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End-of-Life Battery Management in the U.S. Electric Vehicle Transition

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Abstract

The rapid growth of electric vehicle (EV) adoption in the United States is creating an unprecedented challenge in managing end-of-life lithium-ion batteries. While EV batteries typically retain substantial residual capacity after automotive use, inadequate recycling and reuse infrastructure risks environmental harm, resource inefficiency, and missed economic opportunities. This article examines the technical, economic, regulatory, and environmental dimensions of battery recycling and second-life applications within the U.S. EV ecosystem. It reviews current and emerging recycling technologies, evaluates second-life use cases across grid, commercial, and residential energy storage, and analyzes economic viability, policy frameworks, and circular economy business models. The study situates battery lifecycle management within the broader EV and energy transition, highlighting the roles of grid integration, digital tracking, and artificial intelligence in enabling scalable solutions. The findings suggest that coordinated investment, regulatory harmonization, technological innovation, and stakeholder collaboration are essential to transforming retired EV batteries from waste liabilities into strategic assets. Establishing a robust circular battery economy is critical for long-term EV sustainability, resource security, and grid resilience in the United States.

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1. Introduction

The United States stands at the cusp of a transformative shift in transportation, with electric vehicle adoption accelerating rapidly due to technological advances, policy incentives, and changing consumer preferences (Adil Shah *et al.*, 2026) [3]. Projections suggest that tens of millions of EVs will populate American roads by 2030, representing a fundamental restructuring of the automotive landscape and energy systems. However, this transition generates a consequential challenge: managing the vast quantities of lithium-ion batteries that will eventually reach end-of-life in vehicular applications.

EV batteries typically retain 70-80% of their original capacity after 8-10 years of automotive use, at which point they no longer meet the performance standards required for transportation but remain viable for less demanding applications. Without strategic end-of-life management, these batteries risk becoming environmental liabilities, waste management challenges, and missed economic opportunities. Conversely, effective recycling and second-life utilization can transform retired EV batteries into valuable resources, recovering critical materials, supporting grid stability, and creating new economic value streams.

This article explores the technical, economic, regulatory, and environmental dimensions of battery recycling and second-life applications in the United States. We examine current recycling technologies, emerging second-life markets, policy frameworks, economic barriers and enablers, and strategic pathways toward establishing a circular battery economy. The analysis draws on recent research regarding infrastructure development (Shah *et al.*, 2026) [5], charging systems (Adil Shah *et al.*, 2025) [1], and grid integration (Shah *et al.*, 2024) [6], situating battery lifecycle management within the broader EV ecosystem.

2. The Scale of the Battery End-of-Life Challenge

2.1. Current and Projected EV Battery Volumes

As of 2024, the United States has approximately 3 million EVs on the road, representing roughly 1.5% of the total vehicle fleet. However, adoption rates are accelerating, driven by improving vehicle economics, expanding model availability, enhanced charging infrastructure, and supportive policies at federal and state levels. Industry projections suggest that EVs could represent 50% or more of new vehicle sales by 2030, with the total EV fleet potentially exceeding 30 million vehicles by 2035.

Each EV contains battery packs ranging from 40 kWh for smaller vehicles to over 100 kWh for larger models and trucks, translating to hundreds of kilograms of battery materials per vehicle. As the earliest waves of mass-market EVs, introduced in the early 2010s, approach retirement, the volume of end-of-life batteries will grow exponentially. Estimates suggest that by 2030, the United States could face approximately 1-2 million tons of retired EV batteries annually, escalating to 3-5 million tons by 2040.

2.2. Material Composition and Value

Lithium-ion batteries contain valuable materials including lithium, cobalt, nickel, manganese, aluminum, copper, and graphite. The specific composition varies by battery chemistry, with common EV chemistries including nickel-cobalt-manganese (NCM), nickel-cobalt-aluminum (NCA), and lithium-iron-phosphate (LFP). High-nickel chemistries contain particularly valuable materials, with cobalt and nickel representing significant portions of battery costs.

At current commodity prices, the material value in a typical 60 kWh battery pack ranges from $1,000 to $3,000, depending on chemistry and market conditions. However, extracting this value through recycling involves substantial processing costs, creating economic challenges that influence recycling viability. Fluctuating commodity prices, particularly for lithium and cobalt, create uncertainty in recycling economics, alternately enabling or constraining profitability.

2.3. Environmental and Resource Security Implications

Improper disposal of lithium-ion batteries poses environmental hazards including heavy metal contamination, fire risks, and toxic chemical releases. Landfilling batteries wastes valuable materials while creating long-term environmental liabilities. Conversely, effective recycling mitigates these environmental risks while recovering materials that would otherwise require energy-intensive mining and processing.

From a resource security perspective, recycling reduces dependence on imported critical minerals, many of which originate from geopolitically complex regions with concentrated supply chains. China dominates processing and refining capacity for most battery materials, creating supply vulnerabilities for the United States. Developing domestic recycling capacity enhances resource security by creating secondary material sources that reduce import dependencies and buffer against supply disruptions.

3. Battery Recycling Technologies and Processes

3.1. Collection and Disassembly

Battery recycling begins with collection systems that aggregate end-of-life batteries from various sources including automotive dealerships, dismantlers, recycling centers, and fleet operators. Establishing efficient collection networks presents logistical challenges due to battery weight, transportation regulations governing hazardous materials, and geographic dispersion of end-of-life batteries.

Once collected, batteries undergo disassembly processes that separate battery packs into modules and individual cells. This stage involves safely discharging batteries to eliminate electrical hazards, removing packaging and structural components, and sorting cells by chemistry and condition. Automation of disassembly remains limited due to the wide variety of battery pack designs across manufacturers and models, though standardization efforts could facilitate more efficient automated processing.

3.2. Pyrometallurgical Recycling

Pyrometallurgical processes involve high-temperature smelting that recovers metals through thermal treatment. Batteries are fed into furnaces reaching temperatures of 1,400-1,700°C, where organic materials combust and metals form alloy products that can be further refined. This approach efficiently recovers cobalt, nickel, and copper, which alloy together and can be separated through hydrometallurgical processing.

Advantages of pyrometallurgy include the ability to process mixed battery chemistries without extensive sorting, established industrial infrastructure based on traditional metal smelting, and relative insensitivity to contamination or impurities in feed materials. However, pyrometallurgical recycling consumes substantial energy, generates emissions requiring pollution control, and generally does not recover lithium economically, as it becomes incorporated in slag rather than alloy products. Recovery rates for valuable metals typically range from 50-70%, leaving significant material value unrecovered.

3.3. Hydrometallurgical Recycling

Hydrometallurgical processes use aqueous chemical solutions to leach metals from battery materials, followed by precipitation, solvent extraction, or electrochemical recovery to isolate individual elements. This approach typically begins with mechanical processing that shreds batteries into small particles, separating metals, plastics, and active materials. The resulting "black mass" containing lithium, cobalt, nickel, and manganese undergoes leaching in acidic solutions, dissolving metals into solution where they can be selectively recovered.

Hydrometallurgical recycling offers several advantages including higher recovery rates (often exceeding 95% for major metals), ability to recover lithium economically, lower energy consumption compared to pyrometallurgy, and production of battery-grade materials suitable for direct reintegration into manufacturing. However, these processes require careful chemistry control, generate chemical waste streams requiring treatment, and can be sensitive to feed material variations.

3.4. Direct Recycling

Emerging direct recycling approaches aim to preserve battery material structures, particularly cathode materials, avoiding the breakdown to elemental constituents required in pyrometallurgical and hydrometallurgical processes. These methods typically involve separating battery components, removing binders and conductive additives, and regenerating or directly reusing cathode materials in new battery production.

Direct recycling promises superior economics by avoiding energy-intensive processing to break down and reconstruct materials, potentially reducing recycling costs by 50% or more compared to conventional approaches. However, direct recycling requires sorting batteries by chemistry type, as different cathode materials cannot be mixed. Additionally, cathode materials must be regenerated or rejuvenated to restore performance characteristics degraded during use. While promising, direct recycling remains largely in pilot or early commercial stages, requiring further development before widespread deployment.

3.5. Current U.S. Recycling Capacity

As of 2024, U.S. battery recycling capacity remains limited relative to projected future volumes. Several facilities operate at commercial or pilot scale, including Redwood Materials in Nevada, Li-Cycle in New York and Arizona, Ascend Elements in Georgia, and facilities operated by traditional metal recyclers. Total current capacity is estimated at approximately 50,000-100,000 tons annually, far below the multi-million ton volumes anticipated by 2030.

Substantial investments are expanding capacity, driven by policy incentives including the Inflation Reduction Act, which provides tax credits for domestic battery material production including recycled content. However, capacity expansion requires years to plan, permit, construct, and commission facilities, creating urgency for accelerated investment and streamlined regulatory processes.

4. Second-Life Applications

4.1. Concept and Rationale

Second-life battery applications involve repurposing retired EV batteries for less demanding uses where their reduced capacity and performance remain adequate. Rather than immediately recycling batteries upon automotive retirement, second-life utilization extends useful service, deferring recycling while extracting additional economic value. This approach aligns with circular economy principles by maximizing resource utilization before material recovery.

The economic logic of second-life applications rests on cost differentials: if retired EV batteries can be acquired and repurposed for less than the cost of new stationary storage batteries, second-life systems offer economic advantages. Since batteries retain 70-80% of original capacity at automotive retirement, substantial energy storage capability remains available for applications tolerating lower performance than transportation requires.

4.2. Grid Energy Storage

Grid energy storage represents the most promising second-life application, addressing multiple grid challenges including renewable integration, peak demand management, frequency regulation, and backup power. The integration of EV charging systems with grid infrastructure creates natural synergies for second-life battery deployment (Shah *et al.*, 2024) [6].

Second-life batteries can provide cost-effective storage for several applications. Time-shifting renewable energy involves charging batteries during periods of excess solar or wind generation and discharging during high-demand periods, enhancing renewable utilization. Peak shaving reduces demand during highest-cost periods, lowering electricity costs for commercial and industrial customers. Frequency regulation provides rapid response to grid frequency fluctuations, maintaining stability. Backup power supplies critical loads during outages, enhancing resilience.

Several pilot and commercial projects demonstrate second-life grid storage viability. California utilities have deployed second-life systems for renewable integration and demand management. Microgrid applications, particularly in remote or underserved areas, utilize second-life batteries for reliable power supply. Community energy storage projects aggregate retired batteries to provide neighborhood-scale services.

4.3. Commercial and Industrial Applications

Commercial and industrial facilities represent significant markets for second-life batteries, driven by opportunities to reduce electricity costs and enhance energy resilience. Demand charge reduction motivates installations that discharge during peak demand periods, lowering monthly utility bills. Backup power systems ensure business continuity during outages, particularly critical for data centers, hospitals, and manufacturing facilities where downtime imposes severe costs.

Electric vehicle charging infrastructure can integrate second-life batteries to buffer grid connections, enabling fast charging without expensive utility service upgrades. This application creates circular synergies where retired EV batteries support active EV charging, potentially reducing infrastructure costs (Adil Shah *et al.*, 2025; Shah *et al.*, 2026) [1, 5].

4.4. Residential Energy Storage

Residential energy storage markets, driven by rooftop solar installations and grid resilience concerns, could absorb significant second-life battery volumes. Homeowners seek storage to maximize solar self-consumption, provide backup power during outages, and potentially participate in utility demand response programs.

However, residential second-life applications face challenges including customer perceptions regarding used products, warranty and reliability concerns, and installation costs that represent significant portions of system expenses regardless of battery costs. Building consumer confidence in second-life products requires robust quality testing, clear performance warranties, and education regarding safety and reliability.

4.5. Technical Challenges in Second-Life Deployment

Implementing second-life applications confronts several technical challenges. Testing and certification processes must assess individual battery pack condition, capacity, and safety, requiring specialized equipment and expertise. Battery management systems designed for automotive applications may require modification or replacement for stationary use. Thermal management systems must be adapted to different duty cycles and environmental conditions.

Standardization challenges arise from diverse EV battery designs across manufacturers and models, complicating integration into standardized second-life products. Developing modular designs that accommodate various battery types could enhance scalability. However, this requires industry cooperation and potentially regulatory interventions to establish standards.

Degradation prediction remains imperfect, creating uncertainty about second-life battery longevity and performance. Improved diagnostic techniques, including machine learning approaches, could enhance lifecycle predictions and reduce uncertainty (Shah *et al.*, 2023) [9]. Such advances would strengthen business models by enabling more accurate valuation and warranty structuring.

5. Economic Considerations

5.1. Recycling Economics

Battery recycling economics depend on multiple factors including material recovery rates, commodity prices, processing costs, transportation and collection expenses, and regulatory requirements. Recycling profitability fluctuates with commodity markets, particularly lithium and cobalt prices, which have exhibited extreme volatility in recent years.

Processing costs vary by technology, with hydrometallurgical approaches generally requiring higher capital investment but achieving superior recovery rates compared to pyrometallurgical methods. Direct recycling, if successfully commercialized, could offer the most favorable economics by minimizing processing intensity. However, achieving economies of scale requires substantial throughput, creating challenges for emerging recyclers in ramping operations.

Extended Producer Responsibility (EPR) policies, where manufacturers assume financial or physical responsibility for end-of-life product management, can improve recycling economics by ensuring funding and material flows. Several U.S. states are considering or implementing EPR frameworks for batteries, potentially creating more stable economic foundations for recycling infrastructure.

5.2. Second-Life Economics

Second-life battery economics depend on acquisition costs, refurbishment expenses, system integration costs, performance characteristics, and market prices for competing new storage products. As new battery costs continue declining, maintaining economic competitiveness requires minimizing second-life processing costs and maximizing performance.

Acquisition costs vary depending on whether batteries are purchased from automotive recyclers, obtained through manufacturer take-back programs, or acquired from fleet operators. Establishing transparent pricing mechanisms and standardized valuation methods would enhance market efficiency. Some automakers are developing second-life programs that package batteries with warranties and support services, potentially commanding premium prices while offering greater customer assurance.

Performance degradation during second-life use eventually necessitates retirement to recycling, creating interdependencies between second-life and recycling economics. Optimizing total lifecycle value requires coordinating second-life utilization with eventual material recovery, potentially through vertically integrated business models that manage both stages.

5.3. Circular Economy Business Models

Emerging business models seek to capture value across the entire battery lifecycle, integrating manufacturing, first use, second-life applications, and recycling. Battery-as-a-service models, where customers lease rather than purchase batteries, enable manufacturers to retain ownership and control end-of-life disposition, facilitating second-life and recycling optimization.

Collaborative approaches involving automakers, recyclers, second-life system integrators, and energy companies can create ecosystem-wide value chains. Blockchain technologies may enhance transparency and traceability in battery supply chains, enabling better lifecycle management and material tracking (Shah *et al.*, 2023) [12].

6. Regulatory and Policy Framework

6.1. Federal Policies

Federal policies significantly influence battery recycling and second-life markets. The Inflation Reduction Act provides substantial tax credits for domestic battery production, including credits for recycled content, incentivizing recycling investment. The Bipartisan Infrastructure Law includes funding for battery recycling research, demonstration projects, and infrastructure development.

The Department of Energy's Battery Recycling Prize and related programs support innovation in recycling technologies and business models. Federal procurement preferences for domestic and recycled content create demand signals supporting market development. However, gaps remain in federal regulatory frameworks, particularly regarding second-life battery standards, safety certifications, and liability provisions.

6.2. State and Local Regulations

State policies vary considerably, with California, New York, and several other states implementing or considering battery stewardship programs, recycling mandates, and EPR frameworks. California's requirements for demonstrating battery recycling pathways before EV sales create accountability while potentially driving innovation. However, regulatory fragmentation across states creates compliance challenges for national recyclers and second-life operators.

Building codes and electrical standards influence second-life applications, with some jurisdictions lacking clear provisions for used battery installations. Harmonizing standards across jurisdictions would reduce barriers and facilitate market scalability.

6.3. International Comparisons

European Union regulations establish comprehensive frameworks including mandatory recycling targets, minimum recycled content requirements, and carbon footprint declarations. China implements producer responsibility systems with specific collection and recycling rate targets. These international frameworks offer models potentially adaptable to U.S. contexts, though implementation must account for different market structures and regulatory traditions.

Learning from international experiences can accelerate effective U.S. policy development while avoiding pitfalls encountered elsewhere. However, policy transfer requires contextual adaptation rather than direct imitation.

7. Environmental and Social Considerations

7.1. Environmental Benefits

Recycling reduces environmental impacts compared to primary mineral extraction, which involves significant energy consumption, ecosystem disruption, water pollution, and greenhouse gas emissions. Life cycle assessments indicate that using recycled battery materials can reduce carbon emissions by 30-50% compared to virgin materials, though exact figures depend on recycling technology, energy sources, and transportation distances.

Second-life applications extend product lifespans, deferring recycling-associated energy use while displacing new battery production. However, comprehensive lifecycle analysis must account for efficiency losses in second-life applications, transportation emissions, and refurbishment energy requirements to accurately assess net environmental benefits.

7.2. Social and Equity Dimensions

Battery material supply chains, particularly cobalt mining in the Democratic Republic of Congo, have been associated with human rights concerns including child labor and unsafe working conditions. Increasing recycled content reduces reliance on problematic supply chains, potentially improving social sustainability. However, recycling operations themselves must ensure worker safety, fair labor practices, and environmental justice.

Siting recycling facilities raises environmental justice concerns when concentrated in communities already bearing disproportionate environmental burdens. Equitable facility siting, robust community engagement, and stringent environmental controls can mitigate these concerns while ensuring that economic benefits reach affected communities.

Workforce development in recycling and second-life sectors can create employment opportunities, particularly in regions affected by fossil fuel industry transitions. Training programs, partnerships with educational institutions, and inclusive hiring practices can maximize social benefits while building skilled workforces.

8. Technology Integration and Innovation

8.1. Artificial Intelligence and Automation

Artificial intelligence applications can enhance battery recycling and second-life operations through improved diagnostics, quality prediction, and process optimization. Machine learning models can assess battery condition more accurately than traditional methods, enabling better second-life valuations and longevity predictions (Shah *et al*., 2023) [9]. Automated disassembly systems guided by computer vision could accelerate processing while reducing labor costs and safety risks.

Predictive analytics can optimize collection logistics, forecast material flows, and identify optimal routing between collection points and processing facilities. Digital twins simulating battery performance could enhance second-life system design and operation.

8.2. Digital Infrastructure and Tracking

Digital tracking systems using blockchain or distributed ledger technologies can provide transparent battery lifecycle documentation, recording manufacturing specifications, usage histories, maintenance records, and disposition pathways (Shah *et al*., 2023) [12]. This information enhances second-life valuations, facilitates regulatory compliance, and enables better recycling process optimization.

Battery passports, increasingly mandated in Europe, provide standardized digital documentation of battery characteristics, materials, carbon footprints, and supply chain information. Implementing similar systems in the United States would enhance transparency while supporting circular economy development.

8.3. Advanced Materials and Chemistry Evolution

Evolving battery chemistries influence recycling and second-life considerations. Solid-state batteries, if successfully commercialized, may require different recycling approaches than current lithium-ion technologies. Sodium-ion batteries, increasingly deployed for stationary storage, present distinct material recovery challenges and opportunities.

Designing batteries for recyclability and second-life use—through standardized form factors, simplified disassembly, durable construction, and material selection favoring recovery—could substantially improve circular economy outcomes. Design for circularity should become a standard consideration in battery development, potentially incentivized through regulatory requirements or market mechanisms.

9. Strategic Pathways Forward

9.1. Infrastructure Investment Priorities

Scaling U.S. battery recycling and second-life capacity requires sustained investment in processing facilities, collection networks, research and development, and workforce training. Prioritizing investment in advanced recycling technologies, particularly hydrometallurgical and direct recycling approaches offering superior recovery rates and economics, can enhance competitiveness.

Developing regional recycling hubs that consolidate processing capacity while minimizing transportation distances could optimize logistics and economics. Co-locating recycling facilities with battery manufacturing plants creates closed-loop material flows reducing transportation costs and environmental impacts.

9.2. Market Development and Standardization

Establishing transparent market mechanisms for end-of-life and second-life batteries would enhance economic efficiency and investment certainty. Standardized testing protocols for battery condition assessment, industry-wide specifications for second-life applications, and certified quality grades would facilitate market development.

Demonstration projects showcasing second-life applications across diverse use cases can build market confidence and generate performance data supporting business case development. Public-private partnerships can share risks while accelerating innovation and deployment.

9.3. Research and Innovation Needs

Continued research addressing technical, economic, and policy challenges can accelerate circular battery economy development. Priority areas include developing lower-cost, higher-efficiency recycling processes; improving battery diagnostic and prognostic techniques; optimizing second-life system designs; understanding long-term degradation mechanisms; and assessing environmental and economic tradeoffs across lifecycle stages.

Interdisciplinary research integrating engineering, economics, policy, and social science perspectives can address the multifaceted challenges of battery circularity. University-industry collaborations, federally-funded research programs, and international cooperation can mobilize diverse expertise and resources.

9.4. Consumer Engagement and Education

Building public awareness of battery recycling importance and second-life opportunities can enhance collection rates and market acceptance. Educational campaigns highlighting environmental benefits, resource security advantages, and economic value creation can motivate consumer participation in collection programs.

Addressing safety concerns through transparent information about battery handling, testing, and certification processes builds confidence in second-life products. Consumer protections including clear warranties, performance guarantees, and reliable customer support enhance market development.

10. Conclusion

Battery recycling and second-life applications represent critical components of a sustainable U.S. electric vehicle ecosystem. As EV adoption accelerates in response to technological improvements, policy support, and shifting consumer preferences (Adil Shah *et al*., 2026) [3], establishing robust end-of-life management infrastructure becomes increasingly urgent. The coming decade will see exponential growth in retired battery volumes, creating both challenges and opportunities for environmental stewardship, economic development, and resource security.

Effective recycling can recover valuable materials, reduce environmental impacts, and enhance critical mineral security by creating domestic secondary supply sources. Second-life applications extend battery utility, support grid modernization, and enable renewable energy integration (Shah *et al*., 2024) [6] while generating economic value that improves overall EV economics. Together, these circular economy approaches can transform potential waste streams into valuable resource flows, enhancing the sustainability and viability of electric mobility.

Realizing this vision requires coordinated action across multiple dimensions: investing in recycling infrastructure and second-life markets; developing supportive regulatory frameworks at federal and state levels; advancing technologies for efficient material recovery and battery diagnostics; establishing standardized testing, certification, and market mechanisms; educating consumers and stakeholders about opportunities and benefits; and fostering collaboration among automakers, recyclers, energy companies, policymakers, and researchers.

The transition toward circular battery management parallels the broader EV transition in requiring technological innovation, infrastructure development, policy support, and market transformation. Just as charging infrastructure proves critical for EV adoption (Shah *et al*., 2026; Adil Shah *et al*., 2025) [5, 1], recycling and second-life infrastructure will prove essential for long-term EV ecosystem sustainability. The economic, environmental, and strategic imperatives for action are clear; the pathway forward demands sustained commitment, strategic investment, and collaborative execution across all stakeholders in the electric mobility revolution.

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