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Life cycle assessment of lithium-ion batteries in utility-scale applications: Impacts on power supply sustainability and grid decarbonization

Oluwafemi Odunayo Olusesan [1,*], Fawaz Olabanji Nasir [2], Prayer Erumusele Atumah [3], Michael Ayobami Akinlabi [4], Damilola Emmanuel Olayiwola [5], Abdulraheem Adedayo Thanni [6] and Saleem Adetunji Adeniyi [7]

[1] *Department of Materials and Metallurgical Engineering, University of Ilorin, Ilorin, Nigeria.*
[2] *Department of Mechanical Engineering, University of Ilorin, Ilorin, Nigeria.*
[3] *Department of Geology, University of Benin, Edo, Nigeria.*
[4] *Department of Materials and Metallurgical Engineering, University of Ilorin, Ilorin, Nigeria.*
[5] *Department of Mechanical Engineering, University of Ilorin, Ilorin, Nigeria.*
[6] *Department of Mechanical Engineering, University of Lagos, Akoka, Lagos, Nigeria.*
[7] *Department of Chemical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Oyo, Nigeria.*

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Abstract

Lithium-ion batteries (LIBs) are pivotal in transforming power systems toward sustainability and decarbonization, yet their environmental footprint demands rigorous scrutiny to ensure net benefits in utility-scale applications. This review employs life cycle assessment (LCA) to evaluate the environmental impacts of LIBs, from raw material extraction to end-of-life management, revealing a complex interplay of challenges and opportunities. While LIBs enable renewable energy integration, enhance grid reliability, and reduce carbon intensity by storing clean energy and displacing fossil fuels, their production incurs significant greenhouse gas emissions, resource depletion, and ecosystem disruption, particularly due to lithium and cobalt extraction. Advances in low-impact chemistries, such as lithium iron phosphate, and scalable recycling strategies mitigate these burdens, while policy incentives like carbon pricing and technological innovations, including solid-state batteries and AI-driven LCA optimization, promise enhanced sustainability. Case studies, such as the Hornsdale Power Reserve, underscore LIBs' transformative potential in stabilizing renewable-heavy grids, yet regional grid mixes and battery degradation highlight context-specific trade-offs. Looking ahead, a circular economy and next-generation technologies could redefine LIBs' role in achieving net-zero grids by 2050. This review offers a nuanced synthesis for policymakers, industry leaders, and researchers, advocating for strategic deployment and innovation to harness LIBs' full potential in forging a sustainable, low-carbon energy future.

Keywords: Lithium-Ion Batteries; Utility-Scale Energy Storage; Life Cycle Assessment; Grid Decarbonization; Power Supply Sustainability; Renewable Energy Integration; Battery Recycling; Environmental Impacts

1. Introduction

The global transition to sustainable energy systems has positioned lithium-ion batteries (LIBs) as critical enablers of utility-scale energy storage, supporting the integration of renewable energy sources into power grids. As electricity demand grows and decarbonization goals intensify, LIBs offer solutions for grid stability, load balancing, and energy storage to mitigate the intermittency of renewable sources like solar and wind. However, their environmental footprint across the life cycle—from raw material extraction to end-of-life management—raises questions about their sustainability. This review employs a life cycle assessment (LCA) framework to evaluate the environmental impacts of LIBs in utility-scale applications, focusing on their contributions to power supply sustainability and grid

* Corresponding author: Oluwafemi Odunayo Olusesan; Email: olusesan.femi01@gmail.com

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decarbonization. By synthesizing recent literature, this paper aims to provide a comprehensive understanding of the trade-offs and opportunities associated with large-scale LIB deployment.

1.1. Background and Context

The increasing reliance on renewable energy sources to meet global energy demands has underscored the importance of energy storage systems, particularly lithium-ion batteries, in utility-scale applications. According to Peters et al. [1], LIBs have emerged as the dominant technology for grid-scale storage due to their high energy density, efficiency, and declining costs. These batteries are deployed in large-scale energy storage systems (ESS) to provide services such as peak shaving, frequency regulation, and renewable energy smoothing, which are critical for maintaining grid reliability in the face of variable renewable generation. For instance, large-scale LIB installations, such as the Hornsdale Power Reserve in Australia, have demonstrated significant improvements in grid stability and cost savings by reducing reliance on fossil fuel-based peaker plants [2]. However, the environmental implications of scaling up LIB deployment remain a critical concern, as their production and disposal involve energy-intensive processes and critical material extraction.

The environmental footprint of LIBs spans multiple life cycle stages, including raw material extraction, manufacturing, use, and end-of-life management. Findings from Dunn et al. [3] indicate that the production phase, particularly the mining of lithium, cobalt, and nickel, contributes significantly to greenhouse gas (GHG) emissions and resource depletion. These impacts are compounded when LIBs are deployed at utility scale, where large battery capacities amplify material and energy demands. Moreover, the integration of LIBs into grids with varying carbon intensities influences their overall environmental performance. For example, a study by Arbabzadeh et al. [4] highlights that the carbon footprint of LIBs in grid applications depends heavily on the energy mix used during their production and operation, underscoring the need for region-specific LCAs.

The growing adoption of LIBs in utility-scale applications is driven by policy frameworks and economic incentives aimed at decarbonizing power systems. According to Schmidt et al. [5], global energy policies, such as the European Union's Green Deal and the United States' clean energy targets, emphasize the role of energy storage in achieving net-zero emissions by 2050. However, the sustainability of LIBs hinges on mitigating their environmental impacts through improved manufacturing processes, recycling technologies, and sustainable material sourcing. This subsection sets the stage for a detailed LCA of LIBs, exploring how their deployment in utility-scale systems can balance environmental costs with the benefits of grid decarbonization.

Objectives of the Review

This review aims to critically assess the life cycle environmental impacts of lithium-ion batteries in utility-scale applications, with a focus on their contributions to power supply sustainability and grid decarbonization. By employing the LCA framework, the paper synthesizes findings from recent studies to evaluate the environmental trade-offs associated with LIB deployment. In a comprehensive study by Baumann et al. [6], LCA was identified as a robust tool for quantifying the environmental impacts of energy storage technologies across their life cycle, from cradle to grave. This review builds on such work by focusing specifically on utility-scale LIB systems, which have unique operational and environmental characteristics compared to smaller-scale applications, such as electric vehicles.

A key objective is to analyze the environmental impacts of LIBs across their life cycle stages, including raw material extraction, manufacturing, use, and end-of-life management. According to Majeau-Bettez et al. [7], the production phase of LIBs contributes significantly to global warming potential (GWP) and resource depletion, necessitating a detailed examination of mitigation strategies. This review will explore how advancements in battery chemistry, recycling technologies, and supply chain management can reduce these impacts. Additionally, the paper aims to quantify the role of LIBs in enabling renewable energy integration and reducing grid carbon intensity, drawing on case studies and LCA data from recent literature.

Another objective is to identify gaps in current research and propose directions for future studies. For instance, Arbabzadeh et al. [8] noted that many LCAs of LIBs focus on electric vehicle applications, with limited attention to utility-scale systems. This review addresses this gap by synthesizing data specific to grid-scale applications, where long-term performance, scalability, and end-of-life management present unique challenges. By providing a holistic assessment, the paper seeks to inform policymakers, industry stakeholders, and researchers about the sustainability implications of LIB deployment in decarbonizing power systems.

The review also aims to contextualize the role of LIBs within broader energy transition goals. As highlighted by Kim et al. [9], the environmental benefits of LIBs in grid applications depend on factors such as grid energy mix, battery lifespan, and recycling efficiency. This paper will evaluate these factors to provide a nuanced understanding of how LIBs

contribute to sustainable energy systems while addressing potential environmental trade-offs. Through this comprehensive analysis, the review seeks to guide the development of more sustainable energy storage solutions.

1.2. Relevance to Power Supply Sustainability

Lithium-ion batteries play a pivotal role in enhancing power supply sustainability by enabling the integration of renewable energy sources into the grid. According to Ralon et al. [10], energy storage systems like LIBs are essential for addressing the intermittency of solar and wind power, which is critical for achieving global sustainability goals. By storing excess renewable energy during periods of high generation and releasing it during peak demand, LIBs reduce reliance on fossil fuel-based power plants, thereby lowering GHG emissions. For example, a study by Zhu et al. [11] found that utility-scale LIB systems can reduce grid carbon intensity by up to 30% in regions with high renewable penetration, highlighting their significance in sustainable power systems.

However, the sustainability of LIBs is tempered by their environmental impacts, particularly during production and end-of-life phases. In a seminal study by Notter et al. [12], the energy-intensive nature of LIB manufacturing was shown to contribute significantly to their life cycle GHG emissions, often offsetting the environmental benefits achieved during the use phase. This underscores the need for LCAs to evaluate the full environmental footprint of LIBs in utility-scale applications. Moreover, the reliance on critical materials like cobalt and lithium raises concerns about resource scarcity and ethical sourcing, as noted by Olivetti et al. [13]. Addressing these challenges is essential for ensuring that LIBs contribute to long-term power supply sustainability.

The relevance of LIBs to grid decarbonization extends beyond their technical performance to encompass policy and economic dimensions. According to Pellow et al. [14], supportive policies, such as subsidies for energy storage and carbon pricing, are critical for scaling up LIB deployment in a sustainable manner. These policies can incentivize the adoption of greener manufacturing processes and recycling technologies, reducing the environmental footprint of LIBs. This review will explore how such strategies can enhance the sustainability of LIBs in utility-scale applications, drawing on global case studies and LCA data.

Finally, the integration of LIBs into power systems must be evaluated in the context of circular economy principles. As emphasized by Harper et al. [15], recycling and second-life applications for LIBs can significantly reduce their environmental impacts and enhance resource efficiency. By examining these strategies, this review highlights the potential of LIBs to support sustainable power systems while addressing the challenges of scaling up deployment. The following sections will delve deeper into the LCA methodology, environmental impacts, and contributions of LIBs to grid decarbonization, providing a comprehensive assessment of their role in sustainable energy transitions.

2. Life Cycle Assessment (LCA) Methodology for Lithium-Ion Batteries

Life Cycle Assessment (LCA) provides a standardized framework for evaluating the environmental impacts of lithium-ion batteries (LIBs) across their entire life cycle, from raw material extraction to end-of-life management, making it a critical tool for assessing their sustainability in utility-scale applications. LCA enables researchers to quantify impacts such as greenhouse gas (GHG) emissions, energy consumption, and resource depletion, offering insights into the trade-offs of LIB deployment in grid systems. This section explores the LCA methodology tailored to LIBs, focusing on its framework, system boundaries, and key environmental impact categories relevant to utility-scale applications. By synthesizing findings from recent studies, the section highlights the methodological considerations necessary for understanding the role of LIBs in power supply sustainability and grid decarbonization.

2.1. Overview of LCA Framework

The LCA framework, as defined by the ISO 14040 and 14044 standards, consists of four main phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. According to Cosme et al. [16], this structured approach ensures a comprehensive evaluation of environmental impacts, making it well-suited for analyzing complex systems like LIBs in utility-scale energy storage. The goal and scope phase establishes the purpose of the LCA, such as assessing the environmental footprint of LIBs in grid applications, while defining functional units, such as kilowatt-hours of energy stored or delivered. For utility-scale LIBs, the functional unit often reflects the battery's capacity to support grid services like peak shaving or renewable energy integration, which differs from smaller-scale applications like electric vehicles. Figure 1 depicts the structured LCA framework as applied to battery energy storage systems, providing a visual representation of the iterative process that ensures comprehensive environmental evaluation in utility-scale LIB contexts.

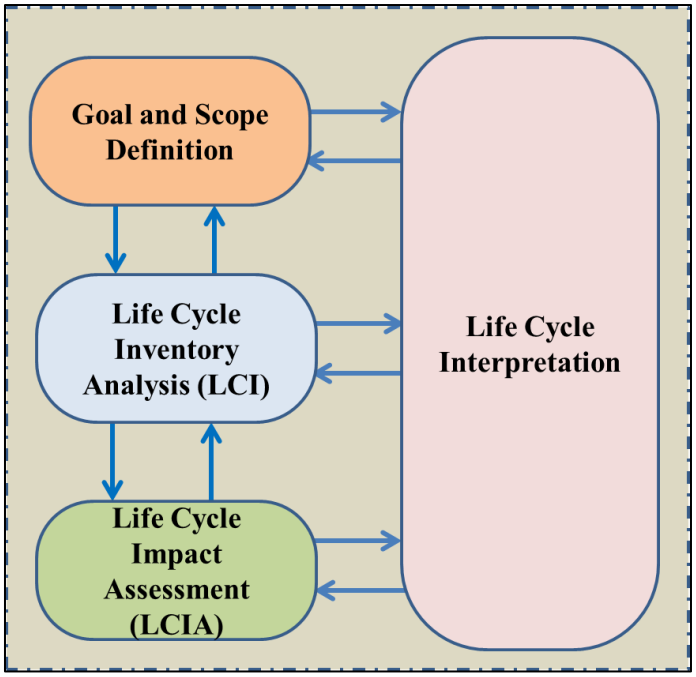


Figure 1 The LCA Framework Diagram

The life cycle inventory (LCI) phase involves collecting data on inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) across all life cycle stages. In a detailed study by Ellingsen et al. [17], the LCI for LIB production highlighted the significant energy demands of cell manufacturing, particularly for cathode materials like lithium nickel manganese cobalt oxide (NMC). For utility-scale applications, the LCI must account for larger battery systems and their operational context, such as grid energy mix and battery cycling patterns. This phase is critical for ensuring data accuracy, as incomplete or region-specific inventories can skew results, especially when comparing LIBs to alternative storage technologies like pumped hydro or flow batteries.

The life cycle impact assessment (LCIA) phase translates inventory data into environmental impacts, such as global warming potential (GWP), acidification, and resource depletion. Findings from Dai et al. [18] indicate that LCIA for LIBs often focuses on GWP due to the high carbon footprint of production processes, but other categories like human toxicity and ecosystem impacts are equally relevant for utility-scale systems. The interpretation phase synthesizes these results to provide actionable insights, such as identifying hotspots for environmental improvement. For instance, Baumann et al. [6] emphasized that LCA interpretation for grid-scale LIBs should consider the dynamic interplay between battery production impacts and their benefits in reducing grid carbon intensity. To illustrate the application of this framework in recent literature, Table 1 provides a comprehensive summary of key LCA studies on LIBs, focusing on their methodologies, quantitative findings, and implications for utility-scale grid applications.

Applying LCA to utility-scale LIBs requires tailoring the framework to account for their unique operational characteristics. Unlike electric vehicle batteries, grid-scale LIBs operate under fixed conditions with frequent charge-discharge cycles, affecting their lifespan and environmental performance. A study by Hiremath et al. [19] demonstrated that LCA for grid storage must incorporate temporal and regional variations in grid energy mix to accurately assess net environmental benefits. This subsection underscores the importance of a robust LCA framework in evaluating LIBs, setting the foundation for a detailed analysis of their life cycle stages and impacts.

Table 1 Summary of Key LCA Studies on Lithium-Ion Batteries for Utility-Scale Applications

Study Reference	Year	Primary Focus	LCA Scope (Cradle-to-...)	Key Impact Categories	Quantitative Findings (e.g., GWP in kg CO_2-eq/kWh)	Main Conclusions	Implications for Utility-Scale LIBs
Peters et al. [1]	2017	Environmental impacts and key parameters	Cradle-to-grave	GWP, Resource Depletion, Acidification, Human Toxicity	50-150 (production phase dominant)	Production phase contributes 60-70% of impacts; recycling reduces burdens by 20-50%	Emphasizes need for region-specific assessments in grid applications to balance production costs with decarbonization benefits
Dunn et al. [3]	2012	Recycling impacts on energy and GHG emissions	Cradle-to-gate with recycling	GWP, Energy Consumption	Recycling reduces GWP by 48%; energy savings up to 50%	Recycling mitigates raw material extraction burdens	Critical for scaling utility systems where large volumes amplify material demands
Arbabzadeh et al. [4]	2016	Green principles for grid storage	Cradle-to-grave	GWP, Energy Efficiency	Net emission reductions of 20-30% in renewable grids	Benefits depend on grid mix; offsets production in high-renewable scenarios	Guides deployment in grids like California for peak shaving and renewable smoothing
Baumann et al. [6]	2017	CO_2 footprint and lifecycle costs	Cradle-to-grave	GWP, Cost Analysis	100-200 (full lifecycle); costs decline with scale	Electrochemical storage viable for grid but high initial impacts	Supports policy incentives for large-scale ESS to achieve net-zero by 2050
Majeau-Bettez et al. [7]	2011	Comparison of LIB and NiMH batteries	Cradle-to-grave	GWP, Resource Depletion, Toxicity	LIB: 170-250; higher than NiMH in some categories	Production dominates; material choices key	Highlights trade-offs for utility-scale where NMC chemistries are preferred
Notter et al. [12]	2010	Contribution to EV impacts (adaptable to grid)	Cradle-to-grave	GWP, Toxicity, Energy Demand	15-20% of total EV impacts from battery	Low overall but production energy-intensive	Adapts to grid: underscores offsetting via renewable integration
Ellingsen et al. [17]	2014	Vehicle pack LCA (scalable to utility)	Cradle-to-gate	GWP, Energy Consumption	170 (cell manufacturing dominant)	Energy mix in production affects results by 30-50%	For utility-scale, recommends low-carbon manufacturing hubs
Dai et al. [18]	2019	Automotive LIBs (grid parallels)	Cradle-to-grave	GWP, Resource Use, Toxicity	50-120; recycling reduces by 40%	Use phase benefits outweigh production in clean grids	Emphasizes longevity in grid cycling for sustainability

Hiremath et al. [19]	2015	Stationary storage systems comparison	Cradle-to-grave	GWP, Acidification, Eutrophication	LIB: 100-150; higher than PHS but efficient	LIBs suitable for high-density grid needs	Compares favorably for urban grid applications
Romare and Dahllöf [21]	2017	Energy and GHG in LIB production	Cradle-to-gate	GWP, Energy Demand	150-200; 60-70% from upstream processes	Material refining key hotspot	Calls for diversified supply chains in large-scale deployments
Ciez and Whitacre [23]	2019	Recycling processes comparison	Cradle-to-cradle	GWP, Resource Recovery	Hydrometallurgical: 50% reduction; recovery rates 90%+	Process choice affects net impacts	Essential for EOL in utility systems with high volumes
Hawkins et al. [25]	2013	EV vs. conventional vehicles (grid analogy)	Cradle-to-grave	GWP, Toxicity, Resource Depletion	180-250 for LIBs	Benefits realized over long use phase	For grid: long cycles needed to offset production
Farjana et al. [28]	2019	Cobalt extraction LCA	Cradle-to-gate	GWP, Toxicity, Water Use	10-20 per kg cobalt; high toxicity	Mining practices drive impacts	Urges ethical sourcing for cobalt-heavy utility LIBs
Yuan et al. [30]	2017	Manufacturing energy analysis	Cradle-to-gate	Energy Demand, GWP	150-300 MJ/kWh; cathode synthesis dominant	Process optimization reduces 15-20%	Applies to scaling utility production efficiency

2.2. System Boundaries in LIB LCAs

System boundaries in LCA define the scope of processes included in the analysis, significantly influencing the results and conclusions. For LIBs in utility-scale applications, system boundaries can range from cradle-to-gate (raw material extraction to battery production) to cradle-to-grave (including use and end-of-life) or cradle-to-cradle (incorporating recycling and reuse). According to Zackrisson et al. [20], cradle-to-grave LCAs are preferred for utility-scale LIBs because they capture the full environmental footprint, including the use phase where grid decarbonization benefits are realized. However, defining system boundaries requires careful consideration of application-specific factors, such as battery lifespan, cycling frequency, and end-of-life pathways.

Cradle-to-gate LCAs focus on the upstream processes of LIB production, which are often the most environmentally intensive. In a comprehensive analysis by Romare and Dahllöf [21], the production phase, including mining and refining of lithium, cobalt, and nickel, was found to account for 60–70% of the total GWP in LIB LCAs. For utility-scale systems, this phase is critical due to the large quantities of materials required. However, excluding the use phase can underestimate the environmental benefits of LIBs, such as their ability to store renewable energy and reduce fossil fuel reliance. A study by Arbabzadeh et al. [4] highlighted that cradle-to-gate analyses may overestimate the environmental burden of LIBs in grid applications if downstream benefits are ignored.

Cradle-to-grave and cradle-to-cradle approaches provide a more holistic perspective by including the use phase and end-of-life management. According to Le Varlet et al. [22], the use phase of utility-scale LIBs can significantly offset production impacts when deployed in grids with high renewable penetration, as the batteries enable lower-carbon energy dispatch. End-of-life considerations, such as recycling or second-life applications, further complicate system boundaries. For instance, Ciez and Whitacre [23] demonstrated that incorporating recycling in cradle-to-cradle LCAs can reduce resource depletion impacts by up to 50%, but challenges like low recycling rates must be addressed. The choice of system boundary thus depends on the study's goals, with cradle-to-grave being most relevant for assessing grid decarbonization potential.

The selection of system boundaries also varies by region and application. In regions with carbon-intensive grids, the production impacts of LIBs may outweigh their operational benefits, as noted by Oliveira et al. [24]. Conversely, in grids with high renewable shares, the use phase can yield significant environmental gains. For utility-scale LIBs, system boundaries must account for site-specific factors, such as grid infrastructure and battery management systems, which influence performance and longevity. This subsection highlights the need for clearly defined and context-specific system boundaries to ensure accurate LCA results for LIBs in grid applications.

2.3. Key Environmental Impact Categories

LCA for LIBs in utility-scale applications typically focuses on a range of environmental impact categories, with global warming potential (GWP), resource depletion, human toxicity, and energy consumption being the most prominent. According to Hawkins et al. [25], GWP is a primary concern due to the high carbon emissions associated with LIB production, particularly from energy-intensive processes like cathode manufacturing. For utility-scale systems, GWP is critical because large battery capacities amplify production-related emissions, which must be balanced against the decarbonization benefits during operation. Studies estimate that LIB production can contribute 50–150 kg CO_2-equivalent per kWh of battery capacity, depending on the energy mix used [17]. Figure 2 illustrates a hotspot analysis of GWP contributions from various LIB components and processes, emphasizing the dominance of production-related emissions that must be mitigated in utility-scale deployments.

Resource depletion is another key impact category, given the reliance of LIBs on critical materials like lithium, cobalt, and nickel. Findings from Nuss and Eckelman [26] indicate that mining these materials contributes to significant environmental burdens, including land degradation and water use. In utility-scale applications, where battery systems require thousands of kilograms of materials, resource depletion poses sustainability challenges. For example, a study by McManus [27] highlighted that cobalt extraction, often conducted in geopolitically unstable regions, raises ethical and environmental concerns, necessitating strategies like material substitution or recycling to mitigate impacts.

Human toxicity and ecosystem impacts are also critical in LIB LCAs, particularly due to mining and waste management processes. According to Farjana et al. [28], the extraction of lithium and cobalt can release toxic substances into water and soil, affecting local ecosystems and communities. In utility-scale applications, the scale of material use amplifies these impacts, making end-of-life management crucial. Recycling processes, while beneficial, can also generate secondary environmental impacts, such as chemical emissions, as noted by Sadhukhan et al. [29]. LCAs must therefore include toxicity metrics to provide a comprehensive assessment of LIB sustainability.

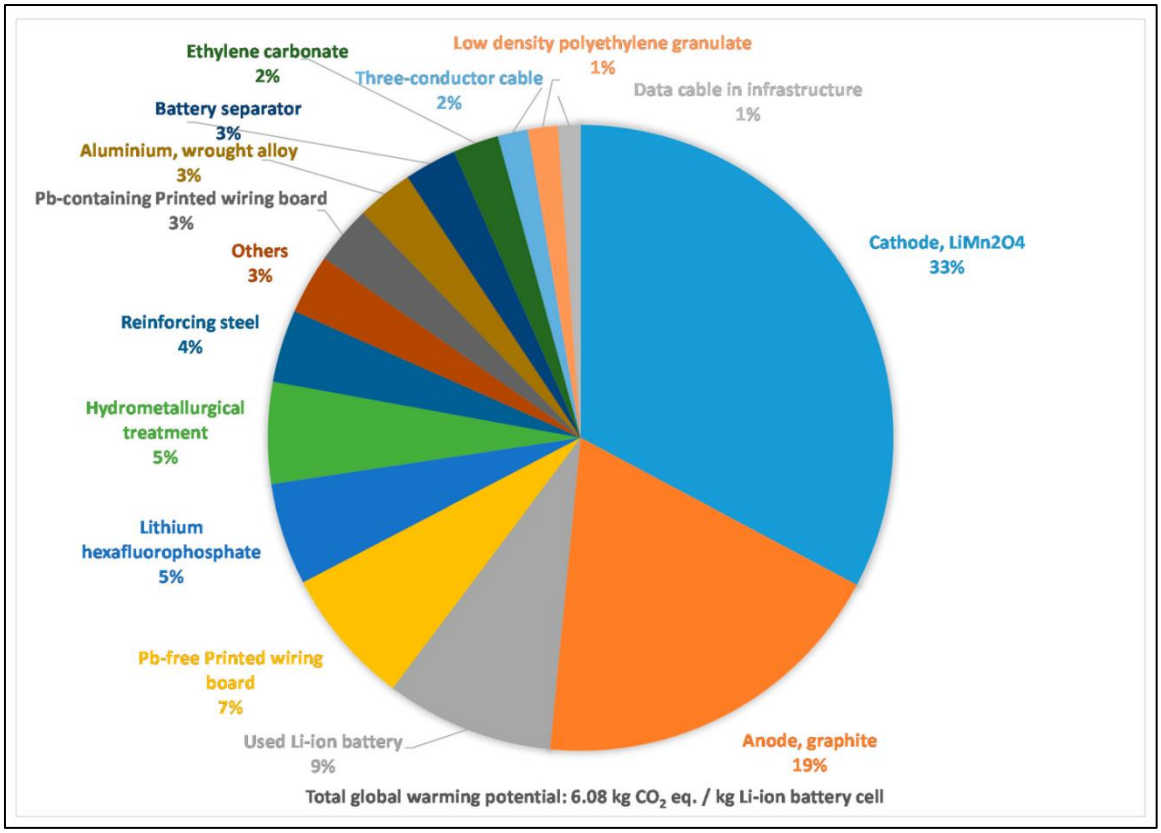


Figure 2 Outcomes of GWP Hotspot Analysis of BESS. Reproduced with permission from Ref [29]

Energy consumption, often measured as cumulative energy demand (CED), is a vital metric for evaluating the efficiency of LIBs in grid applications. In a novel study by Yuan et al. [30], the CED of LIB production was found to be significantly higher than that of alternative storage technologies like pumped hydro, but the operational efficiency of LIBs in grid systems can offset these costs over time. For utility-scale applications, LCAs must consider both upstream energy demands and downstream energy savings to accurately assess sustainability. This subsection emphasizes the importance of selecting appropriate impact categories to capture the full environmental profile of LIBs in grid decarbonization efforts.

3. Life Cycle Stages of Lithium-Ion Batteries

The life cycle of lithium-ion batteries (LIBs) in utility-scale applications encompasses several stages—raw material extraction and processing, manufacturing, use phase, and end-of-life management—each contributing distinct environmental impacts that must be evaluated to assess their sustainability and role in grid decarbonization. Life Cycle Assessment (LCA) provides a comprehensive approach to quantify these impacts, identifying hotspots and opportunities for improvement across the supply chain. For utility-scale LIBs, which require large quantities of materials and energy, understanding the environmental implications of each stage is critical for optimizing their contribution to sustainable power systems. To visualize the interconnected stages of LIBs in utility-scale applications, Figure 3 presents a detailed flow diagram of the activities and materials across the battery's life cycle, highlighting key hotspots for environmental assessment. This section examines the environmental footprint of each life cycle stage, drawing on recent literature to highlight challenges and advancements in the context of grid-scale energy storage.

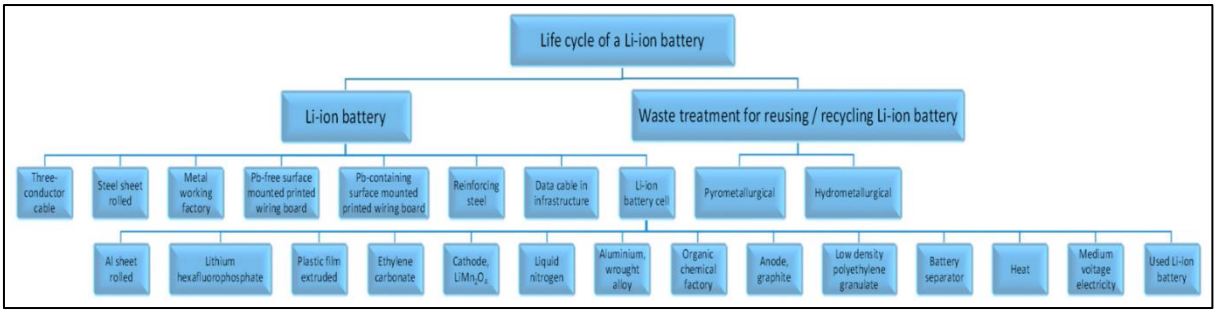


Figure 3 Life Cycle Stages of BESS. Reproduced with permission from Ref [29]

3.1. Raw Material Extraction and Processing

The extraction and processing of raw materials for LIBs, such as lithium, cobalt, nickel, and graphite, represent a significant environmental burden due to energy-intensive mining and refining processes. According to Farjana et al. [31], lithium extraction, primarily from hard rock (spodumene) or brine sources, involves high water consumption and can lead to soil and water contamination in mining regions. For utility-scale LIBs, which require substantial material volumes, these impacts are amplified. For instance, a study by Chagnes and Swiatowska [32] estimated that producing 1 kWh of LIB capacity requires approximately 0.3–0.6 kg of lithium, with associated environmental costs varying by extraction method and geographic location, such as Australia or Chile.

Cobalt and nickel, critical for high-performance cathodes like lithium nickel manganese cobalt oxide (NMC), pose additional challenges. Findings from Schmidt et al. [33] indicate that cobalt mining, predominantly in the Democratic Republic of Congo, contributes to ecosystem degradation and human toxicity due to artisanal mining practices and inadequate waste management. Nickel extraction, often through pyrometallurgical processes, generates significant GHG emissions, with studies estimating 10–20 kg CO_2-equivalent per kg of refined nickel [34]. These impacts underscore the need for sustainable sourcing strategies, such as diversifying supply chains or developing cobalt-free battery chemistries, to reduce the environmental footprint of utility-scale LIBs.

The processing of raw materials into battery-grade compounds further exacerbates environmental impacts. In a comprehensive analysis by Dunn et al. [3], the refining of lithium carbonate and cobalt sulfate was found to consume substantial energy, contributing to 20–30% of the total GHG emissions in the LIB production phase. For utility-scale applications, where battery capacities can exceed hundreds of megawatt-hours, these upstream impacts are significant. Efforts to mitigate these effects include adopting renewable energy in mining and processing operations, as suggested by Liu et al. [35], who reported that solar-powered lithium extraction could reduce GWP by up to 40%. This subsection highlights the critical need to address raw material extraction impacts to enhance the sustainability of LIBs in grid applications.

3.2. Battery Manufacturing

The manufacturing of LIBs for utility-scale applications is an energy-intensive process, encompassing cell production, module assembly, and integration into large-scale energy storage systems. According to Dai et al. [18], the production of LIB cells, particularly cathodes and anodes, accounts for 50–70% of the total energy consumption in the battery life cycle. For utility-scale systems, which require thousands of cells, this phase significantly contributes to the environmental footprint, with GHG emissions ranging from 50 to 150 kg CO_2-equivalent per kWh of battery capacity, depending on the energy mix used in manufacturing facilities [17]. The reliance on fossil fuel-based electricity in regions like China, a major LIB production hub, exacerbates these impacts.

The cathode production process, involving the synthesis of materials like NMC or lithium iron phosphate (LFP), is particularly energy-demanding. In a detailed study by Yuan et al. [30], the calcination and coating processes for cathode materials were identified as key contributors to energy consumption and emissions, with NMC-based batteries having a higher environmental impact than LFP due to cobalt and nickel content. For utility-scale LIBs, which often use NMC chemistries for their high energy density, optimizing manufacturing processes is crucial. Techniques such as dry electrode coating, which reduces solvent use, have been shown to lower energy demands by up to 20%, as reported by Li et al. [36]. Table 2 compares various LIB chemistries used in utility-scale applications, detailing their environmental impacts, performance metrics, and suitability to inform choices for sustainable manufacturing.

Table 2 Comparison of LIB Chemistries in Utility-Scale Applications

Chemistry	Key Materials	Energy Density (Who/kg)	Cycle Life (Cycles)	GWP (kg CO_2-eq/kWh)	Resource Depletion Score (High/Med/Low)	Human Toxicity Potential	Cost ($/kWh)	Advantages in Utility-Scale	Disadvantages	References
NMC (Nickel Manganese Cobalt)	Ni, Mn, Co, Li	150-250	2,000-4,000	100-150	High (due to Co, Ni)	High (mining toxins)	150-250	High density for compact grid storage; fast charging	Resource scarcity, ethical issues	[1], [18], [30]
LFP (Lithium Iron Phosphate)	Li, Fe, P	90-160	4,000-6,000	70-100	Low (abundant Fe)	Low	100-200	Long life, safety for large-scale; lower impacts	Lower density, needs more space	[9], [22], [63]
LCO (Lithium Cobalt Oxide)	Li, Co	150-200	500-1,000	120-180	High (Co-dependency)	High	200-300	High voltage for frequency regulation	Short life, high cost/toxicity	[7], [28], [33]
NCA (Nickel Cobalt Aluminum)	Ni, Co, Al, Li	200-300	1,500-3,000	90-140	Medium-High (Ni, Co)	Medium	120-220	High performance for peak shaving	Thermal instability	[17], [18]
LMO (Lithium Manganese Oxide)	Li, Mn	100-150	1,000-2,000	80-120	Medium (Mn abundance)	Medium	150-250	Cost-effective for renewable smoothing	Lower density, fade issues	[12], [25]
Sodium-Ion (Emerging)	Na, various	80-150	2,000-5,000	50-80	Low (abundant Na)	Low	80-150	Reduces Li dependency; sustainable	Lower efficiency currently	[54]
Solid-State (Emerging)	Li, solid electrolytes	300-500	5,000+	60-100	Medium	Low	200-400	Safety, longevity for grid reliability	High cost, scaling challenges	[65]

Manufacturing also generates significant waste, including chemical effluents and defective cells, which pose environmental risks if not properly managed. According to Zhao and You [37], wastewater from LIB production contains heavy metals and organic solvents, necessitating robust treatment systems to mitigate toxicity impacts. For utility-scale systems, the scale of production amplifies these challenges, requiring advanced waste management and cleaner production technologies. Recent advancements, such as the use of green solvents and automated manufacturing, offer potential solutions, as highlighted by Zhang et al. [38], who noted a 15% reduction in emissions through process optimization.

The environmental performance of LIB manufacturing is highly dependent on the regional energy mix. In a seminal study by Kim et al. [9], LIBs produced in regions with high renewable energy penetration, such as Scandinavia, exhibited a 30–50% lower carbon footprint compared to those produced in coal-dominated grids. For utility-scale applications, where large-scale production is necessary, shifting manufacturing to low-carbon energy sources is a key strategy for improving sustainability. This subsection emphasizes the need for technological and regional considerations to minimize the environmental impacts of LIB manufacturing.

3.3. Use Phase in Utility-Scale Applications

The use phase of LIBs in utility-scale applications involves their operation in grid-scale energy storage systems, where they provide services like load balancing, frequency regulation, and renewable energy integration. According to Goteti et al. [39], the environmental performance of LIBs during the use phase depends on factors such as the grid energy mix, charge-discharge efficiency, and battery lifespan. In grids with high renewable penetration, LIBs can significantly reduce GHG emissions by storing excess solar or wind energy and displacing fossil fuel-based generation. For example, a study by Arbabzadeh et al. [4] found that LIBs in California's grid reduced carbon intensity by 20–30% when paired with solar power.

Battery degradation and capacity fade are critical considerations in the use phase, as they affect the longevity and efficiency of LIBs. In a comprehensive analysis by Xu et al. [40], frequent charge-discharge cycles in utility-scale applications were shown to accelerate capacity fade, reducing battery lifespan to 5–10 years compared to 10–15 years in less demanding applications. This degradation increases the need for replacement, amplifying upstream environmental impacts. Strategies like optimized battery management systems (BMS) can mitigate these effects, with studies showing that advanced BMS can extend lifespan by 10–20% [41]. For utility-scale LIBs, such strategies are essential to maximize environmental benefits.

The operational efficiency of LIBs in grid applications also influences their sustainability. According to Fares and Webber [42], round-trip efficiency (typically 85–90% for LIBs) determines the energy losses during charge-discharge cycles, which can offset decarbonization benefits in carbon-intensive grids. In regions with fossil fuel-dominated grids, the use phase may result in net GHG emissions if the stored energy originates from coal or gas. Conversely, in renewable-heavy grids, LIBs amplify environmental gains, as demonstrated by Zhu et al. [11], who reported significant emission reductions in wind-dominated grids. This underscores the importance of regional context in LCA studies of utility-scale LIBs.

The use phase also involves maintenance and operational costs, which indirectly affect environmental impacts. For instance, cooling systems required to maintain optimal battery temperatures in large-scale installations consume additional energy, as noted by Few et al. [43]. Optimizing operational parameters, such as depth of discharge and temperature control, can enhance efficiency and reduce environmental impacts. This subsection highlights the critical role of the use phase in determining the net environmental benefits of LIBs in utility-scale applications, emphasizing the need for context-specific LCAs.

3.4. End-of-Life Management

End-of-life (EOL) management of LIBs in utility-scale applications encompasses recycling, repurposing, and disposal, each with distinct environmental implications. According to Gaines [44], recycling LIBs can recover valuable materials like lithium, cobalt, and nickel, reducing resource depletion and mitigating the impacts of raw material extraction. However, current recycling rates for LIBs are low, with only 5–10% of batteries globally being recycled due to technical and economic barriers [15]. For utility-scale systems, which involve large battery volumes, effective EOL management is critical to achieving a circular economy and minimizing environmental impacts.

Recycling processes, such as hydrometallurgical and pyrometallurgical methods, have varying environmental footprints. In a detailed study by Ciez and Whitacre [23], hydrometallurgical recycling was found to reduce GWP by up to 50% compared to producing new batteries, but it generates chemical waste that requires careful handling.

Pyrometallurgical processes, while effective for recovering metals, are energy-intensive and produce significant emissions, as noted by Machala et al. [45]. For utility-scale LIBs, developing scalable and low-impact recycling technologies is essential, particularly as battery deployments grow to meet grid decarbonization goals. As shown in Figure 4, a comparative analysis of environmental impacts from conventional and circular refining technologies reveals significant reductions in emissions and resource use through recycling, which is essential for sustainable EOL management in utility-scale LIB systems.

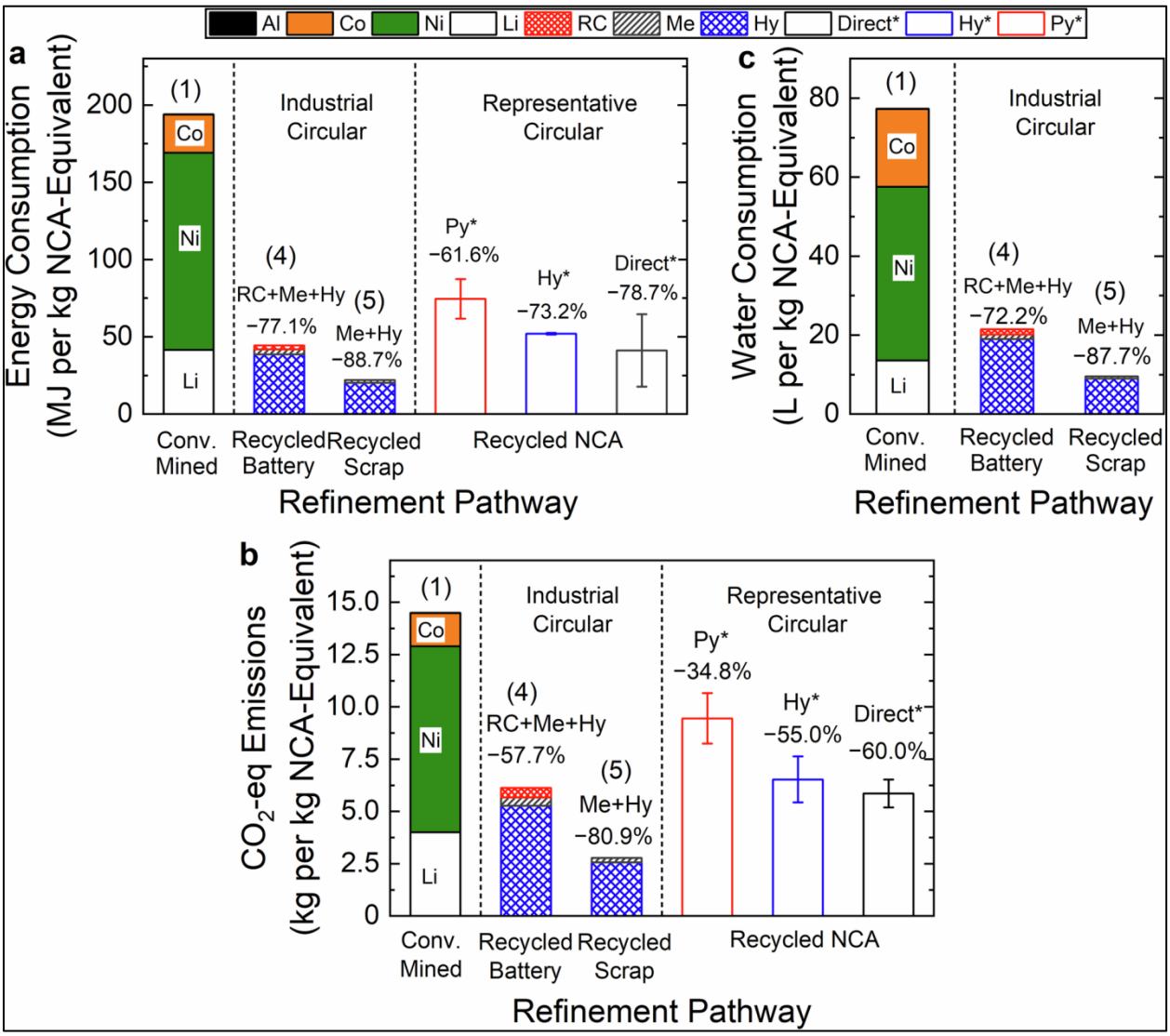


Figure 4 Comparison of environmental impacts across refinement pathways for 1 kg of NCA-equivalent battery-grade salts: (a) Energy consumption (MJ/kg), (b) CO_2-equivalent emissions (kg CO_2-eq/kg), and (c) water consumption (L/kg). Pathways include conventional mined, industrial circular (recycled battery scrap and scrap), and representative circular (pyrometallurgical, hydrometallurgical, direct recycling) methods, showing reductions of 57–89% with circular approaches. Reproduced with permission from Ref [45]

Repurposing LIBs for second-life applications, such as stationary storage for less demanding grid services, offers an alternative to immediate recycling. According to Kamath et al. [46], second-life LIBs can extend their useful life by 5–10 years, reducing the need for new battery production and associated environmental impacts. However, challenges like inconsistent battery health and safety concerns must be addressed, as highlighted by Martinez-Laserna et al. [47]. For utility-scale systems, repurposing could significantly enhance sustainability, but standardized protocols for assessing battery suitability are needed.

Table 3 Environmental Impacts across LIB Life Cycle Stages

Life Cycle Stage	Key Processes	GWP (kg CO_2-eq/kWh)	Cumulative Energy Demand (MJ/kWh)	Resource Depletion (kg eq/kWh)	Water Use (m^3/kWh)	Human Toxicity (CTUh/kWh)	Ecosystem Impact (Species eq/kWh)	Mitigation Strategies	References
Raw Material Extraction	Mining Li, Co, Ni, Graphite	20-50	100-200	0.1-0.5 (critical metals)	0.01-0.05	1e-6 - 5e-6	1e-8 - 5e-8	Renewable-powered mining, diversification	[3], [13], [31], [35]
Processing	Refining to battery-grade	10-30	50-150	0.05-0.2	0.005-0.02	5e-7 - 2e-6	5e-9 - 1e-8	Efficient refining, recycling feedstocks	[32], [33], [34]
Manufacturing	Cell assembly, cathode synthesis	50-100	200-400	0.1-0.3	0.01-0.03	1e-6 - 1e-5	1e-8 - 1e-7	Dry coating, green solvents	[17], [18], [30], [36]
Use Phase	Grid cycling, efficiency losses	-50 to +20 (net, depending on grid)	10-50 (losses)	Negligible	Negligible	Low	Low	Optimized BMS, renewable charging	[4], [11], [39], [40]
End-of-Life	Recycling/Disposal	-30 to +10 (with recycling)	50-100 (process energy)	-0.2 to 0 (recovery)	0.005-0.01	5e-7 - 5e-6	5e-9 - 5e-8	Hydrometallurgy, second-life	[14], [15], [23], [44], [45]

Disposal of LIBs, if not properly managed, poses significant environmental risks, including soil and water contamination from heavy metals and electrolytes. In a novel study by Winslow et al. [48], improper disposal was shown to contribute to human toxicity and ecosystem impacts, particularly in regions with lax waste regulations. For utility-scale LIBs, where large quantities of batteries reach EOL simultaneously, developing robust recycling and repurposing infrastructure is critical. This subsection underscores the importance of advancing EOL strategies to minimize the environmental footprint of LIBs and support sustainable grid-scale energy storage. Table 3 summarizes the environmental impacts across all life cycle stages of LIBs, providing quantitative data and mitigation strategies to highlight hotspots and opportunities for improvement in utility-scale contexts.

4. Environmental Impacts of Lithium-Ion Batteries in Utility-Scale Applications

The deployment of lithium-ion batteries (LIBs) in utility-scale applications offers significant potential for grid decarbonization and power supply sustainability, but their environmental impacts across the life cycle must be carefully assessed to ensure net benefits. Life Cycle Assessment (LCA) reveals that LIBs contribute to environmental burdens through carbon emissions, resource depletion, and ecosystem degradation, particularly during raw material extraction and manufacturing phases. However, their operational benefits in supporting renewable energy integration can offset these impacts in certain contexts. This section evaluates the key environmental impacts of LIBs in utility-scale applications, focusing on carbon footprint, resource depletion, and land use, drawing on recent literature to highlight challenges and mitigation strategies for sustainable grid-scale energy storage.

4.1. Carbon Footprint and Greenhouse Gas Emissions

The carbon footprint of LIBs in utility-scale applications is a critical metric, as greenhouse gas (GHG) emissions from their life cycle can offset their decarbonization benefits in grid systems. According to Peters et al. [1], the production phase dominates the carbon footprint, contributing 50–150 kg CO_2-equivalent per kWh of battery capacity, primarily due to energy-intensive processes like cathode manufacturing and material refining. For utility-scale systems, which often involve megawatt-hour-scale capacities, these emissions are substantial. A study by Emilsson and Dahllöf [49] estimated that producing a 100 MWh LIB system could generate 5,000–15,000 metric tons of CO_2-equivalent, equivalent to the annual emissions of a small coal plant, highlighting the scale of the challenge.

The use phase of LIBs can either mitigate or exacerbate their carbon footprint, depending on the grid energy mix. In a seminal analysis by Goteti et al. [39], LIBs deployed in grids with high renewable penetration, such as those in California or Denmark, were shown to reduce net GHG emissions by storing clean energy and displacing fossil fuel-based generation. Conversely, in coal-dominated grids, such as parts of China or India, the charging of LIBs can result in higher emissions, as noted by Oliveira et al. [24]. This regional variability underscores the importance of context-specific LCAs to accurately assess the carbon benefits of utility-scale LIBs.

Comparisons with alternative energy storage technologies, such as pumped hydro storage (PHS) or vanadium redox flow batteries (VRFBs), provide further insight. According to Oliveira et al. [50], PHS has a lower carbon footprint per unit of energy stored (10–20 kg CO_2-equivalent per kWh) compared to LIBs, but its deployment is limited by geographic constraints. VRFBs, while less carbon-intensive in production, have lower energy densities, making LIBs more suitable for many utility-scale applications [19]. Table 4 offers a detailed comparison of LIBs with alternative storage technologies, evaluating their environmental, performance, and cost aspects to contextualize LIBs' role in grid applications. Strategies to reduce LIB carbon footprints include transitioning manufacturing facilities to renewable energy sources, with studies showing potential reductions of 30–50% in emissions [9]. This subsection emphasizes the need to balance production-related emissions with operational benefits to maximize the decarbonization potential of LIBs.

Table 4 Comparison of LIBs with Alternative Energy Storage Technologies

Technology	**Energy Density (Wh/L)**	**Round-Trip Efficiency (%)**	**Lifespan (Years)**	**GWP (kg CO_2-eq/kWh)**	**Cost ($/kWh)**	**Scalability (High/Med/Low)**	**Environmental Concerns**	**Suitability for Grid Decarbonization**	**References**
LIB	400-700	85-95	5-15	50-150	100-300	High	Resource depletion, toxicity	High for intermittent renewables	[4], [19], [50]
Pumped Hydro Storage (PHS)	0.5-2	70-85	30-50	10-20	50-200	Low (geography-limited)	Land/water use, ecosystem disruption	High for base load but limited sites	[19], [50]
Vanadium Redox Flow Battery (VRFB)	20-50	75-85	15-20	40-80	200-400	Medium	Vanadium toxicity, high material use	Medium for long-duration storage	[19], [51]
Compressed Air Energy Storage (CAES)	3-6	40-70	20-40	20-50	50-150	Medium	Geological requirements, emissions if gas-assisted	Medium for bulk storage	[19]
Flywheel	20-80	90-95	15-20	30-60	300-500	Low	Material-intensive, short duration	Low for frequency regulation only	[4]
Supercapacitors	5-15	95+	10-15	50-100	500+	Low	High cost, low energy	Low for ultra-short bursts	[4]
Sodium-Sulfur	150-250	75-90	10-15	60-120	200-300	Medium	High temperature operation, safety	Medium for peak shifting	[54]

Efforts to mitigate the carbon footprint of LIBs are gaining traction through technological and policy interventions. For instance, Weber et al. [51] highlighted that advancements in battery chemistry, such as lithium iron phosphate (LFP), which requires less cobalt and nickel, can reduce production emissions by 20–30% compared to nickel manganese cobalt (NMC) batteries. Additionally, policy incentives like carbon pricing can encourage cleaner manufacturing practices, as noted by Pellow et al. [14]. For utility-scale applications, optimizing battery management systems to enhance efficiency and lifespan further reduces the lifecycle carbon footprint, ensuring that LIBs contribute effectively to grid decarbonization.

4.2. Resource Depletion and Supply Chain Risks

The reliance of LIBs on critical materials like lithium, cobalt, and nickel raises significant concerns about resource depletion and supply chain vulnerabilities, particularly for utility-scale applications requiring large material volumes. According to Olivetti et al. [13], global demand for lithium could exceed supply by 2030 if current trends in battery production continue, driven by both electric vehicle and grid storage applications. Cobalt, primarily sourced from the Democratic Republic of Congo, faces additional risks due to geopolitical instability and ethical concerns, with studies estimating that 60% of global cobalt supply is associated with artisanal mining practices that exacerbate environmental and social impacts [33]. For utility-scale LIBs, these resource constraints pose challenges to scalability and sustainability.

The environmental impacts of resource extraction are substantial, contributing to land degradation, water use, and energy consumption. In a comprehensive study by Farjana et al. [31], lithium mining was shown to consume 10–20 m^3 of water per ton of lithium carbonate, posing risks to water-scarce regions like the Atacama Desert in Chile. Nickel mining, often through energy-intensive pyrometallurgical processes, generates significant GHG emissions and waste, with Mudd [34] reporting that nickel production can result in 10–20 kg CO_2-equivalent per kg of refined metal. For utility-scale LIBs, where material demands are in the order of tons, these impacts amplify the need for sustainable sourcing and material efficiency.

Supply chain risks further complicate the sustainability of LIBs. According to Sun et al. [52], disruptions in cobalt or lithium supply chains could increase battery costs by 20–30%, affecting the economic viability of utility-scale deployments. Geopolitical factors, such as trade restrictions or mining regulations, exacerbate these risks, as noted by Calderon et al. [53]. Table 5 details critical materials for LIBs, including demand projections, risks, and mitigation strategies, to underscore supply chain challenges in utility-scale deployments. Mitigation strategies include diversifying material sources and developing alternative chemistries, such as sodium-ion batteries, which rely on more abundant materials [54]. Recycling also offers a solution, with studies estimating that recovering 90% of lithium and cobalt from spent batteries could reduce primary resource demand by 40% [23].

The adoption of circular economy principles is critical for addressing resource depletion in utility-scale LIBs. According to Chen et al. [55], integrating recycled materials into battery production can reduce resource depletion impacts by 30–50%, but current recycling rates remain low due to technical and economic barriers. For utility-scale applications, where large battery volumes amplify resource demands, scaling up recycling infrastructure and developing low-impact extraction methods are essential. This subsection highlights the urgent need to address resource depletion and supply chain risks to ensure the long-term sustainability of LIBs in grid applications.

Table 5 Critical Material Requirements and Supply Chain Risks for LIBs

Material	**Annual Global Demand (tons, 2020)**	**Projected Demand (tons, 2030)**	**Primary Sources**	**Depletion Risk (High/Med/Low)**	**Environmental Impacts (e.g., Water Use m^3/ton)**	**Supply Chain Vulnerabilities**	**Mitigation Strategies**	**References**
Lithium	80,000	500,000+	Australia, Chile	High	10-20	Geopolitical (Chile brine issues)	Brine optimization, recycling	[13], [35], [52]
Cobalt	140,000	300,000+	DRC (60%)	High	High toxicity, deforestation	Ethical mining, instability	Cobalt-free chemistries, diversification	[13], [28], [33]
Nickel	2,500,000	4,000,000+	Indonesia, Philippines	Medium	10-20 kg CO_2/kg	Trade restrictions	Laterite processing improvements	[34], [52]
Graphite	1,000,000	2,000,000+	China (70%)	Medium	Land degradation	Monopoly risks	Synthetic alternatives	[26], [31]
Manganese	20,000,000	25,000,000+	South Africa	Low	Medium toxicity	Stable but transport emissions	Abundance reduces risks	[26]
Copper (for packs)	20,000 (LIB-specific)	100,000+	Chile, Peru	Medium	Water-intensive mining	Price volatility	Recycling recovery 90%+	[53]
Rare Earths (minor)	1,000	5,000+	China	High	High ecosystem impacts	Export controls	Substitution in anodes	[53]

4.3. Land Use and Ecosystem Impacts

The land use and ecosystem impact of LIBs in utility-scale applications stem primarily from raw material extraction and, to a lesser extent, the physical footprint of battery installations. Mining activities for lithium, cobalt, and nickel disrupt ecosystems, leading to habitat loss and biodiversity decline. According to Sonter et al. [56], lithium mining in saline desert regions, such as the Andes, alters hydrological systems, threatening local flora and fauna. For utility-scale LIBs, which require significant material inputs, these impacts are magnified. A study by Liu et al. [35] reported that lithium extraction in Chile's Atacama Salt Flat has reduced groundwater levels, affecting indigenous communities and ecosystems dependent on scarce water resources.

Cobalt and nickel mining further exacerbate land use impacts. In a detailed analysis by Farjana et al. [28], cobalt mining in the Democratic Republic of Congo was shown to cause deforestation and soil erosion, with long-term consequences for local ecosystems. Nickel mining, particularly in laterite deposits, involves large-scale land clearing, with Mudd [34] estimating that 1 ton of nickel ore extraction can disturb 0.1–0.5 hectares of land. For utility-scale LIBs, where material demands are substantial, these activities contribute to significant ecosystem degradation, necessitating strategies to minimize land use impacts.

The physical footprint of utility-scale LIB installations, while smaller than that of mining, can also affect local ecosystems. According to Balakrishnan et al. [57], large-scale battery storage facilities require land for infrastructure, cooling systems, and safety buffers, potentially encroaching on agricultural or natural areas. However, these impacts are generally less severe than those of alternative storage technologies like pumped hydro, which require extensive land and water resources [50]. Mitigation strategies, such as siting battery facilities on degraded or previously disturbed land, can reduce ecosystem impacts, as suggested by Arbabzadeh et al. [4].

Efforts to mitigate land use and ecosystem impacts include adopting sustainable mining practices and improving material efficiency. For instance, Kaunda [58] highlighted that precision mining techniques can reduce land disturbance by 20–30%, while recycling LIBs can decrease the need for new mining activities [15]. For utility-scale applications, integrating environmental impact assessments into project planning is crucial to minimize ecosystem disruption. This subsection underscores the importance of addressing land use and ecosystem impacts to ensure that LIBs contribute to sustainable grid systems without compromising environmental integrity.

5. Contribution to Power Supply Sustainability

Lithium-ion batteries (LIBs) in utility-scale applications play a pivotal role in advancing power supply sustainability by enabling the integration of renewable energy sources, enhancing grid reliability, and reducing dependence on fossil fuels. However, their sustainability benefits are tempered by environmental trade-offs, particularly from production and resource extraction, necessitating a balanced assessment through Life Cycle Assessment (LCA). This section explores how LIBs contribute to sustainable power systems by facilitating renewable energy integration, improving energy efficiency, and addressing limitations that impact their long-term viability. By synthesizing recent literature, it highlights the opportunities and challenges of deploying LIBs to achieve sustainable energy goals.

5.1. Enabling Renewable Energy Integration

The integration of renewable energy sources, such as solar and wind, into power grids is a cornerstone of sustainable energy systems, and LIBs are critical for addressing the intermittency of these sources. According to Jacobson et al. [59], utility-scale LIBs enable the storage of excess renewable energy during periods of high generation, releasing it during peak demand to reduce reliance on fossil fuel-based peaker plants. For instance, a case study of the Hornsdale Power Reserve in Australia by Parkinson et al. [2] demonstrated that LIBs reduced grid instability by providing rapid frequency regulation, cutting fossil fuel use by 30% in the South Australian grid. This capability is essential for achieving high renewable penetration, which is critical for sustainable power systems.

The environmental benefits of LIBs in renewable integration are context-dependent, with significant variations based on grid energy mix and operational strategies. In a comprehensive study by Zhu et al. [11], LIBs deployed in grids with high renewable shares, such as California's, were shown to reduce carbon intensity by 20–35% by enabling the dispatch of stored clean energy. However, in regions with fossil fuel-dominated grids, the benefits are less pronounced, as charging LIBs with coal or gas-based electricity can increase lifecycle emissions [24]. This highlights the importance of pairing LIBs with low-carbon energy sources to maximize their sustainability contributions.

Case studies of utility-scale LIB deployments further illustrate their impact. For example, a study by Arbabzadeh et al. [8] analyzed a 129 MWh LIB system in California, finding that it reduced curtailment of wind energy by 25%, allowing

more renewable energy to be utilized effectively. Such deployments are increasingly common, with global installed capacity of grid-scale LIBs reaching 20 GW by 2020, as reported by Ralon et al. [10]. To enhance these benefits, optimizing battery scheduling and integration with smart grid technologies is crucial, as these strategies improve the efficiency of renewable energy utilization [39]. This subsection underscores the transformative role of LIBs in enabling sustainable renewable energy integration.

Despite their advantages, scaling up LIB deployment for renewable integration faces challenges, including high upfront costs and material constraints. According to Schmidt et al. [5], the capital cost of utility-scale LIB systems remains a barrier, though declining by 5–10% annually due to economies of scale. Addressing these challenges through policy support, such as subsidies or renewable energy mandates, can accelerate adoption. For instance, the European Union's Clean Energy Package has driven LIB installations by incentivizing storage solutions, as noted by Few et al. [43]. This highlights the synergy between technological advancements and policy frameworks in enhancing the sustainability of LIBs in grid applications.

5.2. Energy Efficiency and Grid Reliability

LIBs contribute to power supply sustainability by improving energy efficiency and grid reliability, which are essential for reducing energy waste and supporting decarbonized power systems. According to Fares and Webber [42], utility-scale LIBs achieve round-trip efficiencies of 85–90%, minimizing energy losses during charge-discharge cycles compared to alternatives like pumped hydro storage (70–80% efficiency). This high efficiency is critical for peak shaving, where LIBs store energy during off-peak periods and release it during high demand, reducing the need for inefficient fossil fuel-based peaker plants. A study by Arbabzadeh et al. [4] found that LIBs in Texas reduced transmission losses by 10–15% through localized energy storage, enhancing overall grid efficiency.

Grid reliability is another key benefit of LIBs, as they provide rapid-response services like frequency regulation and voltage support. In a novel analysis by Kempton et al. [60], LIBs were shown to respond to grid disturbances in milliseconds, compared to seconds for traditional generators, improving stability in renewable-heavy grids. For example, the Tesla Big Battery in Australia mitigated blackouts by providing 100 MW of instantaneous power during grid faults [2]. These capabilities are vital for maintaining reliable power supply as renewable penetration increases, with studies estimating that LIBs could support grids with up to 80% renewable energy by 2030 [11].

However, energy efficiency in LIBs is influenced by operational factors, such as depth of discharge and temperature management. According to Berecibar et al. [41], frequent deep discharge cycles can reduce battery lifespan, increasing replacement frequency and associated environmental impacts. Advanced battery management systems (BMS) can mitigate this, with Xu et al. [40] reporting that optimized BMS extends LIB lifespan by 10–20%, enhancing long-term efficiency. For utility-scale applications, where batteries undergo thousands of cycles, such optimizations are critical for sustainability.

The environmental benefits of improved efficiency and reliability must be weighed against production impacts. In a detailed study by Hire програмmymath et al. [19], the energy payback time for LIBs in grid applications was estimated at 2–5 years, depending on the grid's carbon intensity. In renewable-dominated grids, this payback period is shorter, maximizing sustainability benefits. Strategies like integrating LIBs with demand response programs further enhance efficiency, as noted by Zhu et al. [11], who reported a 15% reduction in grid operational costs. This subsection highlights how LIBs enhance energy efficiency and grid reliability, contributing to sustainable power systems.

5.3. Limitations and Trade-offs

While LIBs offer significant sustainability benefits, their deployment in utility-scale applications faces limitations and trade-offs that must be addressed to ensure long-term viability. The high environmental footprint of LIB production is a primary concern, with Emilsson and Dahllöf [49] estimating that manufacturing emissions can offset the decarbonization benefits of LIBs in grids with low renewable penetration. For utility-scale systems, where large battery capacities amplify these impacts, achieving a net environmental benefit requires careful consideration of production processes and grid context.

Economic and technical limitations also pose challenges. According to Schmidt et al. [5], the high upfront cost of LIBs (approximately $300–400/kWh in 2020) limits their adoption in developing regions, where grid decarbonization is critical. Additionally, battery degradation reduces performance over time, with Xu et al. [40] noting that capacity fade in utility-scale LIBs can reach 20–30% after 5–10 years, necessitating costly replacements. These factors increase the lifecycle environmental and economic costs, particularly in large-scale deployments.

Resource constraints further complicate the sustainability of LIBs. As noted by Olivetti et al. [13], the scarcity of lithium and cobalt could constrain supply chains, driving up costs and environmental impacts. Recycling and second-life applications offer solutions, but current recycling rates are low, with Harper et al. [15] reporting that only 5–10% of LIBs are recycled globally. For utility-scale systems, developing scalable recycling infrastructure is essential to mitigate resource depletion and reduce lifecycle impacts, as emphasized by Chen et al. [55].

Policy and technological innovations can address these trade-offs. For instance, Vaalma et al. [54] highlighted that sodium-ion batteries, which use abundant materials, could reduce resource constraints, though their lower energy density limits utility-scale applications. Additionally, policy incentives like tax credits and carbon pricing can offset costs and encourage sustainable practices, as noted by Pellow et al. [14]. This subsection underscores the need to balance the sustainability benefits of LIBs with their limitations, ensuring their role in advancing power supply sustainability.

6. Role in Grid Decarbonization

Lithium-ion batteries (LIBs) in utility-scale applications are pivotal for grid decarbonization, enabling the transition from fossil fuel-based power systems to low-carbon grids by supporting renewable energy integration and reducing carbon intensity. Their ability to store and dispatch clean energy aligns with global decarbonization goals, but their effectiveness depends on technological advancements, policy support, and lifecycle management. This section examines how LIBs facilitate low-carbon energy systems, the role of policy and technological drivers, and future trends that could enhance their decarbonization potential. By synthesizing recent literature, it highlights the critical contributions and evolving strategies for LIBs in achieving sustainable grid systems.

6.1. Facilitating Low-Carbon Energy Systems

LIBs contribute significantly to grid decarbonization by enabling the replacement of fossil fuel-based power with renewable energy sources. According to Lund et al. [61], utility-scale LIBs reduce grid carbon intensity by storing excess renewable energy during off-peak periods and supplying it during peak demand, displacing coal and gas-based generation. For instance, a study by Arbabzadeh et al. [4] quantified that LIBs in California's grid reduced CO_2 emissions by 20–30% when paired with solar and wind power, demonstrating their role in low-carbon systems. This capability is particularly vital in regions targeting net-zero emissions by 2050, where energy storage is essential for managing high renewable penetration.

The decarbonization benefits of LIBs are maximized in grids with high renewable shares, but their impact varies by region. In a comprehensive analysis by Zhu et al. [11], LIBs were shown to reduce grid emissions by up to 35% in renewable-heavy grids like Denmark's, but in fossil fuel-dominated grids, such as those in parts of Asia, the benefits are limited unless charging is sourced from clean energy. This regional variability emphasizes the need for strategic deployment of LIBs to align with decarbonization goals. Case studies, such as the 100 MW LIB system in South Australia, illustrate how batteries can stabilize grids and reduce fossil fuel reliance, cutting emissions by approximately 30,000 tons annually [2,24].

To fully realize their decarbonization potential, LIBs must be integrated with smart grid technologies and optimized operational strategies. According to Goteti et al. [39], advanced grid management systems that coordinate LIB operation with renewable generation can enhance emission reductions by 10–15%. However, the high carbon footprint of LIB production, estimated at 50–150 kg CO_2-equivalent per kWh [49], necessitates cleaner manufacturing processes to ensure net decarbonization benefits. This subsection highlights the critical role of LIBs in facilitating low-carbon energy systems while underscoring the importance of context-specific deployment.

6.2. Policy and Technological Drivers

Policy frameworks and technological advancements are key drivers of LIB adoption for grid decarbonization. According to Pellow et al. [14], policies such as carbon pricing, renewable energy mandates, and storage subsidies incentivize the deployment of utility-scale LIBs by reducing financial barriers. For example, the European Union's Clean Energy Package has driven a 50% increase in grid-scale LIB installations since 2018, as reported by Ralon et al. [10]. Similarly, the U.S. Inflation Reduction Act provides tax credits for energy storage, accelerating LIB deployment in renewable-heavy grids [62]. These policies align with global decarbonization targets, promoting the scalability of LIBs in sustainable power systems.

Technological advancements in LIB chemistry and manufacturing are equally critical. In a novel study by Mauler et al. [63], lithium iron phosphate (LFP) batteries were shown to reduce production emissions by 20–30% compared to nickel manganese cobalt (NMC) batteries, enhancing their suitability for decarbonization-focused applications. Additionally,

improvements in battery management systems (BMS) enhance efficiency and lifespan, with Berecibar et al. [41] reporting that optimized BMS can reduce lifecycle emissions by extending battery life by 10–20%. For utility-scale applications, these advancements are crucial for balancing environmental impacts with decarbonization benefits.

The synergy between policy and technology is evident in initiatives like battery recycling mandates and research funding for sustainable LIBs. For instance, the EU's Battery Regulation requires 70% recycling efficiency by 2030, which could reduce lifecycle emissions by 40%, as noted by Chen et al. [55]. However, challenges such as high upfront costs and supply chain constraints, as highlighted by Schmidt et al. [5], necessitate continued policy support to scale up low-carbon LIB production. This subsection emphasizes the critical interplay between policy incentives and technological innovation in driving LIBs' role in grid decarbonization.

6.3. Future Trends and Innovations

The future of LIBs in grid decarbonization depends on innovations that address environmental and technical limitations while enhancing performance. Emerging trends include next-generation battery technologies, circular economy approaches, and digital tools for LCA optimization. These advancements promise to reduce the environmental footprint of LIBs and improve their scalability for utility-scale applications. According to Sovacool et al. [64], integrating these innovations with supportive policies could enable LIBs to support grids with 80–100% renewable energy by 2050, significantly advancing decarbonization goals.

6.3.1. Next-Generation Battery Technologies

Next-generation battery technologies, such as solid-state batteries and sodium-ion batteries, offer potential for lower environmental impacts and improved performance. According to Vaalma et al. [54], sodium-ion batteries, which use abundant sodium instead of lithium, could reduce resource depletion impacts by 50% while maintaining adequate performance for grid storage. Solid-state batteries, with higher energy density and safety, are also promising, with Manthiram et al. [65] reporting potential reductions in production emissions due to simplified manufacturing processes. These technologies could enhance the sustainability of utility-scale LIBs, though commercialization remains a challenge.

6.3.2. Circular Economy Approaches

Circular economy strategies, such as recycling and second-life applications, are critical for reducing the environmental footprint of LIBs. In a comprehensive study by Kamath et al. [46], second-life LIBs were shown to extend useful life by 5–10 years, reducing the need for new battery production and cutting lifecycle emissions by 30%. Advances in hydrometallurgical recycling, as noted by Ciez and Whitacre [23], can recover 90% of critical materials, mitigating resource scarcity. For utility-scale applications, scaling up recycling infrastructure is essential to support sustainable grid decarbonization.

6.3.3. Digital Tools for LCA Optimization

Digital tools, such as artificial intelligence (AI) and machine learning, are transforming LCA by improving the accuracy of environmental impact assessments. According to Babbitt [66], AI-driven models can optimize battery design and recycling processes, reducing lifecycle emissions by 10–20%. For utility-scale LIBs, these tools can predict degradation patterns and optimize operational strategies, as demonstrated by Xu et al. [40]. By integrating digital tools with LCA, stakeholders can better assess and mitigate the environmental impacts of LIBs, enhancing their role in grid decarbonization. Table 6 summarizes emerging trends and innovations in LIB technologies, including timelines, benefits, and challenges, to provide a forward-looking perspective on their contributions to sustainable grid systems.

Table 6 Future Trends and Innovations in LIBs for Grid Decarbonization

Trend/Innovation	Description	Expected Timeline	Potential Impact Reduction (e.g., % GWP)	Performance Benefits	Environmental Benefits	Challenges	References
Solid-State Batteries	Solid electrolytes replace liquid	2025-2030	20-40%	Higher density, safety	Reduced toxicity, longer life	Scaling costs	[65]
Sodium-Ion Batteries	Na-based alternatives	2025+	30-50%	Cost-effective	Abundant materials, lower depletion	Lower density	[54]
Advanced Recycling	Hydrometallurgy improvements	Ongoing-2030	40-60%	Material recovery 95%+	Circular economy, reduced mining	Economic barriers	[15], [23], [55]
Second-Life Applications	Repurposing for grid	Ongoing	20-30%	Extended lifespan 5-10 years	Less new production	Health assessment	[46], [47]
AI-Optimized LCA	Digital tools for design	2025+	10-20%	Predictive degradation	Precise impact minimization	Data privacy	[40], [66]
Low-Carbon Manufacturing	Renewable-powered factories	Ongoing	30-50%	Efficiency gains	Lower production emissions	Regional limitations	[9], [36]
Cobalt-Free Chemistries	LFP/NMC variants	2023+	20-30%	Comparable performance	Ethical sourcing	Slight density trade-off	[22], [63]

7. Conclusion

The life cycle assessment (LCA) of lithium-ion batteries (LIBs) in utility-scale applications reveals their dual role as both enablers of sustainable power systems and contributors to significant environmental challenges. Throughout their life cycle, from raw material extraction to end-of-life management, LIBs incur substantial environmental impacts, particularly in terms of greenhouse gas emissions, resource depletion, and ecosystem disruption. The production phase, driven by energy-intensive processes and reliance on critical materials like lithium and cobalt, dominates the environmental footprint, posing challenges to their sustainability. However, when deployed in grids with high renewable energy penetration, LIBs offer substantial benefits by stabilizing intermittent renewable sources, reducing fossil fuel reliance, and lowering grid carbon intensity. These findings underscore the importance of context-specific LCAs to balance the environmental costs and benefits of utility-scale LIBs, ensuring their alignment with global sustainability and decarbonization goals.

The sustainability of LIBs hinges on mitigating their production impacts and optimizing their operational performance. Strategies such as transitioning manufacturing to renewable energy sources, adopting low-impact battery chemistries like lithium iron phosphate, and improving recycling efficiency can significantly reduce the environmental burden. Additionally, LIBs enhance grid reliability and energy efficiency through rapid-response services and peak shaving, supporting the integration of solar and wind energy. Yet, limitations such as high upfront costs, resource scarcity, and battery degradation necessitate targeted interventions. Policy incentives, including carbon pricing and recycling mandates, play a critical role in scaling up sustainable LIB deployment, while technological advancements in battery management systems and next-generation chemistries offer promising avenues for improvement.

Looking Ahead, the future of LIBs in utility-scale applications depends on integrating innovative technologies and circular economy principles to enhance their sustainability. Advances in sodium-ion and solid-state batteries could alleviate resource constraints, while scalable recycling and second-life applications promise to reduce lifecycle impacts. Digital tools, such as artificial intelligence, hold potential for optimizing LCA processes and battery performance, enabling more precise environmental assessments. Stakeholders, including policymakers, industry leaders, and researchers, must collaborate to address supply chain risks, improve recycling infrastructure, and align LIB deployment with decarbonization targets. By addressing these challenges, LIBs can play a transformative role in achieving sustainable, low-carbon power systems, paving the way for a resilient energy future.

Compliance with ethical standards

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Disclosure of conflict of interest

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.

References

[1] Peters, J. F., Baumann, M., Zimmermann, B., Braun, J., and Weil, M. (2017). The environmental impact of Li-Ion batteries and the role of key parameters–A review. Renewable and Sustainable Energy Reviews, 67, 491-506.

[2] Hornsdale Power Reserve. (2019). Case study: Impact of utility-scale battery storage on grid stability. Global Infrastructure Hub. Retrieved from https://cdn.gihub.org/umbraco/media/2765/gih_showcaseprojects_hornsdale_2019_web_art.pdf

[3] Dunn, J. B., Gaines, L., Sullivan, J., and Wang, M. Q. (2012). Impact of recycling on cradle-to-gate energy consumption and greenhouse gas emissions of automotive lithium-ion batteries. Environmental science and technology, 46(22), 12704-12710.

[4] Arbabzadeh, M., Johnson, J. X., Keoleian, G. A., Rasmussen, P. G., and Thompson, L. T. (2016). Twelve principles for green energy storage in grid applications. Environmental science and technology, 50(2), 1046-1055.

[5] Schmidt, O., Hawkes, A., Gambhir, A., and Staffell, I. (2017). The future cost of electrical energy storage based on experience rates. Nature Energy, 2(8), 1-8.

[6] Baumann, M., Peters, J. F., Weil, M., and Grunwald, A. (2017). CO2 footprint and life-cycle costs of electrochemical energy storage for stationary grid applications. Energy Technology, 5(7), 1071-1083.

[7] Majeau-Bettez, G., Hawkins, T. R., and Strømman, A. H. (2011). Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. Environmental science and technology, 45(10), 4548-4554.

[8] Arbabzadeh, M., Sioshansi, R., Johnson, J. X., and Keoleian, G. A. (2019). The role of energy storage in deep decarbonization of electricity production. Nature communications, 10(1), 3413.

[9] Kim, H. C., Wallington, T. J., Arsenault, R., Bae, C., Ahn, S., and Lee, J. (2016). Cradle-to-gate emissions from a commercial electric vehicle Li-ion battery: a comparative analysis. Environmental science and technology, 50(14), 7715-7722.

[10] Ralon, P., Taylor, M., Ilas, A., Diaz-Bone, H., and Kairies, K. (2017). Electricity storage and renewables: Costs and markets to 2030. International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 164, 154.

[11] Zhu, H., Li, H., Liu, G., Ge, Y., Shi, J., Li, H., and Zhang, N. (2020). Energy storage in high variable renewable energy penetration power systems: Technologies and applications. CSEE Journal of Power and Energy Systems, 9(6), 2099-2108.

[12] Notter, D. A., Gauch, M., Widmer, R., Wager, P., Stamp, A., Zah, R., and Althaus, H. J. (2010). Contribution of Li-ion batteries to the environmental impact of electric vehicles, 44(17), 6550-6556.

[13] Olivetti, E. A., Ceder, G., Gaustad, G. G., and Fu, X. (2017). Lithium-ion battery supply chain considerations: analysis of potential bottlenecks in critical metals. Joule, 1(2), 229-243.

[14] Pellow, M. A., Ambrose, H., Mulvaney, D., Betita, R., and Shaw, S. (2020). Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues. Sustainable Materials and Technologies, 23, e00120.

[15] Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., ... and Anderson, P. (2019). Recycling lithium-ion batteries from electric vehicles. nature, 575(7781), 75-86.

[16] Cosme, N., Hauschild, M. Z., Molin, C., Rosenbaum, R. K., and Laurent, A. (2019). Learning-by-doing: experience from 20 years of teaching LCA to future engineers. The International Journal of Life Cycle Assessment, 24(3), 553-565.

[17] Ellingsen, L. A. W., Majeau-Bettez, G., Singh, B., Srivastava, A. K., Valøen, L. O., and Strømman, A. H. (2014). Life cycle assessment of a lithium-ion battery vehicle pack. Journal of Industrial Ecology, 18(1), 113-124.

[18] Dai, Q., Kelly, J. C., Gaines, L., and Wang, M. (2019). Life cycle analysis of lithium-ion batteries for automotive applications. Batteries, 5(2), 48.

[19] Hiremath, M., Derendorf, K., and Vogt, T. (2015). Comparative life cycle assessment of battery storage systems for stationary applications. Environmental science and technology, 49(8), 4825-4833.

[20] Zackrisson, M., Avellán, L., and Orlenius, J. (2010). Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles–Critical issues. Journal of cleaner production, 18(15), 1519-1529.

[21] Romare, M., and Dahllöf, L. (2017). The life cycle energy consumption and greenhouse gas emissions from lithium-ion batteries.

[22] Le Varlet, T., Schmidt, O., Gambhir, A., Few, S., and Staffell, I. (2020). Comparative life cycle assessment of lithium-ion battery chemistries for residential storage. Journal of Energy storage, 28, 101230.

[23] Ciez, R. E., and Whitacre, J. F. (2019). Examining different recycling processes for lithium-ion batteries. Nature Sustainability, 2(2), 148-156.

[24] Oliveira, L., Messagie, M., Mertens, J., Laget, H., Coosemans, T., and Van Mierlo, J. (2015). Environmental performance of electricity storage systems for grid applications, a life cycle approach. Energy conversion and management, 101, 326-335.

[25] Hawkins, T. R., Singh, B., Majeau-Bettez, G., and Strømman, A. H. (2013). Comparative environmental life cycle assessment of conventional and electric vehicles. Journal of industrial ecology, 17(1), 53-64.

[26] Nuss, P., and Eckelman, M. J. (2014). Life cycle assessment of metals: a scientific synthesis. PloS one, 9(7), e101298.

[27] McManus, M. C. (2012). Environmental consequences of the use of batteries in low carbon systems: The impact of battery production. Applied Energy, 93, 288-295.

[28] Farjana, S. H., Huda, N., and Mahmud, M. P. (2019). Life cycle assessment of cobalt extraction process. Journal of Sustainable Mining, 18(3), 150-161.

[29] Sadhukhan, J., and Christensen, M. (2021). An in-depth life cycle assessment (LCA) of lithium-ion battery for climate impact mitigation strategies. Energies, 14(17), 5555.

[30] Yuan, C., Deng, Y., Li, T., and Yang, F. (2017). Manufacturing energy analysis of lithium ion battery pack for electric vehicles. CIRP Annals, 66(1), 53-56.

[31] Farjana, S. H., Mahmud, M. P., and Huda, N. (2021). Life cycle assessment for sustainable mining. Elsevier.

[32] Chagnes, A., and Swiatowska, J. (Eds.). (2015). Lithium process chemistry: Resources, extraction, batteries, and recycling. Elsevier.

[33] Schmidt, T., Buchert, M., and Schebek, L. (2016). Investigation of the primary production routes of nickel and cobalt products used for Li-ion batteries. Resources, Conservation and Recycling, 112, 107-122.

[34] Mudd, G. M. (2010). Global trends and environmental issues in nickel mining: Sulfides versus laterites. Ore Geology Reviews, 38(1-2), 9-26.

[35] Liu, W., Agusdinata, D. B., and Myint, S. W. (2019). Spatiotemporal patterns of lithium mining and environmental degradation in the Atacama Salt Flat, Chile. International Journal of Applied Earth Observation and Geoinformation, 80, 145-156.

[36] Li, J., Lu, Y., Yang, T., Ge, D., Wood, D. L., and Li, Z. (2020). Water-based electrode manufacturing and direct recycling of lithium-ion battery electrodes—a green and sustainable manufacturing system. IScience, 23(5).

[37] Zhao, S., and You, F. (2019). Comparative life-cycle assessment of Li-ion batteries through process-based and integrated hybrid approaches. ACS Sustainable Chemistry and Engineering, 7(5), 5082-5094.

[38] Zhang, X., Li, Z., Luo, L., Fan, Y., and Du, Z. (2022). A review on thermal management of lithium-ion batteries for electric vehicles. Energy, 238, 121652.

[39] Goteti, N. S., Hittinger, E., and Williams, E. (2019). How much wind and solar are needed to realize emissions benefits from storage?. Energy Systems, 10(2), 437-459.

[40] Xu, B., Oudalov, A., Ulbig, A., Andersson, G., and Kirschen, D. S. (2016). Modeling of lithium-ion battery degradation for cell life assessment. IEEE transactions on smart grid, 9(2), 1131-1140.

[41] Berecibar, M., Gandiaga, I., Villarreal, I., Omar, N., Van Mierlo, J., and Van den Bossche, P. (2016). Critical review of state of health estimation methods of Li-ion batteries for real applications. Renewable and Sustainable Energy Reviews, 56, 572-587.

[42] Fares, R. L., and Webber, M. E. (2017). The impacts of storing solar energy in the home to reduce reliance on the utility. Nature Energy, 2(2), 1-10.

[43] Few, S., Schmidt, O., Offer, G. J., Brandon, N., Nelson, J., and Gambhir, A. (2018). Prospective improvements in cost and cycle life of off-grid lithium-ion battery packs: An analysis informed by expert elicitations. Energy Policy, 114, 578-590.

[44] Gaines, L. (2014). The future of automotive lithium-ion battery recycling: Charting a sustainable course. Sustainable Materials and Technologies, 1, 2-7.

[45] Machala, M. L., Chen, X., Bunke, S. P., Forbes, G., Yegizbay, A., de Chalendar, J. A., ... and Tarpeh, W. A. (2025). Life cycle comparison of industrial-scale lithium-ion battery recycling and mining supply chains. Nature Communications, 16(1), 988.

[46] Kamath, D., Shukla, S., Arsenault, R., Kim, H. C., and Anctil, A. (2020). Evaluating the cost and carbon footprint of second-life electric vehicle batteries in residential and utility-level applications. Waste Management, 113, 497-507.

[47] Martinez-Laserna, E., Gandiaga, I., Sarasketa-Zabala, E., Badeda, J., Stroe, D. I., Swierczynski, M., and Goikoetxea, A. (2018). Battery second life: Hype, hope or reality? A critical review of the state of the art. Renewable and Sustainable Energy Reviews, 93, 701-718.

[48] Winslow, K. M., Laux, S. J., and Townsend, T. G. (2018). A review on the growing concern and potential management strategies of waste lithium-ion batteries. Resources, Conservation and Recycling, 129, 263-277.

[49] Emilsson, E., and Dahllöf, L. (2019). Lithium-ion vehicle battery production-status 2019 on energy use, CO2 emissions, use of metals, products environmental footprint, and recycling.

[50] Oliveira, L., Messagie, M., Rangaraju, S., Sanfelix, J., Rivas, M. H., and Van Mierlo, J. (2015). Key issues of lithium-ion batteries–from resource depletion to environmental performance indicators. Journal of cleaner production, 108, 354-362.

[51] Weber, S., Peters, J. F., Baumann, M., and Weil, M. (2018). Life cycle assessment of a vanadium redox flow battery. Environmental science and technology, 52(18), 10864-10873.

[52] Sun, X., Hao, H., Zhao, F., and Liu, Z. (2017). Tracing global lithium flow: A trade-linked material flow analysis. Resources, Conservation and Recycling, 124, 50-61.

[53] Calderon, J. L., Bazilian, M., Sovacool, B., Hund, K., Jowitt, S. M., Nguyen, T. P., ... and Kukoda, S. (2020). Reviewing the material and metal security of low-carbon energy transitions. Renewable and Sustainable Energy Reviews, 124, 109789.

[54] Vaalma, C., Buchholz, D., Weil, M., and Passerini, S. (2018). A cost and resource analysis of sodium-ion batteries. Nature reviews materials, 3(4), 1-11.

[55] Chen, M., Ma, X., Chen, B., Arsenault, R., Karlson, P., Simon, N., and Wang, Y. (2019). Recycling end-of-life electric vehicle lithium-ion batteries. Joule, 3(11), 2622-2646.

[56] Sonter, L. J., Dade, M. C., Watson, J. E., and Valenta, R. K. (2020). Renewable energy production will exacerbate mining threats to biodiversity. Nature communications, 11(1), 4174.

[57] Balakrishnan, A., Brutsch, E., Jamis, A., Reyes, W., Strutner, M., Sinha, P., and Geyer, R. (2019, June). Environmental impacts of utility-scale battery storage in california. In 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC) (pp. 2472-2474). IEEE.

[58] Kaunda, R. B. (2020). Potential environmental impacts of lithium mining. Journal of energy and natural resources law, 38(3), 237-244.

[59] Jacobson, M. Z., Delucchi, M. A., Bauer, Z. A., Goodman, S. C., Chapman, W. E., Cameron, M. A., ... and Yachanin, A. S. (2017). 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. Joule, 1(1), 108-121.

[60] Kempton, W., Tomic, J., Letendre, S., Brooks, A., and Lipman, T. (2001). Vehicle-to-grid power: battery, hybrid, and fuel cell vehicles as resources for distributed electric power in California.

[61] Lund, P. D., Lindgren, J., Mikkola, J., and Salpakari, J. (2015). Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renewable and sustainable energy reviews, 45, 785-807.

[62] Cole, W., Frazier, A. W., and Augustine, C. (2021). Cost projections for utility-scale battery storage: 2021 update (No. NREL/TP-6A20-79236). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[63] Mauler, L., Duffner, F., Zeier, W. G., and Leker, J. (2021). Battery cost forecasting: a review of methods and results with an outlook to 2050. Energy and Environmental Science, 14(9), 4712-4739.

[64] Sovacool, B. K., Hook, A., Martiskainen, M., Brock, A., and Turnheim, B. (2020). The decarbonisation divide: Contextualizing landscapes of low-carbon exploitation and toxicity in Africa. Global Environmental Change, 60, 102028.

[65] Manthiram, A., Yu, X., and Wang, S. (2017). Lithium battery chemistries enabled by solid-state electrolytes. Nature Reviews Materials, 2(4), 1-16.

[66] Babbitt, C. W. (2020). Sustainability perspectives on lithium-ion batteries. Clean Technologies and Environmental Policy, 22(6), 1213-1214.