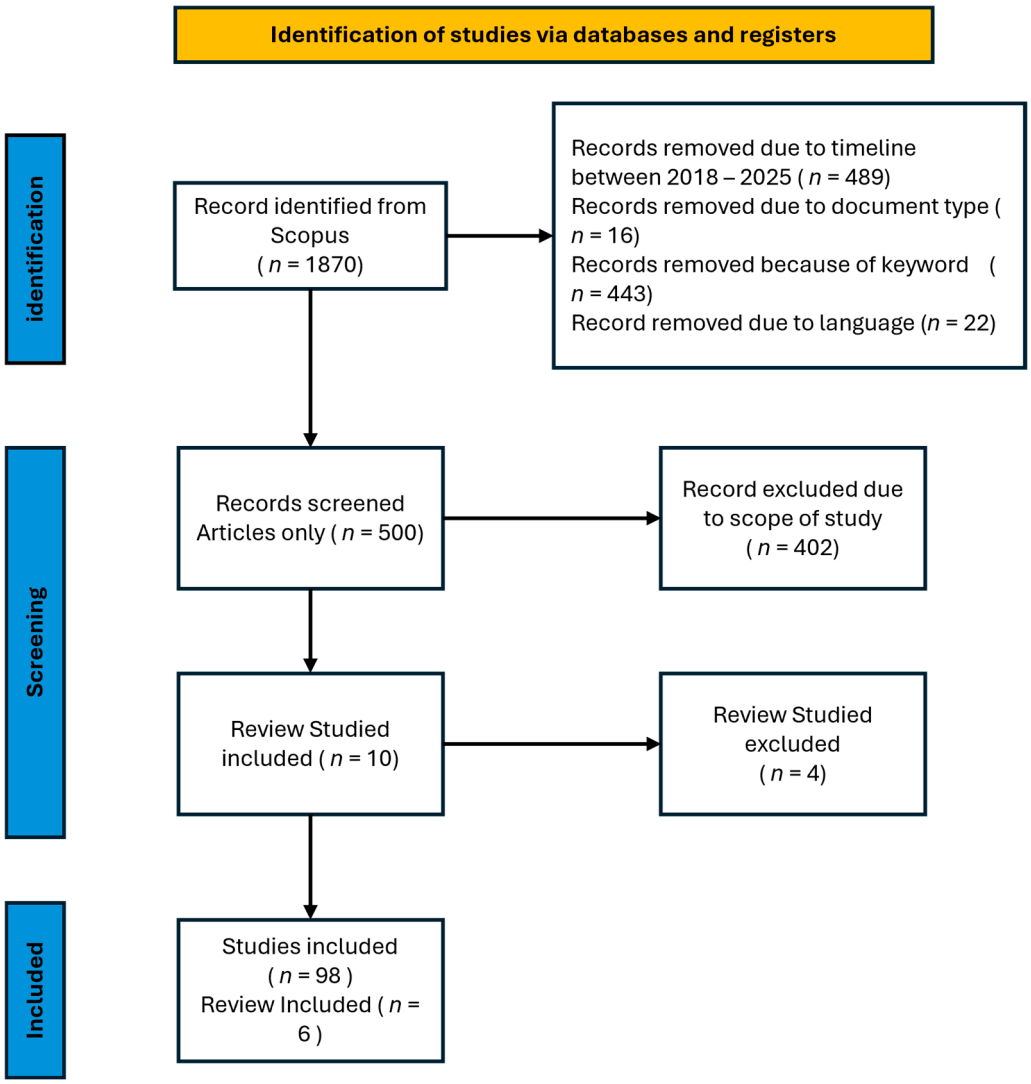



**Figure 1.** Flowchart of the search process through the PRISMA framework.

During this research, we acknowledge the use of Perplexity AI (Pro version) and Paperpal (Pro version) as supportive tools in the preparation of this manuscript. These AI tools were not employed to create original research content but were utilized to assist with the following tasks:

- Literature Summarization: After downloading and evaluating over 100 scientific papers, Perplexity AI (Pro version) aided in extracting key insights, identifying trends, and synthesizing themes, particularly in areas related to functional units, system boundaries and the inclusion of uncertainty used in each study.
- Language and Clarity Improvement: Paperpal AI was used to refine specific sections of the manuscript, enhancing grammatical precision, technical accuracy, and overall readability, focusing on the introduction and the conclusion.
- Structural Critique and Feedback: Both tools served as initial reviewers, offering suggestions on the logical progression of arguments and highlighting areas of redundancy or wordiness in the draft. All feedback provided by the AI was thoroughly reviewed and edited by the authors to maintain alignment with the original source and ensure scientific integrity.

While AI aids efficiency, it presents risks to reproducibility (as the underlying algorithms/models are proprietary and change), potential for hallucinations/inaccuracies

(requiring 100% manual fact-checking), and the inability to replace critical, contextual analysis, or judgment of scientific quality required for LCA studies. We re-emphasize that the authors maintained full control over the final synthesis to uphold scientific integrity.

### *2.2. Life Cycle Assessment Methodology*

Life Cycle Assessment is a robust, internationally standardized (ISO 14040/14044), and systematic methodology designed to evaluate the potential environmental impacts attributable to a product, process, or service throughout its entire life cycle [19,20]. LCA enables the identification of environmental hotspots within a product's life cycle and facilitates comparisons between different products or production pathways [21]. In the context of electric vehicles, LCA has been widely applied to assess various environmental impacts, including greenhouse gas emissions, resource depletion, acidification, and human toxicity [21,22]. This "cradle-to-grave" or, ideally, "cradle-to-cradle" (emphasizing circularity in end-of-life) approach encompasses all stages of raw material acquisition, material processing, component manufacturing, vehicle assembly, distribution, the use phase (including electricity generation for charging and maintenance), and end-of-life (EOL) management. Figure 2 provides a cradle-to-cradle illustration of life cycle assessment stages. At its core, LCA answers the question: "What environmental impacts occur over the entire life cycle of this product or system?"

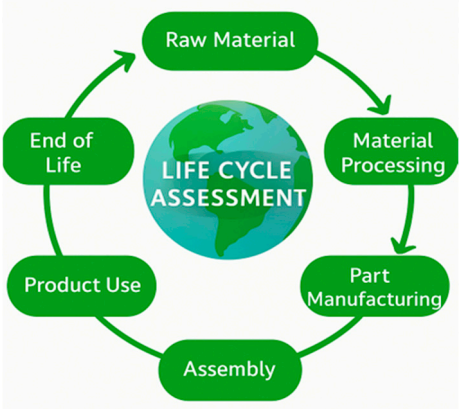



**Figure 2.** Diagram illustrating the stages of a vehicle's LCA, highlighting environmental considerations from raw material extraction through end-of-life disposal with recycling.

The LCA methodology is structured into four distinct phases, which form the organizational basis for the analysis in this review:

- Goal and Scope Definition: This initial phase defines the purpose of the study, product system to be evaluated, functional unit (the basis for comparison, e.g., one kilometer driven), and the system boundaries (which processes are included).
- Life Cycle Inventory (LCI): In this phase, data on all environmental inputs (e.g., energy, raw materials) and outputs (e.g., emissions, waste) are collected for every process within the system boundaries.
- Life Cycle Impact Assessment (LCIA): This phase translates the LCI results into potential environmental impacts. Inventory flows are classified into impact categories (e.g., climate change, acidification) and characterized using scientific models to quantify their potential effects.
- Interpretation: The final phase involved evaluating the results from the LCI and LCIA to draw conclusions, identify significant issues, check for completeness and consistency, and provide recommendations in line with the study's goal.

## 3. Results and Discussion

### 3.1. Goal and Scope Definition

The goal and scope definition phase is foundational in any LCA, establishing the purpose, context, and boundaries of an assessment. A notable observation in the literature reviewed is the prevalent focus on comparative LCA studies [3,23–26]. A study was considered "comparative" when it directly contrasted at least two different vehicle types rather than merely examining various batteries or scenarios within a single vehicle type. Approximately 70% of these studies involved comparative analyses between different vehicle types, with internal combustion engine vehicles serving as the baseline vehicle. This high percentage suggests that most life cycle assessment research in the electric vehicle domain concentrates on evaluating the relative environmental, economic, and social impacts of various vehicle technologies rather than examining single vehicle types in isolation. This comparative approach is essential for understanding the trade-offs and benefits of transitioning from conventional internal combustion engines to electrified vehicle technologies The primary vehicle technologies assessed in these comparative studies include BEVs, PHEVs, HEVs, and FCEV.

#### 3.1.1. Functional Unit

The functional unit provides a quantified reference to which all inputs and outputs are related, thereby ensuring a fair comparison between systems. The goal of the study informs the functional unit used by the authors. The most common functional unit is "per kilometer traveled (v.km)" [27–30]. These studies define this functional unit as the total function of the vehicle over its assumed lifetime, for example, "the transport of a passenger over 150,000 km". In this approach, all life cycle impacts—from raw material extraction and manufacturing through the vehicle's operational life and final disposal—are aggregated and normalized to a single kilometer of travel. Its prevalence is due to its simplicity, ease of communication, and direct relevance to vehicle-specific metrics like energy consumption (MJ/km) and emissions [27,28,31]. However, the primary and most significant limitation of the v.km functional unit is its failure to consider vehicle occupancy. By normalizing the impacts on the vehicle's movement, a car carrying a single driver is treated as functionally equivalent to one carrying four passengers. This is a critical oversimplification when the broader goal is to assess the environmental efficiency of a transportation system, where the ultimate purpose is to move people, not just the vehicle's mass [32,33].

To address the shortcomings of the v.km unit, many studies have adopted the passenger-kilometer (p.km) as the functional unit [32,34]. This functional unit is considered a more accurate representation of the actual service provided by personal transportation. It is calculated by normalizing the total life cycle impacts by the total distance traveled, multiplied by the average vehicle occupancy rate. As noted by Fernando et al. [32], the p.km unit is essential for any analysis that seeks to compare different modes of transportation, such as a single-occupant private car versus a fully occupied bus or train, as it correctly captures the efficiency gains from shared ridership. It is also the most appropriate functional unit for evaluating the environmental impacts of emerging Mobility-as-a-Service (MaaS) models such as carpooling and ride sourcing, where occupancy levels are a key performance indicator [35,36].

Although v·km has the drawback of not considering vehicle occupancy, about 30% of studies preferred it over p·km. This preference is due to its ability to simplify the comparison of vehicle technologies as products, aligning directly with metrics like energy consumption (MJ/km) and lifetime emissions. It eliminates the need for variable occupancy data, which can be specific to regions or behaviors and challenging to standardize. This unit allows for equitable benchmarking across different types of electric vehicles (e.g.,

BEVs vs. HEVs over lifetimes of 150,000–200,000 km) and aligns with industry standards for efficiency ratings. This alignment facilitates the clear communication of results to policymakers and manufacturers who are more focused on vehicle design than on system-level mobility services.

For other studies, especially those centered on batteries or component-level LCA, functional units may be "per kWh of battery capacity" or "per battery system" [12,37,38]. This functional unit allows for a direct comparison of the cradle-to-gate environmental impacts of manufacturing different battery chemistries (e.g., Lithium Iron Phosphate (LFP) vs. Nickel Manganese Cobalt (NMC)) or producing batteries in different regions with different energy mixes [4,11,39,40].

The choice between v.km, p.km and per kWh of battery capacity is therefore not merely technical; it reflects a fundamental difference in the research question, with the focus on either the vehicle as a product, mobility as a service, or component specific.

The following Table 2 provides a consolidated summary and critical evaluation of the discussed functional units in the literature.

**Table 2.** Typology of Functional Units in EV LCA Studies.

| Specific Unit | Description and Rationale | Advantages | Limitations & Biases | Reference Studies |
|---|---|---|---|---|
| Vehicle-kilometer (v.km) | Normalizes the total life cycle impacts to one kilometer driven by the vehicle. The rationale is to compare the environmental efficiency of the vehicle as a product. | It is simple to calculate and communicate. It is directly comparable to vehicle efficiency metrics. | Vehicle occupancy, which is the primary driver of system-level transport efficiency, is ignored. This can be misleading when comparing personal vehicles to public or shared transportation. | [1,3,24,26,41–44] |
| Passenger-kilometer (p.km) | Normalizes total life cycle impacts to the transport of one passenger over one kilometer. The rationale is to assess the efficiency of providing mobility services. | It accounts for occupancy, providing a more meaningful measure of transport system efficiency. Essential for comparing different modes (car, bus, train) and mobility models (private vs. shared). | Accurate data or assumptions on average occupancy rates are required, which can vary significantly by region, trip purpose, and time of day. | [23,25,32,35,36,45–47] |
| Per kWh of battery capacity | Normalizes cradle-to-gate impacts to one kilowatt-hour of battery storage capacity. Rationale is to compare the manufacturing footprint of different battery technologies | Useful for focused, cradle-to-gate comparisons of battery chemistries, manufacturing processes, or production locations | It ignores critical in-use performance metrics, such as cycle life, energy density, and efficiency, which are crucial for the overall vehicle life cycle performance. This can be highly misleading if used for whole-vehicle comparisons. | [4,11,34,39,40,48–52] |

#### 3.1.2. System Boundaries

Defining system boundaries is a crucial initial step in LCA, as it establishes the scope of the assessment and greatly affects its results and comparability. The selection of boundaries determines which life cycle stages and processes are considered, ranging from raw material extraction to end-of-life.

- Cradle-to-Grave: This is the most comprehensive and common approach, used in 53.7% of the reviewed studies. The cradle-to-grave approach is the most comprehen-

sive, encompassing all life cycle stages from raw material extraction, through manufacturing, distribution, vehicle use (including fuel/electricity consumption and maintenance), to end-of-life (EOL) treatments such as disposal or recycling [53,54]. This approach provides a more complete picture of the vehicle's environmental performance but requires more extensive data collection and modeling [55]. It is frequently recommended for making robust comparisons, as demonstrated by Alexander et al. [27] for ICEVs/BEVs, Rashid et al. [56] for HEVs/PHEVs, and Wong et al. [57] for BEVs/FCEVs. This holistic view is essential for capturing the full environmental profile, especially for BEVs, where manufacturing and EOL impacts are significant. However, some cradle-to-grave studies explicitly exclude EOL stages due to a lack of reliable data [33,37], which can be a significant limitation.

- Well-to-Wheel (WTW): This boundary focuses only on the vehicle's operational life, encompassing fuel/electricity production and vehicle operation. This is often divided into Well-to-Tank (WTT) or Well-to-Plug for electric vehicles, covering fuel/electricity production and delivery, and Tank-to-Wheel (TTW) or Plug-to-Wheel, covering vehicle operation efficiency and direct emissions [58,59]. Many fuel cell electric vehicle LCAs tend to concentrate on the WTW scope, emphasizing fuel production pathways, as seen in the studies by Petrauskienė et al. [42] and Wu et al. [34] for evaluating fuel production pathways. Bekel et al. [60] conducted a well-to-wheel LCA for BEVs and FCEVs, crucially and explicitly incorporating the often-neglected fuel supply infrastructure, including charging stations for BEVs and hydrogen production and distribution networks for FCEVs. Yang et al. [29] defined the total life cycle as including both the vehicle life cycle (material extraction, component production, vehicle assembly, distribution, and disposal/recycling) and the fuel life cycle (fuel production and consumption during use). Burchart-Korol et al. [61] accurately described WTW as a subset of LCA, focusing on the fuel production (WTT) and vehicle operation (TTW) stages, typically emphasizing energy consumption and greenhouse gas emissions, while excluding vehicle manufacturing, maintenance, and end-of-life impacts. This distinction highlights the importance of choosing system boundaries that suit the specific research question; WTW analysis alone is inadequate for developing a complete environmental profile of vehicle technology but can be useful for comparing fuel pathways.

Other system boundaries include the Cradle-to-Gate, which is often used solely for the manufacturing phase and is the least used in terms of system boundaries [57], while the cradle-to-cradle concept represents a closed-loop system where EOL products are ideally fully recycled or remanufactured into new products of similar or higher value, minimizing waste, as highlighted in studies such as Liu et al. [62], which incorporated EOL recycling for batteries. Proper recycling of EV batteries can recover valuable materials and reduce the need for virgin resource extraction, thereby mitigating environmental impacts [54]. Figure 3 provides a comprehensive illustration of a vehicle's life cycle, breaking it down into main phases and defining various scopes for environmental assessment.

Studies have shown that battery remanufacturing through recycled materials can reduce carbon emissions by 51.8% compared to battery production with virgin materials [50,53]. Future research should investigate the cradle-to-cradle approach as we advance towards achieving circularity in the economy.

The Table 3 below provides a summary of the boundary type, its advantages, and limitations.

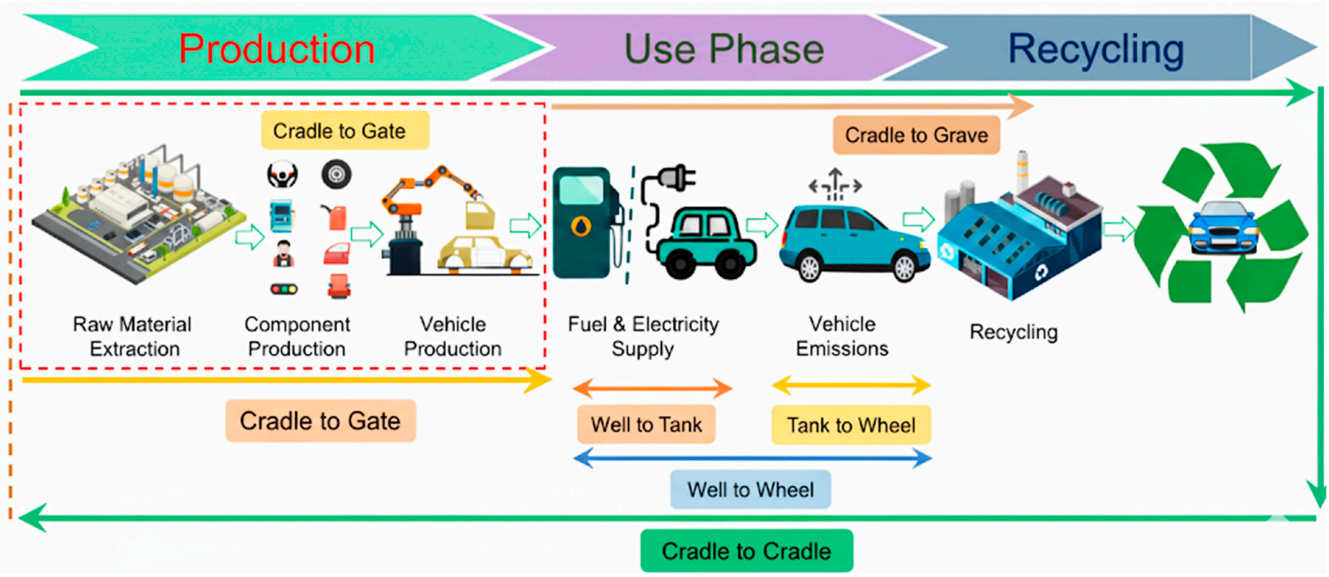



**Figure 3.** Phases and System Boundaries in a Vehicle's Life Cycle Assessment (LCA).

**Table 3.** Summary of System Boundary Types in Electric Vehicle LCA Studies.

| Boundary Type | Scope | Advantages | Limitations | Reference Studies |
|---|---|---|---|---|
| Cradle-to-Grave | Raw materials extraction to end of life | Comprehensive assessment; captures all life cycle stages | Data intensive; higher uncertainties | [27,53,55,56,63] |
| Well-to-Wheel | Focuses on fuel/electricity production and vehicle operation | Highlights the environmental impact of energy carriers | Vehicle manufacturing and end-of-life impacts were excluded. | [24,58–61,64] |
| Other System boundaries | Cradle-to-Gate, end of life analysis | Focuses on manufacturing or recycling impacts; also requires less data | Excludes use phase impacts during modeling of end-of-life scenarios. | [50,57,62] |

#### 3.1.3. Attributional vs. Consequential LCA

EV life cycle studies can be performed using either an Attributional LCA (ALCA) approach, which assesses the average impacts of producing and using an EV in the current context, or a Consequential LCA (CLCA) approach, which examines how impacts would change due to changes in the input parameters of LCA studies [65]. In practice, most LCA's studies reviewed used an attributional approach and typically modeled a single vehicle life cycle with average background processes [15,66,67]. This is appropriate for comparisons between vehicle types under consistent assumptions.

The consequential LCA of EVs is more common in research exploring future scenarios or system-level effects (for instance, studies that consider how the power grid expansion driven by EVs charging might alter the emissions outcome) [30,68,69]. A review by Eltohamy et al. [33] and Das et al. [70] pointed out that the handling of marginal electricity sources is a key methodological divergence among EV LCAs, essentially an ALCA vs. CLCA debate on electricity. Some studies assumed the current grid (attributional, location-based) [24,61], while others assumed a future cleaner grid or a marginal plant (consequential) [62,71,72]. The lack of harmonization leads to different conclusions regarding EV benefits. For example, using a static average grid in a coal-heavy region might show

a high use-phase impact, whereas a consequential view might argue that new renewable capacity would come online for EVs, lowering that impact [24].

In summary, while attributional LCAs dominate current practice for EVs and provide answers to the question, "what is the footprint of this vehicle?", consequential LCAs are employed for questions like "what if a million EV are added to the grid?" or "what policy would achieve the most GHG reduction?"

### 3.2. Life Cycle Inventory (LCI)

In the reviewed papers, the authors predominantly relied on a limited number of well-established life-cycle inventory (LCI) and impact assessment databases. The selection of these databases typically hinges on three factors: (1) the regional availability of high-quality data, (2) the extent of coverage for specific materials, such as battery-grade metals, and (3) their compatibility with life cycle assessment (LCA) software such as SimaPro, GaBi, and OpenLCA.

#### 3.2.1. LCI Databases

Researchers predominantly rely on a few well-established LCI databases. The most prominent databases identified are:

- Ecoinvent: As the most widely used database, appearing in 64.3% of studies, Ecoinvent is often considered the gold standard for LCI data due to its global applicability and comprehensive coverage of all life cycle stages [7,73]. Most academic studies rely on Ecoinvent for processes such as battery cell manufacturing, material production (steel and aluminum), and vehicle components. Its prominence is reinforced by its availability on all major LCA software platforms. Different versions are cited in the literature, reflecting its continuous updates (e.g., v2.2, v3.2, v3.8) [61,73,74]. Ecoinvent is a cornerstone of EV LCA modeling, providing the high-quality background data necessary for robust assessments.
- GREET Model: Although also a software tool, the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model functions as a critical LCI database, particularly for transportation-focused studies. Developed by the U.S. Department of Energy's Argonne National Laboratory, which serves as a benchmark for well-to-wheel analyses in North America [64], GREET contains embedded data for battery manufacturing, electricity generation pathways, and material production. It is frequently used to model the use phase and fuel cycle [23,57,75].
- GaBi Databases: The GaBi databases, developed by Sphera, are another major LCI source, known for being industry-driven and containing detailed proprietary process data from corporate partnerships. These databases offer strong coverage of industrial processes, such as plastics production and specific automotive manufacturing steps, making them a common choice for confidential industry reports [76].
- Regional Databases: Researchers often supplement global databases with localized ones to improve regional accuracy. The European Life Cycle Database (ELCD) provides open-access data for processes within the European Union [64]. Similarly, studies focused on China frequently use the China Life Cycle Inventory Database (CLCD) to access more precise data for Chinese industrial processes and regional electricity grids [53].

A primary concern with databases is that the fast-paced advancements in electric vehicles and their components can quickly render database entries obsolete. For instance, there have been significant improvements in battery energy density and manufacturing efficiency in recent years, which could potentially lessen production impacts [12,37]. However, most databases typically take about a year to update and reflect these changes. Addition-

ally, databases might not fully capture the variety in battery chemistry, manufacturing methods, or photovoltaic technologies [11,39,77]. This issue is particularly relevant for new technologies like VIPV, which may not be specifically included in current databases. Furthermore, production impacts can differ greatly between regions due to variations in electricity sources, manufacturing techniques, and environmental regulations. Many databases offer global data or concentrate on specific areas, which might not accurately reflect the production data of new manufacturing processes, technologies, and new production centers [78]. To overcome these challenges, researchers often enhance database entries with primary data from manufacturers and the literature. However, this method can introduce further uncertainties and may affect the comparability of the studies. Utilizing multiple databases or combining database information with primary data can improve the representativeness and reliability of the LCA results.

Table 4 compares the main databases used in the LCA studies of electric vehicles, highlighting their coverage, strengths, and representative studies.

**Table 4.** Comparison of Life Cycle Inventory (LCI) Databases Used in Electric Vehicle LCA Studies.

| Database | Geography Coverage | Access Type | Key Strength | Limitation | Use in EV | Representative Study |
|---|---|---|---|---|---|---|
| Ecoinvent | Global coverage (datasets for key countries) | Commercial (paid license; academic and professional options) | Large, transparent LCI database (>18 k datasets) covering diverse sectors; regularly updated (v3 series); offers multiple system models (Attributional "cut-off" and Consequential) | Ecoinvent data can be slightly Euro-centric in certain processes (owing to its roots). | Most widely used database in EVs LCA. It provides background data on battery materials, energy supply, and manufacturing processes. Valued for consistency and detail; cited as having strong completeness and documentation. Underpins the majority of academic EV LCAs (usually via SimaPro or OpenLCA). | [24,26,43,61,79–81] |
| GREET | North America | Free (data comes with GREET model download) | Detailed pathways for petroleum fuels, biofuels, electricity generation, and some vehicle material production; focused on energy use, GHGs, and air pollutants | Not a standalone database for full impact LCA (limited impact categories), but a crucial source for transport energy LCI. | Provides well-to-wheel GHG values that are used as benchmarks in policy discussions. Frequently tapped for EV LCA use-phase and production-phase energy/GHG data. | [48,57,80] |
| GaBi database (Sphera) | Global with regional specificity (many datasets tailored to EU, US, China, etc., plus global averages) | Commercial (bundled with GaBi software; subsets available for purchase in OpenLCA) | Extensive LCI database (~15 k datasets) developed with industry input; strong coverage of industrial processes, materials, and region-specific data; updated regularly, aligned with ISO/PEF requirements. | It is less frequently seen in literature due to proprietary nature but recognized as a key data source for EV manufacturing. | Widely used in industry EV LCAs (automotive companies, suppliers) for detailed modeling of vehicle components. Contains auto-specific data (e.g., painting, machining) often not in other | [53,62,76,82,83] |
| Regional Customization (ELCD, CLCD) | Europe, China | Open Access | Region-specific datasets are designed to address regional or local conditions, such as grid mixes and usage patterns. | Its strength is also its weakness. Not widely used for global study. | Provides regional average data (e.g., electricity grid, fuel production, basic materials) which can improve regional accuracy for region-based EV LCAs. | [11,20,84–87] |

#### 3.2.2. LCA Software

LCA software tools facilitate the modeling, calculation, and interpretation of life cycle assessment studies by providing user interfaces, databases, and computational capabilities [55]. The choice of tool can influence study outcomes and reproducibility. Several

software tools were used for conducting LCA studies in the reviewed studies, and the identified software are presented in Figure 4 below.

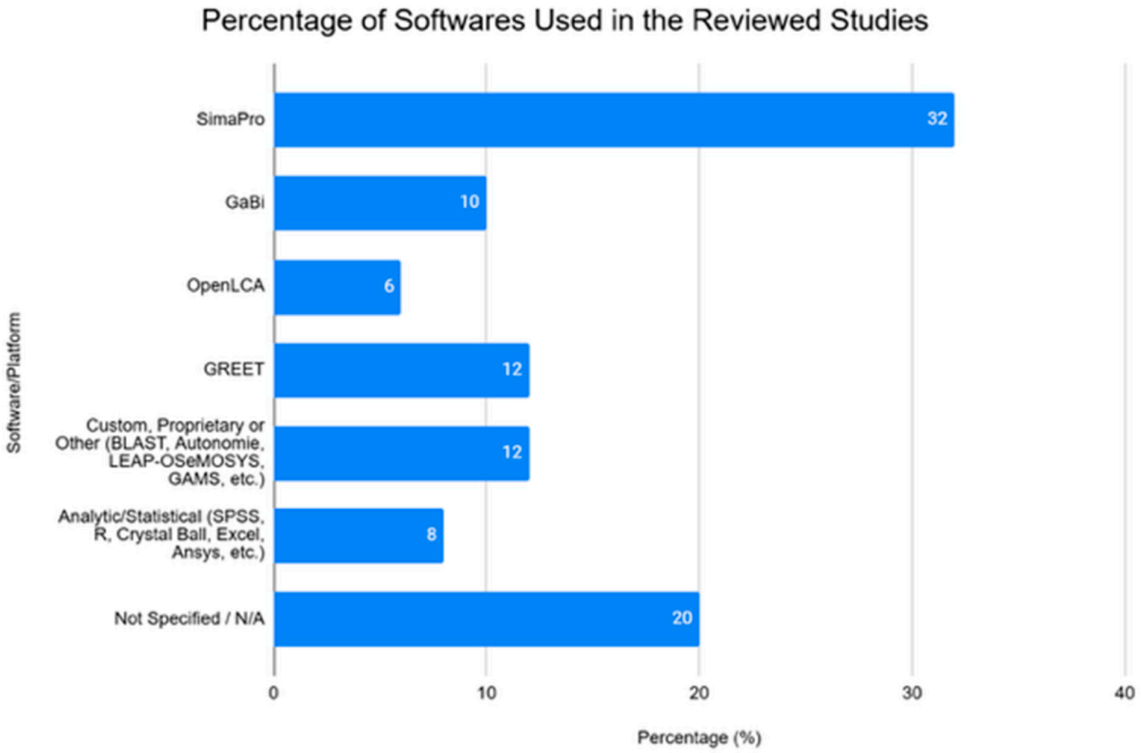



**Figure 4.** Showing the frequency of software usage in the reviewed literature.

- SimaPro: This software was the preferred tool for comprehensive process-based LCAs and was used in 32% of the reviewed studies. It offers compatibility with leading databases like Ecoinvent and a broad suite of impact assessment methods. Its ability to handle multi-stage, multi-impact analyses and Monte Carlo-based uncertainty assessments is often highlighted [19,45,88].
- GaBi: A popular choice, particularly in European and industry-focused research, due to its robust interface and integrated, industry-backed database. It is frequently applied in studies with a strong manufacturing or automotive material focus [74,82].
- GREET Model: This model from the Argonne National Laboratory is widely used for North American, fuel cycle, and well-to-wheel studies due to its specific focus on transportation energy systems and detailed fuel pathway modeling [57,85].
- OpenLCA: An open-source tool that is increasingly adopted in academic studies, especially where flexibility, cost, and integration with custom methods or regional databases are priorities [7,42,43].
- Specialized or Custom Tools: Several studies employed specialized software for specific tasks, such as Autonomie and BLAST for vehicle and battery dynamic modeling [53,89], or statistical software to supplement LCA calculations with scenario modeling and probabilistic uncertainty estimation [3,28,84,89].

Notably, 20% of the studies did not specify the tools used. The critique by Yang et al. [29] regarding the limitations of commercial software suggests that they encountered practical issues related to this lack of transparency and control. The frequent omission of explicit references to specific LCA software and its version in the methods sections of numerous LCA studies can substantially impede the reproducibility and verification of research outcomes. Different software packages, or even varying versions of the same software, may implement LCIA methods, manage allocation procedures, model EoL

scenarios, or conduct certain background calculations in subtly distinct manners. Therefore, it is recommended that every published LCA study should include a dedicated "Tools & Data" subsection stating the software name, version number, database versions, and any custom scripts or macros used. Table 5 compares the main software tools used in LCA studies of electric vehicles, highlighting their features, databases, and user interface.

**Table 5.** Comparison of the main software tools used in LCA studies of Electric Vehicles.

| Name | Main Features | Regional Coverage | Licensing Model | Applications in EV LCA | Reference Study |
|---|---|---|---|---|---|
| SimaPro | Commercial LCA software with comprehensive process modeling and scenario analysis; includes extensive built-in LCIA methods (ReCiPe, CML, TRACI, etc.); supports import of multiple databases (Ecoinvent, Agri-footprint, etc.) | Global use (widely in Europe, North America, Asia); database content primarily global/EU but user can model any region | Proprietary (commercial license) by Pre-Sustainability | Widely used in academic and industry EV studies for full cradle-to-grave analysis; often paired with Ecoinvent to assess EV vs. ICEV impacts (production, use-phase emissions, EoL). | [19,45,88] |
| GaBi | Commercial LCA software and integrated LCI database; strong industry focus with detailed datasets (~15 k); robust scenario and parameter features; supports major impact methods | Global use (common in Europe & industry worldwide); database with region-specific processes (Europe, US, Asia, etc.) | Proprietary (commercial license) by Sphera | Standard tool in automotive industry LCAs used for vehicle component and material LCAs with GaBi database (high detail on manufacturing). It is typically used to model the entire vehicle supply chain and compare design alternatives. | [74,82] |
| OpenLCA | Open-source LCA software; flexible and extensible (scripting, plugin support); no built-in data but can import many databases (ecoinvent, GaBi, etc.); transparent calculation logs | Global (users worldwide; relies on imported data for region-specificity) | Free (GPL open-source) by GreenDelta | It has been used in numerous EVs LCA case studies. Enabled low-cost studies of EVs vs. ICE (e.g., using Ecoinvent data). It is often chosen for its transparency and modifiability in studies examining battery production, charging scenarios, etc. The second most used software in some reviews. | [7,42,43] |
| GREET | Specialized LCA tool for transportation energy and emissions; provides parameterized models of fuel production, vehicle operation, and vehicle manufacturing energy use; outputs GHG, regulated pollutants, energy consumption | Primarily U.S.-focused data (models for US grid, fuels; some international versions like CA-GREET) | Free (publicly available; not fully open-source but free Excel/Standalone) by Argonne National Laboratory | It is commonly used for EV well-to-wheel GHG analysis and policy studies in North America. Frequently integrated into EV LCA for use-phase, such as calculating electricity generation emissions or fuel cycle impacts. | [57,76,85] |
| Custom Models/Spreadsheets | Varies | Customized | GAMS with CPLEX solver; LEAP-OSeMOSYS; COPERT; TISC platform | These tools are used for specific tasks like modeling operations or analyzing policy scenarios. | [3,28,53,88–90] |

### *3.3. Life Cycle Impact Assessment (LCIA)*

Life Cycle Impact Assessment (LCIA) provides a structured approach to translate Life Cycle Inventory (LCI) flows into potential environmental impacts. For electric vehicles, LCIA plays a vital role in determining sustainability trade-offs across climate change, resource use, toxicity, and air pollution. However, the methodological diversity in LCIA introduces variability in the results and their interpretability. The reviewed literature revealed that researchers have adopted a range of LCIA methods depending on geographical scope, regulatory context, and targeted environmental concerns. This diversity leads to what may be described as "methodological pluralism", which, while allowing for tailored assessments, poses challenges for cross-study comparability.

- ReCiPe: Among the reviewed studies, ReCiPe—particularly ReCiPe 2016—was the most widely adopted LCIA model, used in approximately 50% of the papers. It supports both midpoint and endpoint assessments and provides detailed indicators for global warming potential (GWP), acidification, eutrophication, human toxicity (cancer and non-cancer), and resource depletion. ReCiPe is notably favored in studies due to this harmonized and comprehensive framework [41,91,92].
- CML: The CML 2001/2002 method accounts for around 20% of applications and is especially prevalent in older or region-specific LCAs. It is valued for its focus on scientifically robust midpoint categories such as abiotic depletion (ADP), acidification, and eutrophication. Notably, Dér et al. [31] and Zhang et al. [58] relied on this method for resource-oriented analyses.
- IPCC GWP 100a: Studies that prioritized climate change frequently employed IPCC GWP (100-year horizon) factors alone—comprising about 15% of the sample. This was especially common in assessments focused on specific fuel pathways (e.g., hydrogen) where broader impact categories were deemed less relevant [84,88]. While this approach is simple and transparent, it may underrepresent environmental trade-offs by excluding pollutants beyond $CO_2$, $CH_4$, and $N_2O$.
- Other Specialized Methods: Approximately 15% of the studies applied specialized or hybrid approaches. Navas-Anguita et al. [92] used IMPACT 2002+ to assess endpoint indicators such as human health and resource scarcity, while Pinto-Bautista et al. [93] relied on ILCD Midpoint 2011+.

Although the availability of multiple LCIA methods provides flexibility, it can also lead to inconsistencies. For example, studies using ReCiPe and CML may report significantly different outcomes for categories like human toxicity due to differences in characterization factors. This inconsistency creates interpretive challenges for policymakers and highlights the need for transparent justification and consistent reporting across LCA studies. Table 6 provides a summary of the LCIA methods used in the studies reviewed.

**Table 6.** Summary of Life Cycle Impact Assessment (LCIA) Methods in Electric Vehicle LCA Studies.

| LCIA Method | Model Type | Usage Frequency | Key Impact Categories | Geographical Focus | Strengths | Limitations | Representative Studies |
|---|---|---|---|---|---|---|---|
| ReCiPe 2016 (Midpoint & Endpoint) | Midpoint & Endpoint | ~50% | GWP, Acidification, Eutrophication, Human Toxicity, Particular Matter, Land Use, Water Use | Global | Comprehensive; supports midpoint and endpoint views; widely used | Complex; endpoint results involve subjective value choices; gaps for certain critical metals | [11,34,60,80,91] |
| CML 2001/2002 | Midpoint | ~20% | GWP, Acidification, Eutrophication, Human Toxicity, | Global | Robust midpoint framework; well-established in academia | No endpoint modeling: resource indicators may not reflect criticality | [31,94] |
| IPCC GWP 100a | Midpoint (Climate Only) | ~15% | Global Warming Potential ($CO_2$, $CH_4$, $N_2O$) | Global | Transparent and focused; ideal for single-impact studies | Narrow scope; excludes non-GHG pollutants like $NO_x$, PM | [24,29,42,95] |
| Custom Midpoints | User-defined | ~15% | GWP, Water Scarcity, Sulfuric Acid Emissions, Heavy Metal Toxicity | Context-specific | Addresses region- or process-specific concerns not captured by standard methods | Lacks comparability unless normalized and transparently defined | [68,96] |

### *3.4. Interpretation*

The final LCA phase involves evaluating the results to draw robust conclusions. This includes assessing the certainty of the results and synthesizing key findings.

#### 3.4.1. Uncertainty and Sensitivity Analysis

A crucial element of Life Cycle Assessment (LCA) studies is constituted by uncertainty analysis, which permits researchers to assess the robustness of their results through an exploration of how variations in key parameters, assumptions, or scenarios may impact environmental outcomes. Among the studies reviewed, approximately 59.5% were found to have explicitly included such an analysis, a fact that highlights a broad recognition of its importance. In contrast, 40.5% of the studies either omitted this analysis or failed to report it explicitly. Several established methods employed for this purpose are discussed below.

- Sensitivity Analysis: This was the most accessible and frequently applied method. It is designed to gauge the extent to which variations in key factors affect the aggregate results. The key parameters that were most frequently analyzed include the carbon intensity of the electricity grid [82,84,97], the lifetime and degradation rates of the battery [49,53,81], and the operational characteristics of the vehicle, such as annual mileage and energy consumption [29]. Figure 5 shows the frequency of the range of parameters found in the reviewed studies, which reflects the multi-dimensional nature of EV sustainability. However, sensitivity analysis typically employs one-at-a-time methods and does not capture interactions among parameters, limiting its scope for complex systems [98].

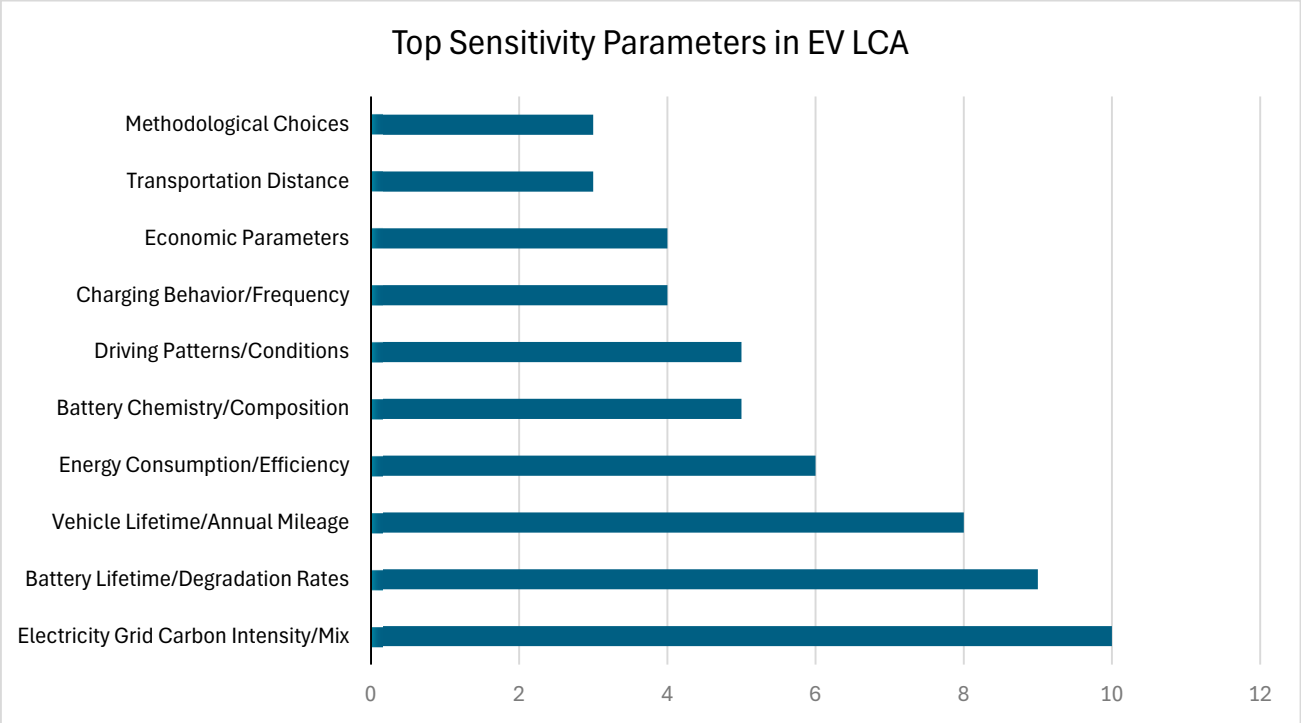



**Figure 5.** Sensitivity Parameter in EV LCAs.

- Scenario Analysis: This approach is designed to address deeper, structural uncertainties through the modeling plausible future conditions, such as changes in the energy mix, technological advancements, or behavioral shifts. Scenario-based studies typically explore discrete "what-if" conditions, particularly focusing on future energy system transitions and policy pathways [92]. Various studies have applied scenario analysis to evaluate the potential effects of evolving electricity grids, extended BEVs lifespans, and different charging behaviors on GHG emissions [58,62,71,72,99,100]. Although this method supports strategic planning for different future scenarios, it relies heavily on expert assumptions and lacks probabilistic rigor.

- Monte Carlo Simulation: This is recognized as the most statistically robust approach as it propagates input uncertainties through the LCA model by utilizing defined probability distributions, thereby yielding confidence intervals and probabilistic results [60,61]. For EV LCAs, Monte Carlo has been used to iterate battery composition uncertainty [79] and compare alternative fuels for EVs [101,102]. Despite the deeper insights afforded by this method, its considerable demands with respect to data and computational resources have limited its widespread adoption [61].

Each of these methods contributes in a distinct manner to the understanding of uncertainty, and it is suggested that their complementary application is often ideal for a comprehensive interpretation of the results of an EV LCA. Table 7 provides a summary of the uncertainty analysis of EV LCA studies.

**Table 7.** Summary of Uncertainty Analysis Methods and Their Characteristics in EV LCA Studies.

| Method | Description | Strengths | Limitations | Representative Studies |
|---|---|---|---|---|
| Parameter-Specific Sensitivity | Varies key input variables individually to assess impact on results | Easy to implement; identifies key influencing variables | Ignore parameter interactions; not probabilistic | [39,49,53,81,84,97] |
| Scenario Analysis | Evaluates future pathways or regional changes (e.g., electricity mix, battery tech, vehicle use) | Captures systemic and structural uncertainties; policy-relevant | Depends on expert assumptions; lacks statistical quantification | [58,62,71,72,99,100] |
| Monte Carlo Simulation | Uses random sampling from input distributions to estimate output uncertainty | Provides probabilistic results; captures interactions | Data- and computation-intensive; requires defined distributions | [60,61,79,101,102] |
| Other/Implicit Methods | Includes pedigree matrices, expert elicitation, or qualitative discussions | Specific to a domain or use case | Usually not reproducible | [78,87,103] |

Sensitivity and scenario analyses were prevalent in uncertainty analysis within the reviewed electric vehicle life cycle assessment studies, with an inclusion rate of 59.5%. This prevalence is attributed to their simplicity, minimal data requirements, and capacity to isolate key parameters, such as grid carbon intensity or battery lifetime, without necessitating comprehensive probability distributions. In contrast, Monte Carlo simulations, although robust in generating probabilistic outputs and analyzing parameter interactions, were less frequently employed (under 20% usage). This is due to their requirement for detailed data input, and high-quality uncertainty data, which is often unavailable for emerging EV technology like VIPV, and significant computational power, increasing the study complexity and time. Consequently, this resource intensity limits their adoption in resource-constrained academic environments, despite their suitability for policy-relevant EV fleet projections.

#### 3.4.2. Synthesis of Key Findings by Technology

The interpretation of LCA results consistently shows that the environmental benefits of EV are highly context dependent. While a detailed summary of every study was beyond the scope of this review, a synthesis of the consensus findings for each technology is presented below.

- Battery Electric Vehicles: BEVs operate exclusively on electric motors and rechargeable batteries, resulting in zero tailpipe emissions. Their life cycle impacts are distinguished by a significant upfront environmental burden from the energy- and carbon-intensive

manufacturing of their components, particularly the lithium-ion battery, which creates a substantial "embodied" carbon footprint [25,75]. However, multiple life cycle assessments have demonstrated that this initial production impact is ultimately offset by the high operational efficiency of the vehicle, provided that the electricity used for charging is derived from low-carbon sources [25,76]. The extent of the life cycle benefit is, therefore, critically contingent upon the carbon intensity of the regional electricity grid; in regions with predominantly renewable energy, GHG emission reductions may be as high as 90% relative to conventional vehicles [13,77], whereas in coal-dependent grids, the life cycle emissions of a BEV can be comparable to those of a gasoline vehicle [63,77–79]. The initial manufacturing impacts are being progressively mitigated through advancements in battery technology and the adoption of circular economy principles, such as the extensive recycling of battery materials, which has been shown to significantly reduce both cumulative carbon emissions and the demand for virgin raw materials [12,38,39,65,79].

- Plug-in Hybrid Electric Vehicles: PHEVs are constituted by a powertrain that integrates a battery-powered electric drivetrain with a conventional internal combustion engine. Due to their dual reliance on both electricity and liquid fuel, PHEVs occupy an intermediate position in life cycle assessment terms; their environmental performance is generally superior to that of conventional ICEVs, yet they do not typically achieve the low-emission profile characteristic of pure BEVs under most scenarios [43,53]. The comparatively smaller battery capacity in a PHEV, relative to that of a BEV, serves to reduce the environmental impacts associated with the manufacturing phase [48,54]. The environmental performance of PHEVs is exceptionally sensitive to their operational parameters, particularly their use and charging patterns. A critical determinant in this regard is the carbon intensity of the electricity grid, in conjunction with the proportion of total distance traversed utilizing electric power as opposed to the internal combustion engine. The greatest $CO_2$ savings are realized when PHEVs are operated predominantly on electricity from a clean grid [32,53,56]. Conversely, in regions characterized by a carbon-intensive electricity grid, or where gasoline engines are frequently used, the relative environmental benefit is markedly diminished [24,40,57]. Although certain exceptional scenarios have been noted wherein an efficient PHEV engine coupled with high-carbon electricity could result in emissions comparable to a BEV, such cases underscore the principle that electricity from carbon-intensive sources can neutralize the advantages of electric operation [34]. Consequently, the optimal application for PHEVs is frequently posited as a transitional technology, particularly when powered by low-carbon electricity and sustainable biofuels [53,56,58]. While studies have reported that PHEVs achieved lower lifetime fuel consumption and emissions than comparable non-plug-in vehicles [40,48,57], their ultimate impact remains contingent upon charging behavior and energy sources.
- **Hybrid Electric Vehicles:** HEVs, which are distinguished as non-plug-in hybrids, are equipped with a comparatively small battery and electric motor that function in concert with an ICEV. The state of charge of battery is maintained exclusively through regenerative braking and the operation of the engine, as these vehicles are not designed to be charged from an external electrical grid [44]. From a life cycle assessment perspective, the manufacturing impacts associated with HEVs are found to be marginally greater than those of a conventional vehicle, an increase attributable to the inclusion of supplementary components such as battery, electric motor, and power electronics [48]. The principal environmental advantage of HEVs is realized during the use phase and is manifested as a reduction in fuel consumption. Through the strategic alternation between electric drive assistance and engine operation, in

conjunction with the capture of energy via regenerative braking, HEVs can achieve a substantial reduction in the consumption of gasoline or diesel per kilometer, which corresponds to a direct and proportional decrease in tailpipe $CO_2$ and pollutant emissions [41]. Within a cradle-to-grave assessment, it is consistently observed that the well-to-wheel fuel cycle is accountable for approximately 80 to 90 percent of the total energy consumption and greenhouse gas emissions, with the manufacturing and end-of-life phases contributing only a minor fraction [41,44,48]. Therefore, although HEVs may contribute to an enhancement of urban air quality and a reduction in GHG emissions relative to conventional vehicles, they do not effectuate the complete elimination of said emissions; rather, they are to be understood as a mitigating technology as opposed to a zero-emission solution [41]. Although the end-of-life management of the battery is crucial for recovering valuable materials [45,51,52], projections indicate that HEVs will likely need to be superseded by 2050 to achieve stringent long-term climate objectives [45].

- Fuel Cell Electric Vehicles (FCEVs): FCEVs are propelled by an electric motor, a characteristic shared with BEVs; however, their mode of energy storage is distinct, as they generate electricity in situ using a hydrogen fuel cell rather than relying on a large-capacity battery. The manufacturing of an FCEV entails the fabrication of several specialized and energy-intensive components, including the fuel cell stack, which frequently incorporates precious metals such as platinum as catalytic agents, and high-pressure hydrogen storage tanks, which are typically reinforced with carbon fibers [34,59]. The preponderant environmental impacts associated with FCEVs are not localized to the vehicle's operational phase of zero tailpipe emissions but are primarily situated within the "well-to-tank" stage, which encompasses the production and distribution of hydrogen fuel [61,62]. It is a matter of critical significance that the environmental performance of an FCEV is overwhelmingly contingent upon the method by which its hydrogen fuel is produced [45,59]. Currently, the predominant method for hydrogen generation is steam methane reforming of natural gas, a process heavily reliant on fossil fuels that yields what is commonly termed "gray" hydrogen. The use of such hydrogen precludes FCEVs from achieving their optimal environmental potential due to substantial upstream emissions [63,64]. Conversely, a remarkable degree of environmental performance can be achieved through the utilization of low-carbon hydrogen. In scenarios where hydrogen is derived from 100 percent renewable electricity, the cradle-to-grave GHG emissions of an FCEV can approach a value of zero, which is analogous to that of a BEV charged with renewable energy [63,64]. The end-of-life phase, which involves the recycling of fuel cell stacks and recovery of precious metals, can further augment the life cycle benefits of FCEVs [62]. The literature consistently underscores that the decarbonization of the hydrogen supply chain is of pivotal importance for rendering FCEVs environmentally competitive [45,62].
- Solar-Powered Vehicles (SPVs)/Vehicle-Integrated Photovoltaics (VIPV): A novel technological development in the domain of sustainable transportation is the integration of solar photovoltaic (PV) panels directly onto vehicle surfaces to provide onboard renewable electricity [63]. VIPV entails the incorporation of PV modules into the body of a vehicle, which enables the generation of a portion of its own requisite energy. The addition of PV cells to a vehicle augments the manufacturing footprint because of the energy consumption and associated emissions involved in solar panel production [65,66]. The determinative trade-off within the life cycle assessment is a function of the quantity of solar energy that the system produces over its operational lifetime, thereby offsetting grid electricity or fuel consumption, in comparison to the manufacturing and added weight penalties of the PV system itself. If the vehicle-integrated PV

system generates a substantial amount of electricity, it has the potential to compensate for the production emissions of the solar hardware by displacing energy that would otherwise be sourced from the grid. Conversely, if a minimal quantity of electricity is generated, the embodied impacts may outweigh the operational benefits [67,68]. Studies have indicated that the benefits of VIPV are maximized under conditions of high solar irradiance and in regions served by carbon-intensive electricity grids [66,69–71]. The $CO_2$ payback period for a vehicular PV system may be on the order of a decade under typical conditions but can be significantly shorter in sunnier locales with carbon-intensive grids [66,70]. As of 2025, SPVs and VIPV systems are predominantly in the pilot or prototype stages, however, they represent an innovative supplement that may enhance the ecological profile of EVs, particularly in regions with high solar insolation. Table 8 provides a summary of LCA finding by vehicle technology.

**Table 8.** Summary of Life Cycle Assessment Findings by Vehicle Technology.

| Vehicle Technology | LCA Summary | Cited References |
| --- | --- | --- |
| Battery Electric Vehicle | Characterized by high manufacturing emissions (embodied carbon), particularly from the battery, but very low use-phase emissions. The overall life cycle benefit is critically dependent on the carbon intensity of the electricity grid used for charging. Circular economy principles, such as battery recycling, are crucial for mitigating initial impacts. | [12,13,25,38,39,65,75–79] |
| Plug-in Hybrid Electric Vehicle | It occupies an intermediate position between BEVs and ICEVs. Performance is highly sensitive to user charging behavior and the carbon intensity of the regional electricity grid. They have lower manufacturing impacts than BEVs due to their smaller batteries, but retain tailpipe emissions from ICE. It is often considered a transitional technology. | [24,32,34,40,43,48,53,56–58] |
| Hybrid Electric Vehicle | The principal environmental benefit is a 15–30% reduction in fuel consumption during the use phase. The well-to-wheel fuel cycle dominates its life cycle impact (80–90%). It is a mitigating, not a zero-emission, technology and is projected to be phased out to meet long-term climate goals. | [41,44,45,48,51,52] |
| Fuel Cell Electric Vehicle | It exhibits zero tailpipe emissions, but its life cycle performance is overwhelmingly dependent on the hydrogen production pathway (“well-to-tank” stage). The use of “green” hydrogen can result in near-zero life-cycle emissions, whereas “gray” hydrogen from fossil fuels offers limited benefits over efficient ICEVs. | [34,45,59,61–64] |
| Solar Powered Vehicle/Vehicle Integrated Photovoltaic | This nascent technology balances the LCA trade-off with the added manufacturing footprint of PV panels against the avoided emissions from displaced grid electricity. The benefits are maximized in regions with high solar irradiance and carbon-intensive electricity grids. | [63,65–68,70,71] |

## 4. Conclusions

This systematic review has consolidated methodological practices in recent life cycle assessments of electric vehicles, identifying significant trends in objectives, inventories, impact assessments, and interpretations that influence environmental outcomes. Key findings revealed the dominance of comparative cradle-to-grave studies, accounting for 70% of analyses, which utilized vehicle-kilometer functional units. There was a notable reliance on the Ecoinvent (64.3%) and GREET databases for inventory data, and the ReCiPe method was frequently employed in impact assessments, appearing in 50% of cases. Additionally, uncertainty handling was uneven, with 59.5% of studies incorporating analyses, predominantly sensitivity-based. These findings highlight the context-specific nature of EV benefits: battery electric vehicles perform optimally on low-carbon grids with enhanced batteries, hybrids act as transitional technologies, and fuel cell EVs depend on the availability of

green hydrogen. Furthermore, the review identifies gaps in research on vehicle-integrated photovoltaics (VIPV) and solar-powered vehicles (SPVs), which offer potential irradiance-dependent advantages as energy grids evolve.

In addressing the objectives delineated in Section 1 of the review, the analysis of goal and scope definition confirmed a predominant focus on comparative electric vehicle technologies, including BEVs, PHEVs, HEVs, and FCEVs, with cradle-to-grave boundaries present in 53.7% of the studies. Attributional modeling was found to be more prevalent than consequential approaches, although the latter remains crucial for policy scenarios such as the impacts of grid expansion. Regarding life cycle inventory, the Ecoinvent database was identified as the primary resource in 64.3% of the reviewed articles with Simapro as the leading software and was often supplemented by GREET and regional sources like ELCD, highlighting the necessity for updated, localized data to accurately reflect advancements in electric vehicle technology. Life cycle impact assessment practices predominantly employed ReCiPe (50%) and CML (25%) methodologies to translate inventories into impact categories such as climate change and resource depletion, revealing methodological divergences which impede direct synthesis and comparison across studies. Finally, in the interpretation phase, uncertainty analysis was inconsistently applied across the literature, with only 18% of studies employing probabilistic methods such as Monte Carlo simulations. Most assessments relied on simplified, single-parameter sensitivity tests, which are insufficient for modeling complex, interacting variables within the system.

Key challenges and proposed directions:

- Database timeliness and transparency: Rapid changes in battery technology and electricity systems can outpace inventory updates; future work should make temporal assumptions explicit, use dynamic use-phase modeling where relevant, and blend curated secondary data with traceable primary data to reduce bias.
- Regional specificity and interoperability: Limited regional coverage and inconsistent data models hinder comparability; expanding region-resolved datasets and adopting conventions for cross-platform exchange and version control will improve alignment across studies.
- Reporting consistency: Variation in functional units, system boundaries, LCIA choices, and software/database versions complicates synthesis; standardized reporting templates should be used to enable reproducible comparisons and support policy use.
- Uncertainty practice: Many studies rely on one-at-a-time sensitivity or qualitative scenarios; broader use of probabilistic, multi-parameter methods (with transparent sensitivity and scenario analyses) is needed to bound decision-relevant ranges.
- Evidence gaps on VIPV/SPV and circular pathways: Comprehensive LCAs should capture irradiance, duty cycles, added mass, durability, logistics, second-life uses, and recycling under dynamic grid scenarios to inform design and deployment choices.

In practical terms, electrification strategies should be coordinated with grid decarbonization, demand-side management, and smart charging to secure consistent use-phase benefits, while researchers and practitioners should align methods and data to improve comparability and reduce uncertainty as technologies and systems evolve. Taken together, these steps provide a clear path to more reliable, policy-ready EV LCAs and help target research where it can most effectively support sustainable mobility at scale.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| EU | European Union |
| EVs | Electric Vehicles |
| ICEVs | Internal combustion engine vehicles |
| FCEVs | Fuel Cell Electric Vehicles |
| VIPV | Vehicle-Integrated Photovoltaics |
| LCA | Life Cycle Assessment |
| BEVs | Battery Electric Vehicles |
| HEVs | Hybrid Electric Vehicles |
| SPV | Solar-Powered Vehicles |
| GWP | Global Warming Potential |
| ELCD | European Life Cycle Database |
| CLCA | Consequential Life Cycle Assessment |
| ALCA | Attributional Life Cycle Assessment |
| EOL | End of Life |
| WTW | Well-to-Wheel |
| CLCD | Chinese Life Cycle Inventory Database |
| WTT | Well-to-Tank |
| PHEVs | Plug-in Hybrid Electric Vehicles |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| MaaS | Mobility as a Service |
| ISO | International Standard Organization |
| NMC | Nickel Manganese Cobalt |
| TTW | Tank-to-Wheel |
| LFP | Lithium Iron Phosphate |
| GREET | Greenhouse gases Regulated Emissions & Energies use in Technologies |
| USA | United States of America |
| GHG | Greenhouse Gases |

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