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Systematic Literature Review:

Life Cycle Assessments of Large Format Batteries

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Abstract

This study systematically reviews how researchers model Large Format Battery (LFB) Life Cycle Assessments (LCAs) and what information is used to conduct Lithium Iron Phosphate (LFP) LCAs across various life cycle stages. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, peer-reviewed articles published between 2015 and 2025 were retrieved from Scopus and Web of Science; 78 studies met the inclusion criteria. A standardized coding framework captured methodological choices (application, chemistry, system boundary, functional unit, life cycle inventory (LCI) sources, life cycle impact assessment (LCIA) methods/indicators, end-of-life pathways, and sensitivity/uncertainty practices), and LFP-specific inventories were additionally extracted and normalized to 1 kWh capacity when feasible. The number of journals published increased sharply after 2022, with studies originating most frequently from Europe (35%), China (22%), and North America (18%). Cradle-to-grave was the most common system boundary (n = 45), but partial boundaries and use-phase exclusions were also frequent, especially in cascading-use studies. Functional units were highly heterogeneous, with variants of “1 kWh” appearing in 35 studies, which alternated between capacity-based and throughput/service-based interpretations, alongside mass-, pack-, and mileage-based units. Predominantly used background database was ecoinvent (n = 57), while foreground inventories relied heavily on modeled or literature-derived inputs. ReCiPe was the frequently used LCIA method (n = 28), although 22 studies reported GWP only. EoL modeling ranged from cutoff assumptions to explicit hydro- and pyrometallurgical routes and system-expansion approaches. Sensitivity analysis was reported in 42 studies, whereas Monte Carlo uncertainty analysis appeared in seven. Overall, the review maps methodological heterogeneity and recurring data gaps, providing a structured evidence base and LFP Bill of Materials (BOM) to support the development of reproducible, open-source LFB LCA models.

Keywords

Large format Batteries; Energy Storage Battery; Electric Vehicle Battery; life cycle assessment; sustainability

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Disclaimers

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Author Contributions

Sindhu Ranganath: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Validation, Visualization, Writing- Original draft preparation.

Joshua Kneifel: Funding acquisition, Resources, Conceptualization, Supervision, Project administration, Writing- Reviewing and Editing.

Sachi Nandurkar: Data curation

Caitlin Grady: Conceptualization, Supervision, Writing- Reviewing and Editing.

1. Introduction and Scope

U.S. industry is competing globally in the rapidly growing market for large format batteries (LFB), which have wide-ranging applications - from consumer vehicles to stationary energy storage, industrial equipment, and specialized transport (e.g., drones) [1–3]. Greater demand for these products has increased the need for inputs to manufacture these products, including critical materials with currently limited domestic availability. For the U.S. industry to remain competitive and accelerate LFB manufacturing, a more efficient, secure, and resilient supply chain for these inputs is necessary. Additionally, there is growing interest from both consumers and industry in differentiating their products through product claims on the provenance of inputs required and environmental and human health impacts associated with their products [4].

One approach to increasing the efficiency and resiliency of critical material supply is to develop a more circular domestic supply chain by reusing and recycling existing LFBs, thereby reducing the need for foreign-sourced critical materials. To evaluate the benefits and costs of increased circularity, it is necessary to quantify the inputs (e.g., raw material, energy, and transportation flows) and outputs (e.g., end product or waste produced during the manufacturing) of an LFB throughout its entire initial life cycle and beyond (second or third life). Quantifying these impacts will also allow for product differentiation through its performance and characteristics relative to competitors (often international). To support such claims, it is vital that the U.S. industry can accurately quantify these inputs and outputs, accounting for full life-cycle characteristics, including supply chain, manufacturing, and end-of-use scenarios. Additionally, information is needed on the recyclability and potential use of recycled content in new LFBs.

Therefore, there is a need for high-quality, transparent life cycle data for LFBs. A common approach to quantify the life cycle impacts is life cycle assessment (LCA), which provides a scientific methodology for calculating the impacts of a product or service over its entire life cycle in accordance with the International Organization for Standardization (ISO) 14040 and ISO 14044 standards [5, 6]. Understanding the state of LCA modeling for LFBs will help develop trusted LCA results and, thus, support industry and company product claims.

This review examines how LCA researchers model the impacts of LFBs. Two common definitions of LFBs are: 1) a battery weighing more than 25 pounds and used in vehicles or industrial energy storage applications, and 2) a rechargeable battery weighing more than 25 pounds or exceeding 2,000 watt-hours [7, 8]. Based on these definitions, this study considers battery LCA modeling across both transportation and stationary applications. The overarching research question guiding this study is: “How are researchers modeling the full life cycle of an LFB, and what information is used to conduct Lithium iron phosphate (LFP) LCAs at different life cycle stages?” The LFP battery chemistry was selected as a focal point because it is one of the most widely used chemistries for LFB and has been a focus of related circularity-related research at NIST. Although focused on LFP, the authors systematically review LCA modeling for all chemistries related to LFBs by extracting and assessing details on modeling decisions, including system boundaries, functional units, life-cycle inventory (LCI) data sources, impact assessment methods, end-of-life pathways, and foreground inventory information. The resulting review is also intended to identify the bill of materials (BOM) that can inform the development of open-source LFB models, particularly for LFP chemistries. Methodologically, most prior reviews employ a result-centric approach, aggregating environmental impact outcomes across chemistries and life-cycle stages, whereas this review focuses on methodology and descriptive statistics, documenting how LCAs are constructed (functional units, boundaries, LCIA methods, and LCI sources).

2. Study Methodology

To address the research question, peer-reviewed literature was systematically collected from the Scopus and Web of Science (WoS) databases following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [9]. The search covered journal publications published in the English language from 2015 to 2025, a period selected to capture the most recent decade of rapid advancements in LFB technology, including improvements in energy density, fast charging, end-of-life strategies, cost-effectiveness, and safety [10]. Only original research articles were included; systematic reviews and non-peer-reviewed sources were excluded. The search strategy targeted studies that modeled LFBs within an LCA framework, using three clusters of search terms shown in Table 1.

Table 1: Keywords of Systematic Search

Category	**Search Term**
Chemistry-specific	"lithium iron phosphate", "LFP", "$LiFePO_4$"
Application-related	"large format batter*", "large-scale batter*", "utility scale batter*", "grid scale batter*", "EV batter*", "electric vehicle batter*", "automotive"
Life cycle related	"life cycle assessment", "LCA", "life cycle analysis", "end of life", "EOL", "reuse", "refurbish*", "recycl*", "second life", "cradle to cradle", "circular economy"

For a publication to be returned in the search, it had to contain at least one term from the “application-related” bin and one term from the “life-cycle–related” bin in all search iterations. In one of the search iterations, chemistry-specific terms were additionally incorporated to further refine the scope. Across the four search iterations, these combinations yielded a total of 397 records from Scopus and Web of Science, which were subsequently reduced to 184 unique records after duplicates removal. Detailed information on variations of the search queries is provided in Appendix A, in SI Table A1 and SI Table A2.

All unique records underwent a two-stage screening process, as shown in Figure 1. First, titles and abstracts were reviewed to determine their relevance to LFB systems in a life-cycle context, resulting in the exclusion of 71 records that did not address LFB configurations. The remaining articles underwent full-text screening by the authors, during which an additional 35 studies were excluded as irrelevant. Although these articles examined LFB technologies, they did not explicitly model either (a) battery production processes or (b) end-of-life pathways within an LCA framework, criteria essential for addressing the research questions. The final set of studies included in this review included n = 78 articles.

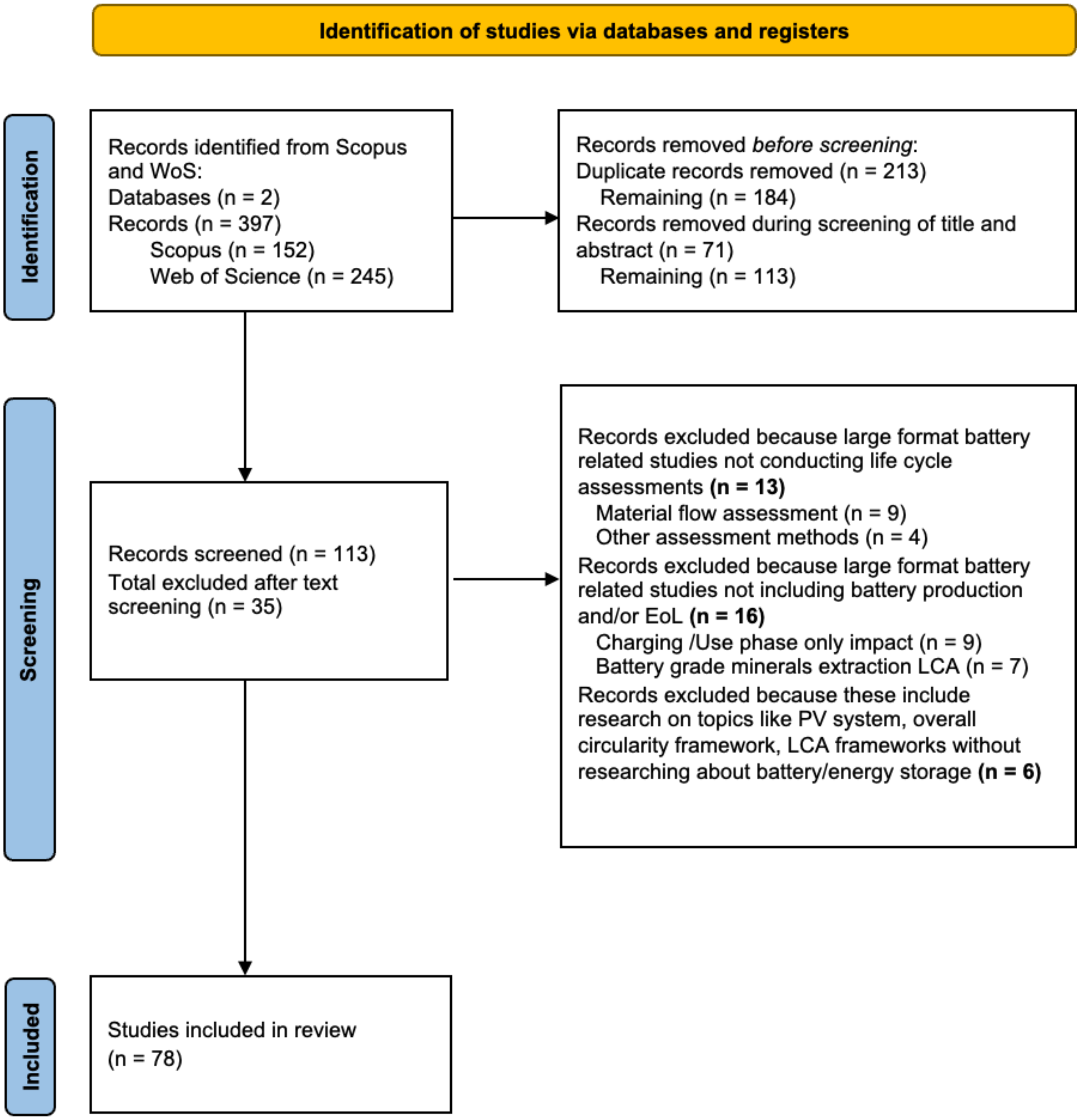

Figure 1: Systematic Review Process (n=78)

2.1. Data Coding and Data Extraction Framework

To enable a systematic comparison of methodological practices across LCA studies on LFBs, a data extraction and coding framework was developed. This framework was designed to capture the methodological choices reported in the studies identified through the review that could influence life-cycle modeling outcomes. Each included paper was reviewed at least once by at least one author to extract key information summarized in Table 2, using a standardized data collection template. The subsequent sections present descriptive information on the methodological metadata extracted from the reviewed studies. Rather than evaluating the influence of individual modeling choices on impact results, which has been the focus of several prior meta-analyses (e.g., [11, 12]), this study emphasizes identifying and organizing the gathered information using descriptive statistics, thereby providing a structured summary of current modeling approaches.

Table 2: Data extracted from the reviewed papers

Parameter	Description / Coding Basis
DOI	Unique ID for collected papers
Authors	All the authors listed on the manuscript
Publication year	Year of study publications
Geographic scope	Geographic scope of the study
Software used	LCA software (e.g., SimaPro, GaBi, openLCA, GREET) and non-LCA software, if any
Assessment framework	Analytical structure used: LCA only, or combined with techno-economic analysis (TEA) or life cycle cost analysis (LCCA), others, if applicable
Battery Chemistry	Battery chemistry assessed (LFP, NMC, NCA, Na-ion, etc.).
Application context	Sector of use (EVs, grid storage, etc.).
System boundary	Life-cycle scope (e.g., cradle-to-gate, cradle-to-grave, etc) with additional explanation
End-of-life (EOL) pathway	Post-use scenarios (e.g., recycling, reuse) with First and/or second life calculation information
Impact assessment method	Impact modeling framework (e.g., ReCiPe, CML-IA, TRACI)
Impact indicators reported	Quantitative environmental indicators (e.g., GWP, AP, EP)
Functional unit	Reference unit used in the assessment (e.g., 1 kWh, 1 km driven)
Foreground and Background data used	Foreground data sources: E.g., Primary data, literature, Background data sources: E.g., ecoinvent, literature

2.2. Bill of Materials (BOM) Collection

In addition to LCA modelling-based metadata extraction, bill of material (BOM) data were also collected from studies that reported quantitative material and energy inputs for the cathode, anode, electrolyte, cell assembly, and other stages of battery production, along with any end-of-life (EOL) data for LFP battery chemistry. To facilitate cross-study comparison and model integration, these inventories were normalized to a common functional unit of 1 kWh of battery capacity when sufficient information was available in the study.

3. Results

The findings from the original research articles reviewed in this study are organized into several key categories to illuminate current practices in LFB LCA modeling. These categories include trends in the number of studies published by year, geographic footprint of the research, and patterns in LCA data usage and assessment frameworks. They also encompass the battery applications and chemistries examined, the functional units employed, the life-cycle impact assessment (LCIA) methods, the impact indicators selected, and the system boundaries defined. Finally, the review summarizes BOM data gathered across studies. Together, these categories provide a structured basis for interpreting the state of the literature.

Number of studies by year

The number of publications on LFB LCAs has shown a steady increase since 2015, with a sharp increase in 2022 (Figure 2), reflecting a growing research interest in electric vehicles and stationary energy storage systems. The lower count observed for 2025 (n = 7) is not indicative of decreased publication activity but rather an artifact of the data collection cutoff on June 1, 2025. To illustrate this effect for 2024, the number of studies that would have been captured had the 2024 search also ended on 1 June 2024 instead of 31 December 2024 is (n = 5). This comparison demonstrates that the reduced count in 2025 is due to partial-year data collection rather than a true decline in research output.

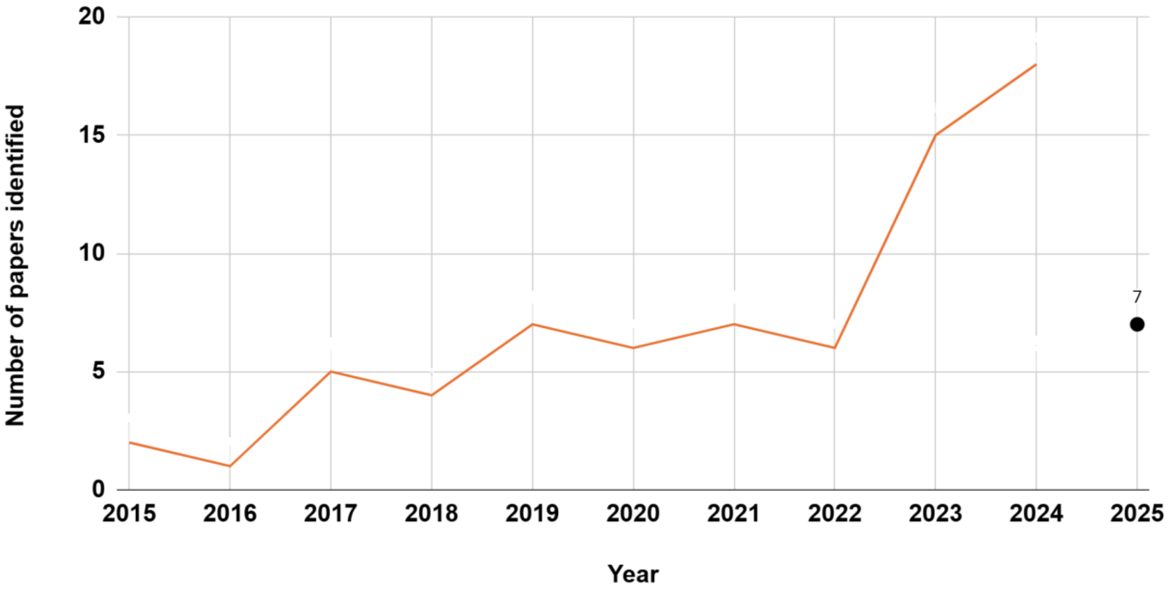

Figure 2: Number of studies conducted per year within the study consideration period (n=78)

Geographic footprint

The studies included in this review represent research conducted across multiple geographic regions (Figure 3). The spatial resolution of the reviewed studies varied substantially, ranging from building-level case studies (e.g., [13]) to continental-scale analyses (e.g., [14, 15]).

Approximately 35% (n = 27) of the studies originated from Europe. Within this subset, some studies explicitly identify the country represented, while others define their scope at the broader continental level. For instance, one study conducted its assessment across Poland and the Czech Republic [16], whereas another study simulated passenger-car markets across all 27 EU member states, using country-specific data to construct a system-level LCA at the EU-27 scale [17]. Studies from China accounted for approximately 22% (n = 17) of the total, reflecting the region's prominence in battery manufacturing and recycling research. North American studies, primarily from the United States and Canada, represented about 18% (n = 14) of the sample. Approximately 14% (n = 11) of the studies reported a global or multi-regional scope, integrating data from multiple countries—often spanning several continents—to reflect the geographically distributed nature of LFB supply chains. Studies grouped under "Others" (n = 8) in Figure 3 include those from regions such as Singapore, Thailand, and South Korea, as well as other emerging economies that are less frequently represented but contribute to the dataset's overall geographic diversity. One study did not explicitly specify a geographic scope [18]. Study-specific details are provided in SI Table A4 of Appendix A.

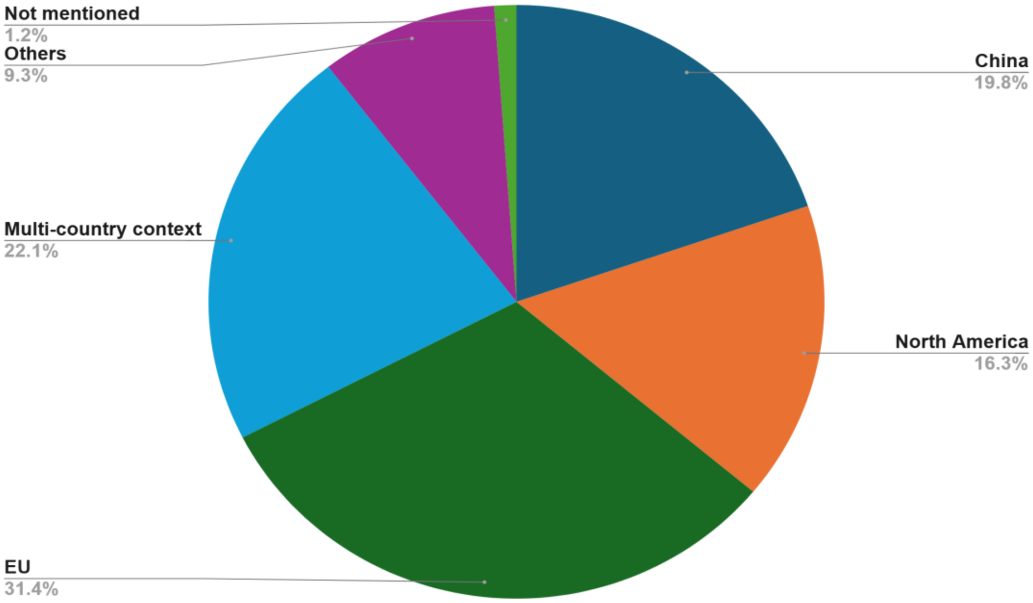

Figure 3: Geographic footprint of different studies under review

Software used

Among the studies reviewed, 30 (38%) used Sima Pro, making it the most widely used software across the reviewed literature. This finding aligns with observations from other systematic reviews, which also identified Sima Pro as the preferred LCA tool [11, 19]. Only a subset of studies reported the software version, which ranged from Sima Pro v7 through v9.5. Other tools frequently used included Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) (n = 10), with some cases involving its use in combination with other tools, such as EverBatt [20] or Economic Input-Output Life Cycle Assessment (EIO-LCA) [21]. One Study used GREET alongside Sima Pro [22]. GaBi was reported in seven studies, openLCA in six, and the

Brightway ecosystem in three. One study did not report using any LCA software package, likely because it was a stand-alone LCI case study and did not require dedicated impact assessment tools [23]. Less commonly used LCA tools included eFootprint (the online version of eBalance) [24], MiLCA [25], LCA2GO [14], and Umberto NXT universal [26]. Eighteen studies did not specify the LCA software used. Of these, one study did not report the use of an LCA tool but noted the use of GAMS and CPLEX, which are mathematical optimization tools employed to construct and run the electricity system model that generated the electricity mix used in their LCA [27].

While most studies relied on a single LCA software or a coherent suite (e.g., GREET/EverBatt or Brightway), several integrated multiple tools to support hybrid modeling approaches. For instance, one study used HOMER Pro and BEopt for energy and economic modeling, with outputs subsequently linked to Sima Pro for environmental impact assessment [28]. Similarly, another study performed LCA modeling in Sima Pro while using MATLAB for resilience and performance simulations [29]. Further details on LCA software usage are summarized in Figure 4, and study-specific details are provided in

SI Table A5 of Appendix A.

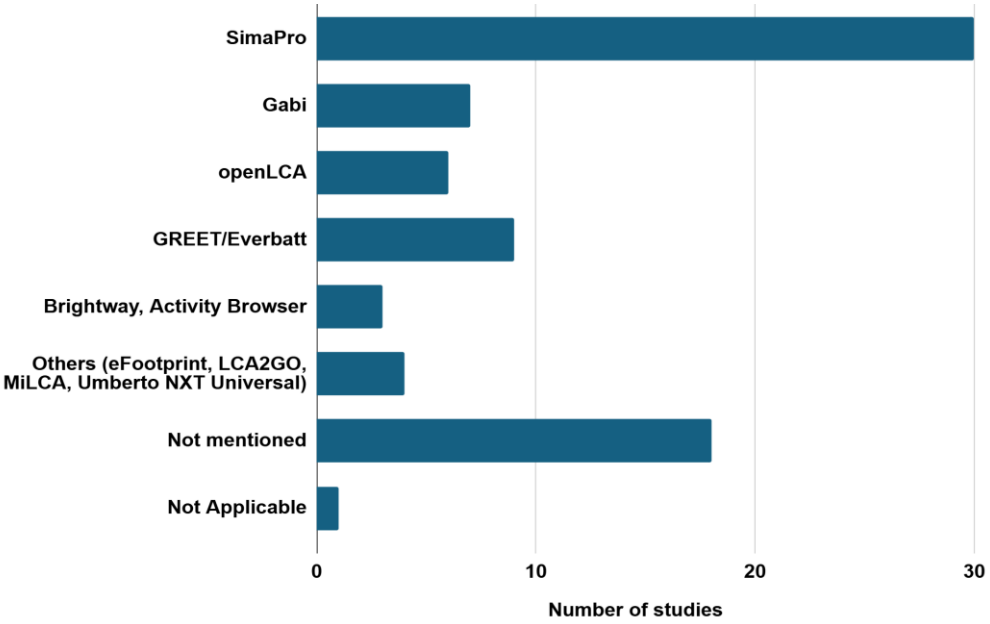

Figure 4 LCA software usage across reviewed studies

Assessment framework

All studies included in this review conducted an LCA. Different categorizations of LCAs were observed, including process-based or hybrid, attributional or consequential, and status quo or prospective. However, these categories are not mutually exclusive, and studies often combine them depending on their modeling goals.

Process-based LCA is an assessment that uses detailed process-level information to reflect how the unit processes of a product system are interconnected through commodity flows [30]. Input-Output (IO)-based LCA is an assessment that relies on aggregate sectoral information from IO tables, which record annual transactions between all productive activities of an economy [30]. Hybrid LCA is defined as a combination of process-based and IO-based LCA, with different degrees of integration between the two constituent methods [30].

Attributional LCA is defined by its focus on describing the environmentally relevant physical flows to and from a life cycle and its subsystems, while consequential LCA is defined by its aim to describe how environmentally relevant flows will change in response to possible decisions [31]. Among the LCAs examined, the most common approach was process-based attributional LCA, reflecting the standard practice of modeling environmental impacts. Two studies also acknowledged the use of a consequential LCA framework to model avoided burdens via substitution [32, 33], which is a type of system expansion [34, 35]. While not categorized as consequential LCAs, six studies also reported using system expansion [36–41]. Based on ISO 14044, system expansion can be achieved in two ways: by adding functions or by subtracting functions [42]. Consistent with these interpretations, the aforementioned studies apply system expansion to either credit avoided products/materials (e.g., new battery production or primary material production) or to broaden system boundaries, such that all functions provided by a battery are represented (whether in first-life, second-life, or recycling scenarios).

Nearly all studies assumed the current state of industrial production for the product studied. Five studies explicitly reported conducting a prospective LCA (pLCA) [17, 43–46]. pLCA provides a systematic approach to evaluating emerging technologies throughout their life cycle and projecting impacts at future industrial scales [47]. The identified studies employed these frameworks to account for future changes in energy systems, technological performance, or market contexts. Additionally, one study conducting pLCA explicitly acknowledged the use of a hybrid LCA framework, combining process-based background data from ecoinvent and the Chinese Life Cycle Database (CLCD) with Chinese regional input–output data to construct a more regionally representative modeling framework [43].

Uncertainty, Sensitivity, and Additional Analyses

To strengthen the robustness of their findings, nearly all studies in this review incorporated at least one form of supplementary analysis, such as scenario, sensitivity, uncertainty, hotspot, or comparative analysis, except for one study focused primarily on LCI development [23].

Previous research has highlighted that uncertainty is a crucial factor that can compromise the quality and applicability of LCA results. In particular, the fidelity of an LCA study is directly tied to the uncertainty of the LCI data, and uncertainty may persist even when primary data are used; reliance on secondary data can introduce additional uncertainty due to proxies, approximations, or limited representativeness [48]. Given that a key contribution of this review is to compile and organize BOM information from published studies to support the development of open-source LFB LCA models, explicitly recognizing the role of uncertainty is essential. Seven studies conducted uncertainty assessment using Monte Carlo simulation, a stochastic (probabilistic) uncertainty analysis method [16, 49–54]. Monte Carlo simulation propagates parameter uncertainty in LCA by repeatedly drawing random samples from input parameter distributions to generate a distribution of output results [55]. In the reviewed literature, Monte Carlo analysis was applied to address parameter uncertainty, including uncertainties in inventory data, technical specifications, technology variability, and use-phase parameters (e.g., efficiency, cycle life, degradation, losses), to quantify how input variability affects environmental impact estimates. Iteration counts ranged from 1,000 to 100,000 across studies. Other studies acknowledged uncertainty qualitatively or explored parameter variation through deterministic sensitivity tests without conducting a detailed stochastic uncertainty assessment [36, 37, 40, 56–58].

Due to the lack of availability of primary data, several assumptions must be made in LCA studies. For this reason, sensitivity analysis also plays a crucial role, where some data and information are difficult to obtain or cannot be disclosed by battery manufacturers due to confidentiality concerns [12]. Across the reviewed literature, 42 studies conducted sensitivity analyses to test the robustness of their LCA results. These analyses encompassed a wide range of factors, including material- and component-related parameters (e.g., recovery rates, precursor materials, and manufacturing energy), battery health and performance assumptions (lifetime, state of health, degradation, and cycling behavior), and energy-flow and electricity-mix variations that affect use-phase impacts. Studies also examined use-phase behaviors, economic assumptions, and methodological choices such as allocation rules and scenario definitions. Collectively, these sensitivity assessments demonstrate how variations in technical, operational, and methodological inputs can substantially influence LFB LCA outcomes.

While LCA was the central focus of the studies reviewed, approximately 32% (n = 25) extended its scope by integrating complementary assessment methods, such as Material Flow Analysis (MFA) and economic assessments. Economic assessments were the most observed complementary framework and were frequently conducted in tandem with LCA. These assessments encompassed several approaches, including LCCA and/or levelized cost assessment to estimate costs across life-cycle stages or to calculate the cost of delivered energy under various scenarios (n = 9) [22, 28, 44, 50, 59–63]. TEA-based studies evaluated the viability of battery systems by linking technical performance with cost and revenue modeling (n = 3) [29, 64, 65]. Cost–benefit analyses and total cost of ownership studies provided detailed cost breakdowns for specific life-cycle stages and overall ownership (n = 2) [20, 58]. Other studies conducted additional economic analyses to evaluate key cost drivers across the production, use, reuse, and end-of-life stages (n = 5) [21, 66–69].

A subset of studies used MFA-based and stock–flow modeling approaches to quantify how batteries and their constituent materials move through production, use, and end-of-life stages over time (n = 5) [17, 45, 59, 67, 70]. These studies employed dynamic stock–flow or substance-flow models to assess long-term material requirements, supply risks, and the balance between primary and secondary (recycled) materials under evolving EV adoption scenarios. Collectively, these MFA-type analyses support system-level understanding of battery life cycles by capturing temporal dynamics, regional differences, and the implications of recycling efficiency, collection rates, and market growth on resource availability and circularity performance.

In addition to MFA-based approaches, some studies employed systems-level modeling frameworks to capture broader technological, spatial, and operational dynamics of battery systems (n = 6) [21, 33, 37, 59, 67, 71]. These included multi-objective optimization to examine trade-offs among cost, environmental impact, material criticality, and energy density; energy-system and system-dynamics models to simulate battery flows, second-life adoption, and long-term material and economic trends; and geospatial supply-chain and reverse-logistics models to identify optimal facility siting, transportation routes, and regional end-of-life collection strategies. Other studies used resilience performance modelling [29], eco-efficiency analysis [65], and multi-criteria decision-making to integrate technical, economic, and environmental considerations, allowing system-level evaluation under different operational conditions and stakeholder priorities [50]. Frequently conducted analyses across the reviewed literature also included, but were not limited to, battery health modeling (degradation, cycle aging, lifetime analyses), energy flow assessments (charge–discharge behavior, dispatch, load matching), and circularity and end-of-life pathway assessments.

Battery Application and Chemistry

Among the studies assessed, approximately 49% (n = 39) evaluated batteries used in EV transportation systems. Another 11 studies (14%) examined non-transportation applications such as stationary energy storage, utility-scale installations, and communication base-station systems. The next 26 studies investigated cascading use pathways in which first-life EV batteries are repurposed for second-life applications, most commonly as stationary storage. Two remaining studies compared multiple applications in parallel as independent systems rather than within a reuse framework. Study-specific battery application information is provided in Appendix A SI Table A6.

Across these application domains, the reviewed literature covered a wide range of battery chemistry. Lithium-ion cathode chemistries included LFP, NMC (111, 333, 442, 532, 622, 811, 955), NCA, LMO, LCO, and LMO–NMC blends. Other technologies assessed included Li–S (sulfur cathode and lithium-metal anode), sodium-based systems (Na-ion and Na–NiCl), flow batteries (vanadium redox and zinc–bromine), Al-ion, lead–acid (VRLA/PbA), and supercapacitors. Two studies also evaluated LTO-based configurations, in which LTO serves as a non-graphite anode paired with various lithium-ion cathodes (e.g., NMC–LTO, LFP–LTO, NCA–LTO, LMO–LTO).

NMC was the most frequently assessed chemistry (n = 41), followed by LFP (n = 37). These two chemistries dominate both EV and stationary storage markets and are widely recognized as the most commercially mature lithium-ion chemistries used in LFB applications [72, 73]. A smaller number of studies assessed NCA (n = 10) and LMO (n = 11); eleven studies did not specify the exact chemistry assessed. This distribution aligns with global market trends: NMC accounted for approximately 60% of EV battery market share, followed by LFP at just under 30% and NCA at around 8% in 2022 [74]. More information about chemistry specific to the study is provided in SI Table A7. Figure 5 summarizes the batteries studied in the review.

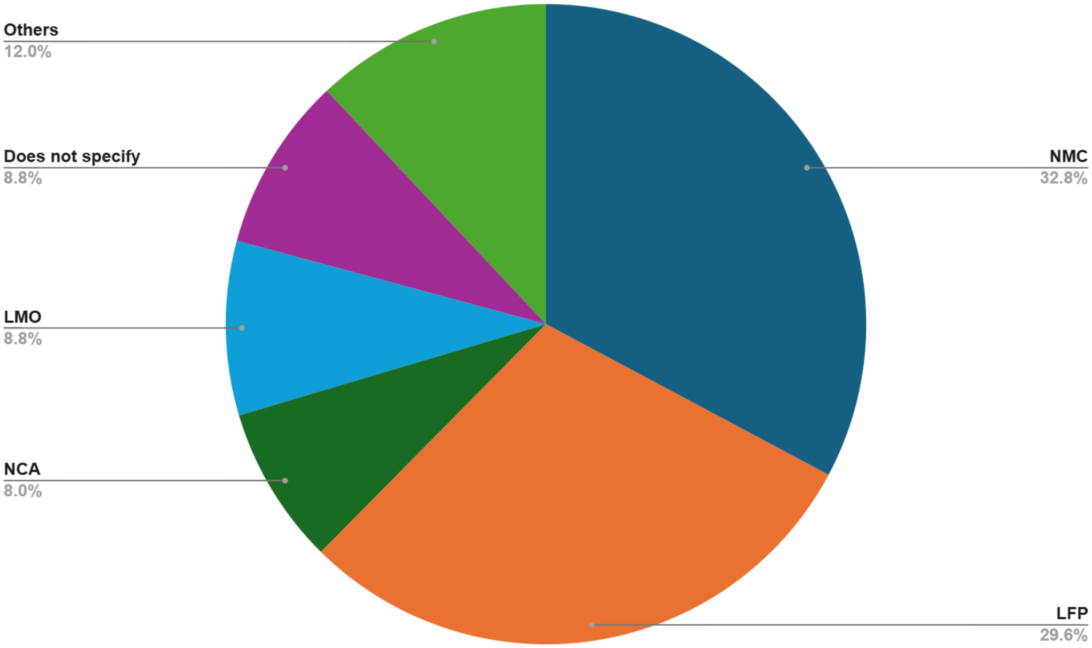

Figure 5: Battery chemistry assessed

Others include Al-ion, PbA/VRLA, Li-S, LCO, Na-IB, NaNiCl, VRFB, ZBFB

Life cycle stages/system boundary

ISO14040 [5] and ISO14044 [6] define the system boundary as the set of criteria that specifies which unit processes are included within a product system. The standards further require that system boundary choices be consistent with the goal and scope of the study and that all criteria used to establish these boundaries be clearly identified and justified. The LCA system boundary is illustrated in Figure 6.

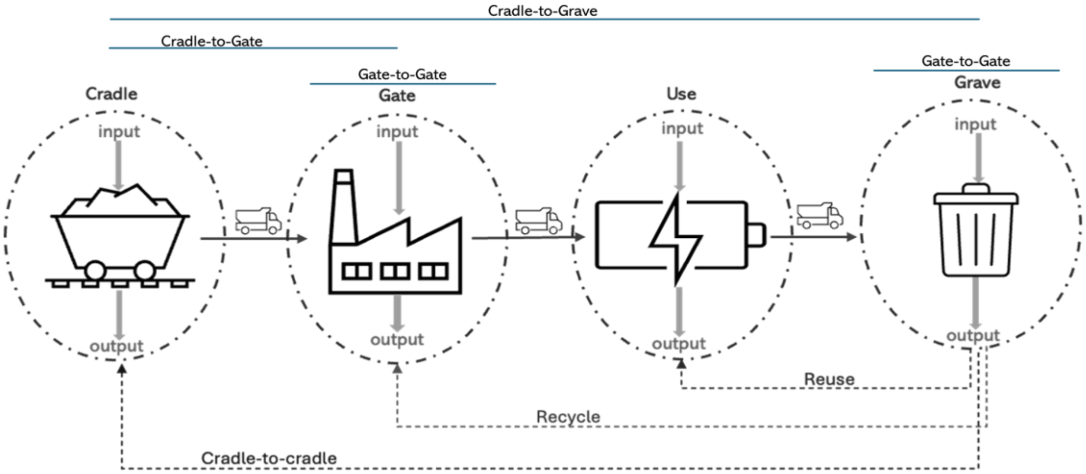

Figure 6: System boundary in LCA studies

LCA studies commonly define system boundaries using terms such as *cradle-to-gate, cradle-to-cradle, and cradle-to-grave*. In *cradle-to-grave* assessments, the system boundary encompasses the entire life cycle of a product—from raw material extraction ("cradle") through manufacturing and use to final disposal or recycling ("grave") [75]. Cradle-to-gate studies narrow this scope by including raw material extraction and manufacturing but excluding the use and end-of-life stages; this partial life cycle is widely used when downstream processes are outside the study's scope [76]. Cradle-to-cradle design is a framework for designing products and industrial processes that turn materials into nutrients by enabling their perpetual flow within one of two distinct metabolisms: the biological metabolism and the technical metabolism [77]. It denotes a closed-loop or circular approach in which products, after reaching the end of their life, are reintegrated as inputs into new production systems. Gate-to-gate LCA considers the input and output flows of a single process, such as a production step, throughout the entire life cycle. It might, however, have several subprocesses within a single step [78].

Across the studies reviewed, the cradle-to-grave system boundary was the most applied (n = 45), although five studies narrowed this scope by excluding use-phase impacts and/or transportation impacts [21, 64, 79–81]. Three studies explicitly acknowledged the modeling of the cradle-to-cradle system boundary [54, 82, 83]. Other frequently applied boundaries included cradle-to-gate (n = 10) [18, 20, 43, 46, 59, 63, 69, 70, 84, 85], with some studies extending this scope to partially include the use phase, while others explicitly excluded transportation processes (n = 10) [28, 33, 50, 53, 61, 62, 86–90]. Hydrometallurgical and pyrometallurgical recycling were the most modeled end-of-life recycling pathways (n = 30). In studies evaluating cascading utilization, system boundaries included repurposing or remanufacturing processes following first-life automotive use, with batteries subsequently deployed in second-life applications before reaching their final end-of-life treatment. More information about the study-specific system boundaries, end-of-life pathways, and information on first and second life calculation is provided in the "Supplemental Material – PRISMA data coding.xlsx" (see Appendix B for more information)

LCIA method and Life Cycle Impact indicators

The reviewed studies applied a wide range of life cycle impact assessment (LCIA) methods, with ReCiPe, Environmental Footprint (EF 3.0/3.1), CML-IA, Cumulative Energy Demand (CED), and Intergovernmental Panel on Climate Change (IPCC) (for Global Warming Potential (GWP) only assessments) appearing most frequently. All studies evaluated multiple midpoint or endpoint categories, except for 22 studies that limited their analysis to quantifying carbon footprints. ReCiPe was the most used LCIA method (n = 28). Six studies using ReCiPe impact assessment methodology acknowledged reporting endpoint indicators [22, 38, 45, 50, 91, 92]. Of those, one study reported only endpoint indicators, noting that endpoint results were chosen to enhance interpretability for non-experts despite the general scientific preference for midpoint metrics [50]. Less frequently used LCIA methods included ILCD (International Life Cycle Data System), Eco-indicator 99, EDIP (Environmental Design of Industrial Products), and TRACI v2.1. In total, 23 studies used at least one of the following environmental impact assessment methods: Environmental Footprint, ILCD, Eco-indicator 99, or CML (Centrum voor Milieuwetenschappen/ Center for Environmental Science). Most of these studies originated from Europe. However, CML also appeared in several studies representing Asian countries, reflecting its continued adoption in some Asian LCA practices [43, 54, 60, 79, 91, 93]. In contrast, ReCiPe was used globally, across studies from Europe, Asia, and North America. Figure 7 summarizes the LCIA used across various studies.

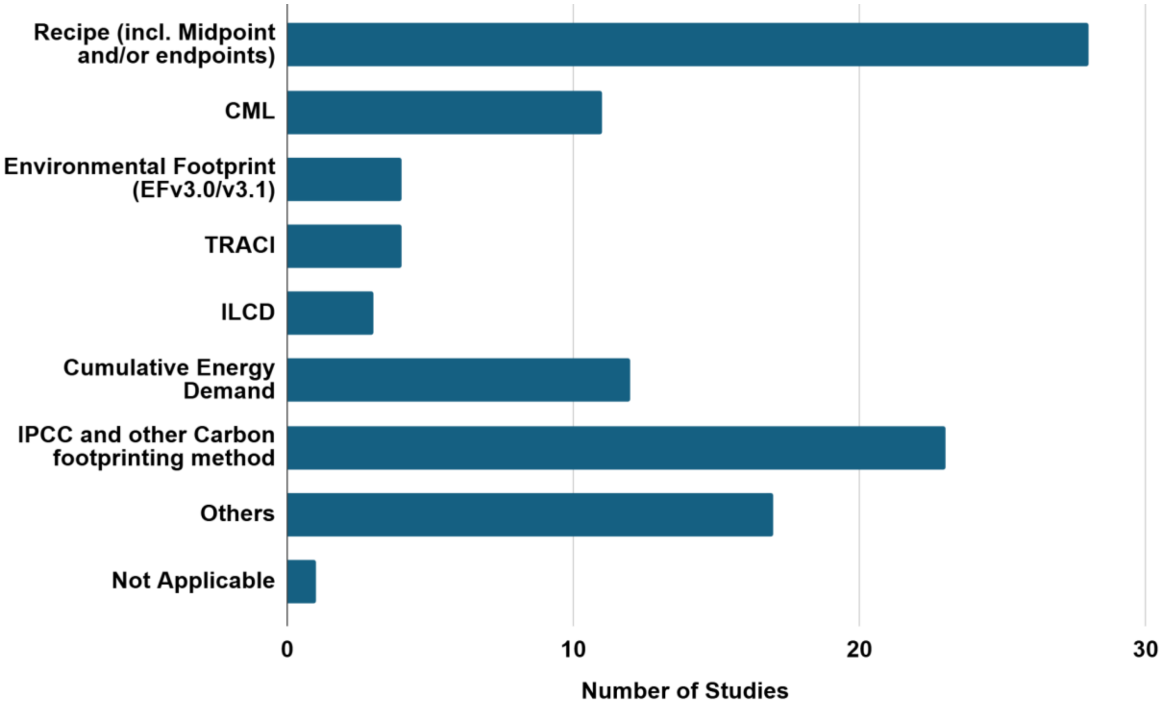

Figure 7: Life cycle impact assessment methods used

Others include studies using impact factors from the IDEA database, EU frameworks such as PEF and PEFCR, GREET tool-based impact assessment, Ecoindicator 99, Environmental Design of Industrial Products, AWARE method, the Hoekstra et al. method for water scarcity, and the Ecological footprint method (land area equivalent).

Except for one study, which reported endpoint indicators only [50], and another, which presented an LCI without conducting an impact assessment [23], all reviewed studies reported GWP, making it the most frequently assessed impact category [12]. Other commonly assessed midpoint indicators included acidification, eutrophication (marine, freshwater, terrestrial), ecotoxicity (marine, freshwater, terrestrial), abiotic resource depletion (fossil and mineral), Ozone depletion, particulate matter formation, and cumulative energy demand. A complete listing of LCIA methods and impact indicators used in each study is provided in the “Supplemental Material – PRISMA data coding.xlsx” (see Appendix B for more information).

Functional Unit

ISO 14040 [5] and ISO 14044 [6] define the functional unit as the quantified performance of a product system, serving as a reference for all input and output flows. As noted by [12], the functional unit must be consistent with the study's goal and scope and serve as a reference for normalizing input and output data. Across the reviewed literature, the functional unit selection is highly heterogeneous [11, 19]. Variants of a “1 kWh” functional unit were adopted in 35 studies; however, the interpretation varied. In some cases, “1 kWh” referred to installed battery energy capacity (manufacturing-oriented, capacity-based functional units), while in others it denoted energy throughput or services delivered by the battery system, such as electricity stored and discharged, lifetime electricity delivery, or grid services (e.g., PV firming or peak shaving).

Beyond conventional 1 kWh capacity or throughput-based definitions, functional units such as time-based functional units (e.g., service over time) and other capacity-based functional units (beyond 1kWh) were identified in 21 studies. System-level functional unit was seen in four studies [40, 65, 94, 95]. Seven studies adopt mass-based functional units, such as 1 kg of battery ([18, 20, 45, 67, 70, 86, 96]). These can highlight material composition or chemistry-related burdens, but, as noted in previous research, mass-based units do not represent functional performance [12]. A related category is the pack-level functional unit used in three studies, in which the entire module or pack (rather than 1 kWh or 1 kg) is treated as the functional reference, especially in EV applications [22, 25, 59]. Eight studies used transport-service functional units, such as mileage-based FU [16, 56, 67, 92, 97–100]. These functional units are appropriate when use-phase systems are modeled alongside the manufacturing and/or end-of-life stages. However, such definitions require careful treatment of battery lifetime assumptions because the battery may not last for the total driving distance assumed [12].

Overall, the literature demonstrates a wide range of functional unit selection, from battery-centric capacity units to system-level energy-service measures. A complete list of functional unit definitions across all reviewed studies is provided in the “Supplemental Material – PRISMA data coding.xlsx” (see Appendix B for more information).

LCA data usage

Data collection is one of the most critical steps in the life cycle evaluation process. It necessitates a comprehensive examination of a system’s complete life cycle, from raw material extraction through manufacturing, use, and end-of-life (disposal, recycling, reuse, etc). [101, 102]. Background data includes energy and materials delivered to the foreground system as aggregated datasets in which individual plants and operations are not identified [102]. ISO defines background data as an indirectly measured, calculated, or obtained quantified value of a unit process or activity and related information within a product system or organization, not based on a specific original source of measurements. [103]. Foreground data is the data from the system of primary concern to the analyst [102]. ISO defines foreground data as a quantified value of a unit process or an activity obtained from a direct measurement or a calculation based on direct measurements at its original source [103].

The most frequently used background database across the studies reviewed was ecoinvent, which was used by 57 studies (73%). This trend is consistent with findings from other systematic reviews [11, 12, 19]. While 37 studies used ecoinvent exclusively, others supplemented it with additional sources such as DataSmart LCI, GaBi, GREET, and other regional or sector-specific datasets. Four prospective LCA studies used ‘premise’ (PRospective EnvironMental Impact asSEment) in combination with ecoinvent to generate future-oriented inventories [17, 44–46].

Premise is a Python tool that projects the ecoinvent database under scenarios from integrated assessment models by modifying market shares, energy pathways, technology efficiencies, and emerging technologies [104]. Beyond ecoinvent, other background data sources included GREET (n = 9), GaBi (n = 2), ELCD (n = 1), and U.S. data sources such as EIA and EPA emission factors (n = 4). Study-specific information about background data usage is provided in the "Supplemental Material – PRISMA data coding.xlsx" (see Appendix B for more information).

In contrast, the use of foreground data showed much higher variability, and similar trends were reported by [11, 12]. Foreground data practices remain heterogeneous, depending heavily on data availability, study scope, and access to primary industry information. Fewer than half of the studies relied on primary data collection for building their LCIs. Many studies drew upon peer-reviewed literature, industry reports, government statistical datasets, technical specifications, and manufacturer documentation. LCA databases, such as ecoinvent, were also used to construct foreground inventories, especially when primary data were unavailable. Tools such as GREET and BatPaC were additionally used to generate modeled or parameterized foreground LCIs. Study-specific information about foreground data usage is provided in "Supplemental Material – PRISMA data coding.xlsx" (see Appendix B for more information).

LCI data gathering

To provide insights into open-source LFB pack models, BOM data were extracted from all studies that explicitly reported them for LFP battery manufacturing and/or end-of-life processes. Parameterized BOMs that required additional scaling to 1 kWh were not included at this stage but may be revisited during model construction. The BOM collected from these articles could serve as a potential data source in the construction of open-source battery pack LCA models. All compiled BOMs are provided in "Supplemental Material – LCI.xlsx" (see Appendix B for more information), organized by their respective sources.

4. Discussion

Taken together, across the 78 LCAs reviewed, the analysis reveals a landscape characterized by shared methodological anchors but diverging modeling choices. Depending on the study goal, a small number assessed cradle-to-cradle boundaries, while most adopted cradle-to-grave boundaries—with several studies intentionally excluding the use phase—others conducted cradle-to-gate assessments, sometimes extending them partially to include limited use-phase processes. In cascading-use studies, system boundaries began at the start of the first life and extended through second-life operation to final end-of-life treatment, whereas studies focused solely on first- or second-life applications assessed EoL only at the conclusion of the stage under consideration. Functional units were similarly heterogeneous, echoing findings from prior reviews: although many studies used “1 kWh,” often representing either installed capacity vs. energy delivered, others applied mass-, pack-, transport-, or system-service–based definitions. LCI practices demonstrated a strong reliance on ecoinvent for background data; however, foreground inventories varied widely, with relatively few studies drawing on primary industrial data and many relying on proxy, modeled, or literature-based inventories, resulting in notable data-quality gaps. For LCIA, ReCiPe, CML, and EF were the most widely applied methods, while TRACI was used exclusively in U.S. studies. GWP appeared in nearly all assessments, although the breadth of additional midpoint indicators differed substantially across studies. End-of-life modeling ranged from simplified cut-off assumptions to detailed hydrometallurgical and pyrometallurgical pathways, while cascading-use analyses further expanded boundaries to include repurposing, second-life operation, and, in some cases, avoided-burden crediting for displaced new battery production. Sensitivity and uncertainty practices were uneven: roughly more than half of the studies conducted formal sensitivity analyses, but only a small subset performed Monte Carlo–based stochastic uncertainty assessment, despite the well-recognized importance of parameter variability in battery LCAs. Battery chemistry and applications were broad, but market-aligned, with NMC and LFP dominating analyses of EVs and stationary storage, while fewer studies examined alternative chemistries or specialized applications.

Collectively, these patterns underscore that, although the literature provides extensive coverage of life cycle assessments for LFB systems, substantial heterogeneity in system boundaries, functional units, data sources, and modeling assumptions—often driven by differing study goals and data availability could pose challenges for cross-study comparability. This aligns with a prior review that notes that existing LCA studies on lithium-ion batteries are “very heterogeneous, and the results are therefore difficult to compare.” [105].

Several prior systematic reviews have examined battery LCAs [11, 12, 19, 105–108]. Besides differences in temporal scope and keyword search strategies, a few notable distinctions emerge between this review and prior systematic reviews of battery LCAs. Except for Arshad et al. (2022) [4], earlier reviews primarily focused on EV batteries and largely excluded stationary or utility-scale applications. In contrast, the present review evaluates LFBs across EV, stationary storage, and cascading second-life pathways. Methodologically, most prior reviews employ a result-centric approach, aggregating environmental impact outcomes across chemistry and life-cycle stages. Additionally, Arshad et al. (2022) utilized an ISO-14040/14044-based completeness checklist [4], whereas the current review is explicitly methodological and descriptive-statistical, documenting how LCAs are constructed (functional units, boundaries, LCIA methods, and LCI sources) and compiling BOM to support the development of an open-source LFB pack model.

Differences also arise in the way methodological choices are characterized. Aichberger and Jungmeier (2020) reported that EV battery LCAs relied exclusively on attributional approaches and observed very few second-life studies; however, these findings reflect their 2005–2020 timeframe. The literature assessed here (2015–2025) identifies at least two studies that explicitly apply the consequential LCA framework, both published in 2022 and 2023 [32, 33]. The current review also shows that, among the studies that included both first- and second-life impact calculations, roughly 70% were published after 2020—patterns not captured in earlier reviews. Peters et al. (2017) excluded end-of-life modeling entirely, arguing that the lack of mature industrial recycling technologies would introduce uncertainties inconsistent with their study goal [86]. In contrast, this review systematically documents EoL modeling choices, system expansion practices, and second-life assumptions as core methodological dimensions. Together, these differences illustrate that this review fills a methodological gap in the existing literature by providing a comprehensive mapping of modeling practices and incorporates more recent advances in battery applications, life-cycle modeling, and data sourcing.

All study characteristics and methodological choices were extracted using a predefined coding framework. Classifications reflect the information reported by authors in their respective studies, and, where necessary, a reasonable interpretation by the reviewers of the present study. Because reporting depth varied substantially across studies, some extracted variables may be incomplete or subject to interpretive uncertainty. Readers are encouraged to consider these limitations when interpreting aggregated results

5. Conclusion

By systematically cataloging LCA modeling practices and compiling the BOM data across EV, stationary, and second-life applications, this review provides a structured characterization of how LFB LCAs are currently constructed. Together, these insights can support future efforts to harmonize battery LCA practice and build more robust, comparable, and policy-relevant assessments. As demonstrated in this review, the literature on lithium-ion (LFP and other chemistries) battery LCAs, particularly for LFBs, has expanded rapidly, accompanied by several systematic reviews addressing different aspects of the field. A future meta-review and bibliometric analysis could help synthesize these reviews, clarify methodological divergences, and map the evolution of analytical practices over time. Building on the present study, subsequent work could focus on developing open-source LFB LCA models for LFP (and other chemistries) and comparing their results with the literature to assess the causes of variability. As this review excluded national laboratory and industry reports (e.g., Argonne National Laboratory's GREET and associated publications [109, 110]. Future model-development efforts should incorporate these additional sources, where accessible, to enhance completeness and representativeness.

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List of Symbols, Abbreviations, and Acronyms

AC
Alternating Current

AD
Abiotic Depletion

ADPF
Abiotic Depletion Potential (Fossil Fuels)

Al-ion
Aluminum-ion battery

AP
Acidification Potential

BESS
Battery Energy Storage System

BOM
Bill of Materials

CED
Cumulative Energy Demand

CCGT
Combined Cycle Gas Turbine

CLCD
Chinese Life Cycle Database

CML
Centrum voor Milieuwetenschappen (Center of Environmental Science) Impact Assessment Method

CO_2e
Carbon Dioxide Equivalent

C2C
Cradle-to-Cradle

C2G
Cradle-to-Gate

C2Grave
Cradle-to-Grave

DC
Direct Current

EDIP
Environmental Design of Industrial Products

EF
Environmental Footprint

EIA
U.S. Energy Information Administration

EIO-LCA
Economic Input–Output Life Cycle Assessment

ELCD
European Life Cycle Database

EoL / EOL
End of Life

EP
Eutrophication Potential

ESS
Energy Storage System

EV
Electric Vehicle

EVB
Electric Vehicle Battery

FAETP
Freshwater Aquatic Ecotoxicity Potential

FU
Functional Unit

GHG
Greenhouse Gas

GREET
Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies

GWP
Global Warming Potential

HMR
Hydrometallurgical Recycling

HOF
Human Toxicity – Non-Cancer Effects

HTP
Human Toxicity Potential

ILCD
International Life Cycle Data System

IO
Input–Output

IPCC
Intergovernmental Panel on Climate Change

IR
Ionizing Radiation

JSON-LD
JavaScript Object Notation for Linked Data

kWh
Kilowatt-hour

LCA
Life Cycle Assessment

LCI
Life Cycle Inventory

LCCA
Life Cycle Cost Analysis

LCIA
Life Cycle Impact Assessment

LCOE
Levelized Cost of Energy

LCOS
Levelized Cost of Storage

LFB
Large Format Battery

LFP
Lithium Iron Phosphate

LIB
Lithium-Ion Battery

Li–S
Lithium–Sulfur Battery

LIPB
Lithium-Ion Phosphate Battery

LMO
Lithium Manganese Oxide

LTO
Lithium Titanate Oxide

LU
Land Use

MCDM
Multi-Criteria Decision-Making

MFA
Material Flow Analysis

MiLCA
Ministry of Economy, Trade and Industry Life Cycle Assessment Tool

MRS
Mineral Resource Scarcity

Na-ion
Sodium-Ion Battery

Na–NiCl
Sodium–Nickel Chloride Battery

NCA
Nickel Cobalt Aluminum Oxide

NCM / NMC
Nickel Manganese Cobalt Oxide

NPi
National Policy Implemented Scenario

ODP
Ozone Depletion Potential

PB-LCA
Process-Based Life Cycle Assessment

pLCA
Prospective Life Cycle Assessment

PM
Particulate Matter

PMR
Pyrometallurgical Recycling

PRISMA
Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PV
Photovoltaic

ReCiPe
A Life Cycle Impact Assessment Method (Midpoint and Endpoint)

SESS
Stationary Energy Storage System

SLBESS
Second-Life Battery Energy Storage System

SoH
State of Health

TA
Terrestrial Acidification

TEA
Techno-Economic Assessment

TET
Terrestrial Ecotoxicity

TRACI
Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

UI
User Interface

USLCI
U.S. Life Cycle Inventory Database

VRFB
Vanadium Redox Flow Battery

WoS
Web of Science

Appendix A. Supplemental Material

A two-stage search was conducted, SI Table A1 demonstrates the first stage, which was conducted on May 25th, 2025. The first-stage search yielded 5,859 records; 1,859 unique records were retained after duplicates were removed. Because the initial dataset was broad and the research question was focused on battery production and/or end of life, a second, more targeted search was undertaken on June 1, 2025 (SI Table A2). Both search stages are summarized in

SI Table **A3**.

SI Table A1: First search attempt conducted on 05/25/2025

Scopus 1	757	(TITLE-ABS-KEY ("**Life cycle assessment**" OR "**LCA**" OR "**life cycle analysis**") AND TITLE-ABS-KEY (**"electric vehicle" battery**)) AND PUBYEAR > **2014** AND (LIMIT-TO (DOCTYPE , **"ar"**) OR LIMIT-TO (DOCTYPE , **"re"**)) AND (LIMIT-TO (LANGUAGE , **"English"**))
Scopus 2	1631	(TITLE-ABS-KEY (**"Life cycle assessment"** OR **"LCA"** OR **"life cycle analysis"**) AND TITLE-ABS-KEY (**battery**)) AND PUBYEAR > **2014** AND (LIMIT-TO (DOCTYPE , **"ar"**) OR LIMIT-TO (DOCTYPE , **"re"**)) AND (LIMIT-TO (LANGUAGE , **"English"**))
Scopus 3	388	(TITLE-ABS-KEY (**"Life cycle assessment"** OR **"LCA"** OR **"life cycle analysis"**) AND TITLE-ABS-KEY (**"energy storage" battery**)) AND PUBYEAR > **2014** AND (LIMIT-TO (DOCTYPE , **"ar"**) OR LIMIT-TO (DOCTYPE , **"re"**)) AND (LIMIT-TO (LANGUAGE , **"English"**))
Scopus 4	2	(TITLE-ABS-KEY (**"Life cycle assessment"** OR **"LCA"** OR **"life cycle analysis"**) AND TITLE-ABS-KEY (**"large format" batter*)**) AND PUBYEAR > **2014** AND (LIMIT-TO (DOCTYPE , **"ar"**) OR LIMIT-TO (DOCTYPE , **"re"**)) AND (LIMIT-TO (LANGUAGE , **"English"**))
WoS 1	1827	TS = (**Battery**) AND TS = (**"Life cycle Assessment"** OR **"LCA"** OR **"Life Cycle analysis"**) and **2025 or 2024 or 2023 or 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015** (Publication Years) and **Article or Review Article** (Document Types) and **English** (Languages)
WoS 2	858	TS = (**"Electric vehicle" Battery**) AND TS = (**"Life cycle Assessment"** OR "**LCA**" OR **"Life Cycle analysis"**) and **2025** or **2024** or **2023** or **2022** or **2021** or **2020** or **2019** or **2018** or **2017** or **2016** or **2015** (Publication Years) and **Article** or **Review Article** (Document Types) and **English** (Languages)
WoS 3	394	TS = **("energy storage" Battery**) AND TS = (**"Life cycle Assessment"** OR **"LCA"** OR **"Life Cycle analysis"**) and **2025** or **2024** or **2023** or **2022** or **2021** or **2020** or **2019** or **2018** or **2017** or **2016** or **2015** (Publication Years) and **Article** or **Review Article** (Document Types) and **English** (Languages)
WoS4	2	TS = (**"large format" Battery**) AND TS = (**"Life cycle Assessment"** OR **"LCA"** OR **"Life Cycle analysis"**) and **2025** or **2024** or **2023** or **2022** or **2021** or **2020** or **2019** or **2018** or **2017** or **2016** or **2015** (Publication Years) and **Article** or **Review Article** (Document Types) and **English** (Languages)

SI Table A2: Second search attempt conducted on 06/01/2025

Scopus 1	n=15	(TITLE-ABS-KEY (**"lithium iron phosphate"** OR **"LFP"** OR **"LiFePO4"**) AND TITLE-ABS-KEY (**"large format"** OR **"large-scale"** OR **"utility scale"** OR **"grid scale"** OR **"automotive"** OR **"EV batter*"**) AND TITLE-ABS-KEY (**"life cycle assessment"** OR **"LCA"** OR **"cradle to cradle"** OR **"circular economy"** OR **"Life cycle analysis"**) AND TITLE-ABS-KEY (**"end of life"** OR **"EOL"** OR **"reuse"** OR **"refurbish*"** OR **"recycl*"** OR **"second life"**)) AND PUBYEAR > **2014** AND (LIMIT-TO (DOCTYPE , **"ar"**)) AND (LIMIT-TO (LANGUAGE , **"English"**))

WoS1	n=16	**"lithium iron phosphate"** OR **"LFP"** OR **"LiFePO4"** (Topic) and **"large forma**t" OR **"large-scale"** OR **"utility scale"** OR **"grid scale"** OR **"automotive"** OR **"EV batter*"** (Topic) and **"life cycle assessment"** OR **"LCA"** OR **"cradle to cradle"** OR **"circular economy"** OR **"Life cycle analysis"** (All Fields) and **"end of life"** OR **"EOL"** OR **"reuse"** OR **"refurbish*"** OR **"recycl*"** OR **"second life"** (All Fields) and **Article** (Document Types) and **2015** or **2016** or **2017** or **2018** or **2019** or **2020** or **2021** or **2022** or **2023** or **2024** or **2025** (Publication Years)
Scopus 2	n=78	(TITLE-ABS-KEY (**"large format batter*"** OR **"large-scale batter*"** OR **"utility scale batter*"** OR **"grid scale batter*"** OR **"EV batter*"** OR **"Electric Vehicle batter*"**) AND TITLE-ABS-KEY (**"life cycle assessment"** OR **"LCA"** OR **"Life cycle analysis"**)) AND PUBYEAR > **2014** AND (LIMIT-TO (DOCTYPE , **"ar"**)) AND (LIMIT-TO (LANGUAGE , **"English"**))
WoS2	n=101	**"large format batter*"** OR **"large-scale batter*"** OR **"utility scale batter*"** OR **"grid scale batter*"** OR **"EV batter*"** OR **"Electric Vehicle batter*"** (Topic) and **"life cycle assessment"** OR **"LCA"** OR **"Life cycle analysis"** (Topic) and **Article** (Document Types) and **2015** or **2016** or **2017** or **2018** or **2019** or **2020** or **2021** or **2022** or **2023** or **2024** or **2025** (Publication Years)
Scopus 3	n=50	(TITLE-ABS-KEY (**"large format batter*"** OR **"large-scale batter*"** OR **"utility scale batter*"** OR **"grid scale batter*"** OR **"EV batter*"** OR **"Electric Vehicle batter*"**) AND TITLE-ABS-KEY (**"life cycle assessment"** OR **"LCA"** OR **"Life cycle analysis"**) AND TITLE-ABS-KEY (**"end of life"** OR **"EOL"** OR **"reuse"** OR **"refurbish*"** OR **"recycl*"** OR **"second life"** OR **"cradle to cradle"** OR **"circular economy"**)) AND PUBYEAR > **2014** AND (LIMIT-TO (DOCTYPE , **"ar"**)) AND (LIMIT-TO (LANGUAGE , "**English"**))
WoS3	n=59	**"large format batter*"** OR **"large-scale batter*"** OR **"utility scale batter*"** OR **"grid scale batter*"** OR **"EV batter*"** OR **"Electric Vehicle batter*"** (Topic) and **"life cycle assessment"** OR **"LCA"** OR **"Life cycle analysis"** (Topic) and **"end of life"** OR **"EOL"** OR **"reuse"** OR **"refurbish*"** OR **"recycl*"** OR **"second life"** OR **"cradle to cradle"** OR **"circular economy"** (Topic) and **Article** (Document Types) and **2015** or **2016** or **2017** or **2018** or **2019** or **2020** or **2021** or **2022** or **2023** or **2024** or **2025** (Publication Years)
Scopus 4	n=10	(TITLE-ABS-KEY (**"large format batter*"** OR **"large-scale batter*"** OR **"utility scale batter*"** OR **"grid scale batter*"** OR **"EV batter*"** OR **"Electric Vehicle batter*"**) AND TITLE-ABS-KEY (**"life cycle assessment"** OR **"LCA"** OR **"Life cycle analysis"**) AND TITLE-ABS-KEY (**"end of life"** OR **"EOL"** OR **"reuse"** OR **"refurbish*"** OR **"recycl*"** OR **"second life"**) AND TITLE-ABS-KEY (**"cradle to cradle"** OR **"circular economy"**)) AND PUBYEAR > **2014** AND (LIMIT-TO (DOCTYPE , **"ar"**)) AND (LIMIT-TO (LANGUAGE , **"English"**))
WoS4	n=68	**"large format"** OR **"large-scale"** OR **"utility scale"** OR "**grid scale"** OR **"automotive"** OR **"EV batter*"** (Topic) and **"life cycle assessment"** OR **"LCA"** OR **"Life cycle analysis"** (Topic) and **"end of life"** OR **"EOL"** OR **"reuse"** OR **"refurbish*"** OR **"recycl*"** OR **"second life"** (All Fields) and **"cradle to cradle"** OR **"circular economy"** (All Fields) and **2025** or **2024** or **2023** or **2022** or **202**1 or **2020** or **2019** or **2018** or **2017** or **2016** or **2015** (Publication Years) and **Article** (Document Types) and **English** (Languages)

SI Table A3: Summary of two-stage systematic search

Stage	Completed	Pub Type	Date range	Broad Search Terms	Results	Notes
1	May 16, 2025	Original research and reviews	2015-2025	(“battery” OR “EV battery” OR “energy storage battery” OR “large format batter*”) AND (“life cycle assessment” OR “LCA” OR “life cycle analysis”)	5,859 records; 1,859 unique after duplicates	See SI Table A1 for detailed search terms and corresponding results

2	June 1, 2025	Original research only	2015-2025	(i) “lithium iron phosphate” / “LFP” / “LiFePO4”; (ii) “large-format” / “grid scale” / “automotive”; (iii) “LCA” / “circular economy” / “end of life” / “recycling.”	397 records; 184 unique after duplicates	See SI Table A2 for detailed search terms and corresponding results

SI Table A4: Geographic scope of studies under consideration

Region	Specific geography	Corresponding study
Europe	Specific European country	[13, 16, 26, 37, 39, 41, 44, 45, 50, 63, 70, 83, 89, 90, 92, 96–98, 111–113] (n=21)
	Continental Europe	[14, 15, 17, 27, 59, 99] (n=6)
China		[23–25, 43, 51, 54, 56, 66, 79, 81, 84, 87, 91, 93, 114–116] (n=17)
North America	USA	[21, 22, 28, 40, 53, 58, 61, 68, 71, 94, 117] (n=11)
	Canada	[29, 36, 67] (n=3)
Multi-country context	Various	[32, 38, 46, 57, 64, 69, 82, 85, 86, 95, 100] (n=11)
Others	Various	[20, 33, 49, 52, 60, 62, 65, 80] (n=8)
Not mentioned	-	[18] (n=1)

SI Table A5: Software used in the study

Software used	Corresponding Studies
Brightway Ecosystem	[45, 46, 59] (n=3)
Sima Pro	[16, 28, 29, 32, 36, 40, 41, 43, 49, 51, 54, 61, 63, 64, 71, 80, 81, 84, 86, 91–93, 96, 97, 100, 111, 112, 114, 118] (n=29)
Sima Pro + GREET	[22] (n=1)
GREET	[53, 56, 68, 82, 83, 94, 117] (n=7)

Software used	Corresponding Studies
GREET + Others	[20, 21] (n=2)
Gabi	[15, 70, 79, 87, 90, 115, 119] (n=7)
openLCA	[18, 50, 60, 67, 69, 85] (n=6)
Others (Umberto NXT universal, LCA2GO, MiLCA, eFootprint)	[14, 24–26] (n=4)
Does not mention LCA software	[13, 17, 27, 33, 37–39, 44, 52, 57, 58, 62, 65, 66, 89, 95, 98, 116] (n=18)
Not applicable	[23] (n=1)
Multiple software (LCA + Non LCA software)	[21, 28, 29, 41, 50, 59, 61, 67, 71, 82, 113, 117] (n=12)

SI Table A6: Application of the LFB

Application	Corresponding Studies
EV	[15–18, 20–23, 25, 27, 43, 45, 46, 53, 54, 56, 58, 59, 67–70, 79–86, 91–94, 97, 98, 100, 113, 119] (n=39)
Stationary usage	[26, 50, 51, 57, 60, 62, 87, 89, 90, 112, 117] (n=11)
Cascading utilization	[13, 14, 24, 28, 29, 32, 33, 36–41, 44, 49, 52, 61, 63, 65, 66, 71, 95, 111, 114–116] (n=26)
Multiple utilization	[64, 96] (n=2)

SI Table A7: Battery Chemistry assessed by different studies

Study	**LFP**	**NMC**	**NCA**	**LMO**	**LCO**	**Li-S**	**Na-IB**	**NaNiCl**	**Al-ion**	**PbA/VRLA**	**VRFB**	**ZBFB**	**Cath. blend**	**Non-Gr ano.**	**Unspecified**
[15]	🟩	🟩													
[49]	🟩														
[80]															🟩
[69]		🟩	🟩										🟩		
[59]	🟩	🟩	🟩										🟩		
[100]		🟩													
[16]				🟩											
[86]	🟩	🟩													

Study	LFP	NMC	NCA	LMO	LCO	Li-S	Na-IB	NaNiCl	Al-ion	PbA/VRLA	VRFB	ZBFB	Cath. blend	Non-Gr ano.	Unspecified
[37]													🟩		
[13]													🟩		
[119]						🟩									
[61]													🟩		
[71]	🟩	🟩	🟩	🟩	🟩										
[28]															🟩
[44]		🟩													
[67]															🟩
[33]	🟩	🟩													
[83]															🟩
[64]	🟩	🟩	🟩												
[21]	🟩	🟩		🟩											
[52]		🟩													
[53]		🟩													
[26]				🟩											
[111]	🟩														
[22]		🟩													
[46]	🟩	🟩	🟩												
[97]															🟩
[40]				🟩											
[65]	🟩						🟩			🟩					
[27]															🟩
[36]	🟩														
[23]	🟩														
[14]				🟩											
[112]	🟩														
[39]														🟩	
[29]															🟩
[50]	🟩	🟩	🟩	🟩				🟩		🟩	🟩			🟩	
[18]	🟩								🟩						
[60]	🟩														
[62]	🟩										🟩	🟩			
[85]		🟩													
[117]	🟩	🟩	🟩	🟩											

Study	LFP	NMC	NCA	LMO	LCO	Li-S	Na-IB	NaNiCl	Al-ion	PbA/VRLA	VRFB	ZBFB	Cath. blend	Non-Gr ano.	Unspecified
[94]	🟩	🟩	🟩												
[92]															🟩
[98]				🟩											
[96]	🟩	🟩	🟩	🟩											
[17]	🟩	🟩	🟩												
[20]	🟩	🟩													
[70]		🟩													
[66]	🟩	🟩													
[38]		🟩													
[81]	🟩	🟩													
[63]	🟩	🟩													
[95]	🟩	🟩													
[41]		🟩													
[45]															🟩
[25]		🟩													
[113]													🟩		
[32]		🟩													
[89]				🟩											
[90]														🟩	
[82]		🟩													
[43]	🟩	🟩				🟩									
[84]	🟩	🟩													
[93]	🟩	🟩													
[114]	🟩						🟩								
[24]	🟩														
[57]		🟩							🟩						
[54]		🟩													
[58]					🟩										
[51]	🟩	🟩									🟩				
[87]	🟩														
[91]	🟩	🟩													
[115]	🟩	🟩													
[79]	🟩	🟩													
[56]		🟩													

Study	LFP	NMC	NCA	LMO	LCO	Li-S	Na-IB	NaNiCl	Al-ion	PbA/VRLA	VRFB	ZBFB	Cath. blend	Non-Gr ano.	Unspecified
[116]															🟩
[68]															🟩

Appendix B. Supplemental Resources

The “Supplemental Material – PRISMA data coding” (.xlsx) file, available at https://doi.org/10.6028/NIST.TN.2370sup1, contains the full dataset extracted from all reviewed articles. Table 2 in the main text provides an overview of the data categories used in the coding framework. ReadMe tabs are provided in the excel workbooks that describe the contents of the workbook.

The “Supplemental Material – LCI” (.xlsx) file, available at https://doi.org/10.6028/NIST.TN.2370sup1, contains the full LCI data extracted from respective articles that reported LFP BOM. ReadMe tabs are provided in the excel workbooks that describe the contents of the workbook.