Life Cycle Assessment of Electric Vehicle Batteries: Review and Critical Appraisal

Ajun Tri Setyoko¹*, Rahmat Nurcahyo², and Sik Sumaedi³.

¹Research Center of Testing and Standardization Technology, National Research and Innovation Agency of Indonesia, Indonesia.
²Department of Industrial Engineering, Faculty of Engineering, Universitas Indonesia, Depok, Indonesia.

Abstract. The most environmentally damaging aspect of using electric vehicles is the batteries. The Life Cycle Assessment (LCA) approach has been widely used to conduct inventory analysis of energy usage and GHG emissions throughout battery production and assembly. There are many analytical frameworks and models for conducting LCA, but each method uses different results. This study aims to investigate numerous LCA studies on electric vehicle batteries using ISO 14040 and its derivatives. We propose the limits of a cradle-to-grave system so that LCA provides optimal results for comparative studies and potential for continuous improvement. A schematic overview of the electric car battery life cycle covers material extraction, material processing, product manufacture, product use, and end-of-life recovery measures. Global warming, eutrophication, acidification, ozone depletion, abiotic depletion, particulate matter, human toxicity, ecotoxicity, and Cumulated Energy Demand (CED) are all impact categories in LCA study.

1 Introduction

Adoption of electric vehicles (EVs) has become one of many governments' initiatives in recent years to reduce air pollution and greenhouse gas emissions [1]. Many countries contribute to the advancement of sustainable transportation technology by implementing EV developments [2]. This adoption increased the sales value of electric cars, with growth of up to 30% per year. In 2010 global electric car users were 17,000 units, and increased to 7.2 million units in 2019 [3]. The rising use of electric vehicles has boosted the demand for batteries. EVs are often promoted as environmentally friendly vehicles due to their zero emissions. However, investigations have revealed that batteries have a considerable environmental impact both during production and use [4]. About 15% of the total environmental burden of electric vehicles comes from the manufacture, maintenance, and disposal of batteries [5].

Several studies have used the Life Cycle Assessment (LCA) approach to assess potential environmental loads for the production of electric vehicle batteries. This method is a systematic tool for calculating a product's environmental impact by taking into account all stages of the product's life cycle, such as material production, energy flow, waste output and emissions during manufacturing and assembly processes, secondary products, and end of life processes [5]. However, the adoption of electric vehicle battery LCA is due to various reasons ranging from the choice of methodology to the need for primary data. This limits LCA's ability to provide scientific research and technological development feedback. It can also limit the ability to correct errors in literature. Life cycle inventories vary across the literature, and most reviews cannot account for the underlying causes of the differences [7].

However, until now, there has yet to be a consensus in the LCA field regarding analyzing the environmental impact of batteries. Several studies employ various system boundaries, functional units, data sources, life cycle inventories, methods, and impact categories [7]. LCA analysis on batteries takes work. There are many options for assessment frameworks and methodologies which significantly influence the outcome. In addition, studies often rely on inventory data from previous publications, not paying attention to differences in loci, equipment use, and technology use. Researchers conducted an extensive review of LCA work on electric vehicle batteries. Several studies focus on determining the scope, system boundaries, function units, impact categories, and assessment methods and using assumptions for key parameters [7].

Ellingsen et al. (2017) [7] investigated greenhouse gas (GHG) emissions during the battery life cycle. According to the study, earlier reported results differ due to direct energy demand for cell manufacture and package assembly. The study by Pellow et al. (2020) [8] focused on gaps in the range of battery use cases and end-of-life management. Nealer and Hendrickson's study [9] focuses on EVs and covers past research findings on the energy and GHG benefits of EVs. Nordelöf et al. [10] review 79 LCAs for hybrid, plug-in hybrid, and battery EV. In contrast to battery technology, the study addresses uncertainty regarding light vehicles and their utilization. Peters et al. (2016)
[5] conducted a review of numerous battery LCAs and provided significant insights into studies employing primary and secondary data. This study also provides an in-depth discussion of battery life and roundtrip efficiency. Peters et al. [5] note that battery manufacturing energy use estimates vary across studies. They did not provide a detailed explanation and only relied on calculating the average results from previous studies.

In this work, the author will conduct a review on LCA analysis on electric vehicle batteries. Batteries are a necessary component of electric vehicles as well as a distinguishing energy source for Internal Combustion Engine (ICE) automobiles. Battery production consumes energy and has environmental consequences, which can limit the benefits of electric vehicles during their use phase in terms of climate change emissions [7]. This study aims to investigate numerous LCA studies on electric vehicle batteries using ISO 14040 and its derivatives. The LCA steps are depicted in Fig. 1 and involve setting objectives and scope, inventory analysis, impact assessment, and interpretation. This review of the literature will result in useful recommendations for future electric vehicle battery LCA investigations.

### 2 Methodology

The author conducted an extensive review of the literature on battery LCA for electric vehicles, evaluation of single battery models, and identification of the key influences of the production process and battery raw materials [12]. In Table 1, it is explained that there were 20 studies conducted in the last six years, 2018 – 2023, which are suitable for this literature review. The author conducted a literature analysis regarding the standards set by ISO 14040 and its derivatives. This study considers of the characteristic of electric car batteries as well as the comparison foundation used in prior studies. This paper discusses following the LCA stages of the standards adopted by the Government of Indonesia, namely SNI ISO 14040: 2016 and SNI ISO 14044: 2017. Figure 1 describes the LCA framework consists of 4 principles, namely determining definition of objectives and scope, inventory analysis, impact assessment, and interpretation.

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

**Table. 1. Documents Analyzed In The Review**

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<th>Authors</th>
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<tr>
<td>Wu, Zhixin et al. [16]</td>
<td>2018</td>
<td>Shu, Xiong et al. [17]</td>
<td>2021</td>
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<td>Cusenza, Maria Anna et al. [18]</td>
<td>2019</td>
<td>Wang, Shuyao and Yu, Jeongsoo [19]</td>
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<td>Dai, Qiang et al. [20]</td>
<td>2019</td>
<td>Wilson, Nicholas et al. [21]</td>
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<td>Ioakimidis, Cristo S. et al. [22]</td>
<td>2019</td>
<td>Ma, Ruifei and Deng, Yelin [23]</td>
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<td>Marques, Pedro et al. [26]</td>
<td>2019</td>
<td>Shafique, Mohammad and Luo, Xiaowei [27]</td>
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<tr>
<td>Raugei, Marco and Winfield, Patricia [28]</td>
<td>2019</td>
<td>Xia, Xiaoning and Li, Pengwei [29]</td>
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3 Result And Discussion

3.1 Definition of Objectives and Scope

In the LCA approach, the system boundary definition is a mechanism for defining which processes across the relevant system's life cycle should be explored or can be omitted for simplification. In the system, only the basic flow of inputs and outputs should be modeled [7]. Setting goals will significantly influence the following assessment process. Four main choices of system limits are used based on ISO 14044 in the LCA study, but in practice, there are two options for electric vehicle batteries, namely cradle-to-grave and cradle-to-gate.

Cradle-to-gate is a determination of the environmental impact of the production of a product, which includes raw material extraction, material processing, production, and battery assembly. Cradle-to-grave is an environmental load assessment that covers the entire product life cycle, starting from the extraction of materials along the production chain and input energy output in all processes, including transportation and use, to the final product in its life cycle [32]. Studies [22], [30], [24], [15], and [29] do not clearly define system boundaries, whereas other documents clearly define system boundaries for their studies. Studies [12], [26], [32], [21], [17], [19], [25], and [33] examining all battery processes (cradle-to-grave), beginning from extraction, raw material manufacturing, battery production, transportation, use phase, end of life with material recycling. Studies [20], [23], and [30] only examined battery manufacturing from the raw material phase and battery assembly (cradle-to-gate). Two studies [12] and [25] compared the environmental effects of several life cycle scenarios to assess the utilization of recovered EV batteries in secondary applications.

The author suggests choosing the cradle-to-grave system limit in LCA analysis to obtain a more comprehensive assessment. In the cradle-to-grave system, battery life and recycling are significant for environmental load calculations [35]. The determination of the battery life of electric vehicles uses a depth of discharge (DoD) of 80%. This is a powerful simplification as the traction battery will be fully discharged once the minimum permissible state of charge (SOC) is 20% [7].

The unit of function commonly used in measuring the performance of an electric vehicle system is a 100 km or 1 Wh ride. The majority of LCA studies on electric car batteries express focus on the production effect of assessing batteries based on storage capacity, i.e., 1 Wh functional units, without taking consumption and battery life. This can lead to wrong conclusions when comparing the results of LCA assessments with different chemical compositions [8]. The author strongly recommends using the unit distance function, namely km, in the LCA assessment. The cumulative consumption of energy on battery assembly and charging can be calculated using this function unit. However, according to reference [28], the recommended function unit is 1 kWh of energy delivered over the lifetime of the battery. Eight studies are using these functional units [14], [20], [28], [17], [19], [21], [27], [31], and [33]. In another study, the authors in [12] and [20] used the value of 100 km traveled as the functional unit, while the distance traveled by the vehicle during its service life was considered in the study [14] and [26].

3.2 Inventory Analysis

The results of the LCA analysis are influenced by the reliability and adequacy of the data inventory of the object being assessed. Data quality assessments include time, geography, technology, precision, completeness, representativeness, consistency, reproducibility, data source, and information uncertainty. In applying LCA to electric vehicle batteries, the authors offer inventory data analysis divided into five phases: raw material extraction, material processing, product manufacturing, product use, and end-of-life (EOL) [6].

The raw material extraction phase includes actions associated with the acquisition of natural resources, such as mining of non-renewable mining materials and biomass, as well as transportation to processing facilities [7]. The materials for the anode, cathode, separator, casing, and electrolyte batteries are also included in this system unit. The material processing phase, namely the processing of natural resources, including smelting and reaction, separation and refining, as well as other stages of change in the manufacture of products, including the transportation of the processed materials to product manufacturing facilities. The product manufacturing phase includes manufacturing of the battery cell components and packaging. The product use phase is the use of the battery during use which is generally expressed in units of distance such as kg material/km, ton CO2-eq/km, and kWh/km. The end-of-life (EOL) phase involves the recovery or treatment of the battery after its service life, such as recycling or secondary usage, to minimise the environmental impact caused [35].

The author distinguishes between primary and secondary data analysis in the LCA analysis. Primary data is obtained directly from system manufacturers and users. Secondary data is derived from secondary sources such as literature and databases. Although technical guidelines in references [11] and [17] strongly suggests using primary data, the majority of extant studies rely on

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<th>Study Description</th>
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<tr>
<td>Burchart-Korol, Dorota et</td>
<td>2020</td>
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<td>Koroma, Michael Samsu et</td>
<td>2020</td>
<td>Tao, Yuan et al. [33]</td>
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secondary data. Only four studies [14], [18], [20], and [17] use primary data in direct collaboration with battery manufacturers. This data contains the material used for each component, the amount of energy consumed during battery production, waste, the proportion of recycled materials used, and battery maintenance operations. One study [23] looked at using primary data to assess battery energy usage during the product's use phase, whereas other studies [14], [16], [26], [28], [32], [21], [23], [31], and [33] only looked at secondary data from the literature and the Ecoinvent database. The use of primary data in LCA analysis is not widely available due to industrial secrecy issues. The lack of primary data availability has an impact on the transparency and replication of many studies [12].

3.3 Impact Assessment

The issue of modeling and analyzing environmental impact categories at the Life Cycle Impact Assessment (LCIA) stage might lead to subjectivity [7]. Data transparency at the impact assessment stage is critical to ensure that assumptions are clearly described and reported. The results of different LCIA methodologies and their units cannot be easily compared. [36]. Table 2 describes several LCIA methods that previous researchers have used. The determination of category indicators is generally divided into the midpoint category and the endpoint impact category. Environmental issues, climate change, human toxicity, ecotoxicity, acidification, eutrophication, land usage, resource use, and other factors are included in the midpoint impact category. The endpoint impact category, namely damage to living things and the environment, includes human health, ecosystems, and resource use [7].

<table>
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<th>LCIA method</th>
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<tr>
<td>Midpoint ILCD</td>
<td>[34][37]</td>
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<td>ReCiPe Midpoint</td>
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<td>CML</td>
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<td>Great Midpoint</td>
<td>[41]</td>
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<td>EI99 Endpoints</td>
<td>[40][5]</td>
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There are six studies[16], [20], [22], [30], [17], and [25] which describe measuring impact categories using the midpoint LCIA method, while studies [18], [26], [32], [25], [27], [31], and [33] measures impact categories but does not specify the LCIA method used. Finally, seven studies [14], [24], [28], [15], [19], [26], and [29] did not report any results that could be evaluated using the LC IA impact category. However, several conclusions can be drawn that the data shows most of the environmental consequences of the battery life cycle occur during the production phase [19] and [28] and the product use phase [20], [23], and [31]. The anode production process is responsible for the effects of eutrophication and acidification, while the cathode production process has a significant impact in terms of global warming and abiotic depletion [31]. The most researched impact category is global warming.

The LCIA results for each impact category are the sum of the indicators for all flows in each system unit. Classification and normalization can use the characterization factors in each LCIA method or other credible sources, such as the GHG characterization factors published by the Intergovernmental Panel on Climate Change (IPCC) report in 2007. However, the authors recommend adjusting the normalization and weighting according to stakeholder agreements or related agencies [6]. LCIA's current practice is limited to environmental issues related to the stated objectives and scope. The author proposes that the LCIA method is limited to environmental issues and energy consumption.

3.4 Interpretation

Interpretation is focused on the point that causes the biggest and essential impact from the results of the LCA study. Interpretations obtained from inventory analysis and LCIA are considered together. Each electric vehicle battery system unit will significantly impact one category. On the other hand, it will hardly affect other categories. The most typically studied impact category was global warming (thirteen studies out of twenty), followed by acidification (eight studies out of twenty) and eutrophication (eight studies out of twenty). Six papers deal with ozone and particulate matter depletion, while eight papers cover Cumulated Energy Demand (CED), abiotic depletion, human toxicity, and ecotoxicity.

Photooxidant production and resource depletion (seven studies), fossil depletion (seven studies), ionizing radiation (four studies), land usage, and water consumption (eight research) are impact categories that have yet to be thoroughly examined. The authors propose nine impact categories that can be used in the LCA analysis of electric vehicle batteries based on the impact categories used in nearly 70% of the studies evaluated, namely global warming, eutrophication, acidification, ozone depletion, abiotic depletion, particulate matter, human toxicity, ecotoxicity, and CED.

4 Conclusion

In the previous six years, research on LCA analysis on electric vehicle batteries has used a variety of LCIA methods, assumptions, and uncertainties that have influenced variances in assessment outcomes. A more comprehensive definition of objectives and scope is to identify the environmental load of all system units in a cradle-to-grave scheme. The author proposes five system units for inventory analysis and nine impact assessment categories. Differences in interpretation are normal with the support of transparency regarding the choice of values, assumptions, methodology limitations, and data quality. The result expected from the electric vehicle battery LCA is energy efficiency efforts,
opportunities for environmental improvement, and human health.

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References


