Sustainability assessment of lithium-ion batteries using multi-criteria decision analysis and life cycle approaches

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1. Abstract

Lithium-ion batteries (LIBs) are essential for accelerating the shift toward electrified transportation systems. Although they must deliver high performance, meeting sustainability standards is equally important. In the present work, multi-criteria decision analysis (MCDA) is employed to assess the sustainability of LIBs. Global warming potential, ecotoxicity, material criticality, cost factors, energy content, safety, and lifespan were considered in the analysis as key parameters of the transition to electric mobility. Through the analysis, it was realized that although specific alternatives, like NCM and NCA, outperform others in terms of specific energy, they exhibit safety concerns, challenges in resource preservation, and negative environmental impacts. Addressing cost-related difficulties is also important for making certain batteries competitive and largely accessible. Overall, while technical parameters are crucial for the advancement of LIBs, it is also important to consider environmental issues, resource availability, and economic factors in the design process.

2. Introduction and Motivation

LIBs are the backbone of electric vehicles (EVs), enabling the shift toward cleaner transportation. Their high energy density and efficiency make them essential for reducing greenhouse gas emissions in the automotive sector. The ongoing growth of EVs stresses the need to assess batteries on a sustainability basis to ensure scalability and wide applicability. In the present work, life cycle assessment (LCA) and MCDA were employed to assess different LIBs, considering technical, environmental, economic, and material criticality issues.

3. Applied Method

Five well-established LIBs are the alternatives for the MCDA: NCM, LFP, NCA, LMO, and LCO. The selected criteria align with the pillars of sustainability to ensure a comprehensive analysis. Figure 1 summarizes the criteria and the weights attributed to them by experts on electric mobility, through a questionnaire. Environmental impacts were quantified through LCA, adopting a cradle-to-grave approach. The technical parameters evaluated are specific energy [1], safety [2], and lifetime of the battery pack [3]. Life cycle cost and residual value at End-of-Life were used to assess economic aspects [4]. The criticality of materials was measured in terms of depletion of resources, stability of the supply chain, and substitutability [5]. Analytic hierarchy process was employed for the MCDA [6].

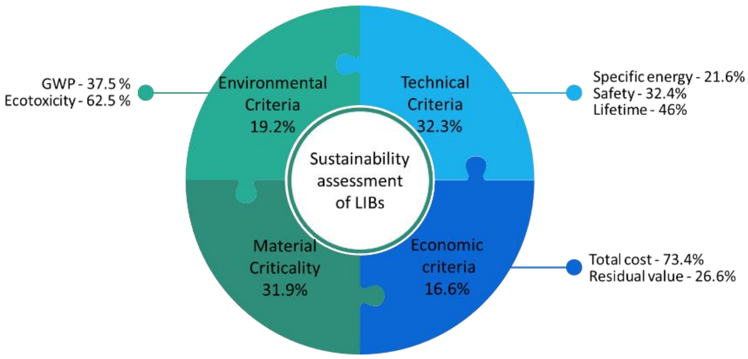

Figure 1. Weights assigned to the criteria for the assessment of LIBs.

4. Results

Figure 2 illustrates the final ranking of the alternatives. LFP is the optimal alternative as it combines low demand for critical materials, a long lifespan, and higher safety. Although NCM and NCA excel in technical features, their content in scarce materials with unstable supply chain lowers their overall performance. LMO battery excels in safety and doesn't require any critical materials. However, its technical performance is inadequate for automotive applications. Finally, LCO is at the bottom of the ranking, primarily due to its high cost and material criticality.

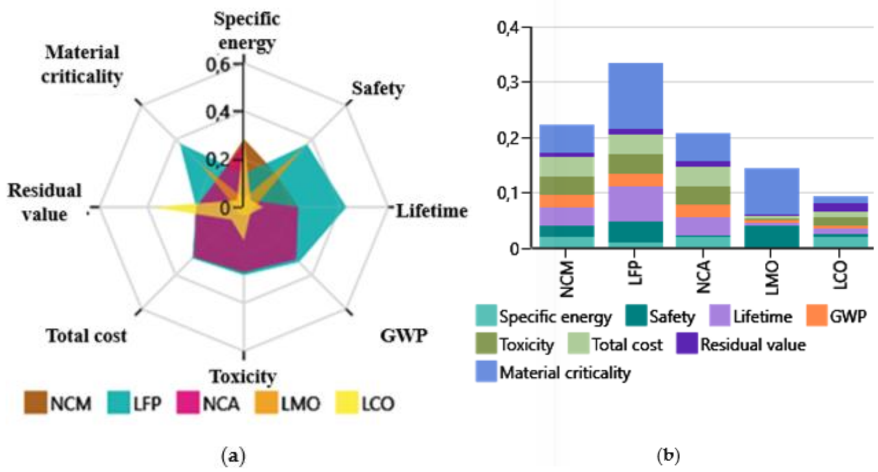

Figure 2. (a) Attributes of the alternatives (b) Weighted attributes of the alternatives.

5. Conclusions

The above results highlight the importance of avoiding scarce materials with uncertain supply chain to ensure the long-term scalability of a technology. This is the main reason why LFP was the top-rated alternative for EVs. Particularly for electric mobility applications, where high performance is required to satisfy market needs, technical features, and cost factors are also important to be considered. NCA and NCM are suitable technologies for EVs, but their reliance on materials like nickel, cobalt, and manganese is a key limitation. LMO can be combined with materials that have a higher energy content. LCO, due to its high reliance on cobalt is very expensive and has an unstable supply chain, but its exceptionally high energy content makes it suitable for applications that require minimum battery mass. Despite the contributions of the present study, emerging technologies, like post-LIBs remain unexplored and future research should focus on such technologies to identify any bottlenecks in their widespread adoption.

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