
Case for Recyclability of Lithium-ion

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The world is electrified, and finite resources fuel it, petrostates have long been in control of demand until the spark of the 21st century batteries, when electro states started to increase lithium sales to countries around the world for a demand in larger quantities for electric cars. This report examines the lifecycle and industry of lithium-ion batteries and why import-heavy demand countries should consider the incentives of recycling the modern energy storage metal.

The global transition to electrification has positioned lithium as a cornerstone of modern energy storage solutions. This report examines the full lifecycle of lithium-ion batteries (LIBs) through a systems thinking approach, from extraction processes in regions like Chile's Salar de Atacama to the refinement and assembly plants in China, to the end-of-life recycling challenges in countries that heavily import lithium-ion products.

Despite representing a critical component in decarbonization efforts, the LIB industry faces significant sustainability challenges: environmentally destructive extraction methods, social injustices in mining communities, inefficient recycling processes, and fragmented regulatory frameworks. Our analysis reveals that while lithium-ion battery recycling currently constitutes just 14.4% of the U.S. battery recycling market (\$158.8 million in revenue), the segment stands at a pivotal growth point as the first major wave of electric vehicle batteries reaches end-of-life between 2025-2030.

This report identifies key leverage points for intervention, including battery design for recyclability, policy standardization, technological innovation, consumer education, and cross-sector partnerships. By addressing these areas, stakeholders can transform the current linear extraction economy into a circular system that reduces environmental impact, promotes social justice, and ensures long-term economic viability of this essential industry.

Lithium Paradox: The Electrification Age, Who is keeping the lights on?

Lithium has become synonymous with the twenty-first century's electrification revolution. As described in the Material World, it forms "the heart of the most powerful batteries, and therefore the heart of the twenty-first-century world." The push to eliminate carbon emissions and phase out fossil fuels has accelerated the demand for lithium-ion batteries in applications ranging from consumer electronics to electric vehicles and grid-scale energy storage solutions.

While batteries represent a critical link in achieving zero carbon emissions, their production creates a paradox: the very technologies enabling a sustainable energy future rely on extraction processes that can cause significant environmental degradation and social disruption. The mining,

processing, and end-of-life management of these batteries present complex challenges requiring systematic approaches to ensure true sustainability.

However, lithium is 99.83% recyclable and reusable. Therefore, through systems thinking, integration of new technologies and tracking products with recycled lithium-ion batteries, countries can increase their exports of lithium to be reused in new devices that require the same core components.

The Core Problem: The Lithium-ion Battery Industry's Problems are Interconnected

The lithium-ion battery lifecycle represents a complex system with multiple interconnected components. The problem is deeper than just building the facilities. It has to do with global logistics and trade. China dominates the assembly and refining market—they are where the devices receive life so to say. The designs are sent to China from the US and other countries, the lithium from Australia, Central America, or China meets it in China at the factory plant. Recycling it would require another journey back to the assembly plant, and then back to the importing country. From this we figured that the lithium we recycle could be stockpiled, used in the current lithium-ion battery recycling industry we have—14.4% of the total American battery market, and weaved into the economy.

Traditional approaches often address individual aspects of this system in isolation, leading to fragmented solutions that fail to address underlying challenges. Systems thinking offers a more holistic perspective by examining the relationships between stakeholders and processes, identifying feedback loops, and understanding the long-term implications of interventions.

Systems thinking for lithium battery sustainability is built on three foundational principles:

Feedback Loops: The outputs of the system influence future inputs and behaviors. For example, the economic impact of recycling on lithium prices can create incentives that drive innovation in recycling technologies.

Interconnections: Every component of the lithium lifecycle influences others. Battery design affects recycling efficiency; consumer behavior impacts collection rates; and regulatory frameworks shape manufacturing practices.

Holistic Perspective: Rather than addressing isolated issues, systems thinking encourages examination of the entire lithium-ion battery lifecycle from extraction to disposal.

The challenge of lithium recycling is influenced by several socio-political, economic, and environmental factors. Economically, the value of lithium as a critical raw material for renewable energy technologies and electric mobility drives demand but also fuels competition among nations and industries for access to lithium resources. Environmentally, mining and extracting lithium causes significant ecological damage, including habitat destruction and water contamination while the end-of-life waste management has shown to be a safety concern with improper disposal. Socio-politically, national and international policies related to waste management, recycling standards, and climate change are shaping the landscape of lithium recycling, with varying levels of

regulation and support across different regions. The lack of uniform global standards for lithium recycling further complicates the issue.

The key stakeholders in the lithium recycling challenge include:

- **Battery manufacturers:** Companies responsible for producing lithium-ion batteries and their components.
- **Lithium Recyclers:** Minimizing processing cost and maximizing Li extraction, they are a company that collects and processes lithium-ion batteries to recover valuable finite metals.
- **Consumers in sales market:** Businesses and individuals who purchase lithium-containing products such as batteries.
- **State/Local governments:** State and Local governments that regulate and enforce waste management, recycling and environmental protection policies in their specific regions, that interface more closely with their constituents.
- **Federal/National/Regional/Global governmental bodies:** National governments and global authorities that regulate waste management, recycling standards, and environmental protection policies.
- **Citizen populations:** Citizens of a nation that are impacted economically or environmentally by the Li and battery industry, but have no further impacts
- **Waste Management:** Business or agency that handles the process of handling and recycling lithium-ion batteries that are no longer in use.
- **Third Party Maintainers (Repair and Maintenance):** a business or process for the upkeep of batteries through recharging or maintenance on battery bodies to extend the use of life.
- **Second Life Firms (Second-Hand Resellers):** Organization that, upon reaching end of life with their primary use in applications, rebuild and repurpose batteries for use in other energy demanding uses.
- **Marketers and Sellers:** Professionals or businesses engaged in the promotion, distribution and sale of lithium and lithium based products.

The lithium recycling challenge involves complex and dynamic interrelationships between technological, economic, and regulatory factors. The efficiency of recycling processes is constrained by technological limitations, such as the difficulty of extracting lithium from used batteries without causing contamination or significant energy consumption or the capability degradation. Economic considerations, including the cost of recycling compared to mining new lithium, influence the scale of recycling operations. Additionally, feedback loops in the system create recurring patterns: as lithium demand grows, so too does the volume of waste batteries, yet the infrastructure to handle these materials lags behind. Past interventions, such as policies promoting recycling or subsidies for green technologies, have had varying degrees of success, but global solutions remain fragmented. The dynamics of the challenge thus revolve around improving recycling technology, creating economic incentives, and fostering international cooperation to address the growing stock of end-of-life lithium-ion batteries.

From the Map the System coursework we learned different ways to frame and approach the problem. We first focused on lithium-ion recycling, and as we zoomed out, we noticed that the overall market and structure had a lot to do with the problems faced by lithium recycling. It has to do with where the lithium ends up after use and how that drives us to mine for more lithium instead of reusing lithium already been used.

Ostrom's Institutional Analysis and Development Framework (IAD): Used to analyze governance structures and stakeholder interactions in resource management (Ostrom, 2009). The seven-step approach includes defining system boundaries, identifying actors, defining resources, analyzing governance mechanisms, evaluating outcomes, identifying success factors, and developing recommendations.

PESTLE Analysis: Applied to understand the broader contextual factors affecting battery lifecycle sustainability, including political, economic, social, technological, legal, and environmental dimensions (Yüksel, 2012).

Iceberg Model:

- **Level 1 (Events):** What is happening in lithium extraction and recycling?
- **Level 2 (Patterns):** What trends are emerging over time?
- **Level 3 (Structures):** What underlying systems create these patterns in the market and create the challenges of input and output in lithium?
- **Level 4 (Mental Models):** What values and assumptions shape the system?

Systems thinking provides several key advantages for addressing lithium battery challenges including positive reinforced perspectives, identifying leverage points from within the tree graph, and preventing unintended consequences from upstream actions.

By considering the entire lifecycle, systems thinking helps avoid short-term solutions that may have unintended consequences. For instance, focusing solely on increasing recycling rates without addressing upstream extraction impacts could perpetuate unsustainable practices.

Analysis of the whole system reveals where small changes can lead to significant improvements. For example, supporting research into better recycling technologies or incentivizing battery designs that facilitate recycling.

A comprehensive understanding of system interconnections helps predict potential side effects of interventions, allowing for the design of solutions that minimize harm. Our rough models and system design acknowledges these potential side effects and gives us a clear view of what can be improved by what our plan seems to touch.

Because of this approach, we are able to see the challenges in our own thinking and plans and address them before shovels get in the dirt. Technologies and the things that fuel them have awarded us the opportunity to spend more time thinking about how we can solve problems, it is

best we use the benefit electricity, lithium, and raw resources we must make more out of what is to come.

Analysis of global lithium production data reveals significant geographic concentration of resources. Chile holds 29% of global reserves, primarily located in the Salar de Atacama region. Australia has emerged as the leading producer of lithium from hard rock sources, accounting for 44% of global production. Argentina possesses 9% of global lithium reserves, while Bolivia contains a substantial 21% of global reserves, though with limited current production capacity. China presents a particularly notable case, controlling only 7% of reserves but dominating with 60% of global processing capacity.

This concentration has created what some researchers term "electro states" with growing geopolitical influence paralleling historic "petrostates" (O'Sullivan et al., 2017). We argue that countries that embrace recycling will become part of the "electro state" guild and provide greater economic advantages and quicker adoption of a more carbon free world.

Brine Extraction: Primarily in the "Lithium Triangle" of Chile, Argentina, and Bolivia, this process involves pumping lithium-rich brines from beneath salt flats into evaporation ponds, where the water evaporates over 12-18 months, leaving behind concentrated lithium chloride.

Hard Rock Mining: Predominantly in Australia, this method involves extracting lithium-bearing minerals like spodumene from open-pit mines, followed by crushing, heating, and chemical processing.

Recycling:

The lithium supply chain currently follows a predominantly linear path:

1. **Extraction** from geographically concentrated sources
2. **Refining** in specialized facilities
3. **Manufacturing** dominated by China
4. **Distribution** to global markets
5. **Use Phase** (3+ years for consumer electronics, 8-12 years for EVs)
6. **Disposal** with limited recycling

While lithium is often touted as being "99.83% recyclable," this claim requires important context. As an element, lithium can theoretically be recovered and reused multiple times without degradation of its fundamental properties, supporting the notion of near-perfect recyclability. However, the practical reality tells a different story. Current recycling processes achieve variable recovery rates between 40-95%, depending on the technology employed, battery design, and economic considerations. Less than 10% of lithium-ion batteries are actually recycled globally, with many recycling operations prioritizing more valuable materials like cobalt and nickel over lithium recovery.

The methods used significantly impact recovery efficiency. Pyrometallurgical processes, which use high-temperature smelting, typically recover cobalt and nickel but often lose lithium to slag, with recovery rates of just 0-30%. Hydrometallurgical processes employing chemical leaching can recover 50-80% of lithium alongside other metals, while emerging direct recycling approaches aim to preserve cathode structures with potential recovery rates of 80-95%, though these remain in early commercialization stages.

Several factors explain the gap between theoretical recyclability and current practice. Economic barriers arise when recovery costs exceed lithium's market value, particularly during price downturns. Technical challenges in separating lithium from other battery components, combined with designs that don't prioritize recyclability, further complicate recovery efforts. Infrastructure gaps in collection and processing capacity also limit recycling rates across many regions.

Despite these challenges, the future looks promising as research advances lithium recovery methods. Advanced hydrometallurgical processes show potential for exceeding 90% lithium recovery, while direct recycling approaches could preserve more material value. Design-for-recycling initiatives aim to make future batteries inherently more recyclable, and rising lithium prices improve the economic case for recovery. The challenge isn't whether lithium can be recycled, but developing the technologies, infrastructure, and economic conditions to make high-efficiency recycling commercially viable at scale as we transition to an increasingly electrified future.

In addressing the challenge of recycling lithium batteries at the end of life, several solutions and interventions have been implemented. These efforts primarily focus on the technological, regulatory, and economic aspects of lithium-ion battery recycling. Understanding the current solutions provides insight into their effectiveness and reveals areas where further development or change is needed.

Current solutions to lithium-ion battery recycling are multifaceted, involving both established and emerging strategies. These include:

- **Battery collection and recycling programs:** Several countries and regions have implemented collection systems, such as dedicated recycling bins or take-back schemes, to ensure spent batteries are properly disposed of and recycled. Some programs are supported by manufacturers who are required to meet recycling targets as part of extended producer responsibility (EPR) laws.
- **Recycling technologies:** Various methods for recycling lithium-ion batteries have been developed, including mechanical processes (e.g., shredding and sorting), pyrometallurgical processes (smelting), and hydrometallurgical processes (leaching). These technologies aim to recover valuable materials such as lithium, cobalt, and nickel, which can be reused in the production of new batteries.
- **Regulatory:** Many governments have introduced regulations to encourage recycling, such as bans on landfilling spent batteries, mandatory recycling quotas for manufacturers, and financial incentives for recycling facilities. The European Union's Waste Electrical and

Electronic Equipment (WEEE) Directive and the Battery Directive are key examples of regulations aimed at reducing waste and promoting recycling.

The existing solutions offer certain strengths but also face significant weaknesses:

- **Strengths:**
 - Increased awareness and participation: EPR programs and public awareness campaigns have led to higher rates of battery collection and recycling in some regions.
 - Advancements in recycling technology: Some recycling methods, like hydrometallurgical processing, have shown promise in improving the recovery rate of valuable materials from spent batteries.
 - Regulatory support: Government regulations and policies, such as mandatory recycling targets, have created incentives for industry players to invest in recycling infrastructure and improve the sustainability of lithium-ion batteries.

- **Weaknesses:**
 - Limited scalability: While recycling programs and technologies have seen success in some areas, they are not yet widely scalable. Many regions still lack adequate infrastructure, resulting in limited access to recycling services, especially in developing countries or rural areas.
 - Inefficient recycling methods: Despite technological advancements, many existing recycling methods still face challenges in terms of efficiency, cost, and the recovery rate of lithium and other critical materials. For example, mechanical processes often result in the loss of valuable materials, while smelting can be environmentally harmful.
 - High cost of recycling: The cost of recycling lithium-ion batteries can be high, particularly when compared to the cost of extracting new lithium from mines. This creates a financial disincentive for businesses to prioritize recycling, especially if demand for recycled materials is low or volatile.
 - Regulatory inconsistencies: While there are some regulations in place, they are often fragmented, with varying requirements and enforcement levels across countries. This lack of standardization creates challenges for manufacturers and recyclers operating in different jurisdictions and may hinder global collaboration.

Unit Economics: The weight of the world's lightest element

The lithium-ion battery recycling segment represents a rapidly evolving component of the broader battery recycling industry, currently accounting for 14.4% of the U.S. battery recycling efforts (IBISWorld, Industry Report on Battery Recycling). It accounts for \$158.8 million in YTD annual

revenue in the United States. Despite its relatively modest size compared to lead-acid battery recycling, the lithium-ion segment is positioned for an uptick in growth driven by the electric vehicle battery depletion, expanding energy storage applications, and growing environmental concerns regarding critical mineral supply chains.

Despite its relatively modest size compared to lead-acid battery recycling, this segment is positioned for significant growth as electric vehicle adoption accelerates and energy storage deployments increase. The lead-acid battery recycling for cars is near 99% in the United States. Lithium-ion has more incentive as lithium is recyclable up to 99.83% efficacy. Technological advances, volatile material prices, regulatory pressures, and sustainability imperatives are transforming the economic fundamentals of lithium-ion recycling from a cost center to a strategic resource recovery opportunity.

Lithium-ion battery recycling represents a specialized segment within the broader recycling industry. Based on the analyzed data, while traditional lead-acid battery recycling dominates the current market (68.1%), the lithium-ion segment has established a significant position at 14.4% of the market, representing approximately \$158.8 million in annual revenue (IBISWorld, Industry Report on Battery Recycling). Despite its relatively modest size compared to lead-acid battery recycling, the lithium-ion segment is positioned for an uptick in growth driven by electric vehicle battery depletion, expanding energy storage applications, and growing environmental concerns regarding critical mineral supply chains.

The growth of this segment has been driven by several factors: increasing volumes of end-of-life lithium-ion batteries from consumer electronics, early returns of electric vehicle batteries, growing recognition of lithium as a critical material with supply constraints, and regulatory requirements for proper battery disposal and recycling.

We modeled the lithium-ion recycling process with working estimates until further research is completed and found the following associated costs in the initial assessment. The lithium-ion recycling value chain involves several economically distinct stages that affect overall viability. Collection and logistics currently represent 15-25% of total costs, while sorting and disassembly remain labor-intensive and account for 20-30% of costs. The technically complex material processing for recovering valuable materials constitutes 40-50% of costs, with the final refinement stage preparing recovered materials for reuse at 10-15% of costs. Economic viability varies significantly across battery chemistries, with higher cobalt content traditionally improving economics due to its high value. The price volatility of lithium carbonate, which ranged from \$70,000 to \$112,000 per ton in 2024-2025, creates both challenges and opportunities for recyclers navigating this emerging market.

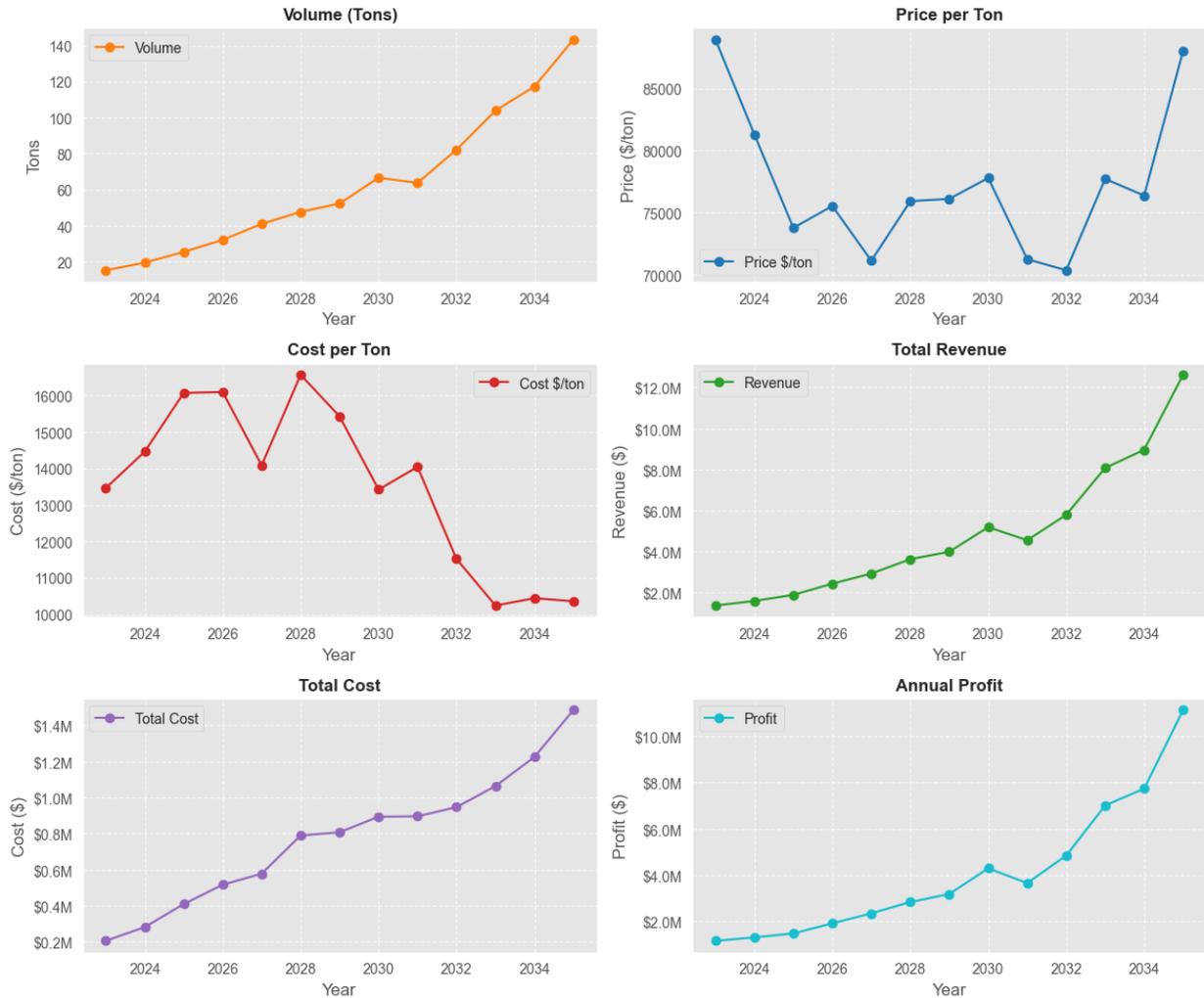
Figure 1: Trading Economics TTM Lithium Prices



source: tradingeconomics.com

The current value of lithium is approximately \$72,000 per ton, making material recovery increasingly economical. Recycling offers a domestic supply alternative, reducing import dependence and creating economic resilience against supply shocks—whether purposeful or unintentional. Each percentage point of lithium demand met through recycling rather than imports represents both economic security and value retention within the domestic economy. Given its strategic location, the United States could potentially serve both European and Asian markets with recycled lithium.

Figure 2: Rough estimates for projections based on IBISWorld and Trading Economics



Technological innovation is also transforming lithium-ion recycling economics through three predominant approaches. Pyrometallurgical processes using high-temperature smelting are currently most common. Hydrometallurgical processes employing chemical leaching and precipitation are seeing growing adoption. Direct recycling, which involves emerging physical separation methods that preserve cathode structures, is in early commercialization. Additional advances include automation reducing labor costs in battery disassembly and sorting, improved battery diagnostics to better assess reuse potential before recycling, and standardized designs reducing processing complexity and costs. These technologies are steadily improving the cost structure, with material recovery efficiencies increasing from 40-50% a decade ago to 70-95% in advanced processes today.

Government intervention is increasingly reshaping lithium-ion recycling economics. Battery regulations such as the EU Battery Directive, US state regulations, and Chinese policies are mandating recycling across markets. Extended Producer Responsibility frameworks are shifting recycling costs to automotive and electronics manufacturers. Emerging recycled content requirements are creating guaranteed markets for recovered materials, while landfill bans on batteries create de facto recycling channels. Government research funding for advanced recycling technologies further accelerates innovation in this space.

The lithium supply chain currently follows a largely linear path that presents opportunities for circular transformation. Extraction is concentrated geographically in Australia, the "Lithium Triangle" of Argentina, Bolivia, and Chile, China, Utah's Great Salt Lake, and emerging sources in Canada, Mexico, Zimbabwe, and Congo. Refining occurs in specialized facilities like Salar del Carmen, Chile (the world's largest refinery run by SQM), Albemarle facilities, and various processing plants in China, with emerging facilities in Australia, North America, and Europe. Manufacturing remains dominated by China, which produces approximately 76% of lithium-ion batteries. After global distribution and a typical use phase of 3+ years for consumer electronics and 8-12 years for EV batteries, materials can be recovered through recycling.

The vision is to transform this linear model into a circular economy where recycled lithium enters new battery production within a year of recycling. For example, batteries recycled in 2028 could supply materials for 2029 model year vehicles, reducing the need for newly extracted lithium and creating a more sustainable, economically efficient system.

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The electric vehicle revolution represents the largest economic opportunity for lithium-ion recycling. The first major wave of EV batteries will reach end-of-life between 2025-2030, creating unprecedented volume for recyclers. Larger, more standardized EV batteries improve the economic efficiency of recycling operations. Automotive manufacturers are already investing in recycling to secure material supplies, while closed-loop systems enabling direct integration of recycled materials into new battery production are beginning to emerge. EV battery recycling alone could potentially expand the lithium-ion recycling market by 5-10 times by 2030 based on projected retirement rates.

New business models are enhancing the economic viability of lithium-ion recycling. Battery-as-a-service approaches allow manufacturers to retain ownership, guaranteeing end-of-life collection. Second-life applications extract additional value through energy storage reuse before recycling. Recycling-as-a-service enables specialized firms to partner with manufacturers for guaranteed material streams. Material buyback agreements provide stable pricing for recovered materials through long-term contracts, while mobile processing reduces transportation costs by processing at collection points.

Vertical integration with battery manufacturing creates important economic synergies for recyclers. Co-location of recycling facilities alongside battery manufacturing reduces logistics costs. Aligning material specifications ensures recycled materials meet manufacturing requirements. Process waste recovery captures and recycles manufacturing scrap, creating additional value streams. Quality guarantees certifying recycled materials for high-value applications further improve economics by enabling premium pricing.

Environment: How much do we have to change it to never have to use it again?

The environmental impacts of LIBs span their entire lifecycle, creating a chain of ecological disruptions. In extraction regions, the consequences are severe and multifaceted. Water usage in lithium production is particularly problematic—Chile's Salar de Atacama operations consume 65% of the region's water supply, with approximately 500,000 gallons required per ton of lithium. Land transformation is equally concerning, with 23% of land in South American salt flats altered by mining operations and 170,000 hectares of Indonesian rainforest lost to nickel mining for battery components.

The carbon footprint contradicts the "clean energy" narrative, with production of one ton of lithium carbonate generating approximately 15 tons of CO₂-equivalent emissions. This is largely because 80% of the global LIB supply chain relies on coal-powered electricity, particularly in China, resulting in 55 million metric tons of CO₂ annually from the industry. End-of-life management remains problematic, with less than 10% of LIBs recycled globally and an estimated 11 million metric tons of LIB waste expected by 2030 if current practices continue.

Human and Social Costs: At what cost of others' time and energy do we achieve our goals?

The social impacts of LIB production disproportionately affect vulnerable populations in resource-rich regions. Labor exploitation is endemic throughout the supply chain. In the Democratic Republic of Congo, which produces 70% of the world's cobalt, approximately 40,000 children work in artisanal mines, with adult miners earning as little as \$80 monthly—far below the \$402 living wage. Hazardous working conditions are common, with 80% of DRC cobalt miners suffering from chronic respiratory diseases.

Community displacement represents another significant social cost. Bauxite mining in Guinea has displaced over 200,000 people from their ancestral lands, while nickel mining in Indonesia has forced relocations with compensation below 20% of land market value. These operations contaminate water sources—80% of local water in Guinea's mining regions contains heavy metals exceeding safe limits by 300-400%, creating public health crises.

The distribution of benefits reveals stark inequities. Despite producing 70% of global cobalt, the DRC receives less than 5% of total revenue from the LIB industry. Mining contracts are frequently secured through corruption, with documented cases of government officials receiving kickbacks in exchange for environmental regulation exemptions. Women and marginalized groups bear disproportionate burdens, with mining operations linked to increased gender-based violence and forced early marriages in economically destabilized communities.

Legislation: The aggregation of the social and political wishes of people and firms

The regulatory landscape governing lithium-ion batteries has evolved considerably over the past two decades, with jurisdictions implementing increasingly comprehensive frameworks to address environmental and safety concerns. In the United States, the Resource Conservation and Recovery Act (RCRA) provides the foundational federal framework for hazardous waste management, though it wasn't specifically designed for battery waste. More targeted legislation has emerged at both

federal and state levels, with California leading through Assembly Bill 2440 (2021), which established one of the nation's first comprehensive lithium-ion battery recycling programs with mandatory producer responsibility requirements. At the federal level, the Battery Act (2020) and the Responsible Battery Recycling Act (2021) represent attempts to create nationwide standards, though their implementation has been fragmented compared to more centralized regulatory approaches elsewhere.

The European Union has developed the world's most comprehensive battery regulatory framework, beginning with the Battery Directive (2006/66/EC) that established collection targets and producer responsibilities for all battery types. This was reinforced by the broader Waste Framework Directive (2008/98/EC), which established the waste hierarchy prioritizing reduction, reuse, and recycling. The EU significantly expanded its approach through the Circular Economy Action Plan (2020) and the subsequent EU Batteries Regulation Proposal (2020), which introduces lifecycle carbon footprint declarations, minimum recycled content requirements, and enhanced due diligence obligations for raw materials. These regulations create a progressive framework that addresses both environmental impacts and social considerations throughout the battery value chain.

China has pursued a different regulatory strategy, focusing on top-down industrial policy that integrates manufacturing and recycling considerations. China's Circular Economy Promotion Law (2009) established the foundation for resource recovery, while more recent Battery Management and Recycling Laws implement Extended Producer Responsibility (EPR) principles that hold manufacturers accountable for end-of-life management. What distinguishes China's approach is the direct regulation of manufacturers, with stringent requirements for design, material use, and recycling infrastructure that have accelerated domestic capacity development. Internationally, the International Electrotechnical Commission (IEC) has developed technical standards for battery safety, performance, and recycling, though these lack the enforcement mechanisms of national legislation.

The effectiveness of these regulatory frameworks varies considerably based on implementation capacity and stakeholder engagement. Primary stakeholders include citizen populations who generate battery waste, federal and state/local governments who enforce regulations, and battery manufacturers who must comply with requirements. The point of regulatory intervention significantly affects outcomes—regulations targeting design specifications tend to facilitate recycling but may constrain innovation, while collection mandates address immediate waste concerns but not underlying material flows. China's approach of heavily regulating manufacturers has created rapid industrial adaptation but raises questions about market competition. As lithium-ion battery use continues to expand globally, these regulatory approaches are likely to converge toward more comprehensive lifecycle management frameworks that balance environmental protection, resource recovery, and economic viability across the entire battery value chain.

The recommendations that our team has agreed upon and think would stimulate recycling lithium are for policy makers, manufacturers, recyclers, investors, and consumers.

FOR POLICYMAKERS: MARKET MECHANISMS THAT DRIVE INVESTMENT

- **IMPLEMENT TRADABLE RECYCLING CREDITS** to create immediate financial upside for battery collection, similar to carbon markets but focused on material recovery rates.
- **ESTABLISH TAX ADVANTAGES** for manufacturers using recycled content, creating direct margin benefits that drive demand for recovered materials.
- **CREATE SOVEREIGN MATERIAL FUNDS** that invest in domestic recycling infrastructure, reducing import dependencies while generating returns through material appreciation.
- **DEVELOP PRICE STABILITY MECHANISMS** that reduce volatility risks, encouraging long-term capital investment in recycling operations.

FOR MANUFACTURERS: COMPETITIVE ADVANTAGES THROUGH CIRCULARITY

- **ADOPT VERTICAL INTEGRATION STRATEGIES** with recyclers to secure price-advantaged material inputs while hedging against supply disruptions.
- **REDESIGN PRODUCTS FOR VALUE RECOVERY**, increasing end-of-life material yields by 15-30% and creating premium recovery streams.
- **LAUNCH CORE EXCHANGE PROGRAMS** offering consumer discounts on new purchases when returning used batteries, creating customer loyalty while securing feedstock.
- **DEVELOP MATERIAL PASSPORTS** that increase recovered material value through improved sorting efficiency and purity.

FOR RECYCLERS: HIGH-GROWTH BUSINESS OPPORTUNITIES

- **ESTABLISH LONG-TERM OFFTAKE AGREEMENTS** with manufacturers to secure capital investment returns through guaranteed material demand.
- **OPTIMIZE FOR CHEMISTRY-SPECIFIC PROCESSING** to maximize recovery of highest-value components (cobalt, nickel) while developing lithium recovery capabilities.
- **IMPLEMENT RECYCLING-AS-A-SERVICE MODELS** that create recurring revenue streams rather than transaction-based economics.
- **DEVELOP REGIONAL PROCESSING HUBS** that minimize transportation costs while achieving scale economies in specialized recovery processes.

FOR INVESTORS AND FINANCIAL INSTITUTIONS:

- **DEPLOY CAPITAL IN EMERGING RECYCLING TECHNOLOGIES** that demonstrate superior recovery yields, particularly for direct recycling methods showing 80-95% material recovery potential.
- **DEVELOP FINANCING INSTRUMENTS** for battery manufacturers that incentivize design-for-recyclability through preferential terms.
- **CREATE COMMODITY HEDGING PRODUCTS** specific to battery materials that reduce price volatility risks for recyclers and manufacturers.
- **ESTABLISH DEDICATED CIRCULAR ECONOMY FUNDS** targeting the 5-10x market expansion projected by 2030.

FOR CONSUMERS AND COMMUNITIES:

- **LEVERAGE BUYING POWER** toward products with trade-in value guarantees that reflect battery material content.
- **PURSUE COMMUNITY-SCALE ECONOMIC DEVELOPMENT** through recycling infrastructure that creates local jobs while reducing waste management costs.
- **NEGOTIATE RESOURCE AGREEMENTS** that ensure extraction regions capture greater value from their natural resources through equity participation rather than mere royalties.

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This research has examined the economic dimensions of the lithium-ion battery lifecycle, revealing significant market inefficiencies in the current predominantly linear model. Our analysis demonstrates that the global supply chain configuration creates substantial economic vulnerabilities, with China's control of 60% of refining capacity and 76% of battery manufacturing presenting notable supplier concentration risks. The resulting economic imbalances are evident in the United States' modest \$158.8 million battery recycling market (2023) despite significant domestic battery demand, illustrating how importing nations effectively export both materials and economic value.

Labor economics throughout the supply chain further compound these inefficiencies. In the Democratic Republic of Congo, which produces 70% of global cobalt, miners earn approximately \$80 monthly against a living wage of \$402, representing artificially suppressed labor costs that distort true production economics while leaving significant human capital potential untapped. These distortions ripple throughout the value chain, affecting price signals and resource allocation decisions.

Our findings indicate substantial market transformation opportunities as the battery recycling sector projects a 21.9% CAGR (2023-2030). The approaching wave of end-of-life electric vehicle batteries (2025-2030) creates a distinct first-mover advantage for businesses developing recycling infrastructure ahead of this demand surge. Scale economics strongly favor early market entrants, with research indicating minimum efficient scale for lithium-ion recycling at approximately 25,000 metric tons annual processing capacity.

The research identifies specific market-driven interventions for key stakeholders that align profit incentives with sustainability outcomes. For policymakers, these include tradable recycling credits and tax advantages for recycled content utilization. Manufacturers can gain competitive advantages through vertical integration with recyclers and product redesign for enhanced value recovery. Recyclers stand to capture high-growth business opportunities through long-term offtake agreements and chemistry-specific processing optimization.

Future research should quantify the economic benefits of specific circular economy interventions, particularly focusing on price stability effects and supply security enhancements. Additionally, developing standardized methodologies for assessing the full economic value of recovered materials would strengthen the business case for accelerated investment. A comprehensive

economic assessment of various policy mechanisms could further identify optimal approaches for market transformation.

The transition to a circular lithium-ion battery economy represents not merely an environmental imperative but a significant economic opportunity. By realigning market incentives to capture currently stranded material value, stakeholders can simultaneously enhance economic returns while addressing sustainability concerns. The findings suggest that proactive investment in circular material flows offers strategic advantages in an increasingly resource-constrained global economy, transforming what has been viewed as an environmental challenge into a compelling economic opportunity.

Battery Recycling in the US Industry Report (OD4511), IBISWorld, 2025

Lithium Battery Manufacturing in the US Industry Report (OD4499), IBISWorld, 2025

Lithium Carbonate Price Data (2024-2025), Trading Economics, TTM