Automotive Experiences
Vol. 7 No. 3 (2024) pp. 429-449
p-ISSN: 2615-6202 e-ISSN: 2615-6636

Review Paper

ROSES are Read, STEEP are Green: Mapping Sustainability Indicators Across Lifecycle Stages in EV Battery Production Through a Systematic Review

Nimas Ayu Arumbinang[1], **Iwa Garniwa**[2], **Raldi Hendrotoro Seputro Koestoer**[1], **Wendy Aritenang**[3]

[1]School of Environmental Science, Universitas Indonesia, Jakarta 10430, Indonesia
[2]Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Depok 16425, Indonesia
[3]Center for Technology and Innovation Studies (CTIS), Jakarta, Indonesia

nimas.ayu@stiemp.ac.id

https://doi.org/10.31603/ae.11648

Published by Automotive Laboratory of Universitas Muhammadiyah Magelang

Article Info
Submitted: 26/06/2024
Revised: 03/12/2024
Accepted: 06/12/2024
Online first: 14/12/2024

Abstract

The rapid expansion of the electric vehicle (EV) market presents a paradox: while increasing production and lowering costs are essential for widespread adoption, these efforts also intensify the environmental and social impacts, particularly in lithium-ion (Li-ion) battery production. Comprehensive sustainability assessments are needed across all stages of battery production. This review employed the ROSES framework to analyze 40 Scopus-indexed research papers systematically. Extracted indicators are categorized by the STEEP (Sociocultural, Technological, Economic, Environmental, and Political-Legal) dimensions. The dual approach identifies critical sustainability gaps and examines the interplay between these dimensions. By mapping each indicator to a specific lifecycle stage—ranging from raw material extraction to end-of-life disposal—the review highlights critical stages for improving sustainability in EV battery production. The study uncovers complex relationships between sustainability factors and establishes a comprehensive framework to address these challenges. As a result, it provides policymakers, industry leaders, and researchers with a solid foundation for developing informed strategies to enhance the sustainability of EV battery production.

Keywords: Electric vehicles; Lithium-ion batteries; Sustainability indicator; STEEP analysis; ROSES framework; Lifecycle

1. Introduction

The global transportation sector strives to meet the Sustainable Development Goals, particularly SDG 7 (clean energy), SDG 11 (sustainable cities), SDG 12 (responsible production), and SDG 13 (climate action) [1]. The electric vehicle (EV) market, expected to grow between 140–245 million units by 2030, stands at the intersection of innovation and environmental necessity [2]. Batteries are vital components of EVs [3], significantly influencing their weight, performance, and cost [4]–[7]. Advancements in battery technology are essential for making EVs more accessible and supporting their widespread adoption [8]. Lithium-ion (Li-ion) batteries have emerged as the dominant technology due to their high energy density, low atomic mass, high electrochemical reactivity, long cycle life, and low self-discharge rates [9]–[11]. Li-ion batteries come in several chemistries, including lithium cobalt oxide (LCO), lithium iron phosphate (LFP), and lithium manganese oxide (LMO). However, nickel manganese cobalt (NMC) is especially favored in EVs for its optimal balance of energy density and cost efficiency [12], [13]. Predictions suggest that the production and use of Li-ion batteries for EVs will surge by over 22% in the 21st century to meet the increasing demands [14].

The surge in demand for Li-ion batteries, projected to rise by up to 70% by 2050 [15], presents significant challenges. These batteries rely on critical raw materials such as lithium, cobalt, and nickel, essential for EV production [14], [16]. Extracting these materials depletes non-renewable resources and causes widespread ecological damage [17], [18]. Mining operations disrupt ecosystems, contribute to deforestation, and pollute air and water. Improper disposal of used batteries exacerbates the issue, with Li-ion waste reaching 42.7 million units in 2020 and potentially growing to 5 million metric tonnes by 2030 [19]–[21]. Social impacts are also significant, particularly in developing countries. As mineral prices rise, developing nations with abundant resources [22]–[24] are increasingly adopting industrial policies to join the global value chain [25]. Expert assessments highlight the importance of social factors in the sustainable production of Li-ion batteries, such as job creation, worker safety, humane treatment, and community involvement, especially in mining [26]–[29]. In addition to social factors, governance issues—often related to supply chain management and recycling rates during the end-of-life phase—also require attention [26], [30]. Together, these environmental and social challenges underscore the paradox of advancing clean energy technologies while perpetuating unsustainable practices, highlighting the need for holistic sustainability assessments across all stages of battery production.

Sustainable production is the production of goods, services, and resources using technologies that meet three key criteria - environmentally friendly, economically feasible, and socially beneficial technologies [31], [32]. It involves manufacturing products that maintain functionality throughout their life cycle, provide economic and societal value [33], foster job creation, reduce costs [34], and build sustainable supply chains [35] all without compromising future generations [36]. While many definitions emphasize the triple bottom line (TBL) [33], they often overlook critical dimensions such as technological innovation and regulatory dynamics. The growing demand for EV batteries highlights the need for a comprehensive sustainability analysis across their entire lifecycle, from extraction to disposal. This approach ensures that interventions can effectively address interconnected challenges, especially in EV battery production. The lifecycle of Li-ion batteries, illustrated in **Figure 1**, spans six stages: (1) mining, (2) semi-finished goods (precursors) production, (3) battery production, (4) EV production, (5) usage, and (6) end-of-life [4], [5], [37]–[39]. Each stage presents unique sustainability challenges and opportunities.

Existing research extensively discusses EV battery production's environmental, social, and economic impacts. Several studies focus on the ecological and social repercussions of material extraction [9], [40]–[44]. Others explore technological advancements and lifecycle management [4], [5], [45], [46]. Another popular subject is economic analysis, which examines market dynamics and cost structure [3], [14], [47]–[49]. However, these studies often isolate sustainability dimensions, neglecting their interdependencies. This fragmented approach underscores the need for a comprehensive framework that integrates diverse dimensions to address the multifaceted nature of sustainability in EV battery production. Systematic reviews could be employed to analyze the current research landscape with a more holistic approach by compiling a comprehensive set of indicators across environmental, social, and economic dimensions [33], [50], [51].

To address these gaps, we introduce a novel approach by integrating the ROSES framework with STEEP analysis to explore sustainability indicators across the lifecycle of EV batteries. STEEP analysis has only been applied as a framework within the context of limited sustainability to energy-related discussions [52]–[56] and there have been no explicitly available studies focused on the issue of sustainable transportation, particularly on sustainable production of EV batteries, as far as we encounter. The ROSES framework ensures a structured and systematic evaluation of existing research, while STEEP analysis categorizes indicators into Sociocultural, Technological, Economic, Environmental, and Political-Legal dimensions [57], [58]. This dual-framework approach uncovers complex interdependencies and provides actionable insights for sustainable practices at various production stages. By combining these methodologies, the study offers a unique pers pective on how sustainability indicators interact and where interventions can be most effective.

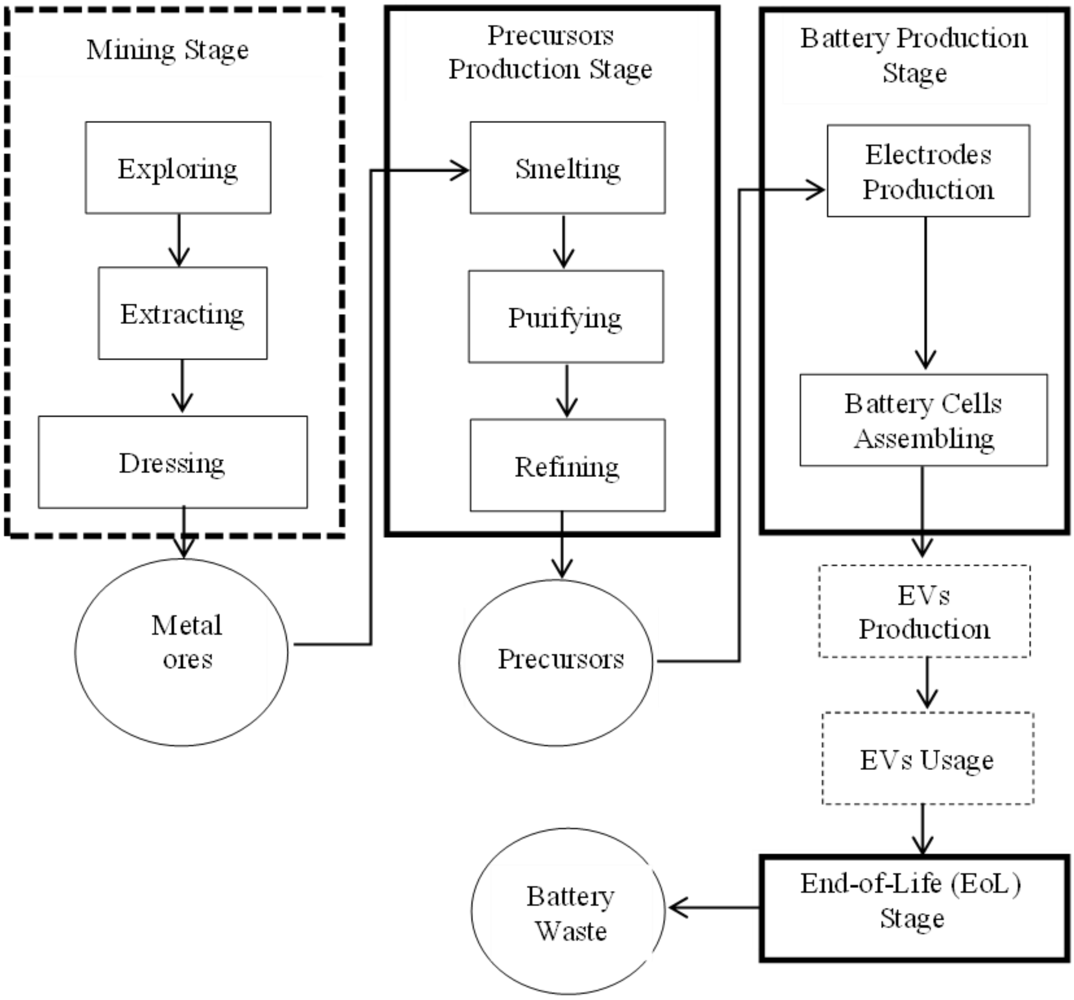

Figure 1. Stages of the Li-ion EV batteries industry value chain

The following questions guide this research:

1. Which dimensions of the STEEP framework remain underexplored, indicating critical gaps in the current research on sustainable EV battery production?
2. Which lifecycle stages of EV battery production are most critical for achieving sustainability, and what are the key indicators for each stage?
3. How do sustainability indicators across the STEEP dimensions interact and influence overall sustainability at different stages of the EV battery lifecycle?

Our primary aim is to conduct a systematic review that compiles and evaluates a wide array of sustainability indicators - encompassing environmental, social, and economic dimensions - guided by the rigor of the ROSES framework. Further, employing the STEEP framework, this research categorizes these indicators, enhancing our understanding of their synergistic effects and pinpointing stages where interventions could be most effective. By mapping these indicators to specific lifecycle stages of EV batteries, the study identifies pivotal points for sustainability enhancement, offering a structured model to guide industry practices and policy development toward holistic sustainability solutions.

The remainder of this study is organized as follows. Section 2 outlines the methodology, detailing the systematic review conducted using the ROSES framework and the categorization of indicators through STEEP analysis. Section 3 presents a detailed discussion of the findings, emphasizing the interactions between sustainability dimensions across lifecycle stages. We then synthesize these findings, offering practical recommendations for policymakers and industry stakeholders. Finally, Section 4 summarizes the study's contributions, identifies its limitations, and suggests future research directions.

2. Methods

The material and method section outlines the data sources, search strategies, article selection criteria, the number of studies included, and the methods or statistics for the analysis. This research conducts a systematic review of sustainable indicators, as discussed in the literature, regarding the production of batteries for electric vehicles. Employing keyword-based searches and adhering to the RepOrting standards for Systematic Evidence Syntheses (ROSES) [58], [59], this study conducted an exploration from the Scopus database on January 2024 using the keywords "lithium-ion" AND "sustainable production" OR "lithium-ion" AND "sustainable*" AND "indicator*", limiting the publication year range up to 2023. A total of 117 references from various source types published between 2009 and 2023 were successfully obtained in the first round.

In the second round, the selection was refined to include only peer-reviewed journal articles written in English. This restriction ensured high quality and reliability, meeting the rigorous standards for systematic reviews. Consequently, other forms of literature, such as conference proceedings, books, and book chapters, were excluded. Non-English articles, such as those written in German and Chinese, were also removed to maintain consistency in data analysis. The second round of screening resulted in 88 relevant articles.

In the third round, content analysis was performed to evaluate how each of the 88 articles addressed sustainability indicators relevant to electric vehicle battery production. The third round resulted in 40 relevant articles discussing or employing at least one indicator of electric vehicle battery production's economic, social, or environmental aspects. The procedural sequences of the three rounds are illustrated in Figure 2. This study then systematically analyzed the indicators and organized them according to the STEEP framework. The framework includes Sociocultural, Technological, Economic, Environmental, and Political-Legal dimensions, which provide a structured approach to categorize and understand the sustainability aspects of electric vehicle battery production.

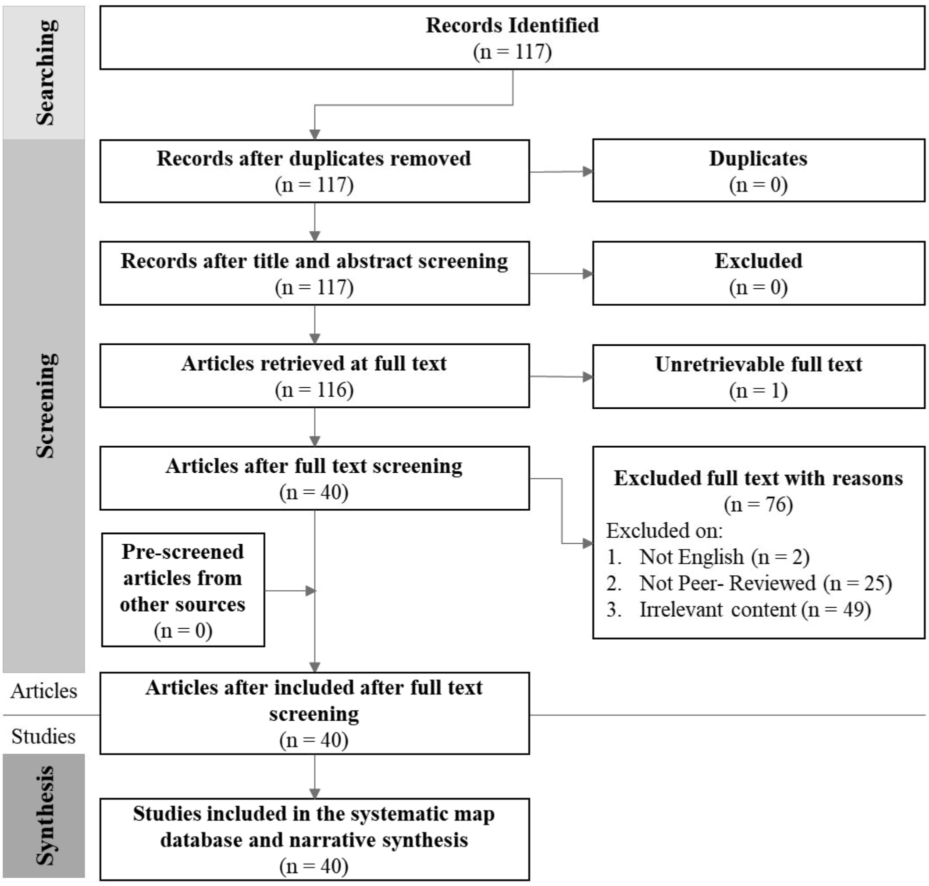

Figure 2. The ROSES Framework

STEEP Analysis, which includes five factors: Sociocultural (S), Technological (T), Economic (E), Environmental (E), and Political and Legal (P). These five criteria serve as an analytical framework to understand and analyze the current and potential future outcomes of business operations. This study adjusts the context and analysis and utilizes pre-existing definitions [57]. The sociocultural factors relate to the effects humans experience in the whole production process of Li-ion batteries. Subsequently, technological factors relate to how advancements can shape future trajectories and boost battery product quality and capacity. Third, economic factors include indicators of all economic costs and factors of production. The ecological factor encompasses all aspects associated with the effects on the environment, both beneficial and harmful, as well as sustainable transportation initiatives. Last, the political and legal factors, which naturally relate to dynamics, actions, and processes of regulations and policies, affect the production process. For the Li-ion battery production for EVs, these five elements are useful for creating meaningful categorization towards sustainable indicators. The STEEP analysis has only been applied as a framework within the context of limited sustainability to energy-related discussions [52]–[56] and there have been no explicitly available studies focused on the issue of sustainable transportation, particularly on sustainable production of EV batteries, as far as we encounter.

3. Results and Discussion

This section provides a detailed analysis of the findings from the screening process, as outlined previously, using the ROSES Framework. The sustainable indicators identified in the 40 filtered articles are categorized according to the five factors of the STEEP framework. Each reference is cited accordingly. The discussion will explore the indicators of sociocultural, technological, economic, environmental, and political-legal factors.

3.1. Sociocultural Factors

We extracted 19 sociocultural aspects related to the manufacturing of Li-ion batteries, highlighting the contribution of six key articles. The first article [26] discusses 11 out of 29 social-related indicators, including economic, environmental, and governance, excluding technology. The second article [27] examines the sustainability of current and future traction battery technologies for electric vehicles based on three factors: economics, environment, and social risk. The same factors are also applied by the third article [60] in assessing the sustainability of car manufacturers through life cycle sustainability assessments (LCSA) and the Energy System 2050 (ES2050) approach [61]. The fourth article [28] examines social risk from the perspective of the cobalt commodities supply chain. The last one [29] compiled 13 indicators from five factors. In contrast to our study, it does not include political aspects or factors in the priority assessment of Battery Energy Storage Systems (BESS).

The initial set of indicators for sociocultural factors deals with labor. There are four indicators related to the workforce's operations in the mining process for raw materials for minerals and throughout all stages of the value chain. Occupational safety and health [26], [60] are major issues, particularly in the mining process. These issues are often associated with inhuman treatment [26]. Forced labor [26]–[28], including child labor [26]–[28], [60], sometimes persists in the mining process. These practices are significant indicators that should be highlighted. Employment should conform to the minimal standards of workers' human rights and include higher requirements such as freedom of association, bargaining power, and enhanced living standards [26]. It is also important to generate employment opportunities [29], particularly in surrounding regions of mining sites, factories, and production hubs. Job creation helps engage local communities [26], [29] and ensure the rights of indigenous communities [26] when necessary.

Equality and fairness [26], [28] must be met. Both are subject to public perception [61], representing public acceptance. Additionally, both serve as an indicator of public welfare [61]. Innovation and patents in the production stage are considered positive indicators [61]. On the other hand, bribery [26] and corruption [26], [27], [60] remain significant barriers to ethical practices and sustainability in the industry. One article utilized the INFORM Human Hazard and Fragile States Index [28] to assess security risks surrounding conflicts, particularly those driven by mineral wealth used in Li-ion battery production. The production stage is partly influenced by consumers' perceptions, provided they are well-informed. Factors such as product quality, safety, security, and data privacy are all factors considered by consumers [26].

3.2. *Technological Factors*

This section focuses on battery production parameters for electric vehicles (EVs) since technological advancements and innovation directly influence the economic efficiency of the product output while minimizing its environmental impact. We have gathered 15 articles corresponding to 12 indicators that can serve as a standard for assessing the progress of technological advancement. One notable study suggested six crucial technological indicators [29]. These indicators encompass energy efficiency, energy intensity, self-discharge rate, cycle life, safety, and specific energy. Experts use them to evaluate and identify the most suitable battery energy storage systems (BESS). Li-ion batteries are included in chemical energy storage systems with 'high cycle efficiency'. Three other articles [62]–[64] consider energy efficiency as a measure of technological aspects. Energy efficiency measures how effectively a system converts input into functionality [65]. It is influenced by the energy mix [63], which refers to the type and quantity of primary energy used and can also affect the environment. Hence, improving energy efficiency helps reduce the Global Warming Potential (GWP) in the cell manufacturing and assembling processes [64].

Building on the discussion of technological advancement, we discovered that material and weight efficiency emerge as additional significant factors to consider. The objective is to get the same functionality while using less material, prolonging lifetime, improving stability and recyclability, and ultimately building lighter and more energy-efficient devices [65]. The energy density of a material is important for determining its material needs and potential effects on cost, carbon footprint, or criticality [66]. Energy density varies with the shape of Li-ion batteries – cylindrical hard-case, prismatic hard-case, or prismatic pouch [67]. Prismatic pouch cells excel in automotive applications, offering higher energy density and better space use. Conversely, cylindrical and hard-case cells offer superior safety and reliability [67]. In this case, a higher gravimetric energy density is being proposed [65], especially for Na-based or Sodium-ion batteries (SIB) [66], [68]. Achieving high gravimetric energy density involves integrating Li-ions into the active materials of electrodes [69]. The gravimetric energy density, as calculated, is also correlated with battery performance [70]. State of Health (SoH) is vital for assessing battery performance and safety [71] as it undergoes constant changes throughout its lifespan [72]. Albeit different, this indicator is related to the state of charge (SoC), a significant metric for assessing Li-on batteries use in the EV industry [73].

Concerning the State of Charge (SoC), the self-discharge rate [29] is also closely linked to energy losses [74] and embodied energy [75]. These factors significantly impact the environment. Embodied energy [75] refers to the total energy required during the product's life cycle from raw materials extraction to disposal or recycling, akin to a carbon footprint. Meanwhile, energy losses [74] occur during the conversion process between production, transmission, and utilization. Li-ion batteries and sodium-nickel chloride batteries have a smaller environmental impact than other types, such as lead-acid, nickel-cadmium, and nickel-metal hydride [74]. The final indicator we deem significant is Human-Robot Collaborative Disassembly (HRCD). This indicator has been extensively debated within the framework of sustainable manufacturing, albeit restricted to economic and environmental aspects [76]. The HRCD's resilience was considered an indicator for measuring the performance of Li-ion battery recycling based on stability, redundancy, efficiency, and adaptability as criteria [77].

3.3. *Economic Factors*

The third section examines the quantification and evaluation of economic factors with 19 indicators extracted from 14 applicable research studies. We then categorized those into two different clusters: profit and cost. Seven indicators were classified into the profit cluster, two of which are observed: the impact of profit on economic development and the creation of employment and production opportunities for local communities [26]. These indicators represent the spillover effect throughout the production process, including the presence of value added [60]. Additionally, it is connected to the profits generated from efficiently using production inputs, such as the energy storage systems profit [29]. These profits can also be seen as a component of capital, with their magnitude indicating capital intensity [29]. The level of capital intensity will also impact investment cost, measured by Present Value (NPV) [78] as one of the most common indicators. The Present Worth Ratio (PWR) [78], calculated by dividing NPV by capital expenditure, is another key economic measure [79]. It is one of the economic assessments used for energy storage systems, equivalent to a profitability index [80].

On the other hand, the cost cluster addresses the allocation of cost to the production process and all life cycle stages, as outlined in the corresponding articles. For instance, Popien et al. [27] assessed the overall battery cost as a key metric. This metric quantifies the extent and sensitivity of changes in the added value in 10 different battery types, including LIBs, lithium-sulfur batteries (LSBs), and all-solid-state batteries (ASSBs). It highlights that labor, energy, and depreciation accounted for 43% of battery costs. The total battery costs, which differ from battery pack cost [70], can be categorized as operation costs [29] or operating costs [61]. These include labor, overhead, maintenance and repair, taxes, and insurance fees. Haase et al. [61] employ levelized total costs (LTC), representing the average cost per unit over a product's lifespan. This indicator is a part of Life Cycle Costing (LCC) [61], covering the total cost incurred throughout a system's operational lifespan. In the context of LCC, the Levelised Cost of Storage (LCOS) indicator [30] can also be utilized in addition to LTC. It measures specific costs for discharging a unit of energy. For instance, an article that examines energy storage technologies (ESTs) and compares electrochemical and hydrogen-based energy storage [80] shows that Li-ion batteries have the most cost-effective LCOS among electrochemical batteries. In addition to considering the life cycle, this cluster also suggests the average cost over a ten-year period as an indicator for comparing 42 SIB cathodes with 8 LIB cathodes [66].

Another relevant indicator related to the life cycle is multi-life cost, an ecologically attractive indicator [81]. This cost is closely related to the total cost of ownership (TCO). Multi-life cost is determined by subtracting the residual value from the total cost of ownership across multiple life cycles. This figure is then divided by the duration of use and then by the average cost per unit of time for the combined single-life products [81]. The TCO often determines the adoption of electric vehicles (EVs). It is driven primarily by their cost advantage over internal combustion engines. The competitive cost structures will solely facilitate a sustained increase in the adoption of EVs in the long run [26].

Despite financial cost [82] and its related indicators being dominant, there are non-financial cost indicators, including eco-cost and exergy cost. The eco-cost represents the virtual cost associated with process emissions. It is calculated by multiplying the mass of CO_2 potentially emitted per kg of material with a global warming potential conversion factor. This number represents the environmental impact and sustainability of obtaining 1 kg of raw mineral [75]. Exergy cost, on the other hand, quantifies the energy or effort needed for manufacturing processes such as mining and metallurgy. Exergy cost also indicates their thermodynamic efficiency and resource intensity [83].

3.4. Ecological Factors

This next section continues the discussion on resources, focusing on ecological factors. We have organized this section into two distinct categories. The first category comprises indicators related to resource management. It includes how resources are utilized and conserved. The second category deals with ecotoxicity, which is the negative environmental impact. The first category includes 22 indicators that assess various aspects of resource management. The second category contains 30 indicators measuring the adverse effects on the environment.

The initial indicator relates to the availability of resources [78] as defined in ReCiPe 2016, influenced primarily by mineral extraction processes [84]. Resource use is further a significant factor, for instance, as a commodity life cycle costs (C-LCC) [85]. The C-LCC evaluates critical materials that are typically at risk of supply shortages. The utilization of resources or materials [26] can contribute to resource depletion [27], [30],

[61], [64], particularly non-renewable resources [84]. These instances include fossil depletion [42], [86] and metal depletion [42], [60]. Mineral and fossil-based resource scarcity, often expressed as raw material criticality [66], [70], is closely related to the issue at hand [87]–[90]. Material criticality refers to how likely a supply disruption of a material renders its vulnerability [91]. For instance, it examines the environmental consequences of material criticality in producing Li-ion batteries compared to SIB [66]. Resources can serve as indicators that measure the extent of harm caused throughout the battery production process, using methods such as IMPACT 2002+ [84] and the Eco-indicator 99 (EI-99) [86]. The environmental impact [29], also known as the environmental intensity of materials [65], influences critical endpoint indicators that directly affect humans. This impact poses risks of harming human health and the ecosystem through exposure to hazardous substances and disrupting value chains from resource scarcity.

Several indicators were also refined by focusing on the implications of abiotic depletion [63] on water and land resources. Water management and consumption [26], [87]–[90], [92] as well as water depletion [42], [64], [93] are impacts of damage to abiotic resources and related to other indicators. For example, land occupation [42], [84], [86], [94] indirectly affects water, air, and land. It made land use [26], [64], [87]–[90] a relevant indicator as well. Discussions around water also advocate introducing the water risk index (WRI) [28]. The WRI involves factors such as water quality, quantity, and regulatory control as part of the Environmental Performance Index (EPI) [28]. This resource management cluster focuses on efficiently using resources that have reached the end of their life cycle and recycling system [26], [95]. For instance, Bae et al. [95] developed a waste-to-lithium (WTL) system that recovered lithium from waste materials through an electrochemical process. Recyclability is crucial in assessing production efficiency and end-of-life process [65]. It is akin to implementing waste management [26], as poorly managed waste, such as ecotoxicity, could harm humans.

The core issue of this category is the significant influence of ecotoxicity [64], which arises from extracting material and its subsequent production stages. This category has the most indicators because it integrates several midpoint and endpoint indicators in the LCA method. In the marine and freshwater ecosystem, the infiltration of respiratory organic and inorganic substances [61], [64], [84] create toxic conditions that lead to severe aquatic ecotoxicity [42], [61], [63], [84], [86]–[90]. Water acidification [63], [84] and eutrophication [30], [42], [60], [61], [63], [84]–[90] are significant problems that disrupt the ecosystems quality [84], [86] and its biodiversity [78] [26]. In addition, the production of batteries releases toxic pollutants [26] and particulate matter formations [42], [85]–[90] that have a substantial impact on ozone layer depletion [42], [60], [61], [64], [84]–[90], [92] and photochemical oxidants/ozone formation/creation [27], [42], [61], [64], [85], [87]–[90], [92]. This, in turn, exacerbates the impact of climate change [26], [27], [30], [60], [61], [63], [64], [78], [82], [84], [85], [88]–[90], [92], [96].

Further, when it comes to terrestrial ecosystems [87], [90], the rapid growth of lithium battery production has various adverse effects. This process leads to soil acidification [30], [61], [64], [85], [92] due to an imbalance of nutrients [42], [60], [84], [87]–[90], or eutrophication [30], [61], [64], [85], [92] which transformed and oxidized land [42], [86], further disrupting ecosystem function. Simultaneously, particulate matter emissions [42], [85]–[90] worsen air pollution, significantly impacting local air quality and global atmospheric dynamics. The presence of pollutants in the atmosphere worsens the problem of toxicity in humans [27], [42], [60], [61], [64], [86], [88], [89], as both carcinogenic and non-carcinogenic pollutants [64], [84], [87]–[90] or ionizing radiation [42], [61], [64], [84]–[90] enter the respiratory organs. This results in a measurable impact on health known as disability-adjusted life years (DALYs) [78], [84], [86], [90]. The situation highlights the growing carbon footprint and intensity [29], [66], [70], [75] from battery production, emphasizing the need for sustainable measures. Despite these challenges, there are signs of optimism in efforts such as the Footprint-Friendly Negative Index (FFNI) [94], which seeks to balance technological advances with environmental commitment.

3.5. *Political and Legal Factors*

This section discusses eight indicators from six reference articles, mainly concerning the link between supply risk and geopolitical risk factors. The Worldwide Governance Indicator (WGI) highlights this link by consistently reporting governance issues [28]. The WGI proves to be more resilient and adaptable across different stages of the material life cycle. According to Cellura et al. [30], WGI is the arithmetic average of the six worldwide governance indicators to gauge the geopolitical stability of the supplier countries. The supply risk for each material is assessed using the supply risk indicator that accounts for several criteria. These include the concentration index of the supplier countries, WGI as geopolitical risk, substitution index, end-of-life recycling rates, and the net import ratio. The indicators are combined to generate a standardized measure of supply risk, which is adjusted based on the battery's energy capacity to determine the relative influence of each material on geopolitical risk. One similar indicator is GeoPolEndpoint, which measures the socioeconomic repercussions of ram mineral resources. It serves as an endpoint indicator in the GeoPolRisk method [97]. Risks associated with sustainability indicators vary significantly across various geographic regions [26]. Hence, both external and internal risks are important.

Apart from supply-related risks, which are external factors, several indicators are associated with the country's internal affairs politics. The frequent discussion of Environmental, Social, and Governance (ESG) standards and their compliance is a practical way to assess and compare sustainability performance and progress across the Li-ion batteries supply chain [26]. Management systems for both sustainability and risk were also important. However, potential risks arise when policymakers focus on specialized and limited issues, potentially leading to difficulties in setting priorities among the views of key stakeholders [26]. It is evident when the legislative product is different between two products, such as the case of legislation for electric vehicles and legislation for batteries in Europe [83]. The disparity often extends to policies related to the energy mix. Energy mix is a potential contributor and parameter due to its largest impact on environmental indicators such as GWP, up to 30% compared to other indicators [63].

3.6. *Discussion*

Our systematic review encompassed 40 studies selected through the ROSES framework. After thoroughly examining each dimension in the STEEP analysis, we compiled sustainable indicators of battery production for electric vehicles. This distribution reflects the current state of research and suggests potential areas for further detailed study, particularly in under-represented dimensions. Ecological indicators were most prevalent, indicating a strong emphasis on environmental impacts in the sustainability assessment of EV battery production. This dominance may indicate that research on environmental aspects is somewhat saturated, potentially overshadowing the importance of other dimensions. In contrast, sociocultural factors are less represented with only 15 indicators. It highlights a significant gap and the need for more thorough research to address social impacts. Technological indicators, totaling 35, reflect ongoing innovations that enhance battery efficiency and lifecycle management. Economic factors, represented by 30 indicators, emphasize cost dynamics and market viability, which is crucial for sustainable practices. Political/legal indicators, though fewer with 20 indicators, underscore the importance of governance and regulatory frameworks in enforcing and guiding sustainability standards. The compiled list of indicators is shown in **Table 1**.

After the sustainable indicators were compiled in **Table 1**, they were mapped to specific stages of the EV battery lifecycle. This mapping reveals distinct patterns that pinpoint where interventions are most effective and showcases the unique interactions among the STEEP dimensions at each stage. During the initial stage of raw material extraction, the convergence of ecological and sociocultural factors is notable. The INFORM human hazard indicator, which evaluates risks to workers and local communities, is intricately linked with ecotoxicity. This intersection highlights a compelling need for comprehensive strategies that safeguard human well-being and the environment from harmful impacts. Technological and economic indicators could reinforce each other in the manufacturing stage. Advances in battery technology boost production efficiency while simultaneously reducing costs, resource use, and adverse environmental impacts. Harnessing this synergy could reshape market standards, advancing electric vehicle affordability and sustainability. Although excluded from this study, the usage phase presents a valuable area for future research. The impact of consumer behavior should be explored, such as charging habits on the battery lifespan and the role of technological advancements in improving user experience. Lastly, the end-of-life stage emphasizes the convergence of ecological, technological, and political/legal factors. Developing robust recycling technologies is crucial for safe and sustainable disposal. Meanwhile, political frameworks, such as battery passports and mass recycling targets, play a key role in setting standards and ensuring accountability.

Table 1. Compiled Sustainable Indicators of Batteries Production for Electric Vehicle

Categories	No.	Indicator	References	Stage(s)
Sociocultural	1	Workers' health and safety from injuries and deaths	[26], [60]	All Stages
	2	Child labor	[26]–[28], [60]	Mining
	3	Forced labor	[26]–[28]	Mining
	4	Inhuman treatment	[26]	Mining
	5	Freedom of association and collective bargaining	[26]	Mining
	6	Livelihood attainment	[26]	All Stages
	7	Job creation	[29]	All Stages
	8	Local community involvement/development	[26], [29]	Mining
	9	Respect for Indigenous people	[26]	Mining
	10	Justness (Income inequality, diversity, inclusion)	[26], [28]	Mining
	11	Public welfare (value added)	[61]	All Stages
	12	Public perception (acceptance)	[61]	All Stages
	13	Innovation/Patent growth rate	[61]	Production
	14	Corruption	[26], [27], [60]	All Stages
	15	Bribery	[26]	Mining
	16	INFORM Human Hazard	[28]	All Stages
	17	Fragile States Index	[28]	Mining
	18	Data security and privacy	[26]	All Stages
	19	Product quality and safety	[26]	Production
Technological	1	State of Charge / Battery Health	[71]–[73]	Production & End of Life
	2	Material and weight efficiency (Energy density, Power density, Synthesis material losses, Recyclability)	[65], [66], [68]–[70]	Production
	3	Energy Efficiency	[29], [63]–[65], [74]	Production
	4	Energy losses (in the battery & due to additional mass of the battery)	[74]	Production
	5	Embodied energy	[75]	Production
	6	Cycle life	[29], [74]	Production
	7	Safety	[29]	Production
	8	Specific energy	[29], [74]	Production
	9	Self-discharge rate	[29]	Production & End of life
	10	Energy intensity	[29]	All stages
	11	Shapes of LIB	[67]	Production
	12	Human-robot collaborative disassembly (HRCD)	[77]	Production
Economic	1	Contribution to local economic development	[26]	All stages
	2	Local supplies and employment	[26]	All stages

Categories	No.	Indicator	References	Stage(s)
	3	Capital intensity	[29]	All stages
	4	Energy storage system profit	[29]	End of life
	5	Value added	[60]	All stages
	6	Net present value (NPV)	[78]	All stages
	7	Present worth ratio (PWR)	[78]	All stages
	8	Cost of Ownership	[26], [81]	All stages
	9	Total battery cost	[27]	Production
	10	Operation/Operating cost	[29], [61]	All stages
	11	Life Cycle Costing (LCC)	[30], [61]	All stages
	12	Levelised Cost of Storage (LCOS)	[30], [98]	Production
	13	Levelised total costs (LTC)	[61]	All stages
	14	Average ten-year cost	[66]	All stages
	15	Battery pack cost	[70]	Production
	16	Eco-cost (EUR/kgCo)	[75]	All stages
	17	Financial cost	[82]	All stages
	18	Multi-life indicator	[81]	All stages
	19	Exergy cost (GJ)	[83]	Production
Ecological		**Resource Management**		
	1	Resource availability	[78]	Mining
	2	Mineral extraction	[84]	Mining
	3	Resources use, minerals, and metals	[85]	Mining
	4	Resources consumption/depletion	[26], [27], [30], [61], [64]	Mining
	5	Fossil depletion/exhaustion	[42], [86]	Mining
	6	Metal depletion	[42], [60]	Mining
	7	Non-renewable energy	[84]	All stages
	8	Mineral resources scarcity	[87]–[90]	Mining
	9	Fossil resource scarcity	[87]–[90]	Mining
	10	Existing raw material criticality	[66], [70]	Mining
	11	Resources	[84], [86]	Mining
	12	Environmental intensity of materials or impact	[29], [65]	All stages
	13	Abiotic depletion	[63]	All stages
	14	Water consumption and management	[26], [87]–[90], [92]	All stages
	15	Water depletion	[42], [64], [93]	Mining
	16	Water Risk Index	[28]	Mining
	17	Environmental Performance Index	[28]	All stages
Ecological	18	Land use	[26], [64], [87]–[90]	Mining
	19	Land occupation	[42], [84], [86], [94]	Mining
	20	Recycled content	[26]	End of life
	21	Recycling system/Recyclability	[65], [95]	Production & End of life
	22	Waste management	[26]	Production & End of life
		Ecotoxicity		
	23	Ecotoxicity	[64]	All stages
	24	Aquatic (marine, freshwater) ecotoxicity	[42], [61], [63], [84], [86]–[90]	All stages
	25	Terrestrial/land ecotoxicity	[42], [63], [84], [86]–[90]	All stages
	26	Human toxicity	[27], [42], [60], [61], [64], [86], [88], [89]	Mining & End of life
	27	Carcinogens	[64], [84], [87]–[90]	Mining & End of life

Categories	No.	Indicator	References	Stage(s)
Ecological	28	Non-carcinogens	[64], [84], [87]–[90]	Mining & End of life
	29	Respiratory organics	[64], [84]	All stages
	30	Respiratory inorganics	[61], [64], [84]	All stages
	31	Ionizing radiation	[42], [61], [64], [84]–[90]	All stages
	32	Human health (Disability Adjusted Life Years/DALY)	[78], [84], [86], [90]	All stages
	33	Ozone (stratospheric) layer depletion	[42], [60], [61], [64], [84]–[90], [92]	All stages
	34	Photochemical Oxidant/Ozone Formation (POF)/ Creation (POCP)	[27], [42], [61], [64], [85], [87]–[90], [92]	All stages
	35	Particulate matter formation	[42], [85]–[90]	All stages
	36	Acidification	[30], [61], [64], [85], [92]	All stages
	37	(Aquatic) acidification	[63], [84]	All stages
	38	Terrestrial acidification/Nutri	[42], [60], [84], [87]–[90]	All stages
	39	Eutrophication	[64], [92]	All stages
	41	Terrestrial eutrophication	[30], [61], [85]	All stages
	42	Water (aquatic, freshwater, marine) eutrophication	[30], [42], [60], [61], [63], [84]–[90]	All stages
	43	Global Warming Potential/Climate Change	[26], [27], [30], [60], [61], [63], [64], [78], [82], [84], [85], [88]–[90], [92], [96]	All stages
	44	Terrestrial ecosystems	[87], [90]	All stages
	45	Natural land transformation	[42], [86]	All stages
	46	Land oxidation	[86]	All stages
	47	Ecosystem quality (Potentially Disappeared Fraction/PDF of Plant Species in m^2 per year)	[84], [86]	All stages
	48	Ecosystem diversity	[78]	All stages
	49	Biodiversity	[26]	All stages
	50	Pollution (air, water, soil)	[26]	All stages
	51	Carbon footprint/intensity	[29], [66], [70], [75]	All stages
	52	Footprint friendly negative index (FFNI)	[94]	All stages
Political and Legal	1	ESG Standards and Compliance	[26]	All stages
	2	Sustainability management systems	[26]	All stages
	3	Risk management systems	[26]	All stages
	4	Energy mix regulation	[26], [63]	All stages
	5	Worldwide Governance Indicator	[28]	All stages
	6	Geopolitical Risk of Materials (GRMs)	[30], [97]	Production
	7	Supply risk	[30], [97]	Production
	8	Mass recycling targets in regulation	[83]	End of life

The mapping of sustainable indicators for each EV battery lifecycle stage underscores the necessity for an integrated approach that addresses ecological and technological improvements while considering sociocultural, political/legal, and economic factors. This study moved beyond the siloed approach and highlighted the importance of a coordinated framework that reflects the interconnectedness of lifecycle stages and dimensions to achieve long-term sustainability in EV battery production. It is vital to develop robust policies and practices that can guide the future of EV battery production towards greater sustainability. The identified gaps and the detailed examination of each lifecycle stage guide future research directions, suggesting that a more focused investigation into less explored areas could lead to significant advancements in sustainable practices. Moreover, these findings support the ongoing development of global standards for responsible EV manufacturing, advocating for a transition that is not only technologically efficient but also socially and environmentally just.

4. Conclusion

This systematic review aims to advance our understanding of sustainable indicators in EV battery production by applying the ROSES framework and the STEEP analysis across various lifecycle stages. From the impact of labor practices and community engagement during the raw material extraction phase to the disposal strategies and recycling application at the end-of-life, our findings underscore the critical roles of each lifecycle stage in achieving sustainable production of EV batteries. The STEEP analysis highlights the complex interdependencies among sociocultural, technological, economic, ecological, and political/legal dimensions. Key findings reveal the roles of community-focused labor practices, breakthrough in battery battery technology, strategic economic investment, and robust political and legal frameworks—each crucial to a more sustainable production across the battery lifecycle.

Although this study concentrated on Li-ion batteries as the current market leaders to provide insights into their sustainability, this narrow focus inevitably limits the scope of our analysis. While we briefly mentioned alternative technologies, such as solid-state and lithium-sulfur, they merit further exploration. Future research should delve deeper into other battery technologies, examining their potential to meet sustainability criteria more comprehensively. Adopting this holistic approach will foster the development of integrated models that address all sustainability dimensions and actively engage diverse stakeholders. This approach will equip policymakers and industry stakeholders with robust data-driven insights, which can be leveraged to craft policies that effectively drive sustainability in EV battery production. By fostering interdisciplinary collaboration and emphasizing empirical validation, this research will support advancing global standards for responsible EV manufacturing, ensuring that the transition to cleaner transportation technologies is both sustainable and equitable.

Acknowledgments

The authors would like to acknowledge The Higher Education Financing Center Ministry of Education, Culture, Research and Technology (BPPT Kemendikbudristek) and Indonesia Endowment Fund for Education Agency (LPDP) for their generous sponsorship and support. We also would like to extend our gratitude to Muhammad Fikruzzaman Rahawarin from the School of Environmental Science Universitas Indonesia for compiling the reviewed articles and providing generous input for our work.

Author's Declaration

Authors' contributions and responsibilities

N.A.A.: Conceptualization; Data curation; Formal analysis; Funding acquisition; Methodology; Writing - original draft; and Writing - review & editing; I.G.: Conceptualization; Supervision, Validation; Writing – review & editing; R.H.S.K.: Supervision; Writing – review & editing; W.A.: Project administration; Resources; Conceptualization, Review.

Funding

This research is funded by The Higher Education Financing Center Ministry of Education, Culture, Research and Technology (BPPT Kemendikbudristek) and the Indonesia Endowment Fund for Education Agency (LPDP).

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Additional information

No additional information from the authors.

Glossary of Terms

Abiotic depletion	:	Reduction in the number of non-living resources (like minerals and metals) due to human activities
BESS (Battery Energy Storage Systems)	:	Systems used to store energy for later use, especially in renewable energy applications, helping to balance supply and demand.
C-LCC (Commodity Life Cycle Costs)	:	The total cost of a commodity throughout its life cycle, including extraction, production, use, and disposal.
Capital Intensity	:	A measure of the capital required to generate profits or output in the production process.
Critical Metals	:	Essential raw materials, such as lithium, cobalt, and nickel, used in battery production.
Ecotoxicity	:	Potential for biological, chemical, or physical stressors to affect the ecosystem
Electrochemical reactivity	:	The performance of materials or systems in terms of their ability to undergo electrochemical reactions, typically related to batteries.
Energy Density	:	The amount of energy stored per unit mass or volume.
Embodied Energy	:	The total energy required to produce a product throughout its life cycle, from raw material extraction to disposal or recycling.
End-of-Life Phase	:	The final stage of a product's life cycle, typically involving disposal or recycling.
ESG (Environmental, Social, and Governance Standards)	:	Standards related to environmental, social, and governance factors that organizations follow to operate sustainably and ethically.
Exergy Cost	:	A measure of the energy or effort required for manufacturing processes, used to evaluate thermodynamic efficiency and resource intensity.
Fragile States Index	:	An index measuring the stability and pressures experienced by nations, indicating their vulnerability to conflict or collapse.
Global Warming Potential (GWP)	:	A measure of the relative contribution of different greenhouse gases to global warming.
GRMs (Geopolitical Risk of Materials)	:	Risks associated with the supply of critical materials due to political and economic instability in source countries.
Gravimetric Energy Density	:	Energy density measured in terms of weight, used to assess battery performance.
HCRD (Human-robot collaborative disassembly)	:	A manufacturing process where humans and robots work together to disassemble products, enhancing recycling efficiency and reducing labor costs.
INFORM Human Hazard and Fragile States Index	:	An index measuring human hazards in regions affected by conflict or instability.
IMPACT 2002+	:	A life cycle assessment method used to quantify environmental impacts.
LCC (Life Cycle Costing)	:	A method of calculating the total cost incurred throughout the operational life of a product.
LCOS (Levelized Cost of Storage)	:	The specific cost for discharging a unit of energy in energy storage systems.
Li-ion Batteries	:	Rechargeable batteries commonly used in electric vehicles, known for their high energy density.
LTC (Levelized Total Costs)	:	The average cost per unit of product generated during its lifespan.
LCSA (Life Cycle Sustainability Assessment)	:	A method for evaluating the sustainability of a product throughout its life cycle.
Multi-Life Cost	:	A metric that subtracts residual value from the total cost of ownership across multiple life cycles.
NPV (Net Present Value)	:	A financial metric used to assess the profitability of an investment or project.

Particulate Matter Formation	:	The generation of fine solid or liquid particles in the air, which pose health risks when inhaled.
PDF (Potentially Disappeared Fraction)	:	A measure used in ecological studies to assess the potential impact of human activities on plant species per square meter per year.
POF/POCP (Photochemical Oxidant/Ozone Formation)	:	The creation of ozone and other oxidants in the atmosphere through reactions of pollutants under sunlight.
Power Density	:	The rate at which energy can be released per unit volume or mass of a substance or system.
PWR (Present Worth Ratio)	:	A ratio calculated by dividing NPV by capital expenditure, used to assess profitability.
Recyclability	:	The ability to reuse materials from end-of-life products.
Recycling Rate	:	The percentage of materials or products that are recycled rather than discarded.
ROSES (RepOrting standards for Systematic Evidence Syntheses)	:	A framework guiding the systematic review process to ensure rigor and reproducibility in research synthesis.
Self-Discharge Rate	:	The rate at which a battery loses its charge when not in use.
STEEP Analysis	:	An analytical framework used to consider five broad categories of factors—Sociocultural, Technological, Economic, Environmental, and Political-Legal—that impact strategic planning and decision-making.
Substitution Index	:	A metric that assesses the potential for substituting one material for another in production.
TCO (Total Cost of Ownership)	:	The total cost of acquiring, operating, and maintaining a product throughout its life.
WGI (Worldwide Governance Indicator)	:	A composite indicator that measures governance effectiveness globally, reflecting dimensions such as the rule of law, regulatory quality, and control of corruption.
Water Depletion	:	The reduction of available water resources, often due to overuse or contamination.
WRI (Water Risk Index)	:	A tool used to assess the potential risks related to water usage, including quality and quantity.

References

[1] N. C. Onat *et al.*, “How eco-efficient are electric vehicles across Europe? A regionalized life cycle assessment-based eco-efficiency analysis,” *Sustainable Development*, vol. 29, no. 5, pp. 941–956, Sep. 2021, doi: 10.1002/sd.2186.

[2] A. Jinasena, O. S. Burheim, and A. H. Strømman, “A flexible model for benchmarking the energy usage of automotive lithium-ion battery cell manufacturing,” *Batteries*, vol. 7, no. 1, pp. 1–21, 2021, doi: 10.3390/batteries7010014.

[3] X. N. Penisa, M. T. Castro, J. D. A. Pascasio, E. A. Esparcia, O. Schmidt, and J. D. Ocon, “Projecting the price of lithium-ion NMC battery packs using a multifactor learning curve model,” *Energies*, vol. 13, no. 20, Oct. 2020, doi: 10.3390/en13205276.

[4] P. Marques, R. Garcia, L. Kulay, and F. Freire, “Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade,” *Journal of Cleaner Production*, vol. 229, pp. 787–794, Aug. 2019, doi: 10.1016/j.jclepro.2019.05.026.

[5] L. Weimer, T. Braun, and A. vom Hemdt, “Design of a systematic value chain for lithium-ion batteries from the raw material perspective,” *Resources Policy*, vol. 64, Dec. 2019, doi: 10.1016/j.resourpol.2019.101473.

[6] H. Maghfiroh, O. Wahyunggoro, and A. I. Cahyadi, “Low Pass Filter as Energy Management for Hybrid Energy Storage of Electric Vehicle: A Survey,” *Automotive Experiences*, vol. 6, no. 3, pp. 466–484, 2023, doi: 10.31603/ae.9398.

[7] Y. D. Herlambang *et al.*, “Study on Solar Powered Electric Vehicle with Thermal Management Systems on the Electrical Device Performance,” *Automotive Experiences*,

vol. 7, no. 1, pp. 18–27, 2024, doi: 10.31603/ae.10506.

[8] S. Ball, J. Clark, and J. Cookson, "Battery materials technology trends and market drivers for automotive applications challenges for science and industry in electric vehicles growth," *Johnson Matthey Technology Review*, vol. 64, no. 3, pp. 287–297, Jul. 2020, doi: 10.1595/205651320x15783059820413.

[9] D. Chiriță, S. Istrițeanu, G. I. Gheorghe, and V. Băjenaru, "Aspects Related To Current Recycling Methods and Trends in Implementing the Principles of the Circular Economy for Lithium-Ion Batteries," 2021. doi: 10.17683/IJOMAM/ISSUE10/V2.16.

[10] H. Ambrose and A. Kendall, "Understanding the future of lithium: Part 2, temporally and spatially resolved life-cycle assessment modeling," *Journal of Industrial Ecology*, vol. 24, no. 1, pp. 90–100, Feb. 2020, doi: 10.1111/jiec.12942.

[11] A. D. Shieddieque, I. Rahayu, S. Hidayat, and J. A. Laksmono, "Recent Development in LiFePO4 Surface Modifications with Carbon Coating from Originated Metal-Organic Frameworks (MOFs) to Improve the Conductivity of Cathode for Lithium-Ion Batteries: A Review and Bibliometrics Analysis," *Automotive Experiences*, vol. 6, no. 3, pp. 438–451, 2023, doi: 10.31603/ae.9524.

[12] T. Kim, W. Song, D.-Y. Son, L. K. Ono, and Y. Qi, "Lithium-ion batteries: outlook on present, future, and hybridized technologies," *Journal of Materials Chemistry A*, vol. 7, no. 7, pp. 2942–2964, 2019, doi: 10.1039/C8TA10513H.

[13] P. Maxwell and M. Mora, "Lithium and Chile: looking back and looking forward," *Mineral Economics*, vol. 33, no. 1–2, pp. 57–71, Jul. 2020, doi: 10.1007/s13563-019-00181-8.

[14] H. Ali, H. A. Khan, and M. G. Pecht, "Circular economy of Li Batteries: Technologies and trends," *Journal of Energy Storage*, vol. 40. Elsevier Ltd, Aug. 2021, doi: 10.1016/j.est.2021.102690.

[15] A. Upadhyay, T. Laing, V. Kumar, and M. Dora, "Exploring barriers and drivers to the implementation of circular economy practices in the mining industry," *Resources Policy*, vol. 72, Aug. 2021, doi: 10.1016/j.resourpol.2021.102037.

[16] A. Alessia, B. Alessandro, V.-G. G. Maria, V.-A. A. Carlos, and B. Francesca, "Challenges for sustainable lithium supply: A critical review," *Journal of Cleaner Production*, vol. 300, p. 126954, Jun. 2021, doi: 10.1016/j.jclepro.2021.126954.

[17] S. Wang and J. Yu, "A comparative life cycle assessment on lithium-ion battery: Case study on electric vehicle battery in China considering battery evolution," *Waste Management and Research*, vol. 39, no. 1, pp. 156–164, Jan. 2021, doi: 10.1177/0734242X20966637.

[18] Z. Yang, B. Wang, and K. Jiao, "Life cycle assessment of fuel cell, electric and internal combustion engine vehicles under different fuel scenarios and driving mileages in China," *Energy*, vol. 198, May 2020, doi: 10.1016/j.energy.2020.117365.

[19] M. A. Cusenza, F. Guarino, S. Longo, M. Ferraro, and M. Cellura, "Energy and environmental benefits of circular economy strategies: The case study of reusing used batteries from electric vehicles," *Journal of Energy Storage*, vol. 25, Oct. 2019, doi: 10.1016/j.est.2019.100845.

[20] Z. Siqi, L. Guangming, H. Wenzhi, H. Juwen, and Z. Haochen, "Recovery methods and regulation status of waste lithium-ion batteries in China: A mini review," *Waste Management and Research*, vol. 37, no. 11, pp. 1142–1152, Nov. 2019, doi: 10.1177/0734242X19857130.

[21] N. Fallah, C. Fitzpatrick, S. Killian, and M. Johnson, "End-of-Life Electric Vehicle Battery Stock Estimation in Ireland through Integrated Energy and Circular Economy Modelling," *Resources, Conservation and Recycling*, vol. 174, Nov. 2021, doi: 10.1016/j.resconrec.2021.105753.

[22] A. Boute and A. Zhikharev, "Vested interests as driver of the clean energy transition: Evidence from Russia's solar energy policy," *Energy Policy*, vol. 133, Oct. 2019, doi: 10.1016/j.enpol.2019.110910.

[23] B. Probst, V. Anatolitis, A. Kontoleon, and L. D. Anadón, "The short-term costs of local content requirements in the Indian solar auctions," *Nature Energy*, vol. 5, no. 11, pp.

842–850, Nov. 2020, doi: 10.1038/s41560-020-0677-7.

[24] U. E. Hansen, I. Nygaard, M. Morris, and G. Robbins, "The effects of local content requirements in auction schemes for renewable energy in developing countries: A literature review," *Renewable and Sustainable Energy Reviews*, vol. 127. Elsevier Ltd, Jul. 2020, doi: 10.1016/j.rser.2020.109843.

[25] S.-H. H. Lin and Y. Weng, "Can strengthening the local content requirements meet a government's need to raise industrial productivity and production?," *Journal of Applied Economics*, vol. 23, no. 1, pp. 316–328, Jan. 2020, doi: 10.1080/15140326.2020.1753468.

[26] M. Gebhardt, J. Beck, M. Kopyto, and A. Spieske, "Determining requirements and challenges for a sustainable and circular electric vehicle battery supply chain: A mixed-methods approach," *Sustainable Production and Consumption*, vol. 33, pp. 203–217, 2022, doi: 10.1016/j.spc.2022.06.024.

[27] J. L. Popien, C. Thies, A. Barke, and T. S. Spengler, "Comparative sustainability assessment of lithium-ion, lithium-sulfur, and all-solid-state traction batteries," *International Journal of Life Cycle Assessment*, vol. 28, no. 4, pp. 462–477, 2023, doi: 10.1007/s11367-023-02134-4.

[28] L. da Silva Lima, L. Cocquyt, L. Mancini, E. Cadena, and J. Dewulf, "The role of raw materials to achieve the Sustainable Development Goals: Tracing the risks and positive contributions of cobalt along the lithium-ion battery supply chain," *Journal of Industrial Ecology*, vol. 27, no. 3, pp. 777–794, Jun. 2023, doi: 10.1111/jiec.13336.

[29] A. R. Mishra, D. K. Tripathi, F. Cavallaro, P. Rani, S. K. Nigam, and A. Mardani, "Assessment of Battery Energy Storage Systems Using the Intuitionistic Fuzzy Removal Effects of Criteria and the Measurement of Alternatives and Ranking Based on Compromise Solution Method," *Energies*, vol. 15, no. 20, 2022, doi: 10.3390/en15207782.

[30] S. Cellura, A. Mazza, E. Bompard, and S. Corgnati, "An Extended Approach to the Evaluation of Energy Storage Systems: A Case Study of Li-Ion Batteries," *Electronics (Switzerland)*, vol. 12, no. 11, 2023, doi: 10.3390/electronics12112391.

[31] F. Liu, K. hung Lai, and W. Cai, "Responsible production for sustainability: Concept analysis and bibliometric review," *Sustainability (Switzerland)*, vol. 13, no. 3, pp. 1–27, Feb. 2021, doi: 10.3390/su13031275.

[32] R. P. Mohanty and A. Prakash, "Searching for definitions and boundaries in sustainable production system," 2017. doi: 10.1504/IJSOM.2017.083339.

[33] J. Bonvoisin, R. Stark, and G. Seliger, "Field of Research in Sustainable Manufacturing," pp. 3–20, 2017, doi: 10.1007/978-3-319-48514-0_1.

[34] V. Roy and S. Singh, "Mapping the business focus in sustainable production and consumption literature: Review and research framework," *Journal of Cleaner Production*, vol. 150, pp. 224–236, 2017, doi: 10.1016/j.jclepro.2017.03.040.

[35] E. Niesten and R. Lozano, "Making, buying and collaborating for more sustainable production and consumption," *Journal of Cleaner Production*, vol. 100, pp. 1–3, 2015, doi: 10.1016/j.jclepro.2015.03.014.

[36] G. M. Krolczyk *et al.*, "Ecological trends in machining as a key factor in sustainable production – A review," *Journal of Cleaner Production*, vol. 218, pp. 601–615, 2019, doi: 10.1016/j.jclepro.2019.02.017.

[37] A. Acquaye *et al.*, "Measuring the environmental sustainability performance of global supply chains: A multi-regional input-output analysis for carbon, sulphur oxide and water footprints," *Journal of Environmental Management*, vol. 187, pp. 571–585, Feb. 2017, doi: 10.1016/j.jenvman.2016.10.059.

[38] S. Xiong, Y. Wang, B. Bai, and X. Ma, "A hybrid life cycle assessment of the large-scale application of electric vehicles," *Energy*, vol. 216, Feb. 2021, doi: 10.1016/j.energy.2020.119314.

[39] J. Baars, T. Domenech, R. Bleischwitz, H. E. Melin, and O. Heidrich, "Circular economy strategies for electric vehicle batteries reduce reliance on raw materials," *Nature*

Sustainability, vol. 4, no. 1, pp. 71–79, Jan. 2021, doi: 10.1038/s41893-020-00607-0.

[40] J. C. Kelly, Q. Dai, and M. Wang, "Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries," *Mitigation and Adaptation Strategies for Global Change*, vol. 25, no. 3, pp. 371–396, Mar. 2020, doi: 10.1007/s11027-019-09869-2.

[41] S. Jenu, I. Deviatkin, A. Hentunen, M. Myllysilta, S. Viik, and M. Pihlatie, "Reducing the climate change impacts of lithium-ion batteries by their cautious management through integration of stress factors and life cycle assessment," *Journal of Energy Storage*, vol. 27, Feb. 2020, doi: 10.1016/j.est.2019.101023.

[42] F. Antonanzas-Torres, J. Antonanzas, and J. Blanco-Fernandez, "Environmental life cycle impact of off-grid rural electrification with mini grids in West Africa," *Sustainable Energy Technologies and Assessments*, vol. 47, no. July, p. 101471, 2021, doi: 10.1016/j.seta.2021.101471.

[43] M. Iturrondobeitia *et al.*, "Environmental Impacts of Aqueous Zinc Ion Batteries Based on Life Cycle Assessment," *Advanced Sustainable Systems*, vol. 6, no. 1, Jan. 2022, doi: 10.1002/adsu.202100308.

[44] A. R. Kurniawan, T. Murayama, and S. Nishikizawa, "A qualitative content analysis of environmental impact assessment in Indonesia: a case study of nickel smelter processing," *Impact Assessment and Project Appraisal*, vol. 38, no. 3, pp. 194–204, May 2020, doi: 10.1080/14615517.2019.1672452.

[45] A. Beaudet, F. Larouche, K. Amouzegar, P. Bouchard, and K. Zaghib, "Key challenges and opportunities for recycling electric vehicle battery materials," *Sustainability (Switzerland)*, vol. 12, no. 14. MDPI, Jul. 2020, doi: 10.3390/su12145837.

[46] J. Neumann *et al.*, "Recycling of Lithium-Ion Batteries—Current State of the Art, Circular Economy, and Next Generation Recycling," *Advanced Energy Materials*, vol. 12, no. 17, May 2022, doi: 10.1002/aenm.202102917.

[47] H. T. Kim, Y. G. Jin, and Y. T. Yoon, "An economic analysis of load leveling with battery energy storage systems (BESS) in an electricity market environment: The Korean case," *Energies*, vol. 12, no. 9, 2019, doi: 10.3390/en12091608.

[48] L. Mauler, F. Duffner, and J. Leker, "Economies of scale in battery cell manufacturing: The impact of material and process innovations," *Applied Energy*, vol. 286, p. 116499, Mar. 2021, doi: 10.1016/j.apenergy.2021.116499.

[49] M. U. Rehman and X. V. Vo, "Energy commodities, precious metals and industrial metal markets: A nexus across different investment horizons and market conditions," *Resources Policy*, vol. 70, no. June 2020, p. 101843, Mar. 2021, doi: 10.1016/j.resourpol.2020.101843.

[50] Z. A. Kader, A. Marshall, and J. Kennedy, "A review on sustainable recycling technologies for lithium-ion batteries," *Emergent Materials*, vol. 4, no. 3. Springer Nature, pp. 725–735, Jun. 2021, doi: 10.1007/s42247-021-00201-w.

[51] E. Pallaro, N. Subramanian, M. D. Abdulrahman, and C. Liu, "Sustainable production and consumption in the automotive sector: Integrated review framework and research directions," *Sustainable Production and Consumption*, vol. 4, no. July, pp. 47–61, 2015, doi: 10.1016/j.spc.2015.07.002.

[52] A. Ljovkina *et al.*, *Renewable energy in Russia: System analysis of barriers*, vol. 8, no. 2. 2021.

[53] A. A. Tofigh and M. Abedian, "Analysis of energy status in Iran for designing sustainable energy roadmap," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 1296–1306, 2016, doi: 10.1016/j.rser.2015.12.209.

[54] F. M. Alptekin and M. S. Celiktas, "Review on Catalytic Biomass Gasification for Hydrogen Production as a Sustainable Energy Form and Social, Technological, Economic, Environmental, and Political Analysis of Catalysts," *ACS Omega*, vol. 7, no. 29, pp. 24918–24941, 2022, doi: 10.1021/acsomega.2c01538.

[55] N. Bayomi and J. E. Fernandez, "Towards sustainable energy trends in the Middle East: A study of four major emitters," *Energies*, vol. 12, no. 9, 2019, doi: 10.3390/en12091615.

[56] M. Alipour, S. Alighaleh, R. Hafezi, and M. Omranievardi, "A new hybrid decision

framework for prioritizing funding allocation to Iran's energy sector," *Energy*, vol. 121, pp. 388–402, 2017, doi: 10.1016/j.energy.2017.01.024.
[57] G. Fisher, J. E. E. Wisneski, and R. M. M. Bakker, "STEEP," in *Strategy in 3D*, vol. 11, no. 1, Oxford University PressNew York, 2020, pp. 36–45.
[58] N. R. R. Haddaway, B. Macura, P. Whaley, and A. S. S. Pullin, "ROSES Reporting standards for Systematic Evidence Syntheses: Pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps," *Environmental Evidence*, vol. 7, no. 1, pp. 4–11, 2018, doi: 10.1186/s13750-018-0121-7.
[59] N. R. Haddaway, B. Macura, P. Whaley, and A. S. Pullin, "ROSES flow diagram for systematic maps. Version 1.0," 2017. .
[60] C. Thies, K. Kieckhäfer, and T. S. Spengler, *Activity analysis based modeling of global supply chains for sustainability assessment*, vol. 91, no. 2. Springer Berlin Heidelberg, 2021.
[61] M. Haase *et al.*, "Prospective assessment of energy technologies: a comprehensive approach for sustainability assessment," *Energy, Sustainability and Society*, vol. 12, no. 1, pp. 1–42, 2022, doi: 10.1186/s13705-022-00344-6.
[62] C. Caldeira, M. Costa Figueiredo, L. Dodakian, C. R. B. De Souza, S. C. Cramer, and Y. Chen, "Towards Supporting Data-Driven Practices in Stroke Telerehabilitation Technology," *Proceedings of the ACM on Human-Computer Interaction*, vol. 5, no. CSCW1, pp. 1–33, 2021, doi: 10.1145/3449099.
[63] P. Zwolinski and S. Tichkiewitch, "An agile model for the eco-design of electric vehicle Li-ion batteries," *CIRP Annals*, vol. 68, no. 1, pp. 161–164, 2019, doi: 10.1016/j.cirp.2019.04.009.
[64] M. L. Carvalho, A. Temporelli, and P. Girardi, "Life Cycle Assessment of Stationary Storage Systems within the Italian Electric Network," *Energies*, vol. 14, no. 8, p. 2047, Apr. 2021, doi: 10.3390/en14082047.
[65] L. A.-W. W. Ellingsen *et al.*, "Nanotechnology for environmentally sustainable electromobility," *Nature Nanotechnology*, vol. 11, no. 12, pp. 1039–1051, Dec. 2016, doi: 10.1038/nnano.2016.237.
[66] M. Baumann *et al.*, "Prospective Sustainability Screening of Sodium-Ion Battery Cathode Materials," *Advanced Energy Materials*, vol. 12, no. 46, Dec. 2022, doi: 10.1002/aenm.202202636.
[67] R. Schröder, M. Aydemir, and G. Seliger, "Comparatively Assessing different Shapes of Lithium-ion Battery Cells," *Procedia Manufacturing*, vol. 8, no. October 2016, pp. 104–111, 2017, doi: 10.1016/j.promfg.2017.02.013.
[68] I. Hasa *et al.*, "Challenges of today for Na-based batteries of the future: From materials to cell metrics," *Journal of Power Sources*, vol. 482, no. September 2020, p. 228872, 2021, doi: 10.1016/j.jpowsour.2020.228872.
[69] S. Y. Lai, C. Cavallo, M. E. Abdelhamid, F. Lou, and A. Y. Koposov, "Advanced and Emerging Negative Electrodes for Li-Ion Capacitors: Pragmatism vs. Performance," *Energies*, vol. 14, no. 11, p. 3010, May 2021, doi: 10.3390/en14113010.
[70] J. Baars, F. Cerdas, and O. Heidrich, "An Integrated Model to Conduct Multi-Criteria Technology Assessments: The Case of Electric Vehicle Batteries," *Environmental Science and Technology*, vol. 57, no. 12, pp. 5056–5067, 2023, doi: 10.1021/acs.est.2c04080.
[71] Z. Wang, X. Zhao, L. Fu, D. Zhen, F. Gu, and A. D. Ball, "A review on rapid state of health estimation of lithium-ion batteries in electric vehicles," *Sustainable Energy Technologies and Assessments*, vol. 60, no. April, p. 103457, 2023, doi: 10.1016/j.seta.2023.103457.
[72] J. Xie, Y. Weng, and H. D. Nguyen, "Health-Informed Lifespan-Oriented Circular Economic Operation of Li-Ion Batteries," *IEEE Transactions on Industrial Informatics*, vol. 19, no. 3, pp. 2749–2760, 2023, doi: 10.1109/TII.2022.3178375.
[73] M. S. Hossain Lipu *et al.*, "Data-driven state of charge estimation of lithium-ion batteries: Algorithms, implementation factors, limitations and future trends," *Journal of Cleaner Production*, vol. 277, 2020, doi: 10.1016/j.jclepro.2020.124110.

[74] J. Matheys, J. M. Timmermans, J. Van Mierlo, S. Meyer, and P. Van Den Bossche, "Comparison of the environmental impact of five electric vehicle battery technologies using LCA," *International Journal of Sustainable Manufacturing*, vol. 1, no. 3, pp. 318–329, 2009, doi: 10.1504/IJSM.2009.023977.

[75] A. Fahimi *et al.*, "Sustainability Analysis of Processes to Recycle Discharged Lithium-Ion Batteries, Based on the ESCAPE Approach," *Materials*, vol. 15, no. 23, 2022, doi: 10.3390/ma15238527.

[76] Q. Liu, Z. Liu, W. Xu, Q. Tang, Z. Zhou, and D. T. Pham, "Human-robot collaboration in disassembly for sustainable manufacturing," *International Journal of Production Research*, vol. 57, no. 12, pp. 4027–4044, Jun. 2019, doi: 10.1080/00207543.2019.1578906.

[77] G. Yuan, X. Liu, C. Zhang, D. T. Pham, and Z. Li, "A new heuristic algorithm based on multi-criteria resilience assessment of human–robot collaboration disassembly for supporting spent lithium-ion battery recycling," *Engineering Applications of Artificial Intelligence*, vol. 126, no. PB, p. 106878, 2023, doi: 10.1016/j.engappai.2023.106878.

[78] L. Stougie *et al.*, "Multi-dimensional life cycle assessment of decentralised energy storage systems," *Energy*, vol. 182, pp. 535–543, Sep. 2019, doi: 10.1016/j.energy.2019.05.110.

[79] S. E. Adekunle, "Management: Applying Integrated Project-Management Methodology to Hydrocarbon-Portfolio Analysis and Optimization," *Journal of Petroleum Technology*, vol. 59, no. 02, pp. 44–49, Feb. 2007, doi: 10.2118/0207-0044-JPT.

[80] E. Drury, P. Denholm, and R. Margolis, "The Impact of Different Economic Performance Metrics on the Perceived Value of Solar Photovoltaics," National Renewable Energy Laboratory, Colorado, 2011.

[81] A. Jeppe, H. Proff, and M. Eickhoff, "Economic Potentials of Ecologically Attractive Multi-Life Products—The Example of Lithium-Ion Batteries," *Sustainability (Switzerland)*, vol. 15, no. 14, 2023, doi: 10.3390/su151411184.

[82] G. Gonzales-Calienes, M. Kannangara, and F. Bensebaa, "Economic and Environmental Viability of Lithium-Ion Battery Recycling—Case Study in Two Canadian Regions with Different Energy Mixes," *Batteries*, vol. 9, no. 7, 2023, doi: 10.3390/batteries9070375.

[83] A. Ortego, A. Valero, A. Valero, and E. Restrepo, "Vehicles and Critical Raw Materials: A Sustainability Assessment Using Thermodynamic Rarity," *Journal of Industrial Ecology*, vol. 22, no. 5, pp. 1005–1015, 2018, doi: 10.1111/jiec.12737.

[84] Y. Wang, Y. Yu, K. Huang, B. Chen, W. Deng, and Y. Yao, "Quantifying the environmental impact of a Li-rich high-capacity cathode material in electric vehicles via life cycle assessment," *Environmental Science and Pollution Research*, vol. 24, no. 2, pp. 1251–1260, 2017, doi: 10.1007/s11356-016-7849-9.

[85] M. L. Carvalho, M. A. Cusenza, G. Mela, A. Temporelli, I. Quinzeni, and P. Girardi, "LCA and C-LCC Indicator as Tools for Sodium-Ion Batteries' Eco-Design," *Energies*, vol. 16, no. 17, 2023, doi: 10.3390/en16176220.

[86] L. Wang, H. Wu, Y. Hu, Y. Yu, and K. Huang, "Environmental sustainability assessment of typical cathode materials of lithium-ion battery based on three LCA approaches," *Processes*, vol. 7, no. 2, 2019, doi: 10.3390/pr7020083.

[87] I. Rey, M. Iturrondobeitia, O. Akizu-Gardoki, R. Minguez, and E. Lizundia, "Environmental Impact Assessment of Na 3 V 2 (PO 4) 3 Cathode Production for Sodium-Ion Batteries," *Advanced Energy and Sustainability Research*, vol. 3, no. 8, Aug. 2022, doi: 10.1002/aesr.202200049.

[88] M. Iturrondobeitia, C. Vallejo, M. Berroci, O. Akizu-Gardoki, R. Minguez, and E. Lizundia, "Environmental Impact Assessment of LiNi1/3Mn1/3Co1/3O2Hydrometallurgical Cathode Recycling from Spent Lithium-Ion Batteries," *ACS Sustainable Chemistry and Engineering*, vol. 10, no. 30, pp. 9798–9810, 2022, doi: 10.1021/acssuschemeng.2c01496.

[89] M. Iturrondobeitia, O. Akizu-Gardoki, O. Amondarain, R. Minguez, and E. Lizundia, "Environmental Impacts of Aqueous Zinc Ion Batteries Based on Life Cycle Assessment," *Advanced Sustainable Systems*, vol. 6, no. 1, Jan. 2022, doi: 10.1002/adsu.202100308.

[90] I. Rey, C. Vallejo, G. Santiago, M. Iturrondobeitia, and E. Lizundia, “Environmental Impacts of Graphite Recycling from Spent Lithium-Ion Batteries Based on Life Cycle Assessment,” *ACS Sustainable Chemistry and Engineering*, vol. 9, no. 43, pp. 14488–14501, 2021, doi: 10.1021/acssuschemeng.1c04938.

[91] S. Glöser, L. Tercero Espinoza, C. Gandenberger, and M. Faulstich, “Raw material criticality in the context of classical risk assessment,” *Resources Policy*, vol. 44, pp. 35–46, 2015, doi: 10.1016/j.resourpol.2014.12.003.

[92] M. Rinne, H. Elomaa, and M. Lundström, “Life cycle assessment and process simulation of prospective battery-grade cobalt sulfate production from Co-Au ores in Finland,” *International Journal of Life Cycle Assessment*, vol. 26, no. 11, pp. 2127–2142, 2021, doi: 10.1007/s11367-021-01965-3.

[93] D. P. Souza, A. T. Pontes, K. R. A. Nunes, J. A. Rodrigues, and V. J. M. F. Filho, “Development of a life cycle based process for cobalt recovering from cell batteries,” *Cleaner Waste Systems*, vol. 3, no. July, p. 100050, 2022, doi: 10.1016/j.clwas.2022.100050.

[94] H. Wu, Y. Hu, Y. Yu, K. Huang, and L. Wang, “The environmental footprint of electric vehicle battery packs during the production and use phases with different functional units,” *International Journal of Life Cycle Assessment*, vol. 26, no. 1, pp. 97–113, 2021, doi: 10.1007/s11367-020-01836-3.

[95] H. Bae, S. M. Hwang, I. Seo, and Y. Kim, “Electrochemical Lithium Recycling System toward Renewable and Sustainable Energy Technologies,” *Journal of The Electrochemical Society*, vol. 163, no. 7, pp. E199–E205, 2016, doi: 10.1149/2.0691607jes.

[96] P. Mandade, M. Weil, M. Baumann, and Z. Wei, “Environmental life cycle assessment of emerging solid-state batteries: A review,” *Chemical Engineering Journal Advances*, vol. 13, no. November 2022, p. 100439, 2023, doi: 10.1016/j.ceja.2022.100439.

[97] J. Santillán-Saldivar *et al.*, “Design of an endpoint indicator for mineral resource supply risks in life cycle sustainability assessment: The case of Li-ion batteries,” *Journal of Industrial Ecology*, vol. 25, no. 4, pp. 1051–1062, Aug. 2021, doi: 10.1111/jiec.13094.

[98] L. Li *et al.*, “Comparative techno-economic analysis of large-scale renewable energy storage technologies,” *Energy and AI*, vol. 14, no. June, p. 100282, 2023, doi: 10.1016/j.egyai.2023.100282.