Regulatory frameworks and economic instruments for promoting a circular economy in electric vehicle battery and material supply chains

Issah Babatunde Majeed[1*], *Ernest* Boadu Osei[2], *Bernard* Arthur-Aidoo[3], and *Peter* Nyanor[4]

[1]Department of Electrical and Electronics Engineering, Accra Technical University, Accra, Ghana
[2]Department of Data Science and Analytics, Thrive Africa, Accra, Ghana
[3]Department of Building Technology, Accra Technical University, Accra, Ghana
[4]Department of Mechanical Engineering, Accra Technical University, Accra, Ghana

Abstract. Global electric vehicle (EV) battery supply chains are predominantly linear, as end-of-life lithium-ion batteries lack formal recycling. This paper explores how regulatory frameworks and economic tools can accelerate the transition of EV battery and critical mineral supply chains into a circular economy. A document-based, qualitative design approach was used, including lifecycle regulatory analysis, cost-revenue feasibility modelling, comparative policy benchmarking, and structured interviews with ten sector-specialist informants across four jurisdictions: the European Union, China, South Korea, and the United States. The results showed that producer responsibility systems with long-term producer liability have a greater investment effect than collective ones. Hydrometallurgical recycling is economically viable at a price of Lithium carbonate above $18,000 per tonne, but with a combination of policy initiatives, this drops to $ 9,000 per tonne. Green procurement specifications changed supplier behaviour, with certified suppliers showing evidence of 15-25% increases in volumes of public contracts. This research bridges a critical gap between regulatory analysis and commercial feasibility and identifies the integration of emerging economies into circular battery governance as an under-researched academic priority.

1. Introduction

Electric mobility is transforming the global industry. EV sales exceeded 10 million in 2023, and more than 60% of new vehicle sales are projected to be electric by 2030 [1]. Battery production depends on lithium, cobalt, nickel, and manganese, whose geographically concentrated extraction creates environmental and geopolitical challenges [2]. Strategic minerals increasingly shape energy security, industrial competitiveness, and environmental sustainability. The Democratic Republic of the Congo supplies most of the world's cobalt, while the Lithium Triangle, which includes Chile, Argentina and Bolivia, dominates lithium production [3]. The geographic concentration of EV supply chains increases vulnerability to disruption, illustrated by lithium carbonate prices rising more than 400% during 2021–2022 [4, 5].

Against this backdrop, the notion of a circular economy (CE) has become an inspiring policy and business response to resource scarcity and waste accumulation in battery supply chains [6]. The circular economy seeks to decouple growth from finite resources through reuse, repair, remanufacturing, and recycling [7]. For EV batteries, circularity encompasses eco-design, second-life applications, and material recovery via recycling.

New regulatory systems play a critical role in facilitating this change. The Battery Regulation by the European Union (EU 2023/1542) may be the most detailed legislative tool to date for introducing mandatory recycled-content levels, carbon-footprint statements, and collection-rate targets for both industrial and EV batteries [8, 9]. Moreover, Shqairat et al. asserted that the same regulatory motivation is evident in Extended Producer Responsibility (EPR) in China, New Energy Vehicle Batteries, and the South Korean Resource Circulation Act, indicating a global shift towards lifecycle management of battery materials [9].

Economic instruments complement regulation by improving the business case for circularity. These include carbon pricing, eco-modulation, sustainable design reward-fee policies, and public procurement policies that establish captive demand for recycled-content goods. However, the relationship between regulatory ambition and market readiness remains contested [5].

Despite rising regulatory scrutiny, global EV battery supply chains remain predominantly linear. Fewer than 5% of end-of-life lithium-ion batteries enter formal recycling systems globally [1]. This reflects inadequate collection systems, weak economic incentives, and fragmented regulatory enforcement [9]. Managing end-of-life batteries is challenging due to a lack of strict regulations, leading to illegal disposal, environmental hazards, and GHG emissions, undermining the EV transition.

Mineral price volatility compounds these difficulties. Because recycling profitability depends

*Corresponding author: issahmajeed@gmail.org

directly on the values of recovered lithium, cobalt, and nickel [10], price declines compress margins and threaten financial viability without subsidies [5]. The recycling operations face financial difficulties when commodity prices drop, as profit margins narrow, making them unsustainable without government assistance [5]. Geopolitical tensions, including export restrictions on critical minerals, create market uncertainty, making it difficult for businesses to invest capital over extended periods [9]. The current economic framework offers limited, fragmented support for second-life battery applications and recycling. While EV batteries have potential for stationary energy storage, many regions lack regulatory and commercial structures to establish a second-life market. Growth is restricted by the absence of standardised health metrics, liability frameworks, and grid standards [2, 5, 9].

This study addresses four core objectives: evaluating the effectiveness of EPR systems in driving EV battery circularity; modelling policy impacts on recycling and second-life financial break-even points; assessing the effects of trade regulation on mineral security and resilience; and examining green procurement frameworks for sustainable material sourcing.

The paper was guided by four research questions: (i) The study investigates the effectiveness of EPR frameworks, which drive circular outcomes in EV battery supply chains through their specific design elements. (ii) The study assesses which economic conditions make battery recycling profitable while examining how policy instruments impact the break-even point. (iii) International trade policies, which include export restrictions and strategic bilateral agreements, will determine how both mineral security and supply chain resilience are affected. (iv) The study investigates which procurement incentives achieve maximum success in promoting sustainable material sourcing while assessing their effects on long-term economic competitiveness.

The paper makes a significant contribution by integrating sustainable engineering systems with economic governance through comprehensive lifecycle policy analysis and cost-revenue modelling. It bridges the domains of electric vehicle (EV) battery engineering, material performance, and policy formulation, thereby offering valuable interdisciplinary insights. The findings indicate that regulatory coherence, transparent investment signals, and strategic resource management collectively influence the effectiveness of the circular economy within high-technology manufacturing sectors and underpin wider decarbonisation initiatives.

2. Methods and materials

2.1 Research design

The study uses a qualitative, document-based design that combines regulatory analysis, economic feasibility assessment, and comparative policy benchmarking. This approach studies circular economy governance over time in complex systems. Regulatory analysis identifies requirements, economic assessment checks financial viability, and benchmarking compares jurisdictions for operational differences and best practices.

2.2 Data source

Data are drawn from secondary sources, including key policy documents such as the EU Battery Regulation (2023/1542), China's EPR Measures for NEV Batteries (2018, revised 2021), South Korea's Resource Circulation Act (2016), and the US Infrastructure Investment and Jobs Act (2021). Cost and revenue data originate from Benchmark Mineral Intelligence, BloombergNEF, and Circular Energy Storage. Trade data come from the International Trade Centre, OECD databases, and customs records. Second-life battery insights are drawn from reports by RMI, Fraunhofer ISI, and the IEA [1, 11].

Ten experts from regulators, industry, and research institutions were interviewed using a structured protocol on EPR design, economic drivers, trade barriers, and green procurement. Thematic analysis and Cohen's kappa ensured reliability. Limitations include small sample size, selection bias, and social desirability bias, but triangulation and member checking helped validate results.

2.3 Analytical framework

The study is structured around four components: lifecycle policy analysis of regulatory instruments across extraction, manufacturing, use, reuse, and recycling stages; cost-revenue modelling using published data to estimate recycling and repurposing break-even points under varying prices and subsidies; trade policy analysis of tariffs, export controls, and agreements on supply chains; and institutional evaluation of incentives for circular economy actors.

The cost-revenue feasibility model defines the net margin per kilowatt-hour processed (NM) as in (1).

$$NM = R_{mat} + S_{pol} - C_{proc} - C_{trans} \tag{1}$$

The break-even lithium carbonate price P_{Li}^* in (2) occurs when $NM = 0$,

$$R_{mat}(P_{Li}^*) = C_{proc} + C_{trans} - S_{pol} \tag{2}$$

The study assumes that 88% of lithium will be recovered while maintaining transport costs at $0.45 per kilowatt-hour. Sensitivity analysis across five policy scenarios (testing lithium prices from $8,000/t to $30,000/t) showed a stable break-even point of $9,000/t, regardless of shifts in processing costs.

The study examines lithium-ion batteries, including NMC and LFP chemistries, and their supply chains, focusing on economic and regulatory aspects. It uses only secondary data and case studies, excluding primary quantitative modelling. Findings are analytical and limited by data. Table 1 summarises jurisdictions and policy tools.

Table 1. Summary of jurisdictions and key policy instruments examined

Jurisdiction	Key Regulatory Instrument	EPR Frame work	Recycling Target (Year)	Notable Feature
European Union	EU Battery Regulation 2023/1542	Yes	70% (2030)	Mandatory recycled content & carbon passport
China	EPR Measures for NEV Batteries	Yes	75% (2025)	Centralised producer registry; traceability system
South Korea	Resource Circulation Act (2016)	Yes	60% (2027)	Eco-design standards & state collection subsidies
United States	Infrastructure Investment & Jobs Act (2021)	Partial	50% (2030)	Federal grants for domestic recycling capacity

Source: Compiled from national regulatory documents [8, 12,13]

3. Results

Results are organised into four thematic domains aligned with the research questions. Interview extracts are italicized and coded by respondent, and findings are analyzed using both descriptive and evaluative approaches.

3.1 Extended producer responsibility effectiveness

Across the four jurisdictions, EPR frameworks improve battery collection outcomes, though effectiveness depends on design and enforcement capacity. As shown in Table 2, the EU Battery Regulation sets 65% collection targets for portable batteries and 70% for EV batteries for 2025 and 2030, respectively. China's traceability system achieves 75% compliance with registration requirements but lacks robust third-party auditing of collections.

"A recycling partnership delayed for two years was approved immediately after traceability regulations established individual producer responsibility, providing the regulatory certainty needed to justify investment and secure financial commitment." (IN02, Male, Head of Sustainability, Tier-1 EV Battery Manufacturer, Germany).

EPR frameworks use eco-design incentives via eco-modulation fees, helping producers save money if batteries meet disassembly and recyclability criteria. The Korean Resource Circulation Act shows eco-modulation spurs design changes that ease recycling cell-to-pack bonding. The economic effects of recycling remain limited until commodity prices enable workable gate-fee structures.

"Eco-design regulations compelled engineering teams to adopt innovative assembly methods, achieving improvements that internal initiatives had failed to deliver. The redesigned modules became easier to disassemble, reducing recycling costs and improving end-of-life processing efficiency. (IN05, Female, Chief Technology Officer, Battery Module Producer, South Korea).

EPR frameworks impose significant financial obligations on manufacturers. EU Battery Regulation cost models show fees increase battery pack costs by EUR 8-15, depending on market share and collection efficiency. Firms in concentrated markets pass costs to consumers, while non-compliant imports distort competition. Fragmented reporting increases compliance burdens for small producers.

Table 2. EPR collection rate performance across selected jurisdictions (2018–2023)

Jurisdiction	2018	2021	2023	Target (Year)	Enforcement Mechanism
	Collection Rate (%)				
European Union	38	47	58	70% (2030)	National competent authorities; fines up to 4% turnover
China	22	51	64	75% (2025)	Centralised registry; production licence suspension
South Korea	44	54	61	60% (2027)	Producer fee waivers; state audits
United States	18	27	34	50% (2030)	Grant conditionality; state-level variation

Source: Compiled from IEA [1], European Environment Agency [14], Korean Ministry of Environment [13], and BloombergNEF [15]

3.2 Economic viability of recycling and second-life applications

The economic feasibility of electric vehicle battery recycling depends on three interacting factors: the costs of processing operations, the revenues from recovered materials, and the financial assistance provided by government policies. The cost analysis, which uses data from BloombergNEF [15] and Circular Energy Storage, shows that the hydrometallurgical NMC 622 battery recycling process incurs processing expenses of \$1.20-\$1.80 per kilowatt-hour of battery capacity, while the pyrometallurgical process incurs \$0.80-\$1.20 per kilowatt-hour. Transport and pre-processing costs, like battery discharge and disassembly, add \$0.30 to \$0.60 per kWh, raising total expenses to \$1.10-\$2.40 per kWh, as shown in Table 3.

The economic viability of recycling operations depends entirely on the revenue streams generated by processed materials. The efficiency of hydrometallurgical processes for lithium recovery has historically been limited, but major companies can now achieve recovery rates of 85-92%. The market value of lithium recovery ranges from approximately $0.90 to $ 1.10 per kilowatt-hour, given a lithium carbonate price of $20,000 per tonne. Cobalt and nickel remain high-value co-products, with cobalt contributing $0.40–0.80 per kilowatt-hour, depending on cathode chemistry. The introduction of lower-cobalt NMC 811 and cobalt-free LFP chemistries requires policy instruments to offset their negative effects on recycling economics.

Second-life battery systems for stationary energy storage provide an essential revenue stream that aligns with core commercial activities. EV batteries retain 70 to 80% of their original capacity after their vehicles' operational lives end, making them suitable for less-demanding stationary storage applications, including grid frequency regulation, commercial peak shaving, and renewable energy buffering. The Rocky Mountain Institute's 2022 market analysis shows that the global second-life battery market will reach $ 30 billion by 2030.

"Second-life is not a charity project; it is a genuine value chain. Extending a battery's economic life through stationary storage use for five to seven years generates revenue, reduces future recycling costs, and provides essential grid services needed for the energy transition. The regulatory gap is the problem: there is no standardised state-of-health certification that gives energy storage buyers confidence." (IN08, Female, CEO, Second-Life Battery Integrator, Netherlands)

Table 3. Break-Even analysis for battery recycling under different policy scenarios

Policy Scenario	Processing Cost	Revenue at Li $ 20k/t	Break-Even Li Price ($/t)	Viability Assessment
No policy support	($/kWh)			Marginally viable; volatile
	1.70	1.85	~18,500	
EPR gate fee subsidy ($ 0.50/kWh)	1.70	1.85 + 0.50	~12,000	Viable across commodity cycles
Carbon credit revenue ($ 0.30/kWh)	1.70	1.85 + 0.30	~14,500	Viable in a moderate-price environment
EPR + carbon credit	1.70	1.85 + 0.80	~9,000	Robust; resilient to price shocks
Second-life pre-processing credit	1.20	1.85	~11,500	Viable; depends on SoH assessment cost.

Note: Li = Lithium carbonate; SoH = State of Health. Processing costs reflect mid-range hydrometallurgical estimates. Source: Author's analysis based on IEA [1], BloombergNEF [15], and Circular Energy Storage

3.3 Trade policy and raw material security

The current international trade framework for essential battery minerals is increasingly shaped by export restrictions, strategic international partnerships, and domestic content requirements, reflecting a growing shift toward a security-driven approach to critical mineral supply chains. Rather than relying solely on open-market mechanisms, governments are treating minerals such as lithium, cobalt, nickel, and graphite as strategic resources essential for the energy transition and industrial competitiveness. Resource-rich countries are adopting policies to retain greater value from mineral extraction, while importing nations are pursuing long-term supply agreements to secure stable access to critical raw materials.

As evinced in Table 4, Indonesia's 2020 ban on nickel ore exports aimed to drive domestic value creation through processing and serves as a model case study. It resulted in increased domestic nickel processing investments while causing processed nickel prices to rise by 12–18% according to international importing countries.

The export restrictions China imposed on graphite in 2023, given its role as a vital anode material, and China's dominance of over 70% of global cobalt refining capacity exemplify the fundamental supply chain risks faced by electric vehicle battery manufacturers.

"The graphite restrictions were a wake-up call for our procurement team. We had built a supply chain on the assumption that the lowest-cost global supplier would always be accessible. The restrictions demonstrated that we need to include geopolitical risk in our pricing for supply contracts while developing our strategy to diversify our suppliers, even if it leads to higher short-term expenses." (IN01, Male, VP of Supply Chain, Tier-1 EV Manufacturer, Japan)

Multilateral initiatives such as the US Minerals Security Partnership (MSP) and the EU Critical Raw Materials Act act as strategic measures to address vulnerabilities in bilateral supply chains. The MSP, operational since 2022, oversees investment and project development across its 14-member countries and enforces environmental and social governance standards. The EU Critical Raw Materials Act mandates that member states fulfil 10% of their strategic mineral requirements through domestic mining by 2030, whilst EU processing capacities will satisfy 40% of their strategic mineral demands, potentially leading to trade disputes with principal supplier nations.

“Bilateral agreements are useful but not enough on their own. The industry needs a multilateral governance system for critical minerals, similar to the Energy Charter, to protect investors, secure supply chains, and set environmental standards. The existing patchwork of bilateral deals creates notable gaps.” (IN09, Female, Senior Policy Advisor, International Energy Forum)

Table 4. Geopolitical concentration and supply risk indicators for key battery minerals (2022-2023)

Mineral	Share %		Price Volatility (±%)	Supply Disruption Risk	Domestic Recycling Potential (2030)
	Top Producer	Top Processor			
Lithium	Australia (47%)	China (58%)	±420%	High	35% of demand
Cobalt	DRC (70%)	China (72%)	±85%	Very High	45% of demand
Nickel	Indonesia (37%)	China (35%)	±55%	Moderate	28% of demand
Graphite (Anode)	China (65%)	China (90%)	±40%	Critical	20% of demand
Manganese	South Africa (35%)	China (95%)	±30%	High	25% of demand

Source: Compiled from Benchmark Mineral Intelligence [4] and IEA Critical Minerals Market Review

As shown in Figure 1 below, China has made the most significant progress, with its performance increasing from 22% in 2018 to 64% in 2023, the highest development rate among jurisdictions.

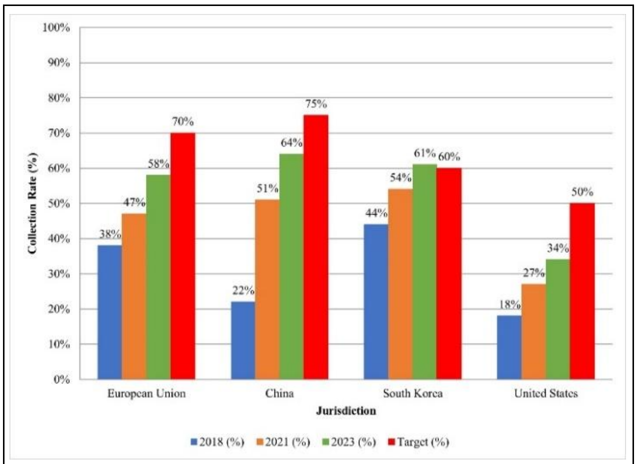

Fig. 1. EPR Battery Collection Rate Trends and Targets by Jurisdiction, 2018–2030

South Korea is the only jurisdiction that has already met or exceeded its target, which requires 61% in 2023 to reach a 60% goal by 2027. The European Union is on a steady upward trajectory, rising from 38% to 58%, as the organisation works to achieve its 70% target by 2030. The United States remains in last place because it achieved only 34% progress in 2023, falling short of its 50% target for 2030, due to its uncoordinated state-level enforcement system.

3.4 Green procurement and sustainable sourcing

The increasing importance of green procurement standards serves as a demand-side mechanism that helps businesses achieve sustainable sourcing practices. Public procurement accounts for approximately 12 per cent of GDP in OECD countries, representing substantial market influence. Public buyers must establish minimum recycled-content standards and responsible-sourcing certification requirements in line with the EU Green Public Procurement standards, which govern batteries under the Clean Vehicles Directive.

Initial pilot programs in Germany and Sweden show that suppliers altered their behaviour after setting a 12% recycled-cobalt and 4% recycled-lithium content requirement, with certified suppliers winning 15-25% more public contracts than non-certified ones.

"The Responsible Minerals Initiative certification we obtained helped us win public tenders by enhancing our competitiveness. The change to the procurement specification created two distinct supplier categories by establishing the precise incentive effect required by business objectives. The business case for certification would have lost most of its strength without the public procurement anchor." (IN04 Male Commercial Director Battery Materials Supplier Belgium)

Moreover, cost differences between conventional and sustainable sourcing pose an ongoing obstacle, preventing organisations from adopting sustainability practices in markets where procurement is not required. The certified cobalt, sourced responsibly under the Responsible Minerals Assurance Process certification system, sells at a price 8 to 14% above non-certified cobalt due to the costs of auditing, traceability, and custody management. Companies will achieve economic parity between recycled and primary lithium by 2027 to 2028, when recycled lithium production reaches commercial scale.

A country's economic competitiveness through green procurement standards affects its economy beyond the financial impact on its specific businesses. Countries that establish domestic recycled-content production facilities through procurement methods, such as Germany, which built its battery recycling system, gain operational advantages in circular-economy sectors that will expand over the next 20 years. Countries that postpone their circular economy standards will become dependent on imported recycled materials as regulations mandating recycled content become more common worldwide.

4. Discussions

The results confirm theories about circular economy governance, security of critical minerals, and green industrial policy and offer empirical evidence for some of the literature's arguments. They also generate fresh ideas that advance scholarship and are significant for the potential future development of public policy.

4.1 Regulatory coherence and market stability

The study confirms that individual producers' accountability in EPR settings leads to higher investment responses than collective responsibility settings. Individualised responsibility maintains producer-level incentives and enhances environmental performance better. Results from the GRS program in

Germany indicate that collective schemes undermine incentives for eco-design innovation and investment.

However, EPR is an effective policy tool, yet regulatory fragmentation continues to impede the instrument's efficiency. Administrative differences between jurisdictions call into question the premise that harmonisation will ensure efficiency. The findings from the interviews and collection rates data suggest the need for standardised reporting systems and cross-border data interoperability to minimise compliance costs. This data corroborates research indicating that effective implementation depends on having the right regulatory goals.

The study shows competitive distortions from inconsistent regulation and arbitrage, with producers shifting impacts by moving to looser standards. Programs like battery passports and border adjustment schemes can address this if equivalence assessments remain strict.

Lastly, harmonised recycling standards include unified technical specs and recovery efficiency standards. The EU Battery Regulation benchmarks this, but global regulatory fragmentation persists. Improved market stability, reduced regulatory arbitrage, and increased investment confidence require OECD-level recycling standards.

4.2 Investment signals and private sector response

Reducing regulation risks and making future conditions more predictable makes firms more inclined to invest. When implemented, EPR has been proven to stimulate earlier investments in recycling.

Break-even analysis shows that carbon pricing can be used alongside EPR to boost the recycling margin by \$0.30–\$0.50 per kilowatt-hour via carbon credit revenues. This result is in line with environmental taxation theory and recent carbon pricing. The effectiveness of carbon price volatility and policy reversibility, however, is limited without mechanisms to provide a price floor.

The research also demonstrates that even when markets offer good investment opportunities, technical uncertainty can prevent investment. Lack of common state-of-health metrics hinders private investment in second-life battery markets. This is critical to enabling the potential second-life battery business valued at \$30 billion [11].

Finally, public development finance is significant in enabling recycling investments. However, more robust evaluation methods and counterfactuals are required to quantify the extra value of public funding for market development.

4.3 Strategic resource governance

This study identifies geopolitical supply concentration in graphite and cobalt as a significant strategic vulnerability within EV battery supply chains. Supply restrictions raise costs, create investment uncertainty, and weaken supply chains.

The findings emphasise domestic recycling capacity as a critical strategy for reducing dependence on imported minerals. This conclusion supports research on metal criticality, which identifies recycling as an effective mechanism for mitigating critical material supply risks. However, successful recycling systems require efficient battery-collection networks, material-purity standards, and demand-enhancing policies for recycled materials.

The results also reveal a tension between free trade and mineral security. Liberal trade regimes can be undermined by export restrictions that increase costs and slow clean-energy transitions. Conversely, strategic trade measures, including local content requirements and import tariffs, may support circular-economy infrastructure development and reduce long-term import dependence [1]. The study finds that multilateral mineral governance frameworks that combine open trade with environmental and social standards effectively reduce geopolitical risks and prevent a race to the bottom.

4.4 Policy implications for emerging economies

The study shows EPR and green procurement impact emerging economies differently than advanced economies. Effective EPR needs regulatory institutions, auditing, and collection systems that many developing countries lack. Developmental state literature emphasises that institutional capacity must align with regulatory ambition for policy effectiveness [1, 6]. Transplanting EPR frameworks from advanced economies often creates implementation challenges.

The informal recycling sector dominates battery end-of-life management in many developing countries, presenting both opportunities and risks. Although informal recyclers operate with lower capital costs and greater flexibility, they generally achieve lower recovery rates and expose workers to hazardous conditions. Evidence from Ghana’s e-waste formalisation initiative and India’s Hazardous Waste Management Rules suggests that gradual formalisation, rather than outright prohibition, offers a more practical solution.

Furthermore, international mineral governance frameworks should incorporate capacity building, technology transfer, and preferential market access to support responsible sourcing in developing countries. Without such measures, circular-economy regulations developed by advanced economies may create barriers that limit developing countries' participation in recycling and manufacturing value chains. This remains a significant gap in current policy research.

5. Conclusion and recommendation

The study examined regulatory frameworks and economic instruments to promote circular economy principles in EV battery supply chains. The findings show that EPR policies involving individual producer responsibility, enforcement rules, and eco-design considerations are most effective at enhancing battery collection rates and fostering design-for-recyclability innovation. The findings also show that the effectiveness of policy permanence and regulatory certainty as signals for investment outweighs the effect of the size of financial incentives, highlighting the need for policy sequencing and communication.

Recycling cathode economics remain viable under current chemistries and support levels when lithium prices exceed \$18,000–\$20,000 per tonne. Long-term viability increasingly depends on EPR gate fees and carbon credit mechanisms, especially for lower-cobalt cathodes. Second-life batteries offer revenue potential, but state-of-health standardisation remains a key market constraint.

Trade policies such as export restrictions and local content rules increase supply risks and costs, thereby reducing the gains from globalised production. The viability of circular EV battery supply chains depends on investment in recycling, diversified sourcing, regulatory cooperation, green procurement, harmonised standards, targeted financial support, and coordinated global governance frameworks.

Key policy priorities include harmonising EPR reporting standards, implementing permanent carbon price floors, and developing standardised state-of-health criteria for second-life batteries. Developing countries should strengthen their participation in global circular battery value chains and governance frameworks to enhance resource security and economic opportunities. Future research should examine regulatory effectiveness, market dynamics, and investment strategies through data-driven empirical studies.

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