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PERSPECTIVE

Reusing EV Batteries is Not Automatically Circular: A Perspective on Conditional Reuse, Battery Intelligence, and Responsible End-of-life Management

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Abstract

The rapid expansion of electric vehicles creates a new sustainability challenge: managing used lithium-ion batteries that no longer meet vehicle requirements but still retain capacity for lower-demand uses. Used EV batteries can extend material value, reduce waste, support renewable energy integration, and advance circular economy transitions. However, they are not automatically sustainable. Their benefits depend on accurate state-of-health assessment, safety screening, lifecycle data, economic feasibility, social acceptance, circular business models, and eventual recycling. Hence, the central argument of this perspective is that used EV batteries should be managed through conditional circularity; reuse should be prioritized over recycling only when residual performance, safety, lifecycle environmental benefit, economic feasibility, data traceability, and final recycling responsibility can be demonstrated. Recent studies show potential applications in stationary storage, microgrids, renewable energy systems, and energy access, but barriers remain, including degradation uncertainty, thermal safety, standardization, data transparency, and market confidence. The main contribution of this perspective is a lifecycle decision framework for operationalizing conditional circularity in used EV battery management. The framework links battery diagnostics, sustainability assessment, planetary-boundary thinking, circular business models, risk assessment, AI-enabled battery management, and final recycling responsibility to determine when reuse, cascading, or direct recycling is the most responsible pathway.

Keywords Used EV Batteries · Circular Economy · Battery Passport · Sustainability Assessment · Planetary Boundaries · Battery Intelligence · Battery Recycling · Used Lithium-ion Batteries

1. Introduction

The transition to electric mobility has accelerated global demand for lithium-ion batteries, but it has also created an emerging end-of-life challenge. As electric vehicle (EV) batteries age, they may become unsuitable for vehicle use because of capacity fading, power limitation, or safety concerns. However, many used EV batteries can still be used in less demanding stationary applications such as renewable energy storage, backup power, microgrids, EV charging stations, and industrial energy management. Recent studies continue to identify used EV batteries as a promising pathway for reducing waste and extending the value of critical materials before recycling occurs (Alam & Gheewala, 2026b; Roslan et al., 2025; Huether, 2025).

From a circular economy perspective, used EV batteries represent a value-retention strategy. Instead of treating used batteries as immediate waste, their residual capacity can be redirected into new energy services. This approach can reduce pressure on raw material extraction, lower the environmental burden of new battery production, and support energy storage systems needed for renewable energy integration. Yet, used EV

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batteries deployment also involves uncertainty. Each battery has a different chemistry, history, degradation pathway, safety profile, and remaining useful life. Therefore, reuse decisions require reliable diagnostic tools, transparent lifecycle data, and risk-based governance.

This perspective advances a more focused claim: used EV batteries should not be governed by a simple reuse before recycling hierarchy. Instead, they require a conditional circularity approach, in which reuse is justified only when it delivers verified lifecycle benefits without compromising safety, reliability, economic feasibility, social acceptance, data traceability, or eventual material recovery.

In some cases, circularity may conflict with sustainability if reuse creates additional burdens that outweigh the benefits of extending battery life. For example, long-distance transport, energy-intensive testing, repurposing losses, low round-trip efficiency, short remaining useful life, or delayed recycling may reduce or even offset the expected environmental benefits. Circularity should therefore be understood not as an automatic outcome of reuse, but as a decision process that determines when batteries should be reused, when they should enter lower-demand applications, and when they should be sent directly to recycling.

Against this background, the aim of this perspective is to develop a lifecycle decision framework for operationalizing conditional circularity in used EV battery management. The guiding research question is: under what conditions should a used EV battery be reused, cascaded into lower-demand applications, or sent directly to recycling within a responsible circular economy framework? This question is addressed by positioning reuse not as an automatic circular outcome, but as an evidence-based decision that depends on safety, residual performance, lifecycle sustainability, economic feasibility, social acceptability, data traceability, business accountability, and final recycling responsibility.

The originality of this perspective lies in reframing used EV battery circularity as a conditional decision problem rather than a fixed waste-management hierarchy. Existing studies have made important contributions by demonstrating the technical feasibility, environmental potential, economic opportunities, and market barriers of second-life EV batteries. However, much of this literature still treats reuse as a generally desirable circular strategy. This paper advances a different argument: the central issue is not only whether used batteries can be reused, but whether they should be reused in a particular context.

To operationalize this argument, the main analytical contribution of the paper is a lifecycle decision framework that connects battery diagnostics, safety screening, lifecycle sustainability assessment, business accountability, data traceability, planetary-boundary thinking, AI-enabled battery management, and final recycling responsibility into one decision logic. In this framework, conditional circularity provides the conceptual basis, while lifecycle decision-making provides the practical structure for determining whether a used battery should enter second-life use, lower-demand cascading, or direct recycling. The subsequent sections should therefore be read as components of this framework rather than as separate contributions: sustainability assessment defines the environmental, economic, and social conditions for reuse; planetary boundaries introduce absolute sustainability limits; business models define accountability and return-flow responsibility; risk assessment defines safety thresholds; AI-enabled battery management supports diagnosis and prediction; and third-life/end-of-life pathways define the exit conditions for recycling. Together, these elements clarify when second-life or third-life use is justified, when direct recycling is preferable, and how circular battery systems can avoid both premature recycling that wastes residual value and unsafe over-extension that undermines safety and sustainability. This overall logic is synthesized visually in the integrative framework presented in Section 4, which positions the lifecycle decision framework as the organizing structure connecting the paper's major analytical dimensions.

The paper is structured as follows. Section 2 positions conditional circularity within relevant circular economy, second-life battery, digital traceability, risk, business model, and absolute sustainability debates. Section 3 introduces the circular economy foundation for used EV batteries and explains why cascading use requires careful governance. Section 4 presents the lifecycle decision framework as the main analytical contribution of the paper. Sections 5–10 then develop the key decision dimensions of this framework: sustainability assessment, planetary-boundary thinking, circular business models, risk assessment, AI-enabled battery management, and third life/end-of-life pathways. The planetary-boundary perspective is included to move the analysis beyond relative circularity benefits and to ask whether reuse contributes to reducing environmental pressures within the safe operating limits of the planet. Section 11 discusses implications for decision-makers and future research, while Section 12 concludes the paper.

2. Conceptual Foundations and Literature Positioning

The concept of conditional circularity developed in this perspective is grounded in an integrative reading of several related but often separately discussed literature streams. The literature was selected purposively to capture the main knowledge domains required for responsible decision-making on used EV batteries: circular value retention, second-life assessment, battery diagnostics, safety governance, lifecycle traceability, circular business accountability, and absolute sustainability.

First, the circular economy and cascading-use literature provides a foundation for viewing used EV batteries as value-retention assets rather than immediate waste (Vullum-Bruer et al., 2024; Dietrich et al., 2025). Studies on second-life batteries emphasize their potential contribution to stationary storage, renewable energy integration, waste reduction, and material value extension before final recycling (Roslan et al., 2025; Huether, 2025; Alam & Gheewala, 2026a; Alam & Gheewala, 2026b). However, this stream often treats reuse as generally preferable without fully specifying when reuse remains safe, economically feasible, and environmentally justified.

Second, techno-economic and life cycle assessment studies show that second-life benefits are highly context-dependent (Fendt et al., 2026). Reuse and recycling outcomes depend on chemistry, residual capacity, testing and repurposing burdens, transport, electricity mix, remaining useful life, application type, avoided production, and recycling route (Meng et al., 2023; Ma et al., 2024; Al-Alawi et al., 2025; Machala et al., 2025; Zhang et al., 2025; Alex et al., 2026). This evidence directly informs the "conditional" dimension of the proposed concept: reuse is not automatically beneficial but must be assessed case by case.

Third, the literature on battery passports, lifecycle traceability, and data transparency shows that future-life decisions require reliable information on chemistry, origin, state of health, use history, safety events, and dismantling requirements. Digital battery passports are therefore important not only for compliance, but also for market confidence, circular coordination, and end-of-life responsibility (Losa & Torjesen, 2025).

Fourth, AI-enabled battery management, state-of-health estimation, remaining useful life prediction, and degradation modelling provide the diagnostic basis for conditional circularity. Because used batteries are heterogeneous and residual capacity alone cannot determine reuse suitability, AI-supported classification and monitoring are needed to direct batteries toward second-life use, lower-demand cascading, or recycling (Li et al., 2025; Murphy & Crawford, 2025; Gotz et al., 2025; Wang et al., 2025).

Fifth, safety and risk-governance literature show that used batteries may pose thermal, electrical, mechanical, environmental, and social risks if deployed without adequate screening. Recent studies on recycling, safety, and socio-environmental impacts reinforce the need for controlled handling, liability clarity, and technically responsible end-of-life management (Chacana-Olivares et al., 2025; Das et al., 2026; Esmaeilian et al., 2026).

Sixth, circular business model literature highlights that reuse requires ownership clarity, certification, warranties, insurance, predictable return flows, and responsibility for final recycling (Huether, 2025; Losa & Torjesen, 2025; Alam & Gheewala, 2026a). Finally, planetary-boundary and absolute sustainability literature extends the analysis beyond relative improvement by asking whether circular battery strategies help reduce pressures within Earth's safe operating limits (Paulillo & Sanyé-Mengual, 2024; Sakschewski et al., 2025; Kronemeyer et al., 2025).

Based on these streams, conditional circularity is defined as a decision-oriented approach in which used EV battery reuse is justified only when residual performance, safety, lifecycle environmental benefit, economic feasibility, social acceptability, data traceability, and final recycling responsibility can be demonstrated. The concept builds on circular economy and second-life battery research, extends it by integrating diagnostics, risk, traceability, business accountability, and absolute sustainability, and departs from simple reuse-before-recycling hierarchies by explicitly asking when reuse should not occur.

3. Circular Economy Foundation for Used EV Batteries

Building on the literature positioning in Section 2, this section establishes the circular economy logic that underpins the proposed conditional circularity framework. It explains why used EV batteries may retain functional and material value after their first mobility use, but also why value retention alone is not sufficient

to justify reuse. In this sense, Section 3 provides the conceptual bridge between the literature streams discussed above and the lifecycle decision framework developed.

This circular economy logic begins with the aim of reducing waste, extending product life, retaining material value, and returning resources to productive use. In the battery sector, this includes repair, reuse, repurposing, remanufacturing, and recycling. Used EV batteries fit strongly within the concept of "cascading use," where a product moves from a high-performance application to a lower-performance application before final recycling (Alam & Gheewala, 2026a).

For batteries, the circular pathway usually begins with raw material extraction and battery manufacturing, continues through first-life use in EVs, and then moves into collection, diagnosis, repurposing, second-life use, possible third-life use, and recycling. This sequence is important because immediate recycling may recover valuable materials but may also destroy remaining functional value. Recent market and technical studies emphasize that second-life stationary storage can reduce waste while supporting grid flexibility and renewable energy integration (Roslan et al., 2025; Huether, 2025).

However, circular economy strategies must be designed carefully. Reusing a battery without proper diagnostics may create fire, reliability, or liability risks. Similarly, delaying recycling for too long may lock critical materials into inefficient systems. Therefore, used batteries should not be treated simply as "green technology." They must be governed as part of a circular battery ecosystem that includes safety standards, battery passports, artificial intelligence (AI) monitoring, business incentives, and recycling obligations. The visual representation of circular lifecycle pathway of EV batteries can be seen in Figure 1.

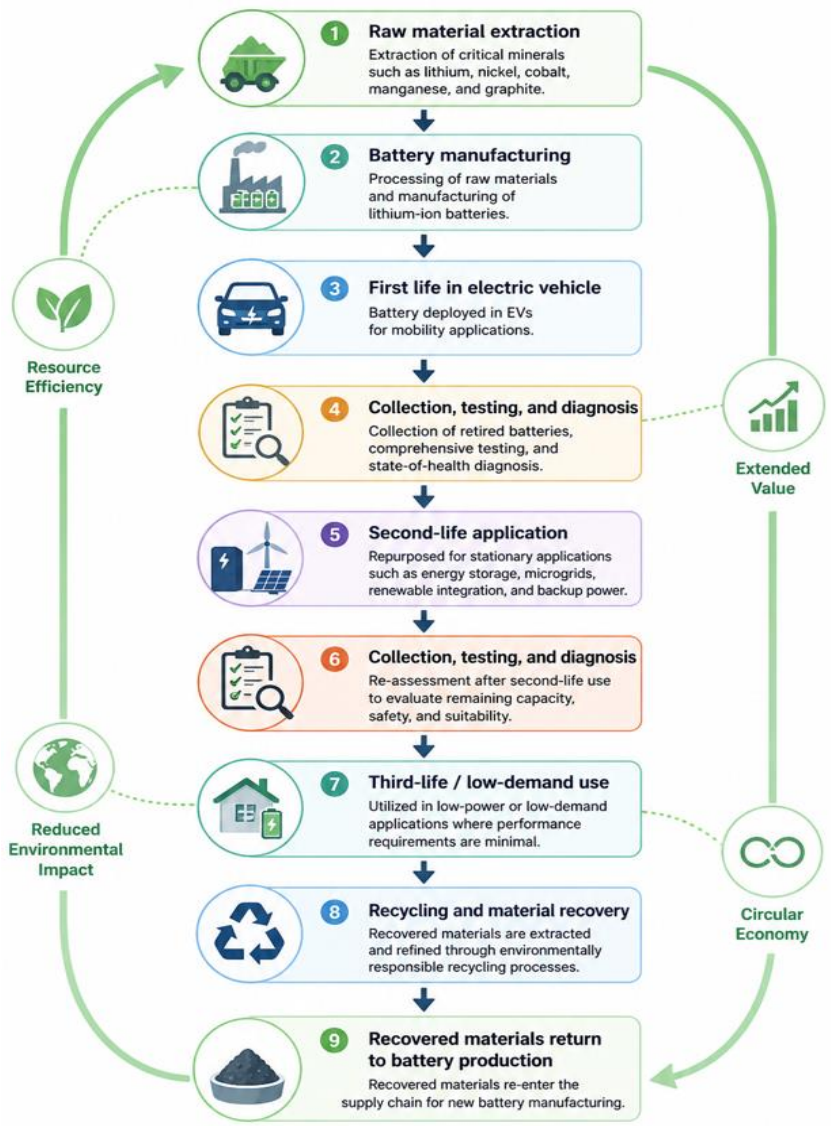


Figure 1. Circular lifecycle pathway of EV batteries from first-life mobility use to second-life stationary applications, third-life use, and final recycling [Sources: (Alam & Gheewala, 2026a; Roslan et al., 2025; Huether, 2025)].

The next section builds directly on this pathway by introducing the decision logic needed to determine whether reuse, lower-demand cascading, or direct recycling is the most appropriate option for a specific battery.

4. Lifecycle Decision Framework for Operationalizing Conditional Circularity

The lifecycle decision framework is the main analytical contribution of this perspective. It translates the concept of conditional circularity into a practical decision structure for used EV battery management. Rather than treating reuse, cascading, and recycling as a fixed hierarchy, the framework asks which pathway is justified for a specific battery at a specific lifecycle stage. A used battery should move into second-life use, lower-demand third-life use, or recycling only after evidence has been generated on three core questions: whether the battery is safe, whether reuse creates a net sustainability benefit, and whether a credible pathway to final recycling remains available.

Figure 2 presents the overarching integrative framework developed in this perspective. It synthesizes the main analytical areas discussed throughout the paper and shows how battery diagnostics, sustainability assessment, planetary-boundary thinking, risk assessment, battery passports, data traceability, circular business models, and AI-enabled battery management jointly inform lifecycle decision-making for conditional circularity. The framework is designed to clarify how used EV batteries can be directed toward second-life use, lower-demand cascading, or direct recycling based on evidence rather than assumption.

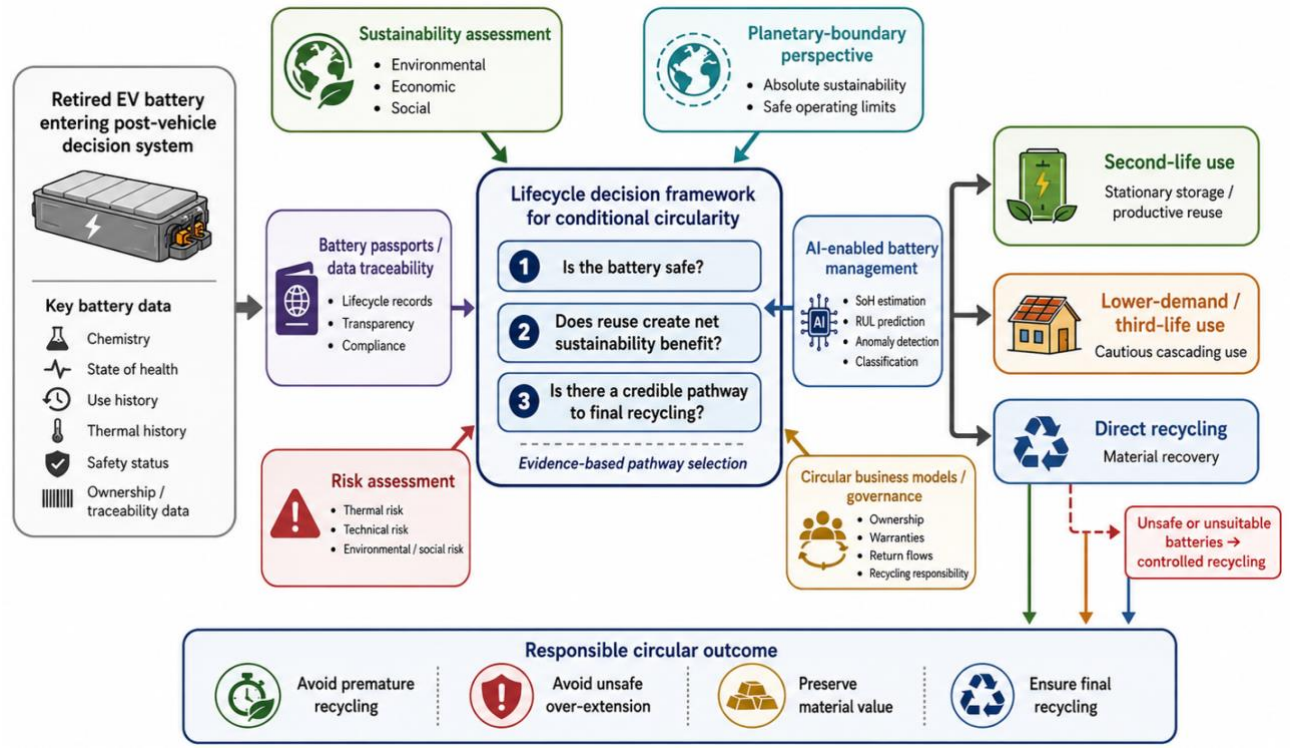


Figure 2. Integrative framework for operationalizing conditional circularity in used EV batteries [Source: Authors' own conceptual framework].

The colors in the framework are used to distinguish the main decision dimensions: green indicates sustainability and value-retention considerations, teal indicates planetary-boundary and absolute sustainability limits, purple indicates battery passports and lifecycle traceability, red indicates risk and safety screening, blue indicates artificial intelligence-enabled battery management and pathway decision-making, and orange indicates circular business models and governance accountability. The pathway boxes on the right use different colors to distinguish the possible outcomes: second-life use, lower-demand or third-life use, and direct recycling.

Although this perspective is conceptual, several real-world examples illustrate why used EV battery circularity must be treated as conditional rather than automatic. The Johan Cruijff ArenA in Amsterdam demonstrates how used EV batteries can support commercial-building energy storage and backup power when they are integrated into a controlled stationary system (Eaton, n.d.). Renault's Advanced Battery Storage project illustrates how EV batteries can be redirected into grid-scale stationary storage but also highlights the need for coordination between vehicle manufacturers, energy operators, and storage-system developers (Renault Group, 2022). B2U Storage Solutions provides another example of large-scale second-life deployment, using used EV battery packs in stationary battery energy storage systems (B2U Storage Solutions, n.d.). BMW's battery farm at Plant Leipzig further shows how used EV batteries can be linked with renewable electricity storage (BMW Group, 2021). These cases show that second-life deployment is possible, but only when batteries are supported by appropriate diagnostics, system integration, monitoring, ownership arrangements, and eventual recycling pathways. They therefore reinforce the central argument of this paper: reuse can support circularity, but only when embedded within an evidence-based lifecycle decision framework.

This framework acts as the organizing structure for the rest of the paper. Sustainability assessment, planetary-boundary thinking, circular business models, risk assessment, AI-enabled battery management, and third life/end-of-life planning are not separate themes, but decision dimensions that determine whether conditional circularity can be achieved. Chemistry, state of health, degradation history, accident records, thermal exposure, dismantling information, ownership structure, monitoring capacity, and recycling access are therefore not merely technical or managerial details; they are decision variables that determine whether reuse is justified. Recent AI and health-estimation studies emphasize that accurate state-of-health prediction is essential for safe and reliable second- and third-life deployment (Li et al., 2025). The lifecycle stage mapping for used EV batteries is summarized in Table 1.

Table 1. Lifecycle evidence required for conditional circularity decisions

Lifecycle stage	Circular economy role	Key data required	Main challenge	Main actor
Manufacturing	Material efficiency and traceability	Chemistry, material origin, embedded carbon	Supply-chain transparency	Battery manufacturer
First life in EV	Mobility and performance use	SoH, charging history, thermal history, accident data	Data ownership and access	Original Equipment Manufacturer (OEM), vehicle owner
Collection and diagnosis	Reuse decision-making	Capacity, internal resistance, safety status	Testing cost and standardization	Collector, diagnostic firm
Second life	Value extension and stationary storage	Residual capacity, RUL, degradation rate	Safety, warranty, market trust	Repurposer, storage operator
Third life	Low-demand reuse	Remaining safety margin and residual performance	Economic feasibility	Aggregator, community operator
End-of-life	Recycling and material recovery	Battery composition, dismantling data	Recovery efficiency and cost	Recycler

Note: Authors' own synthesis based on the conditional circularity framework and literature on battery diagnostics, data traceability, second-life use, and recycling pathways (Losa & Torjesen, 2025; Li et al., 2025; Ma et al., 2024; Roslan et al., 2025).

This framework highlights why data continuity is central to conditional circularity. Without reliable lifecycle data, reuse decisions may overestimate remaining useful life, underestimate safety risks, or delay recycling beyond the point of environmental benefit. Battery passports can therefore serve not only as compliance tools, but as decision infrastructure for determining whether a used battery should be reused, cascaded, or recycled.

The following subsections develop each decision dimension of the lifecycle framework. Sustainability assessment defines the environmental, economic, and social conditions for reuse; planetary-boundary thinking introduces absolute sustainability limits; circular business models define the accountability mechanisms for implementation; risk assessment establishes safety thresholds; AI-enabled battery management supports diagnosis and prediction; and third life and end-of-life pathways define the exit conditions for recycling.

4.1. Sustainability Assessment: Environmental, Economic, and Social Dimensions

Sustainability assessment represents the first decision dimension of the lifecycle framework because reuse is justified only when it creates environmental, economic, and social benefits relative to alternative pathways. Used EV batteries are often promoted as environmentally beneficial because they extend battery life and delay waste generation. Environmental benefits may include reduced need for new stationary batteries, lower demand for primary raw materials, reduced greenhouse gas emissions, and improved renewable energy integration. However, environmental outcomes are context specific. They depend on battery transport distance, testing energy, repurpose processes, efficiency losses, application type, and the carbon intensity of the electricity system. Recent techno-economic and environmental studies show that circular pathways can possibly, though not always, reduce lifecycle burdens and must be assessed case by case (Al-Alawi et al., 2025; Repurposing of EV Batteries for Stationary Storage, 2025).

Economic assessment is equally important. A used EV battery must compete with increasingly cheaper new batteries. The success of used EV battery repurpose depends on the availability of a supporting infrastructure and business ecosystem, including collection networks, diagnostic facilities, certification standards, skilled labor, warranty systems, and second-life market channels. If these costs are too high, used batteries may lose their economic advantage. Studies on market landscape and business feasibility note that reusing used EV batteries require standardization, predictable supply, clear warranties, and customer confidence (Huether, 2025; Alam and Gheewala, 2026a).

Social assessment remains less developed but is essential. Used EV batteries may create jobs in diagnostics, repair, repurpose, software, energy storage, and recycling. They can also support energy access in communities that need affordable storage. However, social risks include fire safety concerns, unequal exposure to hazardous systems, weak regulation, informal recycling, and limited consumer trust. Recent sustainability-oriented studies links reusing EV batteries to the sustainable development goals, especially affordable and clean energy, but also show the need for governance and safety systems (Alam et al., 2025). The visual representation of sustainability assessment framework can be seen in Figure 3 below.

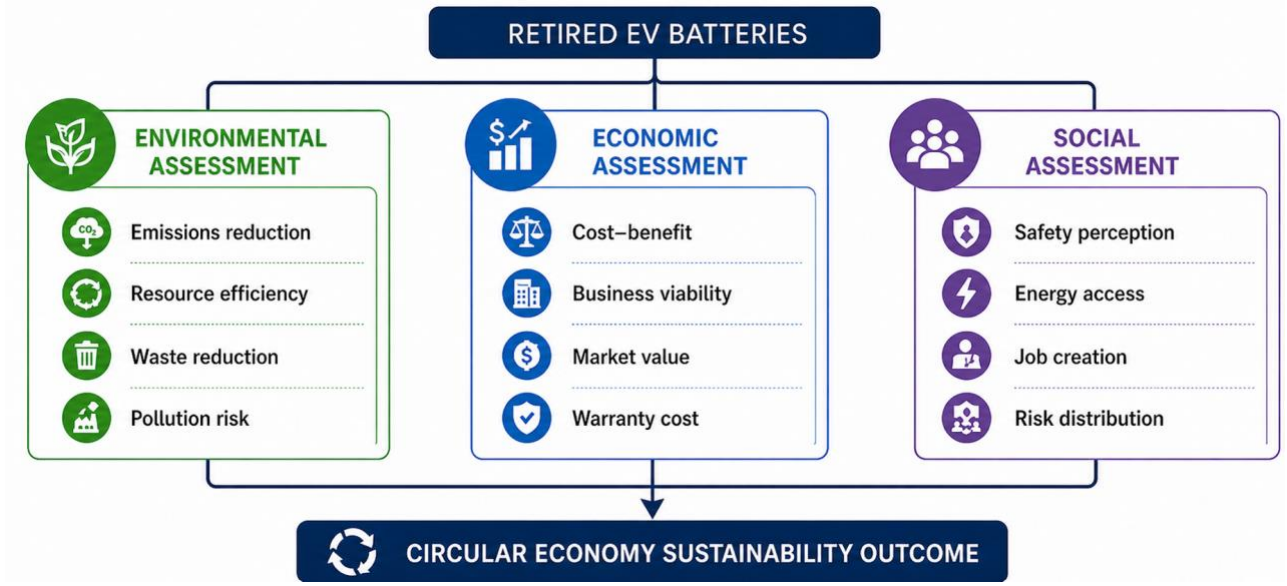


Figure 3. Integrated sustainability assessment framework for used EV batteries [Sources: (Al-Alawi et al., 2025; Huether, 2025; Alam et al., 2026)].

4.2. Planetary Boundaries Perspective

Planetary-boundary thinking extends the lifecycle framework from relative improvement to absolute sustainability by asking whether reuse helps reduce environmental pressures within the safe operating limits of the planet. A planetary boundaries perspective strengthens the assessment of used EV batteries by shifting the question from “Is reuse circular?” to “Is reducing the pressure enough to bring it within Earth-system

limits?" This distinction is important because seven of the nine planetary boundaries have already been transgressed, including climate change, biosphere integrity, land-system change, freshwater change, biogeochemical flows, and novel entities (Sakschewski et al., 2023). Therefore, used EV battery reuse should be assessed not only as a circular strategy, but also as a potential contribution to reducing absolute environmental pressure within a safe operating space. This also reinforces the central claim of the paper: used battery circularity must be conditional, evidence-based, and bound by absolute sustainability considerations rather than assumed from reuse alone.

Quantitatively, the battery sector is becoming large enough to affect planetary boundaries. Kronemeyer et al. (2025) estimated that, under current trajectories, battery production could exceed its assigned safe operating space for climate change by a factor of ten in 2030 and could occupy more than 10% of the global safe operating space for climate change by 2040. This makes used EV battery reuse environmentally relevant because extending battery service life can reduce demand for new battery production and delay resource-intensive mining and refining. However, this benefit depends on whether reuse avoids new production while maintaining sufficient efficiency, safety, and remaining useful life.

Recent lifecycle studies support this conditional interpretation. Ma et al. (2024) found that optimized reuse–recycling pathways reduced emissions by about 18% for both lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) batteries compared with direct hydrometallurgical recycling, while improving profits by 58% for LFP and 19% for NMC systems. Machala et al. (2025) showed that circular battery supply chains can reduce environmental impacts by at least 58% compared with mining-based supply chains, although electricity sources can change recycling-related greenhouse gas emissions by up to five times. Meng et al. (2023) reported that battery recycling can reduce greenhouse gas emissions by 17–61%, depending on the recycling route.

Thus, used EV battery circularity is beneficial only when it creates net reductions in climate emissions, material extraction, freshwater pressure, pollution risk, and ecosystem disturbance; compared with linear or direct recycling routes. However, such reductions represent relative environmental improvements and do not necessarily demonstrate that the system operates within Earth-system limits. Therefore, circular battery strategies should also be assessed through absolute sustainability perspectives, such as planetary boundary-based indicators, to determine whether they contribute to operating within safe environmental limits. Reuse should occur before recycling only when avoided production and mining impacts exceed the added burdens of testing, transport, repurposing, monitoring, and final end-of-life treatment (Paulillo & Sanyé-Mengual, 2024; Chacana-Olivares et al., 2025; Esmaeilian et al., 2026).

4.3. Business Models That Enable Conditional Circularity

Building on the circular economy foundation introduced in Section 2, circular business models are treated here as the implementation and accountability mechanism of conditional circularity. In other words, business models will help us to understand how circular economy principles can be operationalized through ownership clarity, warranties, certification, data transparency, return-flow management, and responsibility for final recycling.

Business models are relevant to used EV batteries only if they preserve accountability across reuse and recycling. A second-life market based only on low-cost used batteries may encourage unsafe deployment, weak warranties, or delayed recycling. In contrast, circular business models should make reuse conditional on verified battery health, clear ownership, performance guarantees, data transparency, and responsible end-of-life return.

Among the possible models, three are especially important for conditional circularity. First, battery leasing can keep ownership and end-of-life responsibility with the manufacturer or system operator, reducing the risk that batteries disappear into poorly regulated secondary markets. Second, battery passport-based marketplaces can improve trust by linking price and application suitability to verified lifecycle data rather than uncertain residual capacity alone. Third, integrated reuse-recycling platforms can prevent two undesirable outcomes: premature recycling that wastes remaining functional value, and excessive reuse that delays material recovery or increases safety risk.

Recent real-world developments show that second-life batteries are moving from concept to commercial application. For example, Redwood Materials has developed second-life battery microgrid systems using used EV batteries, showing how reuse and recycling can be integrated within one business ecosystem (Wang et al.,

2025; Alex et al., 2025). These examples suggest that second-life business models may become more attractive as EV retirement volumes increase and demand for stationary storage grows. The highlights for some of the circular business models can be seen in Table 2 below.

Table 2. Business models and their relevance to conditional circularity

Business model	Description	Circular economy benefit	Main barrier
Battery leasing	OEM or operator retains ownership	Improves traceability and return flows	Legal and ownership complexity
Storage-as-a-service	Customer pays for storage performance	Reduces upfront cost	Requires strong warranties
Repurposing hub	Central testing and grading facility	Improve scale and standardization	High diagnostic cost
Battery passport marketplace	Batteries sold with verified data	Improves transparency and pricing	Data interoperability
Reuse-recycle platform	Same actor manages reuse and recycling	Avoid premature recycling and unsafe reuse	Requires strong logistics

Note: Authors' own synthesis based on circular business model and second-life battery market literature (Huether, 2025; Losa & Torjesen, 2025; Alam & Gheewala, 2026a).

4.4. Risk Assessment of Used EV Batteries

Risk assessment provides the safety threshold of the lifecycle framework because batteries that cannot meet technical and safety requirements should move directly to controlled recycling rather than further reuse. Risks are not a secondary barrier to battery circularity; but are one of the key criteria that determines whether circularity exists or not. Risk assessment is central because used EV batteries are heterogeneous. Unlike new batteries, used batteries have already experienced years of cycling, fast charging, temperature variation, vibration, and possible misuse. Their capacity alone does not fully indicate safety. A battery with acceptable capacity may still have internal defects, lithium plating, cell imbalance, or thermal instability. Recent thermal safety research emphasizes that used EV battery risk depends on degradation mechanisms, cell screening, pack configuration, and monitoring systems (Thermal Safety Review, 2026). Broader public safety discussions in 2026 also show increasing concern about lithium-ion battery fires and the need for stronger safety controls (The Guardian, 2026; Das et al., 2026). Some of the core risk categories for used EV batteries can be seen in Table 3 below.

Table 3. Expected Risk categories in used EV battery systems

Risk category	Example risk	Mitigation strategy
Technical risk	Capacity mismatch, resistance growth	Cell grading, module balancing
Safety risk	Thermal runaway, short circuit	Thermal monitoring, fire suppression
Economic risk	Shorter-than-expected lifetime	Warranty, insurance, conservative design
Environmental risk	Improper disposal or delayed recycling	Recycling triggers and tracking
Data risk	Missing lifecycle history	Battery passport and digital twin
Social risk	Public distrust or unequal exposure	Safety standards and transparent governance

Note: Authors' own synthesis based on risk, safety, recycling, and socio-environmental literature on used lithium-ion battery systems (Chacana-Olivares et al., 2025; Das et al., 2026; Esmaeilian et al., 2026).

A risk-based decision process should include battery identification, chemistry classification, state-of-health estimation, safety screening, application matching, real-time monitoring, and end-of-life exit criteria. Batteries that do not meet safety thresholds should move directly to recycling rather than future-life use.

4.5. AI Modelling and Intelligent Battery Management Systems

AI-enabled battery management provides the diagnostic and predictive layer of the lifecycle framework by supporting state-of-health estimation, remaining useful life prediction, anomaly detection, and pathway classification. AI can help address one of the biggest challenges in used EV batteries: uncertainty. Used batteries differ widely in chemistry, degradation pathway, thermal history, and remaining useful life. Manual testing alone may be too slow and expensive for large-scale deployment. AI-enabled BMS can support state-of-health estimation, remaining useful life prediction, anomaly detection, thermal risk prediction, cell balancing, and predictive maintenance.

Recent studies have proposed machine learning frameworks for aging estimation and clustering of used EV batteries, allowing batteries to be classified according to second or third life applications potential (Aging Estimation and Clustering, 2025). Other studies discuss intelligent domain-generalized state-of-health assessment and AI-driven echelon utilization for used EV batteries (Li et al., 2025; AI-Driven Echelon Utilization, 2025). Research on machine learning in future-life BMS also highlights the importance of balancing cells with different capacities and resistances (Gotz et al., 2025). The overview of the intelligent battery framework can be seen in Figure 4 below.

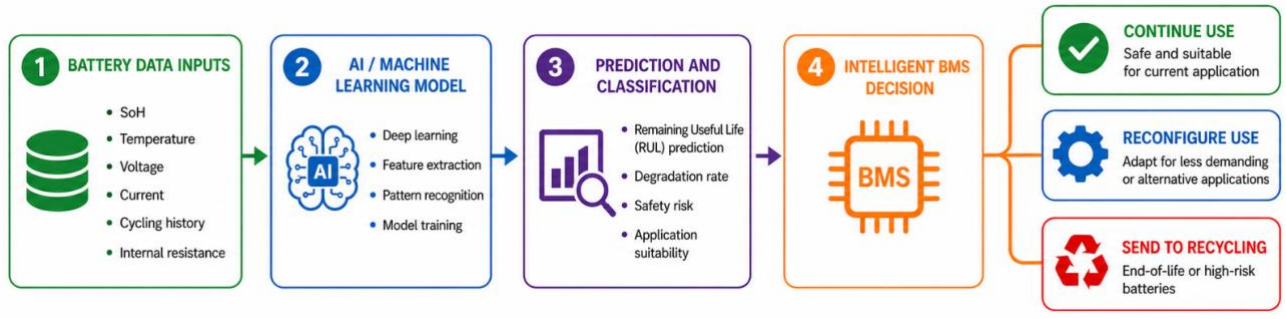


Figure 4. Role of AI-enabled BMS in diagnosis, risk prediction, and lifecycle decision-making [Sources: (Li et al., 2025; Murphy & Crawford, 2025; Gotz et al., 2025; Wang et al., 2025)].

4.6. Third Life and End-of-Life Pathways

Third life and end-of-life planning define the exit conditions of the lifecycle framework by clarifying when continued reuse remains justified and when recycling should occur. Second-life use should not be treated as the final stage of the battery lifecycle. After stationary storage, some batteries may still be suitable for third-life, low-demand applications. Carefully screened third-life batteries may also support affordable energy access in low-income and resource-constrained regions where new battery systems remain difficult to afford. This could contribute to SDG 7 through low-cost storage for small solar, backup power, and community energy uses, but only when safety, monitoring, and final recycling responsibilities are clearly ensured.

These may include small backup systems, educational uses, low-power community energy projects, or controlled demonstration systems. However, third-life use should be approached cautiously because safety risks increase as batteries age. Eventually, all batteries must move to recycling. Recycling is essential for recovering lithium, cobalt, nickel, copper, aluminium, manganese, graphite, and other materials. Recent recycling reviews emphasize that EV battery recycling must become technically effective, economically viable, and environmentally sustainable (Zhang et al., 2025; Chacana-Olivares et al., 2025). A circular economy approach should therefore follow the principle: reuse before recycling but not reuse instead of recycling. Batteries should be reused only when they remain safe and useful. Once safety, performance, or economic thresholds are no longer met, recycling should occur promptly. The decision pathway for used EV batteries can be seen in Table 4 below.

Table 4. Decision pathway for used EV batteries

Battery condition	Recommended pathway	Reason
High residual capacity and safe	Second-life storage	Maximizes functional value
Moderate capacity but safe	Low-demand second-life or third-life use	Extends value cautiously
Low capacity but recyclable	Direct recycling	Recovers critical materials
Damaged or unsafe	Immediate controlled recycling	Avoids safety risk
Unknown history	Diagnostic testing before decision	Prevents unsafe reuse

Note: Authors' own decision pathway developed from the conditional circularity framework proposed in this perspective.

5. Decision-Maker Implications and Future Research Agenda

The conditional circularity framing also has practical implications for decision-makers. It shifts the goal from simply increasing the volume of used EV battery reuse to selecting the most responsible pathway for each battery based on evidence. Policymakers, firms, recyclers, and researchers therefore need decision rules that distinguish between batteries suitable for second-life use, batteries appropriate only for lower-demand cascading, and batteries that should move directly to recycling. The overall decision-making implications are summarized in Table 5 below.

Table 5. Decision-maker implications of conditional circularity for used EV batteries

Decision-maker	Key implication	Recommended action
Policymakers and regulators	Reuse should be promoted only when safety, traceability, and end-of-life responsibility are clear.	Establish diagnostic standards, safety certification, battery passport requirements, and recycling triggers.
Battery manufacturers and OEMs	Future reuse depends on design choices and lifecycle data availability.	Design batteries for disassembly, health tracking, data sharing, and return-flow management.
Repurposers and second-life firms	Residual capacity alone is not enough to justify reuse.	Apply state-of-health testing, safety screening, application matching, warranties, and monitoring.
Energy storage operators	Used batteries should be matched to suitable duty cycles.	Use second-life batteries only where performance demand, safety margin, and remaining useful life are appropriate.
Recyclers	Recycling is the necessary endpoint of responsible circular management.	Coordinate with OEMs and repurposers to recover batteries when reuse thresholds are no longer met.
Investors and insurers	Market confidence depends on verified risk and clear liability.	Support projects with certified battery condition, transparent data, warranties, and defined responsibility.
Researchers and standard-setting bodies	Conditional circularity requires measurable thresholds.	Develop criteria for reuse, third-life use, direct recycling, lifecycle benefit, safety risk, and planetary-boundary alignment.

Note: Authors' own synthesis of decision-maker implications derived from the lifecycle decision framework for conditional circularity.

Building on these decision-making implications, future research should operationalize conditional circularity by developing practical thresholds for when used EV batteries should be reused, cascaded into lower-demand applications, or recycled. This agenda should move beyond isolated technical studies and toward integrated circular battery systems that connect diagnosis, sustainability assessment, business accountability, risk governance, artificial intelligence-enabled monitoring, and final recycling pathways.

Six priorities are especially important. First, sustainability assessment should integrate environmental life cycle assessment, life cycle costing, social life cycle assessment. Second, planetary-boundary assessment would allow reuse decisions to be evaluated not only through relative environmental improvement, but also in relation to absolute sustainability limits. Third, battery passports should be designed not only for regulatory compliance but also for future-life decision-making. They should support battery identification, state-of-health verification, safety screening, market confidence, ownership tracking, and responsibility for final recycling. Fourth, circular business models should include warranties, insurance, ownership structures, and data-sharing

rules. Future work should compare leasing, storage-as-a-service, repurposing hubs, passport-based marketplaces, and integrated reuse-recycling platforms to determine which models best prevent unsafe reuse and ensure return flows. Fifth, risk assessment should combine degradation science, thermal safety, cybersecurity, and social risk. This is necessary to define exclusion criteria for batteries that should not enter second-life or third-life applications. Sixth, AI-BMS models should be trained and validated using real-world future-life battery data rather than laboratory datasets. Field-based validation is particularly important because used batteries vary in chemistry, use history, degradation pathway, safety condition, and remaining useful life.

A strong future framework should connect diagnosis, sustainability assessment, business models, AI monitoring, and recycling. This integrated approach can prevent two opposite failures: premature recycling that wastes remaining battery value, and unsafe over-extension that creates environmental or safety risks. Future empirical studies across different chemistries, countries, grid conditions, business models, and end-use applications would help determine when used EV battery reuse genuinely supports circular economy goals and when recycling is the more responsible pathway.

6. Conclusions

The key message of this perspective is that used EV batteries are not automatically circular, sustainable, or desirable simply because they are reused. Their circularity value is conditional: reuse should be prioritized only when batteries remain safe, diagnostically verified, economically viable, socially acceptable, environmentally beneficial, traceable, and linked to eventual recycling. When these conditions are met, used EV batteries can extend material value, reduce waste, support renewable energy storage, lower demand for primary resources, and create new circular business opportunities. However, when these conditions are not met, direct recycling or controlled end-of-life management may be more responsible than further reuse.

The main theoretical contribution of this perspective is the concept of conditional circularity and its operationalization through a lifecycle decision framework. This contribution builds on circular economy and cascading-use literature by shifting attention from value retention alone to the conditions under which value retention remains responsible. It extends second-life EV battery research by moving the discussion from technical feasibility and environmental potential toward pathway selection: when should batteries be reused, cascaded, or recycled. It also connects several literature streams that are often treated separately, including lifecycle sustainability assessment, planetary-boundary thinking, battery passports, data traceability, AI-enabled battery management, risk governance, circular business models, and recycling responsibility. In doing so, the paper contributes a decision-oriented lens for aligning circular battery strategies with safety, accountability, lifecycle sustainability, and absolute environmental limits.

The lifecycle decision framework developed in this paper integrates sustainability assessment, planetary-boundary thinking, risk assessment, circular business models, battery passports, AI-enabled battery management, and end-of-life recycling responsibility into one decision logic. The framework clarifies that conditional circularity is not achieved by extending battery life alone, but by demonstrating that reuse creates net benefit without delaying necessary recycling or increasing safety and environmental risks. The future of used EV batteries therefore depends not only on whether they can be reused, but on whether reuse can be governed as a safe, transparent, and environmentally meaningful step within a responsible circular battery system.

This perspective also has limitations. First, it is conceptual and does not empirically test the proposed framework using primary data from specific battery systems, chemistries, or regional markets. Second, the literature was selected purposively to support the development of the perspective rather than through a systematic review protocol. Third, the framework does not yet define quantitative threshold values for safety, state of health, remaining useful life, economic feasibility, lifecycle benefit, or planetary-boundary alignment. Fourth, regulatory requirements, battery passport systems, AI-enabled diagnostics, recycling technologies, and second-life business models are evolving rapidly, meaning that the practical application of conditional circularity will require continuous updating.

Overall, this perspective argues that circular battery management should move beyond a simple reuse-before-recycling hierarchy. Used EV batteries should enter second-life or third-life applications only when diagnostic, safety, sustainability, economic, traceability, and recycling-responsibility conditions are satisfied. Otherwise, controlled recycling may provide the more responsible circular pathway.

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Declarations

Competing Interests The authors declare no competing interests.

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