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Research Article

Analyzing the Environmental Burden of Electric Vehicle Batteries: A Life Cycle Assessment Synthesis

V. M. M. Swamy[1*], S. Vidyasagar[2]
[1] *Research Scholar, Department of Electrical and Electronics Engineering, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu, India. smitha.mmswamy@gmail.com*
[2] *Professor, Department of Electrical and Electronics Engineering, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu, India. vidyasas@srmist.edu.in*

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ABSTRACT

Introduction: The rapid growth of the EV market and the associated surge in battery demand raise environmental concerns regarding battery production and disposal. While EVs have zero tailpipe emissions, battery production contributes significantly to their overall environmental burden. Life Cycle Assessment (LCA) is a crucial tool for evaluating this impact, but inconsistencies in methodologies across different LCA studies hinder effective comparison and progress towards cleaner battery technologies.

Objectives: The research aims to analyze numerous existing LCA studies on electric vehicle batteries using a standardized approach based on ISO 14040 guidelines. The goal is to ensure consistent comparisons and identify areas for environmental improvement throughout the battery life cycle.

Methods: This review examines 20 relevant LCA studies on single battery models published between 2018 and 2023. It critically appraises these studies based on the ISO 14040 framework, focusing on the four key stages of LCA: defining objectives and scope, conducting inventory analysis, performing impact assessment, and interpreting the results.

Results: The review found significant variability in methodologies, system boundaries (cradle-to-gate vs. cradle-to-grave), functional units, data sources (primary vs. secondary), and impact assessment methods used in the analyzed LCA studies. The production phase and the product use phase were identified as having the most significant environmental impacts. Global warming was the most frequently studied impact category.

Conclusions: The inconsistency in LCA studies on EV batteries necessitates a more standardized approach. The author recommends using a cradle-to-grave system boundary, a consistent functional unit (like "kilometer traveled" or "kilowatt-hour of energy delivered over the battery's lifetime"), and a core set of nine relevant impact categories. Transparency in methodology, assumptions, and data quality is crucial for ensuring reliable and comparable results, ultimately informing efforts to improve the environmental performance of EV batteries.

Keywords: Environment, Electric Vehicle Batteries, Life Cycle Assessment

INTRODUCTION

The fight against air and climate pollution has driven a global surge in electric vehicles (EVs), a key government initiative in recent years [1]. Many countries are actively developing and implementing sustainable transportation technologies, reflected in the booming EV market with sales value growing by up to 30% annually[2]. This rapid adoption translates to a significant increase in electric car users, jumping from a mere 17,000 units globally in 2010 to a staggering 7.2 million units by 2019 [3]. However, alongside this rise in EVs comes a parallel surge in battery demand. While EVs are often touted for their zero tailpipe emissions, a crucial environmental cost lurks beneath the surface – battery production and disposal [4]. Studies reveal a concerning truth: batteries contribute roughly 15% of an EV's total environmental burden, casting a shadow on their overall sustainability claims [5].

LITERATURE REVIEW

Life Cycle Assessment (LCA) has emerged as a key tool to unravel the environmental impact of electric vehicle batteries across their entire lifespan [5]. This meticulous approach considers everything from the extraction of raw materials (the cradle) to the battery's eventual disposal (the grave), including material production, energy use during manufacturing, waste generation, and emissions. However, the effectiveness of LCA for EV batteries is hampered by inconsistencies in how different studies conduct their assessments (as highlighted in [7]). These inconsistencies include the choice of methodology, the reliance on potentially outdated or geographically irrelevant secondary data, and variations in defining the scope of analysis (system boundaries) and the environmental concerns considered (impact categories). This tangled web of approaches, as identified in [7], makes it challenging to definitively compare studies and hinders LCA's ability to guide research and development towards cleaner battery technologies. Furthermore, the lack of standardized methodologies makes it difficult to pinpoint errors or limitations in existing studies.

Within the field of Life Cycle Assessment (LCA), a consistent methodology for analyzing the environmental impact of electric vehicle batteries remains elusive [7]. This lack of standardization manifests in a multitude of approaches employed across various studies. These discrepancies encompass system boundaries (delineating the scope of analysis), functional units (the basis for comparison), data sources, life cycle inventories (compiling environmental flow data), impact categories (areas of environmental concern), and even the chosen assessment methods themselves [7]. Performing a comprehensive LCA on batteries is a complex endeavor. The sheer number of available assessment frameworks and methodologies significantly influences the final results. Furthermore, the practice of relying on data from prior studies, without considering potential variations in geographical location, utilized equipment, and technological advancements, can introduce inaccuracies [7]. This dependence on potentially outdated data can skew conclusions and hinder the effectiveness of LCA in guiding research and development efforts. Researchers have conducted extensive reviews of LCA work on EV batteries, emphasizing the critical need for standardized approaches, particularly regarding the definition of key study aspects like scope, functional units, and impact categories [7].

Several key studies have shed light on the complexities of analyzing electric vehicle batteries through LCA. Ellingsen et al. (2017) pinpoint the significant influence of manufacturing energy demands on a battery's lifecycle greenhouse gas emissions [7]. Their work highlights inconsistencies in earlier reported results, likely due to variations in how energy consumption during cell manufacture and assembly is accounted for.

Pellow et al. (2020) explored a different aspect of the LCA puzzle, focusing on gaps in how existing studies address battery use cases and end-of-life management [8]. Nealer and Hendrickson's research [9] complements this focus on EVs by delving into past findings on the energy use and greenhouse gas benefits associated with electric vehicles.

Nordelöf et al. broaden the scope by reviewing 79 LCAs encompassing hybrid, plug-in hybrid, and battery electric vehicles[10]. While their work doesn't delve specifically into battery technology, it highlights uncertainties surrounding the environmental impact of light vehicles and their usage patterns.

Turning back to battery-centric studies, Peters et al. (2016) offer valuable insights through their review of numerous battery LCAs [5]. They differentiate between studies employing primary data and those relying on secondary sources. Their analysis also explores battery life and roundtrip efficiency in depth. Interestingly, Peters et al. identify variations in how different studies estimate the energy consumption involved in battery manufacturing [5]. However, they acknowledge a lack of detailed explanations for these discrepancies and simply average results from previous studies.

This work delves into a critical review of Life Cycle Assessments (LCA) applied to electric vehicle batteries. While batteries are essential for EVs and a clear distinction from gasoline-powered vehicles, their production has environmental consequences [7]. This energy consumption can offset the climate change benefits EVs offer during their operational phase. To address this gap, this study aims to investigate a comprehensive range of LCA studies on electric vehicle batteries. The framework employed will leverage the ISO 14040 standard and its associated derivatives.

METHODOLOGY

This review draws upon extensive research on electric vehicle battery Life Cycle Assessments (LCA). It specifically examines single battery models and identifies key factors influencing production processes and raw material selection. By analyzing data from the past six years (2018-2023), as detailed in Table 1, the review focuses on 20 relevant studies to inform its conclusions. This review offers a critical appraisal of Life Cycle Assessments (LCA) applied to electric vehicle (EV) batteries, grounded in the internationally recognized ISO 14040 standard and its associated guidance documents. The analysis acknowledges the distinct characteristics of EV batteries and critically examines the comparative methodologies employed in prior research. Adhering to the established LCA framework outlined in SNI ISO 14040:2016 and SNI ISO 14044:2017, adopted by the Indonesian government, this review delves into the four key stages: (1) defining objectives and scope, (2) conducting inventory analysis, (3) performing impact assessment, and (4) interpreting the results (as illustrated in Figure 1). This systematic approach aims to generate valuable recommendations that can inform and guide future LCA investigations focused on EV batteries, ultimately contributing to the optimization of their environmental performance.

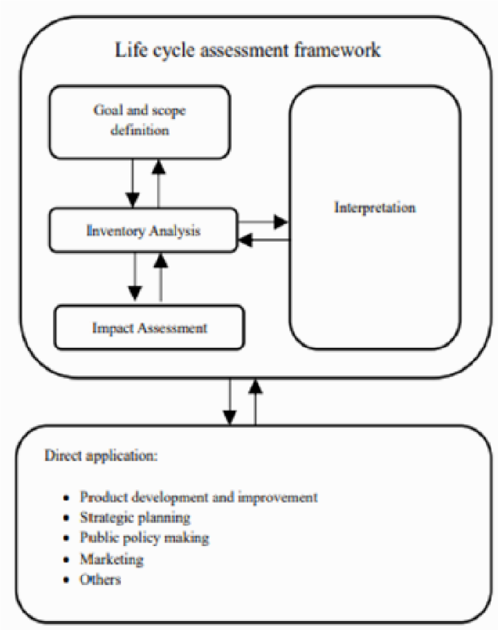

Fig. 1. Life Cycle Assessment Framework (based on SNI ISO 14040:2016)

Table. 1. Documents Analyzed in the Review

Authors	Year	Authors	Year
Bobba, Silvia et al. [14]	2018	Tolomeo, Rosario et al. [15]	2020
Wu, Zhixin et al. [16]	2018	Shu, Xiong et al. [17]	2021
Cusenza, Maria Anna et al. [18]	2019	Wang, Shuoyao and Yu, Jeongsoo [19]	2021
Dai, Qiang et al. [20]	2019	Wilson, Nicholas et al. [21]	2021
Ioakimidis, Cristo S. et al. [22]	2019	Ma , Ruifei and Deng, Yelin [23]	2022
Liu, Chunwei et al. [24]	2019	Picatoste, AItor et al. [25]	2022
Marques, Pedro et al. [26]	2019	Shafique, Muhammad and Luo, Xiaowei [27]	2022
Raugei, Marco and Winfield, Patricia [28]	2019	Xia, Xiaoning and Li, Pengwei [29]	2022
Burchart-Korol, Dorota et al. [30]	2020	Philippot, Maeva Lavigne et al. [31]	2023
Koroma, Michael Samsu et al. [32]	2020	Tao, Yuan et al. [33]	2023

RESULTS AND DISCUSSION

4.1. Definition of Objectives and Scope

Life Cycle Assessment (LCA) relies on a crucial concept – system boundaries. These boundaries define which processes within a product's life cycle are analyzed and which can be excluded for simplification. The goal is to capture the essential flow of materials and energy entering and exiting the system, without getting bogged down in excessive detail [7]. Defining the goals of the LCA study is critical, as it significantly influences how the entire assessment unfolds. While ISO 14044 outlines four primary system boundary options, when it comes to electric vehicle batteries, two approaches are most commonly used: cradle-to-gate and cradle-to-grave.

There are two primary approaches to defining system boundaries in LCA studies of electric vehicle batteries: cradle-to-gate and cradle-to-grave (as outlined in various studies, for instance [12, 15, 20]). Cradle-to-gate focuses on the environmental impact associated with a battery's production phase. This includes everything from the extraction of raw materials to processing, manufacturing, and final assembly (similar to the approach taken in [20, 23, 30]). Essentially, it captures the environmental footprint of bringing the battery into existence. Cradle-to-grave, on the other hand, takes a more comprehensive view by encompassing the entire life cycle of the battery (as emphasized in [12, 21, 26, 32, 33]). This starts with raw material extraction and extends through all stages of production, including energy use for transportation. Crucially, it also considers the use phase of the battery within the vehicle and its eventual end-of-life, including potential recycling processes (as explored in studies like [12, 17, 19, 25, 29]). Some studies have not explicitly defined their system boundaries, making it difficult to compare their results definitively (as observed in [22, 30]). However, several others clearly outline their approach (like the cradle-to-grave approach in [12, 26, 32, 21, 17, 19, 25, 33]) and the cradle-to-gate approach in [20, 23, 30]). Interestingly, a couple of studies delve even deeper by comparing the environmental impact of different scenarios within the battery's life cycle (like [12, 25]). This includes exploring the potential for utilizing recovered EV batteries in secondary applications after their initial use in a vehicle.

The author recommends opting for the cradle-to-grave system boundary in LCA studies to achieve a more holistic environmental assessment. Within this approach, battery lifespan and recycling processes become crucial factors for calculating the environmental burden [35]. While some studies utilize an 80% depth of discharge (DoD) to estimate battery life for electric vehicles, this approach represents a significant simplification. In reality, traction batteries can be fully discharged as long as the state of charge (SOC) remains above the minimum permissible level, which is typically around 20% [7]. This underestimation of usable battery capacity can lead to inaccuracies in environmental impact calculations.

A critical aspect of Life Cycle Assessment (LCA) studies lies in the selection of a functional unit, which serves as the basis for comparing environmental impact. Traditionally, electric vehicle performance is measured in units like "kilometer traveled" or "watt-hour delivered." However, inconsistencies arise within LCA studies of electric vehicle batteries. Many studies focus solely on the production phase, employing a "watt-hour storage capacity" as the functional unit. This approach fails to account for crucial factors like battery lifespan and energy consumption during use. Consequently, significant discrepancies can emerge when comparing batteries with different chemistries, potentially leading to misleading conclusions [8]. The author proposes a shift towards adopting "kilometer traveled" as the functional unit within LCA assessments. This method facilitates the calculation of cumulative energy consumption encompassing both battery assembly and charging phases. An alternative perspective, supported by existing research, suggests employing "kilowatt-hour of energy delivered over the battery's lifetime" as the functional unit [28]. Several studies have demonstrably adopted this approach [14, 17, 19, 20, 21, 27, 31, 33]. Furthermore, some studies referenced in [12] and [20] utilize "100 kilometers traveled" as the functional unit. Similarly, research documented in [14] and [26] considers the total distance traveled by the vehicle throughout its operational lifespan. This lack of standardization in defining the functional unit presents a significant challenge. It hinders the ability to effectively compare LCA studies and draw definitive conclusions regarding the environmental impact of various electric vehicle battery technologies.

4.2. Inventory Analysis

For electric vehicle battery LCAs, researchers often categorize the inventory data analysis into five distinct phases, as outlined in various studies [6]. These phases encompass: raw material extraction, material processing, product manufacturing, the product's use phase, and finally, its end-of-life (EOL) management. The first stage of LCA inventory analysis for electric vehicle batteries focuses on raw material extraction. This includes the acquisition of natural resources, such as mining non-renewable materials or harvesting biomass. Transportation of these resources to processing facilities also falls under this category. The system unit considers all materials used in battery construction, including those for the anode, cathode, separator, casing, and electrolyte. The next phase involves material processing. This encompasses the transformation of raw materials through various stages, including smelting and reaction, separation and refining. Essentially, it tracks all the processes that convert raw materials into usable components for battery production. Transportation of these processed materials to manufacturing facilities is also factored into this stage. The product manufacturing phase then takes center stage, where the processed materials are used to create battery cell components and packaging. Following the manufacturing phase comes the product use phase. This stage focuses on the battery's operational life within the vehicle, typically expressed in units of distance traveled, such as kilograms of material per kilometer, tons of CO2 equivalent per kilometer, or kilowatt-hours per kilometer. The final stage of the LCA inventory analysis is the end-of-life (EOL) phase. This stage considers the management of the battery after its service life is complete. This can involve recycling processes or repurposing the battery for secondary uses, all with the aim of minimizing the environmental impact of battery disposal [35].

The author differentiates between two data sources used in LCA analysis: primary and secondary data.

Primary data is acquired directly from the very systems under study, such as battery manufacturers and users. This data offers valuable insights into the specific materials used for each component, energy consumption during production processes, waste generation, the utilization of recycled materials, and even battery maintenance operations.

Secondary data, on the other hand, is gleaned from existing literature and databases. While technical guidelines recommend prioritizing primary data [11, 17], many existing studies rely heavily on secondary sources.

Only a handful of studies leverage primary data through direct collaboration with battery manufacturers [14, 18, 20, 17]. This approach allows for highly detailed information, including material usage per component, production energy consumption, waste generation, the use of recycled materials, and even battery maintenance practices.

In contrast, studies like [23] focus on using primary data to assess battery energy consumption during the use phase, while others primarily rely on secondary data from published research and databases like Ecoinvent [14, 16, 26, 28, 32, 21, 23, 31, 33].

The limited availability of primary data due to industrial confidentiality concerns can hinder the transparency and replication of many LCA studies [12]. This emphasizes the need for increased openness and data sharing within the industry to facilitate more robust and reliable LCA assessments.

4.3. Impact Assessment

Life Cycle Impact Assessment (LCIA) is a stage within LCA that can introduce subjectivity due to the complexities of modeling and analyzing environmental impact categories [7]. Transparency is paramount at this stage to ensure clear documentation and reporting of any assumptions made. Furthermore, results obtained using different LCIA methodologies often employ distinct units, making direct comparisons challenging [36].

Table 2 summarizes various LCIA methods employed by previous researchers.

The selection of impact category indicators typically falls into two categories: midpoint and endpoint. Midpoint categories focus on specific environmental issues, such as climate change, human toxicity, ecotoxicity, acidification, eutrophication, land use, and resource depletion. Endpoint categories, on the other hand, translate midpoint impacts into broader areas of damage to living things and the environment, encompassing human health, ecosystems, and resource use [7]

LCIA Method	Reference
Midpoint ILCD	[34] [37]
ReCiPe Midpoint	[38] [39] [40]
CML	[35] [34]
Great Midpoint	[41]
EI99 Endpoints	[40] [5]

The analysis of environmental impact categories using the Life Cycle Assessment (LCA) framework can involve some level of subjectivity due to modeling complexities [7]. Transparency is crucial during this stage, ensuring clear documentation and reporting of any assumptions made. It's also important to note that different LCIA methodologies often utilize distinct units, making direct comparisons challenging [36].

Several studies [16, 20, 22, 30, 17, 25] explicitly describe using the midpoint LCIA method for measuring impact categories. Others measure these categories but don't specify the LCIA method employed [18, 26, 32, 27, 31, 33]. Finally, some studies entirely omit results that could be evaluated using the LCIA impact category framework [14, 24, 28, 15, 19, 26, 29]. Despite these variations in approach, the data suggests that most environmental impacts associated with the battery lifecycle occur during the production phase [19, 28] and the product use phase [20, 23, 31]. For instance, the anode production process is linked to impacts like eutrophication and acidification, while the cathode production process significantly influences global warming and abiotic depletion [31]. Global warming is the most commonly studied impact category within LCIA. LCIA results for each category are typically calculated by summing the indicators for all flows within the system unit. Classification and normalization can leverage characterization factors specific to the chosen LCIA method or from other reputable sources, such as the Intergovernmental Panel on Climate Change (IPCC) greenhouse gas characterization factors published in 2007. However, the author suggests that normalization and weighting factors could be adjusted based on stakeholder agreements or guidelines from relevant agencies [6]. The current practice of LCIA is generally limited to environmental issues aligned with the defined objectives and scope of the study. The author proposes further refining the LCIA method to encompass not only environmental concerns but also energy consumption.

4.4. Interpretation

The interpretation stage of LCA focuses on identifying the most significant environmental impacts arising from the analysis results. Here, insights gleaned from both inventory analysis and Life Cycle Impact Assessment (LCIA) are considered holistically.

While each electric vehicle battery system unit will have a noticeable impact on a specific environmental category, its influence on others may be relatively negligible. The most frequently studied category is global warming, addressed in thirteen out of twenty studies. Following closely behind are acidification and eutrophication, each explored in eight studies. A smaller number of studies investigate ozone depletion and particulate matter depletion (six studies each). Similarly, eight studies delve into Cumulative Energy Demand (CED), abiotic depletion, human toxicity, and ecotoxicity. There are several impact categories that remain less thoroughly examined, including photo oxidant production, resource depletion (both investigated in seven studies), fossil depletion (analyzed in seven studies), ionizing radiation (four studies), land usage, and water consumption (eight studies). Based on the impact categories used in nearly 70% of the reviewed studies, the authors propose a core set of nine categories particularly relevant for LCA analysis of electric vehicle batteries. These encompass global warming, eutrophication, acidification, ozone depletion, abiotic depletion, particulate matter, human toxicity, ecotoxicity, and Cumulative Energy Demand (CED). This refined list provides a more focused framework for evaluating the environmental impact of electric vehicle batteries within LCA studies.

CONCLUSION

Research on Life Cycle Assessment (LCA) of electric vehicle batteries over the past six years has shown significant diversity in methodologies, assumptions, and uncertainties, leading to discrepancies in environmental impact assessments. To achieve more consistent results, the author proposes a standardized approach involving a comprehensive definition of objectives and scope, ideally encompassing the entire battery lifecycle from cradle-to-grave. This standardization should also include a specific set of system units for inventory analysis and a core set of nine impact categories for assessment. Transparency is paramount throughout the LCA process, requiring clear documentation of values, assumptions, limitations, and data quality to ensure greater confidence in the interpretation of results across studies. Ultimately, the desired outcome of these LCA studies is to inform efforts aimed at improving energy efficiency, identifying opportunities for environmental improvement throughout the battery lifecycle, and safeguarding human health.

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