



School Of Social Sciences

Supply Chain Management

Postgraduate Dissertation

Ensuring Sustainable Access to Critical Raw Materials for a Carbon-Neutral European Supply Chain: A business case for Lithium, Cobalt, and Rare Earth Elements.

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Patras, Greece, January 2025

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This thesis is dedicated to my son, Stavros.

Abstract

The transition to a carbon-neutral economy in Europe requires a sustainable and resilient supply chain of critical raw materials (CRMs) such as lithium, cobalt and rare earth elements (REE). These materials support key technologies and are essential for renewable energy and digital infrastructures and electric vehicles. However, their extraction, processing and supply chain management present significant environmental, social and geopolitical challenges. The thesis explores the diversity of these challenges and offers a comprehensive analysis to ensure sustainable access to CRMs, while aligning with the objectives of the European Green Deal and the broader decarbonisation agenda.

The thesis initially explores the environmental challenges associated with the mining and processing of CRM, such as resource depletion, excessive water consumption and significant greenhouse gas emissions. It highlights the potential of the provided innovative technologies, such as direct lithium extraction, geothermal recovery and low-carbon metallurgical techniques, to address these issues. By comparing multiple supply chain models, the research shows how integrating renewable energy sources into processing processes can effectively reduce carbon emissions, thereby advancing the EU's climate neutrality goals.

Emphasis is placed on the adoption of circular economy principles, with a focus on recycling and urban mining as key solutions to reduce dependence on primary sources of CRM. Advanced recycling technologies, including hydrometallurgical and direct cathode recovery processes, are evaluated for their potential to recover high-purity materials while minimizing waste and energy consumption. Case studies show how these methods, combined with decentralized recycling facilities and extensive responsibility policies regarding the production process, can improve the sustainability and efficiency of the supply chain.

The social and geopolitical aspects of CRM supply chains are also examined in depth. The concentration of the majority of production of these materials in regions such as the Democratic Republic of Congo and the People's Republic of China has the effect of exposing global supply chains to multiple risks and market volatility. The thesis highlights the importance of ethical sourcing, improved transparency through blockchain technology, and international cooperation to address these vulnerabilities. Furthermore, policy interventions such as the EU Battery Regulation and battery recycling-related directives are explored as tools to mitigate geopolitical risks and promote equitable resource allocation.

The findings highlight that a holistic approach that integrates innovative technologies, policy frameworks and the collaboration of all stakeholders is required to make a CRM supply chain sustainable. By addressing the environmental, social, and economic challenges associated with lithium, cobalt and REEs, this thesis provides actionable strategies to support the EU's transition to a carbon-neutral economy.

Keywords

Critical Raw Materials, Carbon-Neutral Economy, Sustainable Supply Chains, Lithium-ion Battery Recycling, Circular Economy, European Green Deal.

Εξασφάλιση Βιώσιμης Πρόσβασης σε Κρίσιμες Πρώτες Ύλες για μια Κλιματικά Ουδέτερη Ευρωπαϊκή Εφοδιαστική Αλυσίδα: Μια επιχειρηματική ανάλυση για το Λίθιο, το Κοβάλτιο και τις Σπάνιες Γαίες.

Παναγιώτης Σ. Ριζάκος

Περίληψη

Η μετάβαση σε μια οικονομία ουδέτερη από άνθρακα στην Ευρώπη απαιτεί μια βιώσιμη και ανθεκτική αλυσίδα εφοδιασμού κρίσιμων πρώτων υλών (CRM) όπως το λίθιο, το κοβάλτιο και τα στοιχεία σπάνιων γαιών (REE). Αυτά τα υλικά υποστηρίζουν βασικές τεχνολογίες και είναι απαραίτητα για τις υποδομές παραγωγής ενέργειας μέσω ανανεώσιμων πηγών, τις ψηφιακές υποδομές και την κατασκευή κυψελών συσσωρευτών ηλεκτρικών οχημάτων. Ωστόσο, η εξόρυξη, η επεξεργασία και η διαχείριση της εφοδιαστικής της αλυσίδας παρουσιάζει σημαντικές περιβαλλοντικές, κοινωνικές και γεωπολιτικές προκλήσεις. Η διατριβή διερευνά την ποικιλομορφία αυτών των προκλήσεων και προσφέρει μια ολοκληρωμένη ανάλυση για τη διασφάλιση βιώσιμης πρόσβασης στις κρίσιμες πρώτες ύλες, ενώ ευθυγραμμίζεται με τους στόχους της Ευρωπαϊκής Πράσινης Συμφωνίας και την ευρύτερη ατζέντα για την απαλλαγή από τις ανθρακούχες εκπομπές.

Η διατριβή αρχικά διερευνά τις περιβαλλοντικές προκλήσεις που σχετίζονται με την εξόρυξη και την επεξεργασία των CRM και των REE, όπως η εξάντληση των πόρων, η υπερβολική κατανάλωση νερού και οι σημαντικές εκπομπές αερίων του θερμοκηπίου. Υπογραμμίζει τις δυνατότητες των παρεχόμενων καινοτόμων τεχνολογιών, όπως η άμεση εξαγωγή λιθίου, η γεωθερμική ανάκτηση και οι μεταλλουργικές τεχνικές χαμηλών εκπομπών άνθρακα, για την αντιμετώπιση αυτών των ζητημάτων. Συγκρίνοντας πολλαπλά μοντέλα εφοδιαστικής αλυσίδας, η έρευνα δείχνει πώς η ενσωμάτωση των ανανεώσιμων πηγών ενέργειας στις διαδικασίες επεξεργασίας μπορεί να μειώσει αποτελεσματικά τις εκπομπές άνθρακα, προωθώντας έτσι τους στόχους της ΕΕ για την κλιματική ουδετερότητα.

Δίνεται βαρύτητα στην υιοθέτηση των αρχών της κυκλικής οικονομίας, με έμφαση στην ανακύκλωση και την αστική εξόρυξη ως βασικές λύσεις για τη μείωση της εξάρτησης από τις πρωτογενείς πηγές CRMs. Οι προηγμένες τεχνολογίες ανακύκλωσης, συμπεριλαμβανομένων των διεργασιών υδρο-μεταλλουργικής και άμεσης ανάκτησης καθόδου, αξιολογούνται ως προς τη δυνατότητά τους να ανακτούν υλικά υψηλής καθαρότητας, ελαχιστοποιώντας τα απόβλητα καθώς και την κατανάλωση ενέργειας. Μελέτες περιπτώσεων δείχνουν πώς αυτές οι μέθοδοι, συνδυαστικά με εγκαταστάσεις ανακύκλωσης καθώς και με στοχευμένες πολιτικές παρεμβάσεις αναφορικά με τις διαδικασίες παραγωγής, μπορούν να βελτιώσουν τη βιωσιμότητα και την αποτελεσματικότητα των αλυσίδων εφοδιασμού CRM.

Οι κοινωνικές και γεωπολιτικές πτυχές των αλυσίδων εφοδιασμού CRM εξετάζονται επίσης σε βάθος. Η συγκέντρωση της παραγωγής CRM σε περιοχές όπως η Λαϊκή Δημοκρατία του Κονγκό και η Λαϊκή Δημοκρατία της Κίνας εκθέτει τις παγκόσμιες αλυσίδες εφοδιασμού σε

κινδύνους που σχετίζονται με την πολιτική αστάθεια και τις ανήθικες πρακτικές εργασίας. Η διατριβή υπογραμμίζει τη σημασία της ηθικής προμήθειας CRM, τις διαφανείς συναλλαγές μέσω της τεχνολογίας blockchain και την συνεργασία όλων των εμπλεκόμενων μερών για την αντιμετώπιση των τρωτών σημείων που απειλούν την ακεραιότητα της εφοδιαστικής αλυσίδας.. Επιπλέον, οι πολιτικές παρεμβάσεις όπως ο κανονισμός της ΕΕ για τις μπαταρίες και τα απόβλητα των μπαταριών (Κανονισμός (ΕΕ) 2023/1542) και οι οδηγίες σχετικές με την ανακύκλωση των μπαταριών διερευνώνται ως εργαλεία για τον μετριασμό των αυξημένων γεωπολιτικών κινδύνων και την προώθηση της δίκαιης κατανομής των πόρων.

Τα ευρήματα υπογραμμίζουν ότι απαιτείται μια ολιστική προσέγγιση που να ενσωματώνει τις καινοτόμες τεχνολογίες, τα πλαίσια πολιτικής και τη συνεργασία όλων των ενδιαφερομένων μερών για να καταστεί βιώσιμη μια εφοδιαστική αλυσίδα CRM. Αντιμετωπίζοντας τις περιβαλλοντικές, κοινωνικές και οικονομικές προκλήσεις που σχετίζονται με τις εφοδιαστικές αλυσίδες των CRM και των REE, αυτή η διατριβή παρέχει στρατηγικές διαδικασίες που μπορούν να υποστηρίξουν τη μετάβαση της ΕΕ σε μια οικονομία ουδέτερη από άνθρακα..

Λέξεις - Κλειδιά

κρίσιμες πρώτες ύλες, οικονομία ουδέτερη από άνθρακα, βιώσιμες αλυσίδες εφοδιασμού, ανακύκλωση μπαταριών ιόντων λιθίου, κυκλική οικονομία, Ευρωπαϊκή Πράσινη Συμφωνία.

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List of Abbreviations & Acronyms

AI	Artificial Intelligence
AM	Additive Manufacturing
ASM	Artisanal and Small-scale Mining
BEV	Battery Electric Vehicle
BRICS	Brazil, Russia, India, China, South Africa
CE	Circular Economy
CEAP	Circular Economy Action Plan
CIR	Circular Input Rate
CRM	Critical Raw Material
DES	Deep Eutectic Solvent
DLE	Direct Lithium Extraction
DPP	Digital Product Passports
DRC	Democratic Republic of the Congo
EoL	End of Life
EPR	Extended Producer Responsibility
EU	European Union
EUDR	EU Regulation on deforestation-free products
EV	Electric Vehicle
E-Waste	Electronic Waste
GBA	Global Battery Alliance
GHG	Green House Gas
GSCM	Green Supply Chain Management
ICEV	Internal Combustion Engine Vehicle
IE	Industrial Ecology
IoT	Internet of Things
IS	Industrial Symbiosis
LCA	Life Cycle Assessment
LE	Low-carbon Economy
LFP	Lithium Ferro Phosphate
LIB	lithium-Ion Battery
MFA	Material Flow Analysis
NCM	Nickel-Cobalt-Manganese
PHEV	Plug-in Hybrid Electric Vehicle
R&D	Research & Development
RC	Recycled Content
RCS	Recycled Content Standards
REE	Rare Earth Element
S – LCA	Social Life Cycle Assessment
SDG	Sustainable Development Goal
SGSP	Salinity Gradient Solar Pond
SMEs	Small and Medium-sized Enterprises
SSCM	Sustainable Supply Chain Management
TIAM	Times Integrated Assessment Model
WEEE	Waste from Electrical and Electronic Equipment

1. Advancing Sustainable Supply Chains: Integrating Carbon Neutrality, Environmental Sustainability, and Critical Raw Materials.

1.1 Introduction to Sustainable Supply Chain Management and Carbon Neutrality

Sustainable Supply Chain Management (SSCM) has emerged as the key strategy for addressing the environmental impacts associated with global supply chains. It incorporates practices that integrate environmental considerations into supply chain operations that aim to minimize greenhouse gas (GHG) emissions and promote long-term sustainability. The urgency to implement sustainable solutions stems from international agreements, such as the Paris Agreement, aimed at limiting global warming and promoting carbon neutrality. Businesses are not only pressured by the regulatory frameworks that have been created but also by the shift in consumer expectations towards environmentally conscious practices.

However, achieving carbon neutrality presents significant challenges, particularly in balancing the financial return on an investment with environmental commitments. In response to these global pressures, SSCM emphasizes collaboration among stakeholders, technology integration, and innovative resource management. The primary goal is to create resilient and adaptive supply chains capable of achieving net zero emissions while maintaining profitability.

1.1.1 Theoretical Foundations of Sustainable Supply Chain Management

The theoretical framework of SSCM is built on principles that prioritize environmental stewardship alongside economic efficiency. Bai et al. (2022) present in their study a comprehensive multi-objective mathematical model that helps organizations select suppliers and allocate orders in a way that aligns with carbon neutrality goals. The model's structure is designed to optimize supplier portfolios by balancing cost efficiency and environmental impact, demonstrating how strategic decision-making can incorporate carbon offsetting strategies, to achieve sustainability goals (Bai et al., 2022).

Another critical element of SSCM is addressing those emissions that are indirectly generated during the operation of a supply chain network (Scope 3 emissions) and often constitute the largest part of a company's carbon footprint. Bodendorf and Smith (2022) emphasize in their study the complexity of managing these emissions and the need for coordinated efforts across supply chain actors. Addressing Scope 3 emissions is essential for a sustainable SSCM. A data-

driven approach to managing these emissions requires transparency and collaboration with suppliers, highlighting the critical role of partnerships in achieving carbon neutrality (Bodendorf & Smith, 2022).

In their study, Leigh and Li (2015) introduce the concepts of Industrial Ecology (IE) and Industrial Symbiosis (IS), which support a systems thinking approach to environmental sustainability. By promoting resource sharing and energy efficiency among companies, these frameworks significantly reduce overall supply chain emissions. The integration of industrial ecology principles into SSCM highlights the interconnectedness of supply chain actors and the potential for collaborative environmental management (Leigh & Li, 2015).

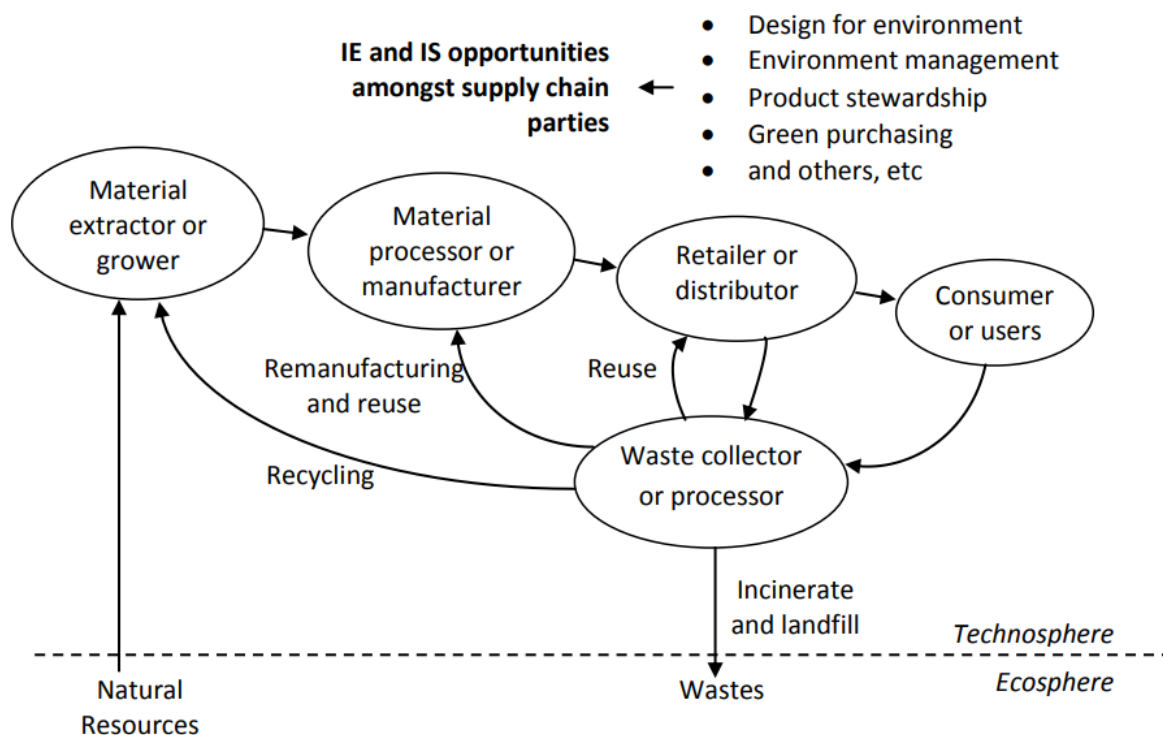


Figure 1 :Supply chain environmentally sustainability development regarding Industrial Ecology and Industrial Symbiosis concepts (Leigh & Li, 2015).

1.1.2 Strategic Approaches for Carbon Neutral Supply Chains

Strategic approaches to achieving carbon-neutral supply chains include integrating emission control measures with business objectives. Lee and Hussain (2024) propose an optimization model to minimize emission risks while maximizing profit. This model exemplifies the importance of aligning environmental targets with economic incentives, ensuring that sustainability efforts do not undermine profitability (Lee & Hussain, 2024).

Coskun et al. (2016) contribute to green supply chain design by providing a model based on consumer segmentation. Their research highlights that understanding consumer behaviour can

enhance the effectiveness of environmental strategies, particularly in optimizing resource use while reducing waste. The consumer-centric approach highlights the importance of demand-driven sustainability initiatives, which can complement broader emission reduction goals (Coskun et al., 2016).

Incorporating circular economy (CE) principles further enhances supply chain sustainability. Yousaf et al. (2023) report in their study on how Industry 4.0 technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), and big data, facilitate resource optimization and emission reduction. These technologies support the transition to carbon-neutral operations by enabling better resource management and reducing emissions throughout the supply chain network (Yousaf et al., 2023). Integrating CE principles with Industry 4.0 technologies demonstrates the transformative potential of digital solutions, making carbon neutrality goals more achievable.

1.1.3 Practical Applications and Case Studies

Real-world applications of SSCM provide insight into how theoretical strategies are implemented across industries. Mu et al. (2023) focus in their study on technological developments in energy storage systems, specifically on the recycling and reuse of lithium-ion batteries (LIBs). This approach highlights the importance of developing sustainable solutions in the field of energy storage, supporting the adoption of renewable energy sources that will lead to a reduction in the environmental footprint (Mu et al., 2023).

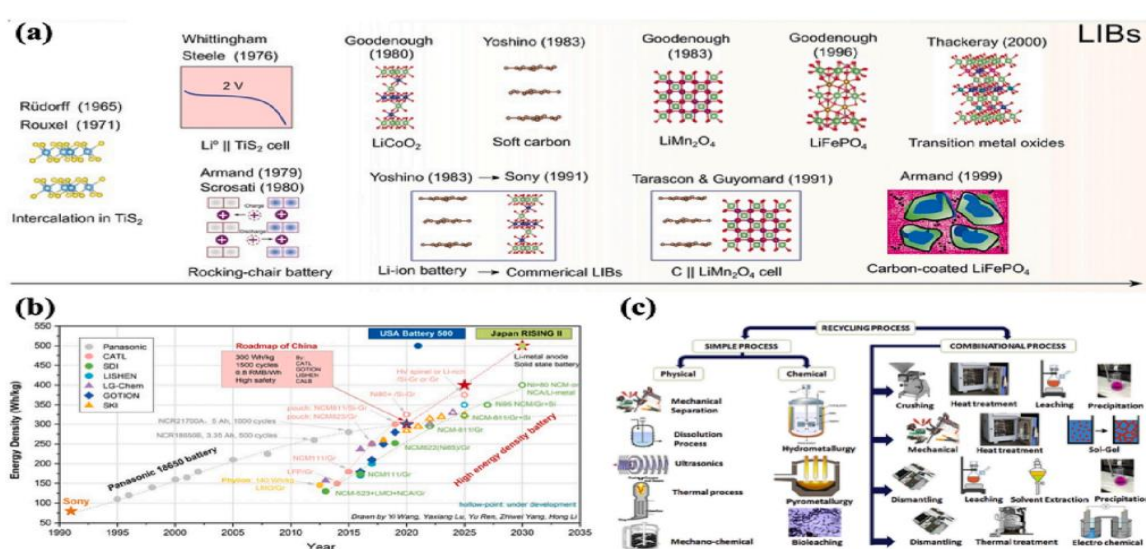


Figure 2: a) The evolution of battery chemistry and key findings of lithium-ion batteries (LIBs) over the past 40 years. (b) Comparison of the gravimetric performance of different batteries for automotive applications. (c) Different processes for recycling of spent LIBs (Mu et al., 2023).

The photovoltaic industry is another area where SSCM principles have been successfully applied. Peters et al. (2024) describe in their study a closed-loop recycling model that ensures minimal waste generation while ensuring sustainable use of materials, emphasizing the benefits of adopting CE practices to achieve carbon neutrality (Peters et al., 2024).

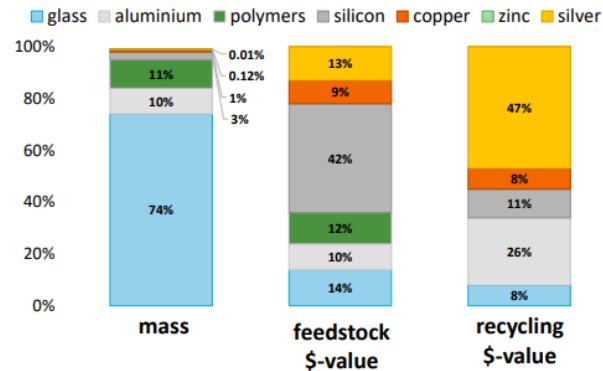


Figure 3: Mass and value of materials in a solar panel. Distribution of mass and values in a silicon solar panel using the initial material feedstock (middle) and the recycling value (right) (Peters et al., 2024).

Qiao et al. (2024) investigate in their study the impact of electric vehicle battery recycling on China's cobalt supply chain. Their research highlights the significant potential of closed-loop systems to reduce dependence on primary resources and support carbon-neutral supply chain efforts. (Qiao et al., 2024).

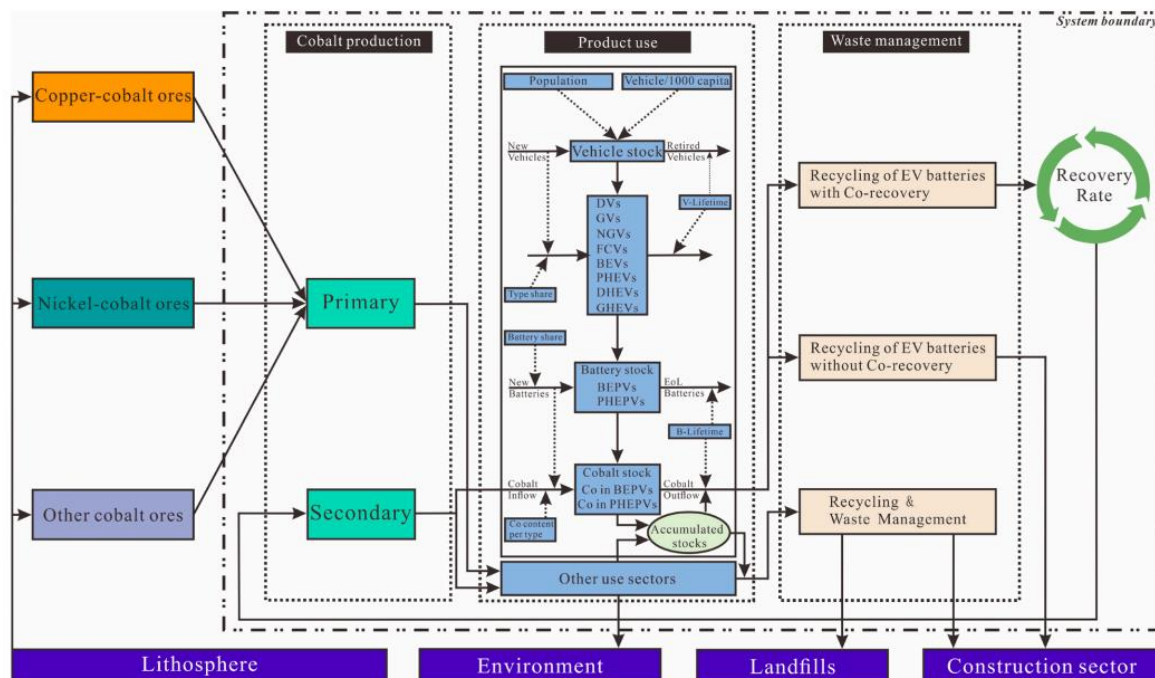


Figure 4: The process and material flow of the cobalt life cycle in China (Qiao et al., 2024).

Zhou et al. (2024) in turn use a model to analyse the role of government, media, and manufacturers in overseeing the adoption of low-carbon technology. Their findings reveal the importance of coordinated efforts among stakeholders to promote sustainable practices and achieve long-term environmental benefits (Zhou et al., 2024). The models and case studies analysed highlight the critical role of stakeholder collaboration and policy support in guiding effective SSCM practices.

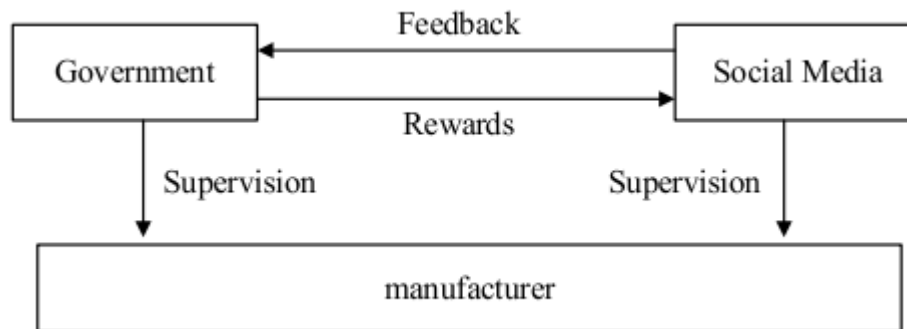


Figure 5: The relationship among the government, manufacturer, and media (Zhou et al., 2024).

1.2 Introduction to Green Supply Chains and Environmental Sustainability

The urgent need to mitigate environmental impacts has transformed supply chain management practices, pressuring companies to incorporate green strategies that aim to reduce waste, lower emissions, and enhance resource efficiency. Green Supply Chain Management (GSCM) is emerging as an integrated approach that emphasizes environmental sustainability across all supply chain activities (Maditati et al., 2018).

1.2.1 Core Concepts and Strategic Drivers

Green supply chains seek to minimize the environmental footprint of production and logistics through practices such as energy - efficient transportation, waste reduction, and optimized resource use. Aldakhil et al. (2018) highlight in their study the importance of green logistics in mitigating GHG emissions. The study on BRICS countries reveals the tension between economic growth and environmental goals, emphasizing that strategic investments in green logistics can lead to long-term sustainability benefits.

Maditati et al. (2018) in their research offer a framework that categorizes GSCM into drivers, practices, and outcomes. Key drivers include regulatory pressure, consumer demand, and corporate responsibility, which force organizations to adopt green procurement, eco-design, and

reverse logistics. These practices are an integral part of CE principles, which aims to create a regenerative system where resources are reused rather than discarded.

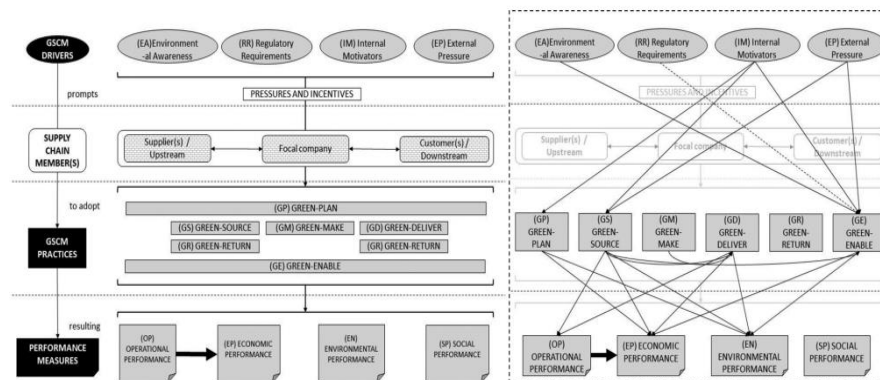


Figure 6 : Comprehensive conceptual framework that represents associations among the GSCM drivers, practice, and performance measures (Meditati et al., 2018).

Integrating existing and emerging environmental concerns into the operational process of supply chains is not merely a response to external pressures, but a strategic opportunity. By adopting GSCM practices, companies can gain a competitive advantage, enhance their brand reputation, and contribute to global sustainability efforts. This strategic alignment is crucial for achieving carbon neutrality, as it drives innovation and efficiency. In Figure 7, the types of stakeholder pressures that influence GSCM adoption are illustrated, mapping how these pressures impact collaborative practices.

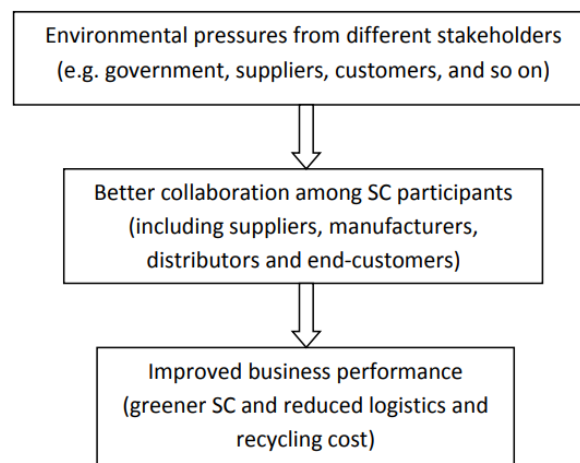


Figure 7: Simple conceptual model of the role of Supply Chain collaboration to achieve a greener Supply Chain (Ramanathan et al., 2014).

1.2.2 Integration, Collaboration, and Technological Advancements

The successful implementation of GSCM relies on the integration of green practices throughout the supply chain, from product development to logistics. Reche et al. (2020) emphasize in their

study that environmental considerations should be incorporated early in product design to ensure that the entire supply chain complies with sustainability standards. Green procurement, integrated waste management, and closed-loop recycling systems are key strategies that enable the seamless integration of sustainable practices into supply chain activities (Reche et al., 2020).

Collaboration among supply chain stakeholders enhances the effectiveness of GSCM. Fontoura and Coelho (2022) highlight in their research that joint research and development (R&D), shared logistics infrastructure and joint development of environmentally friendly products lead to improved resource efficiency and innovation. These collaborative efforts reduce the costs and spread the risks associated with green investments, making them essential for sustainable supply chains (Fontoura and Coelho., 2022).

According to Ramanathan et al. (2014) supply chain collaboration in the UK has facilitated the reduction of CO₂ emissions through joint initiatives. Their study concludes that collaboration is not only beneficial but essential for achieving environmental goals, as it aligns the goals of suppliers, logistics providers and retailers (Ramanathan et al., 2014).

Technological advancements, such as additive manufacturing (AM) and automated Life Cycle Assessment (LCA), are transforming green supply chains. In their research, Naser et al. (2023) discuss how AM minimizes waste and energy use while enabling more efficient manufacturing processes. Automated LCA tools ensure that every stage of the product life cycle is optimized to have acceptable environmental performance, contributing to carbon neutrality goals. Similarly, the adoption of IoT technologies and blockchain facilitates real-time monitoring of emissions and supply chain processes, enabling greater accountability and optimization (Naser et al., 2023).

Area of focus	Description	Examples
Integration of Proceedings	Integrating environmental practices into all supply chain activities, from product design to reverse logistics.	Green procurement, integrated waste management, closed-loop recycling systems.
Collaboration	Collaborate with supply chain partners to achieve shared environmental goals and improve resource efficiency.	Co-development of environmentally friendly products, joint R&D initiatives, shared logistics infrastructure.
Technological Advancements	Using advanced technologies, such as IoT, blockchain, and additive manufacturing, to improve transparency, efficiency, and sustainability.	Real-time emissions monitoring, automated life cycle assessments, energy-efficient production processes.

Table 1: Integration, Collaboration, and Technological Advancements

Table 1 summarizes the focus areas that lead to successful GSCM implementation, emphasizing the integration of practices, collaborative efforts, and the role of advanced technologies. (Reche et al., 2020; Fontoura and Coelho., 2022; Naser et al., 2023).

1.2.3 Policy Impacts and Economic Incentives

Government policies and economic incentives are powerful drivers of GSCM practices. In their research Noh and Kim (2019) examine in their study how GHG emission regulations affect supply chain operations, highlighting the need to optimize under existing environmental constraints. Their research introduces mathematical models that can help companies align production and inventory strategies with regulatory requirements, demonstrating the effectiveness of policy interventions for GSCM adoption (Noh and Kim, 2019).

In their study, Wang and Choi (2020) present an innovative approach through flexible cap-and-trade systems. These systems incentivize companies to adopt low-carbon practices by allowing them to trade emission quotas, aligning financial incentives with environmental goals. Their study shows that coordinated efforts, such as revenue-sharing contracts, can enhance the green supply chain while maintaining profitability. This approach is crucial for emission-dependent industries, especially in the face of stringent global environmental standards (Wang and Choi, 2020).

Subsidies for green investments further complement these policies by reducing the financial burden of adopting environmentally friendly technologies. Such subsidies encourage companies to implement practices such as the use of renewable energy sources, green logistics, and sustainable production processes. These financial incentives, often provided by governments or international bodies, accelerate the transition to environmentally sustainable supply chains (Ghadimi et al., 2019; Maditati et al., 2018).

Policies like cap-and-trade provide a structured pathway for companies to systematically reduce their emissions. By integrating green investments and sharing the financial burden through coordinated strategies, businesses can work seamlessly towards a carbon-neutral future.

Policy	Description	Implications for Supply Chains
Cap-and-Trade System	A market-based approach where companies trade emission allowances to reduce overall carbon emissions.	Encourages companies to invest in low-carbon technologies and improve efficiency.
GHG Regulations	Rules set by governments to limit emissions from industrial activities.	Forces companies to optimize their operations and adopt green logistics practices.
Subsidies for Green Investments	Financial incentives provided to companies for adopting environmentally friendly technologies and practices.	Reduces financial barriers to implementing renewable energy, green logistics, and sustainable manufacturing.

Table 2: Policy Impacts and Economic Incentives in Green Supply Chains

Table 2 summarizes the impact of key policies and economic mechanisms that drive green supply chain practices. Cap-and-trade systems provide incentives for emission reductions through tradable allowances (Wang and Choi, 2020). GHG regulations enforce compliance with sustainability goals (Noh and Kim, 2019). Subsidies mitigate the financial challenges of adopting environmentally friendly technologies and practices. (Ghadimi et al., 2019; Maditati et al., 2018).

1.2.4 Challenges and Future Outlook

While GSCM offers significant benefits, its implementation presents various challenges. One of the most significant barriers is the high cost of adopting sustainable practices. Investments in technologies like renewable energy systems, energy - efficient transportation, and waste management infrastructure require significant initial capital. In their study, Ghadimi et al. (2019) highlight in their study the need for financial support mechanisms, such as government subsidies and public-private partnerships, to reduce this cost and encourage the wider adoption of green practices (Ghadimi et al., 2019).

Technological barriers also hinder the transition to sustainable supply chains. Limited access to advanced tools like the IoT, blockchain, and automated LCA can slow progress, particularly for small and medium-sized enterprises (SMEs). Building technological capacity and fostering partnerships with technology providers are essential to overcome these barriers and ensure the widespread adoption of sustainable innovations (Naser et al., 2023; Naser et al., 2023).

The complexity of managing multi-tiered global supply chains further complicates GSCM adoption. Trujillo-Gallego et al. (2021) highlight in their study the difficulty of coordinating green initiatives across different geographic regions and stakeholders. Enhanced transparency,

real-time monitoring tools, and digital platforms can help address these challenges and improve alignment across the supply chain (Trujillo-Gallego et al., 2021).

GSCM requires continuous innovation to effectively manage and balance economic, environmental and social objectives. Ghadimi et al. (2019) in their study, argue that companies need to invest in R&D to develop adaptive supply chain models and promote innovative operating systems that drive sustainability (Ghadimi et al., 2019).

Addressing these challenges is critical to achieving a carbon-neutral economy. By reducing costs, overcoming technological barriers, and fostering innovation, green supply chains can deliver environmental benefits while maintaining competitiveness in a rapidly evolving market.

1.3 Introduction to Sustainable Supply Chains and Critical Raw Materials

The sustainability of critical raw materials (CRMs) and rare earth elements (REEs) supply chains is an ongoing and pressing challenge in the global transition to a low-carbon economy. These materials are integral to renewable energy infrastructures, high-tech applications, and electric vehicle batteries (EVs) however their mining, processing, and transportation supply chains are suffocating under the weight of multiple environmental, geopolitical, and social issues. This subchapter examines the challenges facing CRMs supply, explores the potential of CE and low-carbon solutions, and highlights innovations that are paving the way for a sustainable future.

1.3.1 Challenges in the Supply of Critical Raw Materials

CRMs and REEs are indispensable for clean energy technologies but face significant sustainability and supply chain challenges. For lithium, its extraction often occurs in arid regions, such as the lithium triangle of South America. Alessia et al. (2021) highlight in their study the depletion of freshwater resources and ecological destruction due to brine evaporation, which is the primary method of extraction. This water-intensive process conflicts with the needs of local communities, raising ethical concerns and making sustainability in lithium supply chain a critical challenge (Alessia et al., 2021).

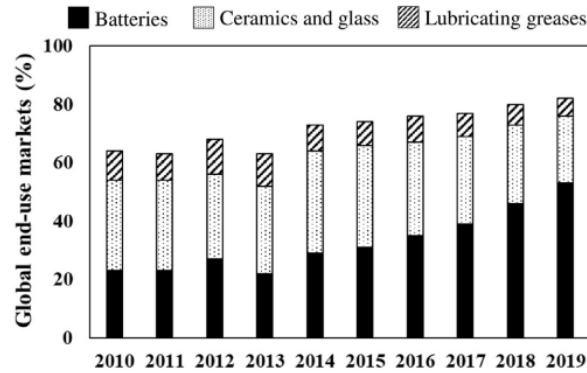


Figure 8: The global market for lithium: The evolution of end-use percentage for the global market for lithium from 2010 to 2019 (Alessia et Al.,2021).

The cobalt supply chain, as Brink et al. (2020) illustrate in their research, is plagued by geopolitical dependencies. Over 70% of cobalt production is concentrated in the Democratic Republic of Congo (DRC), where political instability, weak governance, and unethical labour practices create vulnerabilities. Figure 9 visually illustrates how this concentration disrupts global supply stability and increases the risks of price volatility. Such challenges underline the need to diversify sources and improve traceability.



Figure 9: The geographical map of the cobalt supply chain. This map highlights the global distribution and interconnections in the cobalt supply chain, as well as its concentration in key regions like the Democratic Republic of Congo (DRC) and China (Brink et al., 2020).

For REEs, Silvestri et al. (2021) highlight in their study that mining often involves the removal of significant amounts of overburden (i.e., layers of soil and rock that cover Rare Earth deposits) and the production of toxic by-products (which may include radioactive waste or other hazardous substances, such as heavy metals and chemicals), leading to land degradation and

water contamination. These challenges are exacerbated by China's dominance in global REE production, establishing monopoly supply conditions that threaten global access. Policy interventions such as the EU's recycled content (RC) targets aim to address these issues but have faced criticism. Spooren et al. (2020) warn in their study that rigid targets (regulatory or political) may inadvertently discourage the extension of the lifetime of critical products such as EVs batteries, by reducing their circularity potential (i.e. their ability to be reused or recycled).

1.3.2 Circular Economy and Low-Carbon Solutions

CE practices have emerged as critical strategies for addressing the sustainability challenges inherent in CRM supply chains. The increasing demand for materials such as lithium, cobalt, and REEs has underscored the need for efficient resource use, waste minimization, and material recovery from end-of-life (EoL) products. By integrating CE principles with low-carbon economy (LE) goals, stakeholders can develop sustainable supply chains that align with environmental and economic objectives.

One of the most impactful CE strategies is recycling, which offers the potential to close material loops ((i.e. returning materials to the production and consumption cycle, rather than ending up as waste) and dependence on primary resources. Lehtimäki et al. (2024) emphasize in their research that recycling processes, particularly for lithium and cobalt in EVs batteries, can significantly mitigate supply chain vulnerabilities while reducing environmental impacts. Technologies such as hydrometallurgical and pyrometallurgical methods enable the recovery of high-purity materials, ensuring their reincorporation into new products (Alessia et al., 2021).

Urban mining presents a promising solution for enhancing resource efficiency. This practice involves extracting valuable materials from electronic waste (e-waste) and other anthropogenic sources, which often contain high concentrations of CRMs. By reducing reliance on environmentally harmful primary extraction methods, urban mining not only diversifies material sources but also mitigates supply chain risks associated with geopolitical dependencies (Xie et al., 2023).

Near-zero-waste processing technologies also play a critical role in CE strategies. Spooren et al. (2020) highlight in their study innovations in the processing of low-grade ores and secondary materials, which reduce waste generation and enhance material efficiency. These technologies complement LE practices by reducing the energy intensity of CRM supply chains. For instance, the application of advanced metallurgical techniques minimizes emissions while

maximizing resource recovery, demonstrating alignment between CE and LE objectives (Spooren et al., 2020).

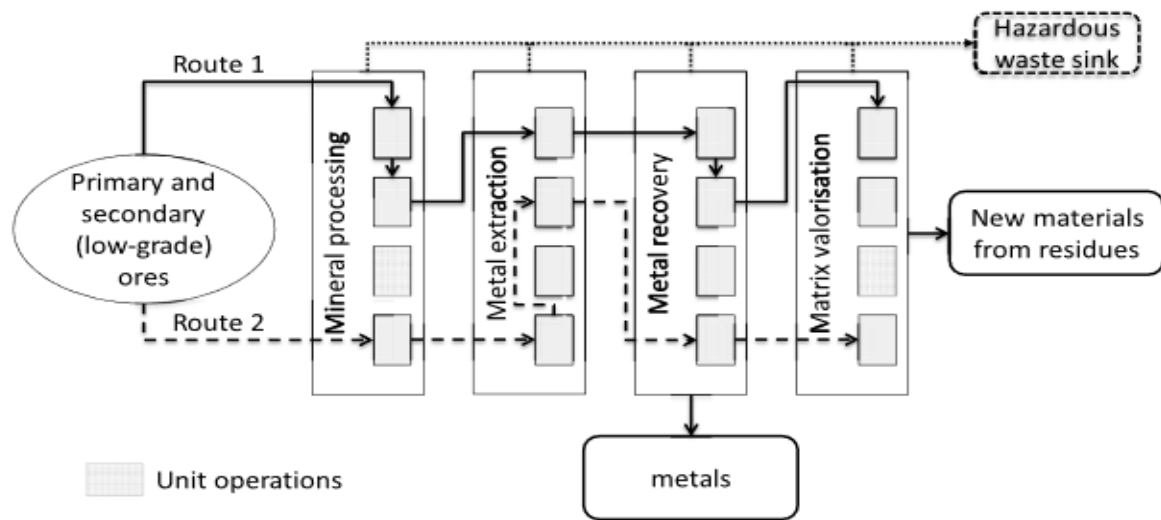


Figure 10: The near-zero-waste new metallurgical systems toolbox. Arrows represent possible process routes connecting different unit operations (Spooren et al., 2020).

The nexus between CE and LE practices is particularly evident in the transition to renewable energy. By reducing the environmental footprint of CRM processing and integrating secondary materials into supply chains, CE practices contribute to decarbonization objectives. Xie et al. (2023) in their study, argues that combining these strategies ensures that environmental and economic benefits are maximized, creating sustainable supply chains capable of supporting a carbon-neutral economy (Xie et al., 2023).

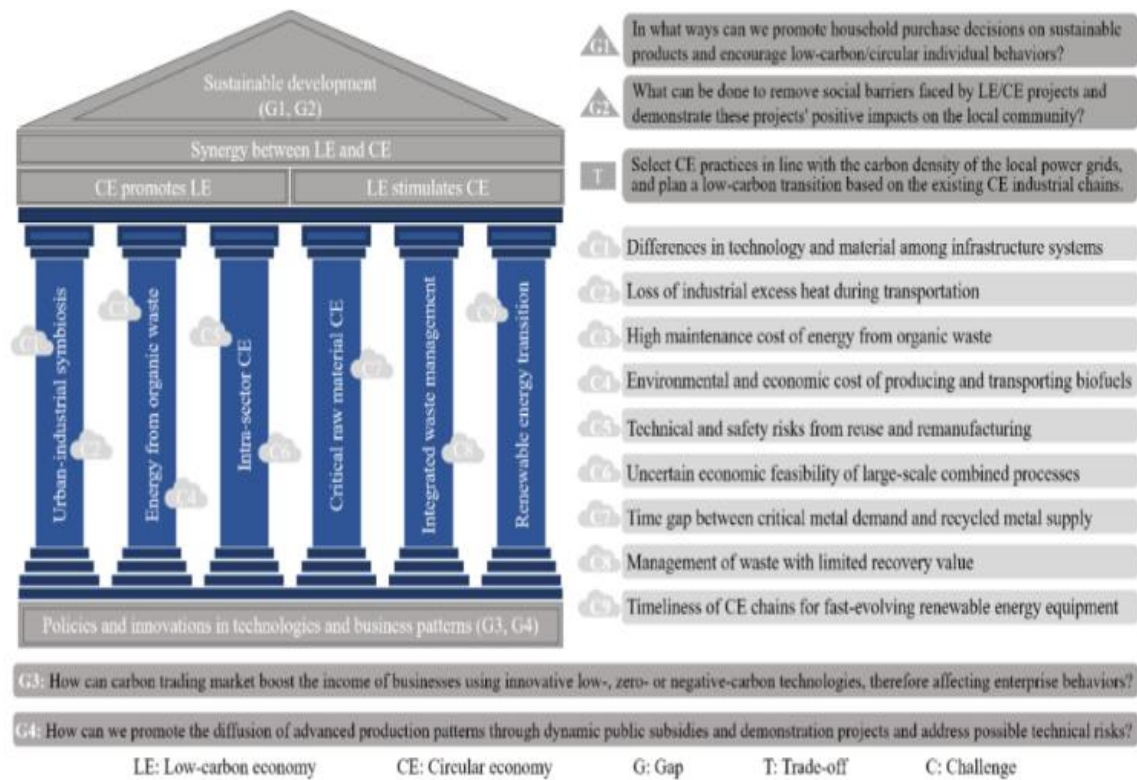


Figure 11: Nexus network of the low-carbon economy and circular economy (Xie et al., 2023).

1.3.3 Innovations and Future Directions

Technological innovations are vital both to address the challenges facing CRM supply chains and to ensure their long-term sustainability. The growing demand for CRMs and REEs requires advanced solutions that reduce environmental impacts, improve material efficiency, and mitigate supply chain vulnerabilities.

One of the most significant advancements lies in recycling technologies. Processes such as hydrometallurgical and pyrometallurgical recycling have been developed to recover high-purity materials from EoL products, particularly EVs batteries. Lehtimäki et al. (2024) highlight in their study the potential of these methods to reduce dependence on primary extraction while minimizing waste. Continued innovation in these technologies, including the development of low-energy alternatives, will be critical to scaling up recycling efforts in line with the increasing demand for CRMs (Lehtimäki et al., 2024).

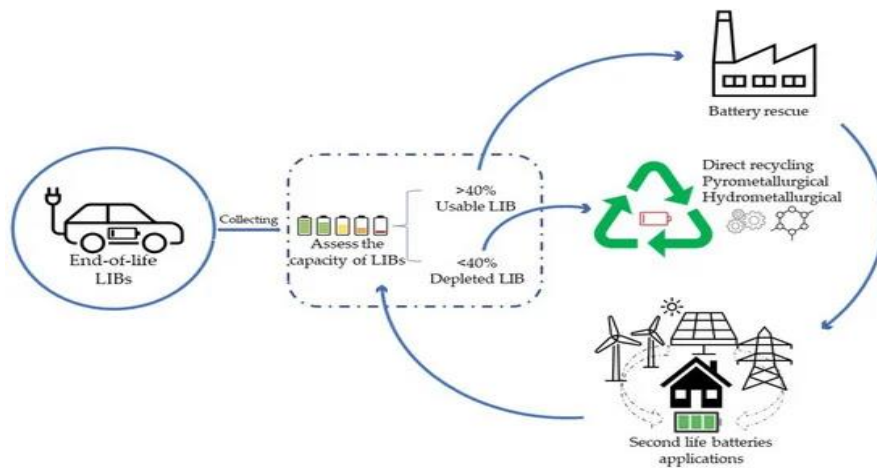


Figure 12: Main end-of-life LIB management processing by reuse and recycling (Noudenget al., 2022).

Urban mining is another transformative approach to CRM management. Xie et al. (2023) highlight in their study the potential of recovering CRMs from e-waste and other urban sources. This approach not only reduces the need for environmentally destructive mining practices but also diversifies supply sources, making supply chains more resilient. Furthermore, the integration of digital tools, such as AI and blockchain technology, enhances the efficiency of urban mining by enabling better material monitoring, optimization of recovery processes, and greater transparency in the supply chain (Xie et al., 2023).

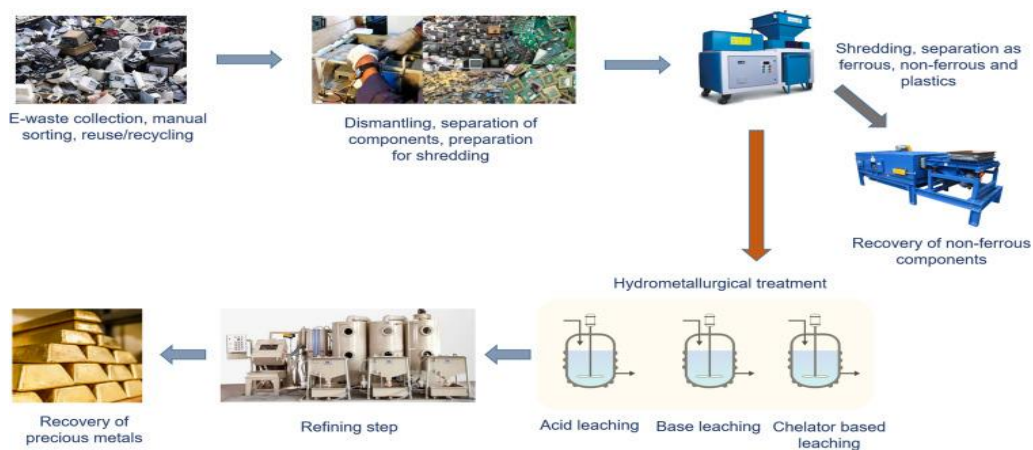


Figure 13: Schematic of precious metal recovery from WEEE using hydrometallurgical options. WEEE contains significant amounts of critical metals such as cobalt, and REEs (Rene et al., 2021).

Advances in battery technology are also reshaping the CRMs usage landscape. The development of solid-state batteries and alternative chemistries hold promise to reduce the dependence on rare materials such as cobalt and nickel. These technologies are more efficient and offer longer lifetimes compared to traditional LIBs. Lehtimäki et al. (2024) underscore in their study the importance of such innovations in meeting the demands of the renewable energy transition

while at the same time mitigating supply chain risks associated with CRMs (Lehtimäki et al., 2024).

1.4 Carbon-Neutral Supply Chain and Europe

The European Union (EU) aims to achieve carbon neutrality by 2050, guided by the Paris Agreement and the European Green Deal. Transforming supply chains is essential to minimize GHG emissions while ensuring access to CRMs and REEs. The EU heavily depends on imports for CRMs, creating vulnerabilities in achieving sustainability goals. CE principles, such as recycling and resource efficiency, play a pivotal role in reducing dependence on external sources and strengthening supply chain resilience (Baldassarre., 2025; Cusenza et al., 2024).

Decarbonization technologies play a pivotal role in mitigating emissions from energy-intensive industries such as steel production. For instance, hydrogen-based steelmaking can significantly reduce emissions compared to traditional methods. However, its widespread adoption faces challenges, including high costs and infrastructure requirements (Suer et al., 2021). Carbon capture and storage (CCS) technologies also complement decarbonization efforts by reducing emissions in hard-to-abate sectors. Strategic planning and investment are crucial for the effective integration of CCS into European supply chains (d'Amore et al., 2019).

The COVID-19 pandemic has highlighted vulnerabilities in the global supply chain, prompting the EU to focus on diversification and CE practices. Strategies such as recycling of EoL products and material reuse enhance resource efficiency and align with the EU's sustainability agenda (Zanoletti et al., 2021; Tyurkay et al., 2024). For instance, the management of EoL wind turbine blades demonstrates how cross-sector collaboration can reduce waste and drive innovation.

Despite progress, challenges remain, including the need for innovation, investment, and cooperation between industries. Addressing these challenges will allow the EU to set a global standard for sustainable, carbon-neutral supply chains, support broader climate goals and ensure sufficient resources for green technologies (Tyurkay et al., 2024; Baldassarre, 2025).

2. Sustainability and Resilience in Critical Raw Material Supply Chains: Environmental, Social, and Technological Dimensions

2.1 Introduction to Lithium Supply Chain and Sustainability

Lithium is a cornerstone of the global energy transition, enabling the production of LIBs that power EVs and store renewable energy. As the demand for lithium increases exponentially (figure 14), driven by decarbonization and electrification goals, its supply chain faces significant challenges, such as environmental degradation, socioeconomic inequalities, and geopolitical dependencies (Mas-Fons et al., 2024; Schenker et al., 2024). Addressing these issues requires a multifaceted approach that combines sustainable extraction, advanced recycling methods, and the integration of CE principles (Weinand et al., 2023; Zhou et al., 2024).

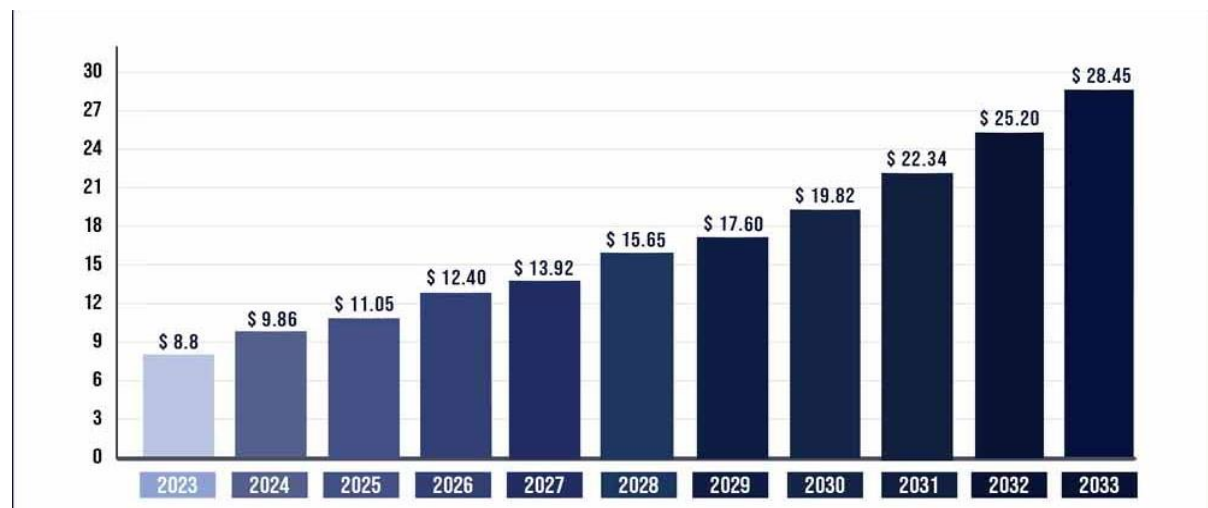


Figure 14: Lithium market size 2023 to 2033 (USD billion) (Kulkarni and Shivarkar., 2024)

2.1.1 Primary Lithium Supply

Lithium is primarily extracted by two main methods: brine extraction and hard rock mining. Brine extraction, which is dominant in South America, involves pumping lithium-rich brine to the surface and evaporating it, leaving behind lithium salts. This method is energy-efficient but water-intensive, leading to significant ecological impacts such as water depletion and soil salinization in arid regions such as the Salar de Atacama in Chile (Mas-Fons et al., 2024; Alessia et al., 2021). Hard rock mining, primarily concentrated in Australia, involves extracting lithium from spodumene ore, which is processed through energy-intensive roasting. While it is less

dependent on water resources compared to brine extraction, it generates high GHG emissions due to its dependence on fossil fuels (Rolinck et al., 2023; Alessia et al., 2021).

Geothermal lithium extraction is emerging as a promising sustainable alternative. This method integrates renewable energy generation with lithium recovery, significantly reducing carbon and water footprints. Pilot projects in the Upper Rhine Graben in Germany and the Salton Sea in the United States (USA) highlight the potential of this approach, though scalability and economic viability remain key challenges (Schenker et al., 2024; Weinand et al., 2023).

Lithium production and processing are also geopolitically concentrated, with over 80% of production occurring in Australia, Chile, and Argentina, while China controls nearly 90% of global refining capacity. This dependence on a few key regions creates vulnerabilities for import-dependent nations, particularly during geopolitical conflicts or trade restrictions (Yan et al., 2020; Yuan et al., 2024). Efforts are being made to diversify supply chains, with investments in domestic refining capabilities in Europe and the US with the aim of reducing dependence on Chinese facilities and enhancing supply chain resilience (Yuan et al., 2024; Niri et al., 2024).

2.1.2 Lithium Supply Chain and Carbon Footprint

Lithium is a cornerstone for achieving the EU's carbon-neutral objectives, but its extraction and processing pose significant environmental challenges. The environmental footprint of lithium production varies depending on the method used. Brine extraction, prevalent in areas such as the Salar de Atacama in Chile, has a relatively low carbon footprint (5.0 to 25.0 kg CO₂-eq per kilogram of lithium carbonate equivalent, Li₂CO₃), but water consumption is significant, reaching up to 7.7 m³ per kilogram. In contrast, hard rock mining, widely practiced in Australia, has a higher carbon footprint (17.1 to 22.3 kg CO₂-eq per kilogram) due to energy-intensive refining but requires significantly less water (0.2 to 0.5 m³ per kilogram) (Mas-Fons et al., 2024).

Advancements such as Direct Lithium Extraction (DLE) hold promise for reducing water use and emissions, although their scalability remains a concern. Geographic factors also affect carbon intensity. Facilities in Europe and North America benefit from the integration of renewable energy sources, resulting in reduced emissions. Meanwhile, areas dependent on fossil fuels, such as parts of China, have higher carbon emissions, although there are exceptions such as Sichuan's reliance on hydropower that yield lower emissions. (Kallitsis et al., 2024).

Lithium extraction and processing account for up to 80% of total GHG emissions in the LIBs value chain. Recycling plays a pivotal role in reducing environmental impacts, with studies showing that substituting 30% of primary lithium with recycled material can lower emissions and water usage by over 10%. Decentralized recycling facilities in Europe further enhance sustainability by reducing transportation emissions and fostering CEs. Policies such as the European Battery Regulation support these initiatives by promoting transparency and investment in clean technologies (Alessia et al., 2021).

Further insights, including process flowsheets for brine and spodumene extraction and lifecycle analysis comparisons, are available in Appendix A. These detailed graphics highlight the operational differences and their associated environmental impacts, reinforcing the importance of transitioning to renewable energy sources for lithium extraction and processing to achieve global sustainability goals (Mas-Fons et al., 2024).

2.1.3 Recycling and Secondary Lithium Supply

Recycling LIBs is critical for reducing reliance on primary lithium sources and minimizing environmental impacts (Vaccari et al., 2024; Zhou et al., 2024). Recycling offers a sustainable pathway by recovering valuable materials, reducing waste and GHG emissions. Hydrometallurgical recycling achieves over 95% recovery rates for lithium, cobalt, and nickel by dissolving battery components in acids, while direct recycling retains cathode materials without extensive chemical processing, offering a cost-effective alternative (Quinteros-Condoretti et al., 2021; Liu et al., 2024). However, both methods face obstacles, such as different battery designs and inadequate collection systems, that complicate large-scale adoption. (Tang et al., 2023; Yuan et al., 2024).

Integrating CE principles into lithium supply chains through recycling reduces the environmental burden of mining virgin materials. For instance, replacing 30% of primary lithium with recycled material reduced carbon emissions and water use by more than 10% (Alessia et al., 2021; Mas-Fons et al., 2024). Policies such as the EU Battery Regulation impose recycled content mandates, such as 12% recycled lithium in new batteries by 2036, encouraging technological developments and circular design practices (Dunn et al., 2022; Zhou et al., 2024).

Despite progress, challenges remain. Inefficient collection infrastructure and diverse battery designs hinder large-scale recycling (Tang et al., 2023). Emerging technologies such as automated disassembly and AI-driven sorting aim to improve efficiency (Niri et al., 2024). Europe is leading the way with robust policies and decentralized facilities, minimizing transportation

emissions and fostering local economies, while regions such as North America and parts of Asia are lagging due to fragmented regulations (Mayyas et al., 2023; Dunn et al., 2022). International cooperation is needed to standardize recycling practices and enhance material recovery worldwide (Niri et al., 2024).

Advanced recycling technologies, such as modular battery designs, support efficient disassembly and recovery, simplifying the process and enhancing scalability (Gebhardt et al., 2022). LCA studies highlight the benefits of CE approaches, linking recycling developments to sustainability goals (Alessia et al., 2021; Mas-Fons et al., 2024). Investments in innovative technologies and policies, combined with global efforts, ensure the sustainability of the lithium supply chain and align with decarbonization and resource efficiency goals. For detailed technical descriptions of recycling methods, regional frameworks, and advanced technologies, additional details are provided in Appendix B.

2.1.4 Policy and Future Directions

The sustainability of lithium supply chains relies heavily on robust policy frameworks and strategic innovations. Governments, international organizations, and industry stakeholders play a pivotal role in aligning lithium mining, processing, and recycling with global sustainability goals. The EU leading the way with comprehensive policies like the Battery Regulation, which mandates life-cycle accountability and recycled content quotas, such as 12% recycled lithium in new batteries by 2036. These policies emphasize transparency, carbon footprint disclosure, and resource efficiency, setting global benchmarks for supply chain sustainability (Dunn et al., 2022; Zhou et al., 2024).

Globally, regulatory landscapes are uneven. While the EU imposes strict mandates, other regions like the US adopt decentralized and voluntary approaches. Emerging economies often lack robust frameworks, leading to environmental degradation and social inequities. Initiatives such as the Responsible Lithium Partnership aim to address these gaps by promoting sustainable mining practices (Slattery et al., 2023) and fostering collaboration among governments, industries, and local communities in regions such as South America and Australia (Thies et al., 2019).

Technological innovation is a cornerstone of policy effectiveness. Governments are increasingly funding sustainable lithium technologies, including DLE and advanced recycling systems. Geothermal lithium mining, for instance, integrates renewable energy with low-impact recovery, aligning with climate neutrality goals while diversifying supply sources (Schenker et

al., 2024; Weinand et al., 2023). Such advancements reduce water and carbon footprints, critical for minimizing environmental impacts.

Harmonization of international regulations remains essential to create a resilient global lithium supply chain. Initiatives such as the Global Battery Alliance (GBA) aim to establish common standards for battery lifecycle management, promoting mining, recycling, and reuse. Collaboration on global policies is crucial to overcome fragmented regulations and ensure that best practices are adopted globally (Niri et al., 2024).

Economic incentives, such as subsidies for recycling facilities and penalties for non-compliance with environmental standards, drive policy adoption. For instance, China's subsidies enhance battery recycling infrastructure, while the EU supports CE initiatives through financial mechanisms (Yuan et al., 2024; Zhou et al., 2024). A more comprehensive discussion of the technical details behind the EU Battery Regulation, regional policy comparisons, and emerging technologies such as DLE and geothermal lithium extraction is available in Appendix C for further reference.

2.2 Introduction to Cobalt Supply Chain and Carbon Footprint

Cobalt, a critical material for LIBs used in EVs, electronics, and energy storage systems, plays an essential role in the global decarbonization transition. Its importance stems from its ability to enhance battery performance, thereby contributing to reducing reliance on fossil fuels and achieving net-zero emissions goals. However, the mining, refining, and transportation of cobalt generate significant GHG emissions, posing a challenge to its sustainability (Brink et al., 2020; Golroudbary et al., 2019). This section explores the carbon footprint associated with each stage of the cobalt supply chain and examines strategies for its reduction.

2.2.1 Carbon Footprint of Mining and Refining

Cobalt mining is concentrated primarily in the DRC, which accounts for approximately 70% of global production (Sun et al., 2019). The mining process relies heavily on fossil fuels to power machinery and chemical processing, leading to significant CO₂ emissions. Furthermore, refining, a process largely carried out in China, contributes significantly to the carbon footprint due to its reliance on coal-fired energy (Zeng & Li, 2015). These two processes represent a significant part of the environmental impact of the cobalt supply chain, highlighting the dual challenge of high energy intensity and geographical concentration (Brink et al., 2020).

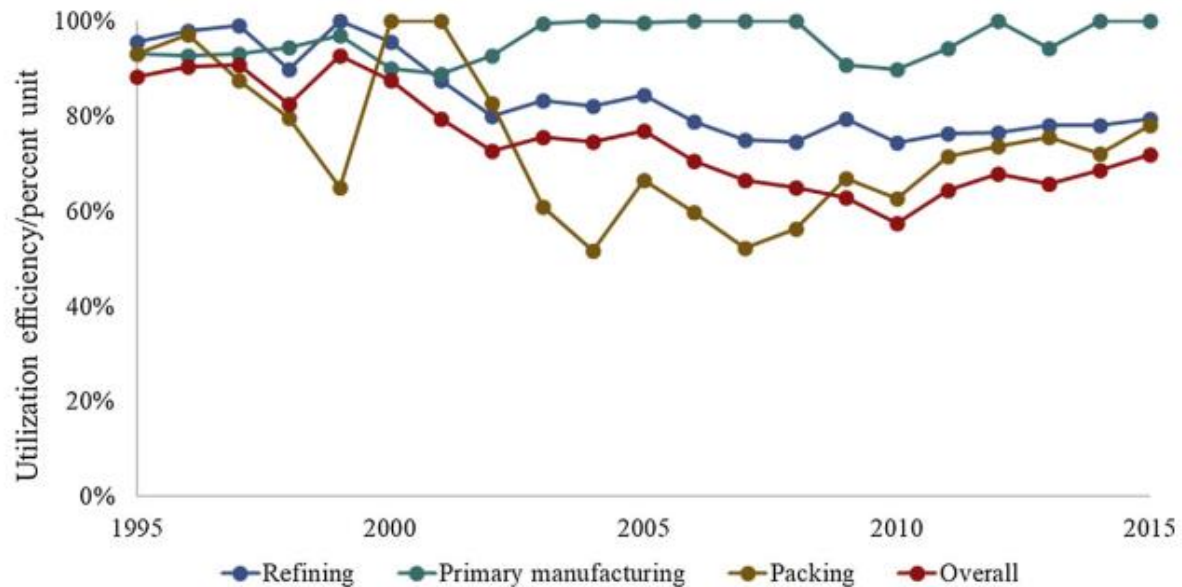


Figure 15: Global annual utilization efficiency of cobalt. This figure illustrates the flows of cobalt through different stages of refining, manufacturing, and packing, ultimately showing the overall utilization efficiency across the lifecycle (Sun et al., 2019).

The networked nature of the cobalt supply chain also increases its vulnerability to disruptions, which can lead to inefficiencies and greater environmental burden. For instance, supply chain bottlenecks or mine closures often require reliance on alternative, less efficient sources, exacerbating the carbon impact (Brink et al., 2020). These findings suggest that diversifying production and refining locations and investing in cleaner energy sources are essential for reducing emissions.

2.2.2 Transportation and Logistics Emissions

The international transportation of cobalt adds significantly to the carbon footprint. The journey from the DRC to refineries in China and then to battery manufacturing hubs in Europe and North America involves extensive maritime shipping, which emits significant amounts of CO₂.

In some cases, air freight is also used, further increasing the environmental cost (Jannesar Niri et al., 2024). Logistical emissions highlight the need for regional supply chain integration, including localized refining and production facilities. By reducing the distance, the cobalt has to travel, such measures can significantly reduce transportation-related emissions while also enhancing the overall supply chain efficiency (Shannak et al., 2024). Therefore, policy interventions to promote regional production hubs could play a pivotal role in achieving carbon-neutral cobalt production.

2.2.3 Cobalt Recycling and Carbon Footprint

Recycling cobalt from EoL LIBs is a viable alternative to primary mining, offering the potential to reduce emissions and alleviate pressure on virgin material mining. However, current recycling technologies, including hydrometallurgical and pyrometallurgical processes, remain energy intensive. In some cases, the emissions from these processes approach or exceed those of primary mining (Golroudbary et al., 2019). Furthermore, challenges in logistics and the quality of recovered materials limit the effectiveness of recycling in reducing the carbon footprint (Mayyas et al., 2023).

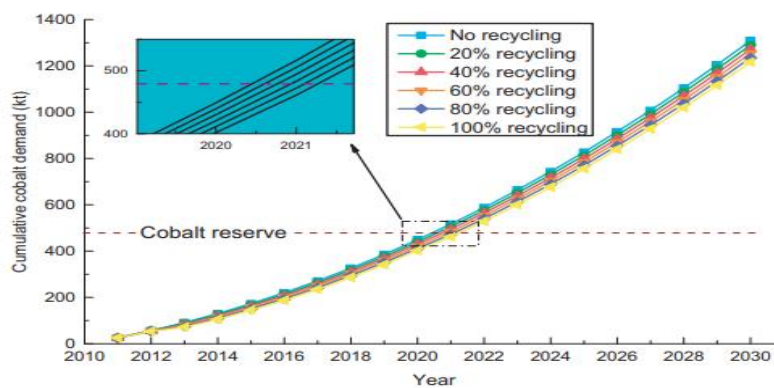


Figure 16: Cumulative demand of cobalt under different recycling scenarios in China (Zeng and Li., 2015)¹.

Despite these challenges, advancements in recycling technology hold promise. Adopting closed-loop supply chains, where materials from used batteries are reintroduced into the production cycle, could significantly enhance resource efficiency while reducing emissions (Qiao et al., 2024). Policymakers and industry leaders must prioritize these innovations to ensure sustainable cobalt use.

2.2.4 Implications and Strategies for Carbon Footprint Reduction

Addressing the carbon footprint of the cobalt supply chain requires a multi-faceted approach, combining technological innovation, policy intervention, and collaborative efforts across the industry. The transition of mining and refining operations to renewable energy sources could reduce emissions significantly (Brink et al., 2020). Similarly, establishing local processing and manufacturing hubs near mining sites could reduce transport-related emissions while enhancing supply chain resilience (Wesselkämper et al., 2024).

¹ This figure visually shows the relationship between recycling rates and cobalt demand, providing evidence for the argument about the importance of scaling up recycling efforts.

Material flow analysis (MFA) and LCA models provide valuable insights into the carbon footprint of the cobalt supply chain. These tools help identify emission hotspots and scale up mitigation strategies (Golroudbary et al., 2019; Zhou et al., 2024). Furthermore, the integration of CE principles, such as improved recycling systems and material recovery, can improve resource efficiency and lower emissions (Mayyas et al., 2023).

To ensure the sustainability of cobalt production, policymakers must incentivize the adoption of low-carbon technologies and enforce stringent environmental standards (Qiao et al., 2024). At the same time, investments in R&D for more energy-efficient recycling technologies will be critical to achieving long-term goals (Zeng & Li, 2015).

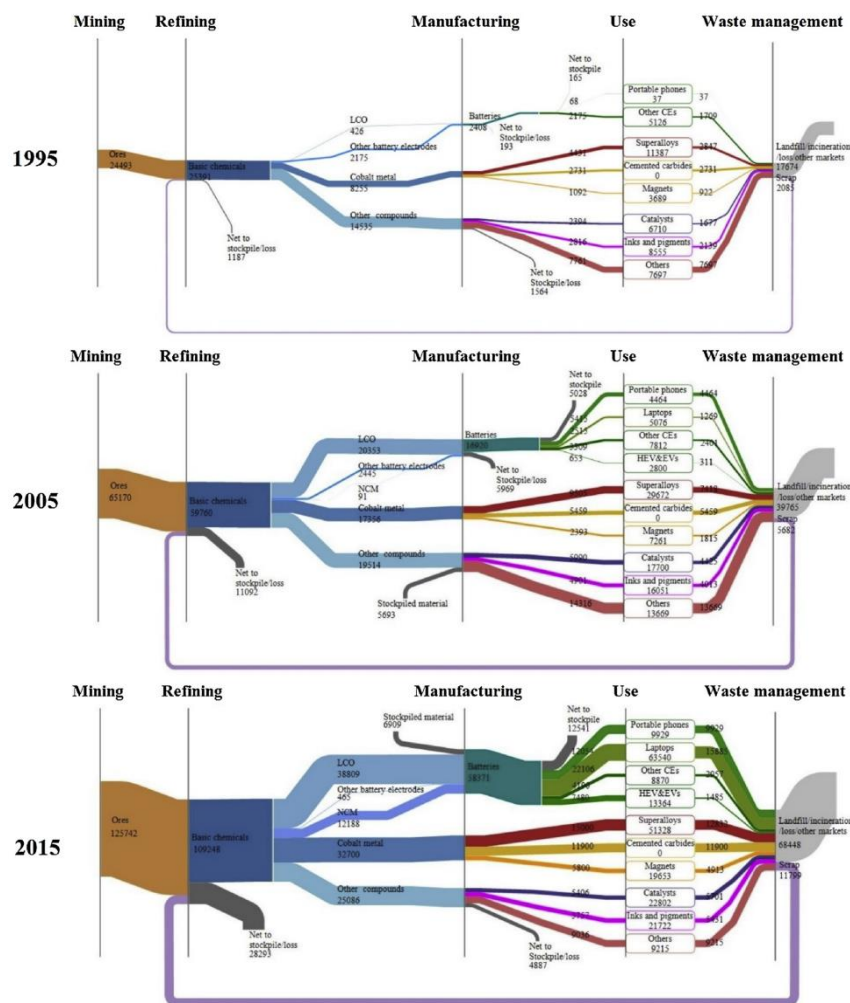


Figure 17: Global cobalt flow cycles for 1995, 2005 and 2015 (The flow direction is from left to right) (Sun et al., 2019).

In conclusion, while cobalt is vital for advancing clean energy technologies, its current supply chain contributes significantly to carbon emissions. Achieving a sustainable and carbon-neutral cobalt supply chain will require a holistic approach that includes technological innovation, policy support, and the integration of renewable energy sources at every stage of the supply chain

(Brink et al., 2020; Sun et al., 2019). However, carbon footprint is only one dimension of the challenges cobalt faces in clean energy transitions. A broader view of sustainability, encompassing social, economic, and ethical considerations, is equally critical to understanding and addressing the complexities of the cobalt supply chain (Zeng & Li, 2015; Zhou et al., 2024).

2.3 Cobalt Supply Chain and Sustainability - Introduction to Sustainability Challenges

Cobalt is indispensable for LIBs, which are central to decarbonizing transportation and energy systems. While the carbon footprint of cobalt's lifecycle highlights the emissions-related challenges associated with its mining, processing, and transportation, sustainability encompasses a broader range of issues. These include environmental degradation from mining, social injustices in production areas, and geopolitical risks due to the concentration of cobalt resources. Addressing these challenges requires a multifaceted approach that includes ethical sourcing, effective recycling, and strong policy frameworks to ensure long-term sustainability (Zeng & Li, 2015; Zhou et al., 2024).

2.3.1 Environmental Sustainability

The environmental challenges associated with cobalt mining and processing are significant. Mining activities in the DRC, the world's largest cobalt producer, contribute to deforestation, soil erosion, and water contamination. As highlighted in sub chapter 2.2, the mining, refining, and transportation of cobalt generate significant GHG emissions and represent a critical area for decarbonization efforts (Wesselkämper et al., 2024).

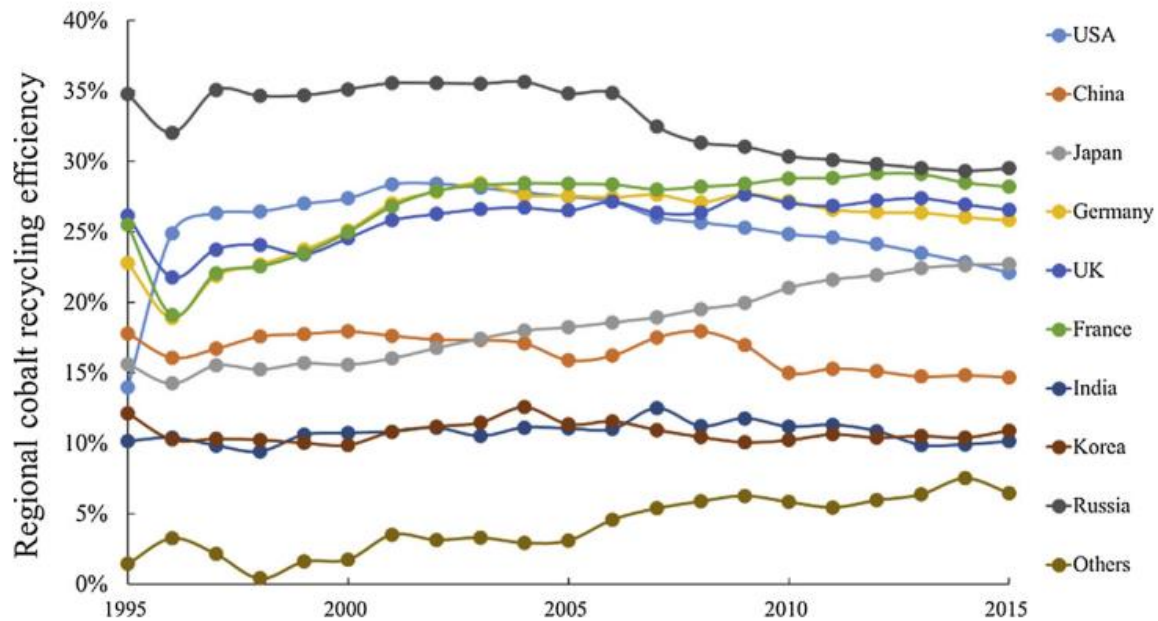


Figure 18: Regional Cobalt recycling efficiency (Sun et al., 2019).

MFA models have proven valuable for understanding cobalt's lifecycle and identifying inefficiencies. Sun et al. (2019) highlights the potential of MFA to identify areas where waste reduction and resource efficiency can be improved. Recycling EoL batteries as part of a CE is a promising solution. This approach reduces dependency on primary extraction, limits environmental degradation, and contributes to a lower carbon footprint (Yan et al., 2020). However, challenges remain in scaling up efficient recycling technologies, such as direct recycling methods, which preserve cobalt in its original cathode form but require further refinement (Golroudbary et al., 2022).

2.3.2 Social and Ethical Sustainability

The social and ethical dimensions of cobalt supply chains are equally critical. Artisanal and small-scale mining (ASM) accounts for a significant portion of cobalt production in the DRC but is often associated with child labour, hazardous working conditions, and human rights violations (Thies et al., 2019). These issues undermine the ethical foundations of the global energy transition.

Social Life Cycle Assessment (S-LCA) frameworks provide tools to evaluate and address these challenges. Thies et al. (2019) highlight in their study that the application of S-LCA can identify intervention points to improve social outcomes, such as fair labour practices and safer work

environments. The introduction of blockchain technology offers an innovative solution for increasing transparency in the supply chain, ensuring that ethically sourced cobalt can be traced and verified (Wang et al., 2025).

Initiatives such as the Fair Cobalt Alliance aim to improve conditions for artisanal miners by promoting safer practices, ensuring fair compensation, and investing in local community development. These programs demonstrate the potential for aligning industry practices with ethical standards while maintaining social equity (Deberdt & Billon, 2021).

2.3.3 Economic and Geopolitical Sustainability

The highly concentrated production of cobalt – over 70% of global production comes from the PRC – creates economic and geopolitical vulnerabilities. Political instability, trade restrictions, and market fluctuations increase the risks of supply chain disruptions, particularly for import – dependent regions such as Europe and the US (Yan et al., 2020). These vulnerabilities amplify not only geopolitical risks but also the environmental costs highlighted in the carbon footprint analysis, as disruptions can force reliance on less efficient and higher emission alternatives.

To mitigate these risks, strategies such as diversification through recycling, substitution of cobalt substitution in batteries, and long-term supply contracts becoming increasingly prevalent. For example, nickel-rich battery technologies, such as nickel-cobalt-manganese (NCM) cathodes, aim to reduce cobalt dependency while maintaining performance. Recycling also plays a critical role in stabilizing the market by providing a secondary source of cobalt, reducing dependence on primary sources (Wesselkämper et al., 2024).

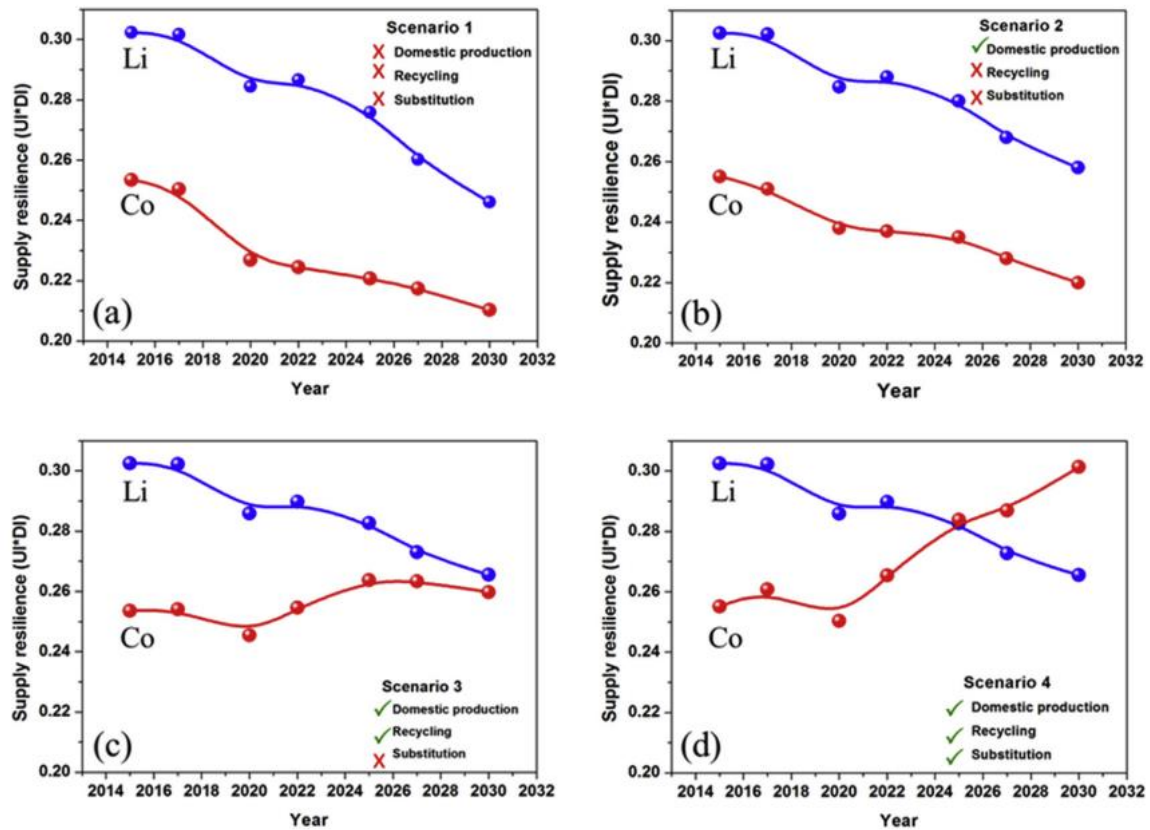


Figure 19: Chinese supply resilience for Lithium (Li) and Cobalt (Co) for three mitigation strategies from 2015 to 2030 – (a) scenario 1, (b) scenario 2, (c) scenario 3, (d) scenario 4 (Yan et al., 2020).

Economic policies, such as the EU - CE directives, are crucial in promoting sustainability. EU targets for recycled content in batteries, requiring 26% recycled cobalt by 2036, provide incentives for recycling while reducing geopolitical dependency. However, achieving these goals requires overcoming technical and logistical barriers, such as improving collection rates and scaling up recycling infrastructure (Zhou et al., 2024).

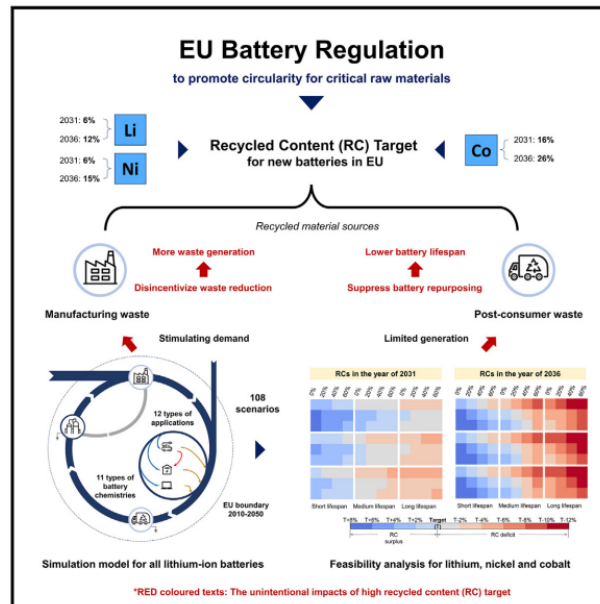


Figure 20: EU battery regulation to promote circularity for critical raw materials (Zhou et al., 2024).

2.3.4 Recycling and Circular Economy Approaches

Recycling forms the cornerstone of a sustainable cobalt supply chain. Current recycling methods, such as hydrometallurgical and pyrometallurgical processes, recover cobalt from spent batteries but are energy-intensive and have environmental implications. Direct recycling methods, which retain cobalt in its original cathode form, offer a more efficient alternative but require further development to achieve widespread adoption (Yan et al., 2020). This dual focus - on reducing emissions while enhancing material recovery - positions recycling as an imperative for both the environment and sustainability.

The MFA demonstrates that achieving circularity in the cobalt supply chain depends on improved collection systems and advanced recycling technologies. Zhou et al. (2024) emphasize in their study that achieving the EU's recycled content targets will require a coordinated effort between policymakers, industry, and researchers. Furthermore, the adoption of CE strategies, such as extended producer responsibility (EPR) schemes, enhances material recovery and minimizes waste (Wesselskämper et al., 2024).

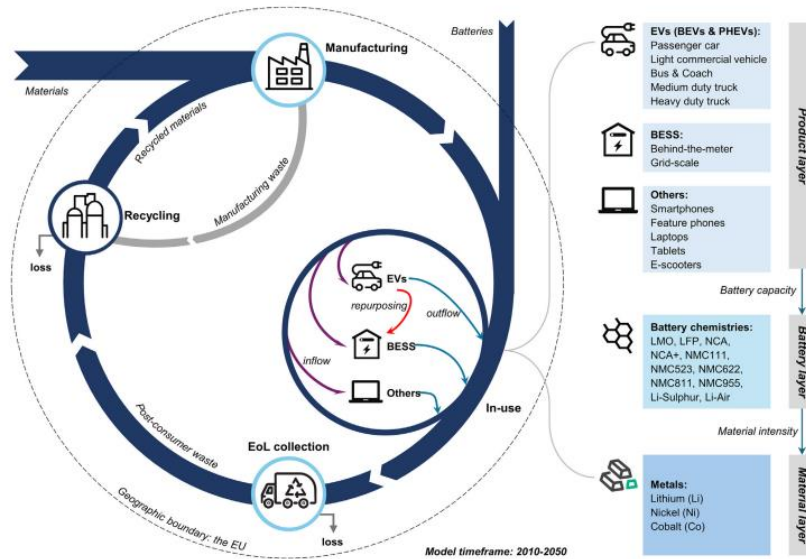


Figure 21: The framework for a dynamic MFA for the EU's LIBs (Zhou et al., 2024).

2.3.5 Implications for a Sustainable Future

Sustainability in the cobalt supply chain requires comprehensive strategies that integrate environmental, social, and economic factors. Transitioning to cleaner production technologies, promoting recycling infrastructure, and enforcing ethical sourcing practices are critical steps toward this goal. International collaboration is also essential to mitigate geopolitical risks and ensure equitable access to cobalt resources (Yan et al., 2020).

The global energy transition depends on a sustainable cobalt supply chain that balances demand for CRMs with the principles of environmental stewardship and social equity. By adopting CE practices, diversifying material sources, and fostering innovation, the cobalt industry can align its operations with the broader goals of a low-carbon and sustainable future.

2.4 Introduction to Rare Earth Elements Supply Chain and Environmental Impact

REEs are vital for advancing renewable energy and high-tech industries. However, their extraction and processing impose significant environmental challenges. This subchapter examines the impacts of REEs production, focusing on ecological degradation, GHG emissions, and waste generation.

2.4.1 Direct Environmental Impacts of REE Mining and Processing

REEs mining and processing involve methods that cause extensive ecological damage. Open-pit mining, the most common extraction technique, leads to habitat destruction, soil erosion, and disruption of local ecosystems. The beneficiation process, which separates REEs from raw ore, often involves large amounts of chemicals that result in acid mine drainage and leaching of heavy metals into surrounding water systems. These local impacts not only harm biodiversity but also create long-term challenges for land restoration (Barakos et al., 2016; Pell et al., 2019).

Furthermore, the energy-intensive nature of REEs processing contributes significantly to GHG emissions. The roasting, leaching, and solvent extraction stages require significant energy inputs, much of which is derived from fossil fuels. LCA studies reveal that producing 1 kilogram of rare earth oxide generates between 17 and 87 kilograms of CO₂ - equivalent emissions. These emissions vary depending on the energy mix and efficiency of processing technologies, with higher impacts observed in countries reliant on coal- fired energy, such as China (Pell et al., 2019).

2.4.2 Toxic Waste and Long - Term Risks

REEs production is also associated with the generation of toxic and radioactive waste, which poses significant environmental risks. Thorium and Uranium, often present in REEs mineral deposits, contribute to the radioactive nature of mining by-products. Inadequate storage and disposal of these wastes can lead to soil and water contamination, with long-term ecological and health consequences (Bonfante et al., 2021).

For instance, the Bayan Obo mine in China, one of the world's largest REEs producers, has faced criticism for its inability to manage the vast amounts of radioactive waste produced²(Nayar, 2021). This has led to widespread environmental degradation and increased public health concerns in surrounding communities (Pell et al., 2019). Such cases highlight the critical need for rigorous waste management practices within the REEs industry.

² There are over 70,000 tons of radioactive thorium stored in this area.

2.4.3 Mitigation through Process Optimization

Efforts to mitigate the environmental impact of REE production have focused on the optimization of processing technologies. Innovations such as acid regeneration systems and the integration of renewable energy sources into treatment plants have shown positive results in reducing emissions and chemical waste. For instance, some projects have implemented closed-loop acid recovery systems that significantly lower both resource consumption and waste generation (Pell et al., 2019).

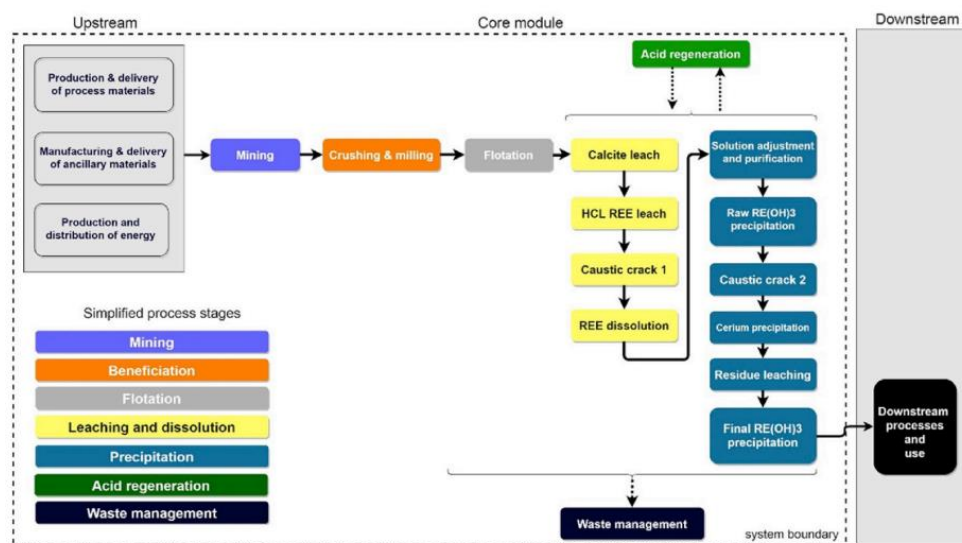


Figure 22: Process flowsheet with the system boundary for life cycle assessment (Pell et al., 2019).

However, these solutions face challenges in scalability and economic feasibility, particularly in regions where capital investment in green technologies remains limited. Addressing these barriers will require coordinated efforts among industry leaders and policymakers to ensure that sustainable practices are prioritized at every stage of the REEs supply chain.

2.5 Introduction to Rare Earth Elements Supply Chain and Sustainability

Achieving sustainability in REEs supply chains is essential for addressing global environmental, economic, and social challenges. This subchapter explores strategies such as CE practices, economic resilience, and policy frameworks that enable a sustainable future for REEs.

2.5.1 Circular Economy and Recycling of REEs

A CE model is at the centre of sustainable REEs supply chain. By emphasizing the reuse and recycling of materials, this approach reduces dependency on primary extraction and minimizes environmental damage. Recycling technologies such as bioleaching, solvent extraction, and microwave-assisted leaching are transforming the recovery of REEs from secondary sources

like NdFeB magnets, batteries, and e-waste (Pell et al., 2019). These methods not only recover valuable materials but also significantly reduce the ecological footprint of REEs production (Yadav et al., 2024; Ghorbani et al., 2025).

Urban mining, which focuses on extracting REEs from waste electrical and electronic equipment (WEEE), is another key pillar of the CE. By harnessing discarded electronics, urban mining addresses both supply chain constraints and global e-waste challenges. For instance, efficient urban mining initiatives could meet up to 50% of the demand for neodymium and dysprosium in Europe (Barakos et al., 2016). However, the scalability of such solutions depends on improving product design for recyclability and enhancing collection infrastructure.

2.5.2 Economic and Social Dimensions of Sustainability

The economic sustainability of REEs supply chains is closely linked to reducing geopolitical dependencies. China currently dominates global REE production, accounting for approximately 70-90% of the market. This concentration poses risks of supply disruptions and price volatility. Diversification efforts, such as urban mining and local recycling initiatives in Europe, are critical to strengthening economic resilience (Barakos et al., 2016).

Social sustainability is equally important. In developing regions, unregulated REEs mining often exposes workers to hazardous conditions and displaces local communities. Ethical sourcing practices and fair labour standards must be integrated into REEs supply chains to align with global sustainability goals. Policy-driven initiatives, such as those promoted by the United Nations Sustainable Development Goals (SDGs), play a vital role in ensuring that REEs projects prioritize social equity and community well-being (Barakos et al., 2016; Ilankoon et al., 2022).

2.5.3 Policy Frameworks and Technological Innovations

Policy frameworks are essential for driving sustainable practices in the REEs industry. The EU Green Deal and CE Action Plan emphasize resource efficiency and the adoption of green technologies (Ghorbani et al., 2025). These policies encourage industries to prioritize recycling, ethical sourcing, and the reduction of environmental impacts (Bonfante et al., 2021).

Technological innovations complement these policies by providing actionable tools for sustainability. LCAs and process simulation models are used to identify hotspots in REEs supply chains and optimize material flows (Bonfante et al., 2021). Furthermore, the development of

REE - free alternatives and AI - driven recycling systems offer promising ways to reduce dependency on primary resources while enhancing operational efficiency (Yadav et al., 2024; Ghorbani et al., 2025).

A sustainable REE supply chain integrates CE principles, ethical practices, and innovative technologies supported by robust policies. Managing these parameters ensures that the REEs industry will support a future of low carbon emissions, resilience and social justice, while meeting growing global demand.

2.6 Critical Raw Materials and Sustainable Sourcing

The Sustainable sourcing of CRMs and REEs is the cornerstone of modern supply chain strategies. Frameworks like the ESSENZ method integrate environmental, social, and economic indicators to classify regions of origin and provide valuable insights into their sustainability (Schneider et al., 2021). Reserve-dominant regions often exhibit high resource availability but low compliance with sustainability standards, while governance-dominant regions exhibit robust regulatory frameworks but limited resources (Schneider et al., 2021).

According to Manjong et al. (2024) the environmental impact of CRMs extraction varies significantly across sourcing regions. Environmental scores and their variability highlight trade-offs between resource availability and sustainability practices. A detailed visual analysis of these metrics is provided in Appendix D. Furthermore, Figure 23 maps the geographical distribution of key CRMs mining locations, showing global dependencies and supply chain vulnerabilities (Mayyas et al., 2023).

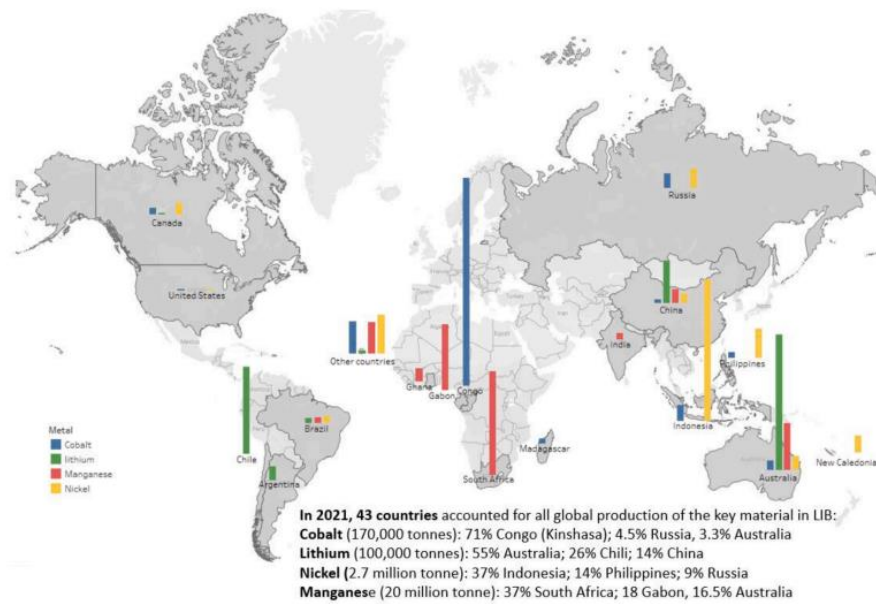


Figure 23: Mining locations of the key elements used in Li-ion batteries (Mayyas et al., 2023).

Recycling technologies, such as hydrometallurgical and pyrometallurgical processes, play a vital role in reducing the dependence on primary sources and enhancing the resilience of the supply chain (Sultana et al., 2022). Table 3 highlights the global production volumes of key LIBs materials, offering insight into supply chain distribution (Sultana et al., 2022). Emerging innovations, including AI-based sorting and automated disassembly, are improving the efficiency and scalability of recycling (Lehtimäki et al., 2024). The stages of LIBs recycling, including the potential for material recovery, are analyzed in Appendix D.

Global production of lithium-ion battery key materials and locations

Raw materials production	Production countries & production rate			
Lithium (43,000 tons)	44% Australia	34%	13%	
		Chile	Argentina	
Natural graphite (1.2 million tons)	67% China	13%	8% Brazil	
		India		
Nickel (2.1 million tons)	11%	10%	9% Russia	9%
	Philippines	Canada		Australia
Manganese (16 million tons)	33% South Africa	16%	14%	
		China	Australia	
Cobalt (110,000 tons)	59% DRC	5%	5%	
		Russia	Australia	

Table 3: Global production of lithium-ion battery key materials and locations (Sultana et al., 2022).

Geopolitical dependencies, particularly on China for lithium and cobalt processing, exacerbate vulnerabilities in CRMs supply chains. Diversification of sourcing areas and promotion of recycling technologies can mitigate these risks (Yan et al., 2020). Regional policies, such as the EU battery regulation that mandates recycled content quotas, promote CE principles and encourage sustainable supply chain practices (Dunn et al., 2022).

2.7 Supply Chain Risks and Critical Raw Materials

The transition to a carbon-neutral European supply chain depends on securing CRMs and REEs, which are essential for renewable energy technologies and EVs. However, supply chains for these materials are fraught with risks spanning geopolitical, environmental, and social dimensions.

Geopolitical risks are among the most pressing concerns due to the concentration of CRMs extraction and processing in a few countries. China dominates the global supply of REEs, controlling more than 80% of their processing, while the DRC produces over 70% of the world's cobalt. These dependencies expose Europe to significant vulnerabilities, such as supply disruptions due to trade restrictions or government dominance in resource management. Events such as the COVID-19 pandemic and the war in Ukraine have highlighted the fragility of global supply chains, underscoring the need for diversification (Rizos et al., 2024; Kamran et al., 2023).

Environmental risks also threaten the sustainability of CRMs supply chains. In Chile, lithium extraction has led to severe water depletion in the Atacama Desert, disrupting local ecosystems and agricultural activities (Zhou et al., 2024). Similarly, cobalt mining in the DRC has resulted in biodiversity loss, soil contamination, and the generation of hazardous waste. These environmental damages have sparked global criticism, calling for stricter regulations and sustainable mining practices (Wesselkämper et al., 2024).

Social risks further complicate CRM sourcing, particularly ASM dependent regions. In the DRC, ASM operations often involve child labour, unsafe working conditions, and exploitation of vulnerable communities. These issues not only raise ethical concerns but also pose significant risks to the continuity of the supply chain as advocacy and regulatory pressures intensify (Zhou et al., 2024).

Economic risks arise from the rapid increase in demand for CRM, driven by the expansion of the renewable energy and EVs industries. This surge in demand has led to price volatility and market uncertainties, which can prevent investment in sustainable technologies. Recycling and

urban mining offer potential solutions to these risks, but their implementation remains limited by technical and logistical challenges (Kamran et al., 2023). Table E.1 in Appendix E categorizes these risks and provides detailed examples.

Mitigating these risks requires a multifaceted approach, including diversification of supply sources, promotion of recycling technologies and implementation of strong regulatory frameworks such as the EU Battery Regulation, which mandates recycled content and promotes CE practices (Dunn et al., 2022; Rizos et al., 2024).

3. Critical Raw Materials and Their Strategic Role in Decarbonizing Supply Chains

3.1 Decarbonization and the Role of Critical Raw Materials

The transition to a carbon-neutral economy is driven by ambitious global and regional policies aimed at mitigating climate change by decarbonizing energy and transport systems. Central to these efforts is the development of renewable energy technologies such as wind turbines, solar panels, and EVs, which rely heavily on materials such as lithium, cobalt and REEs. However, the increasing reliance on these CRMs raises significant concerns about sustainability, supply bottlenecks and socio-environmental impacts, which need to be addressed to ensure a just and efficient transition. (Cristóbal et al., 2020; Valero et al., 2018).

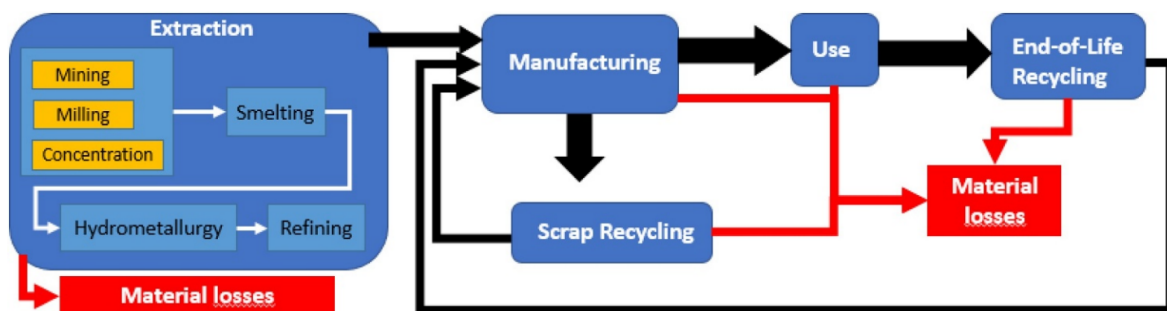


Figure 24: Life cycle system boundaries and stages (Cristóbal et al., 2020).

LCAs reveal hidden inefficiencies in current CRMs management, particularly in renewable energy technologies. These assessments identify losses in the mining, manufacturing, and recycling stages, which can significantly amplify material demand. Cristóbal et al. (2020) emphasize in their study that for certain materials, including praseodymium and gallium, life cycle losses may increase demand by up to 37 times. Such inefficiencies are often overlooked, resulting in underestimation of material requirements to achieve decarbonization goals. As

shown in Figure 24, adopting CE practices can significantly improve material efficiency, reducing waste and environmental damage (Cristóbal et al., 2020).

The demand for lithium and cobalt, essential components of LIBs, is expected to increase dramatically as the adoption of EVs and renewable energy storage systems accelerates. Valero et al. (2018) in their study project a 700% increase in lithium demand by 2050, a figure that highlights the need for robust recycling systems. Current recycling rates for lithium stand at a mere 1%, highlighting the urgent need to develop efficient recovery technologies to reduce dependence on primary resources and mitigate potential supply disruptions. Table 4 details the CRM requirements for key technologies, emphasizing the resource intensity of renewable energy systems (Valero et al., 2018).

Material	Recycling rate (%)	Material	Recycling rate (%)
Ag	30	Mg	33
Al	36	Mn	37
Cd	25	Mo	33
Ce	1	Nb	50
Co	32	Nd	5
Cr	20	Ni	29
Cu	30	Pd	50
Dy	10	Pr	5
Fe	50	Pt	50
Ga	25	Sn	22
Gd	5	Ta	17.5
Ge	35	Te	1
In	37.5	Ti	52
La	5	V	–
Li	1	Zn	22.5

Table 4: Recycling rates used to estimate the amount of materials which come from recycling instead of from primary resources (Valero et al., 2018).

Renewable energy technologies are resource intensive. The material requirements for solar panels, wind turbines, and EVs batteries highlight the scale of CRM reliance. Environmental and social costs further compound these challenges. Figure 25 illustrates the material needs for different wind turbine technologies, highlighting significant variations by installation type. For additional data on solar thermal power systems, see Appendix F, which includes Table F.1 for detailed material analyses (Fallah and Fitzpatrick, 2022).

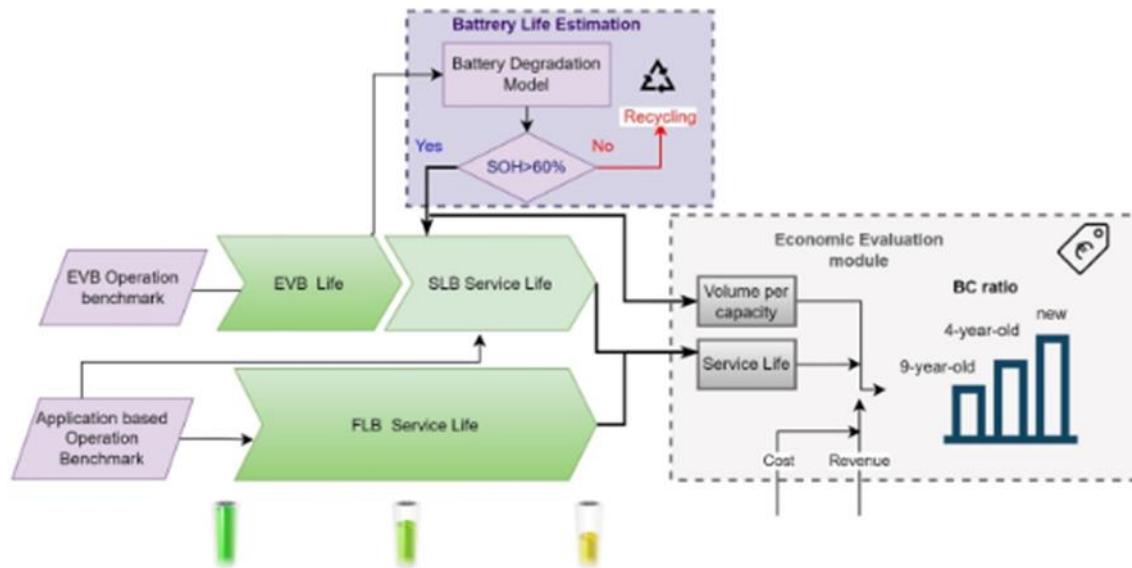


Figure 25: Methodology diagram (Fallah and Fitzpatrick., 2022)

Environmental and social costs present significant challenges. For instance, the Barroso Mine in Portugal, proposed as Europe’s largest lithium mine, has faced opposition due to potential ecological damage and threats to cultural heritage. This highlights the tension between local communities and global decarbonization goals (Dunlap and Riquito, 2023).

Policies such as the EU CRM Act and the Battery Regulation play a vital role in addressing these challenges. By promoting recycling, material substitution, and traceability, they enhance the sustainability and resilience of CRMs supply chains. Technological innovations, such as solid-state batteries and urban mining, also offer long-term solutions to reduce CRM dependency (Fallah and Fitzpatrick, 2022; Valero et al., 2018).

For detailed quantitative data, refer to Appendix F, which includes insights on CRM requirements for renewable energy technologies, material performance, and specific socio-environmental case studies.

3.2 Critical Raw Materials Driving the Low-Carbon Economy

3.2.1 Low - carbon economy and Lithium

The transition to a LE has dramatically increased the demand CRMs, with lithium emerging as a key resource for renewable energy technologies. LIBs, known for their high energy density and efficiency, are crucial for powering EVs, renewable energy storage systems, and portable electronics. Global demand for lithium is projected to increase sharply, driven by the wide-

spread adoption of EVs and renewable energy solutions. By 2040, nearly 80% of lithium consumption is expected to be attributed to these applications (Wang et al., 2024). This growing reliance on lithium highlights its critical role in global decarbonization efforts, while also raising pressing concerns about resource availability and sustainability.

Lithium extraction is primarily concentrated in the Altiplano region of the Andes, often referred to as the "Lithium Triangle," which includes parts of Bolivia, Chile, and Argentina. This region accounts for approximately 65% of the world's known lithium reserves, making it central to global low-carbon energy strategies (Rentier et al., 2024). However, the environmental and social costs associated with lithium brine mining are significant. Mining activities disrupt key variables of geodiversity, such as soil and water systems, negatively affecting biodiversity, ecosystem services, and local indigenous communities. For instance, unsustainable mining practices have been linked to the depletion of water resources, which are vital to local ecosystems and agricultural activities. Such impacts highlight the trade-offs inherent in lithium extraction, where the benefits of low-carbon technologies must be weighed against significant environmental and social challenges (Rentier et al., 2024). To mitigate these impacts, sustainable mining practices and robust environmental monitoring are imperative, ensuring alignment with global SDGs, such as clean energy (SDG 7) and climate action (SDG 13).

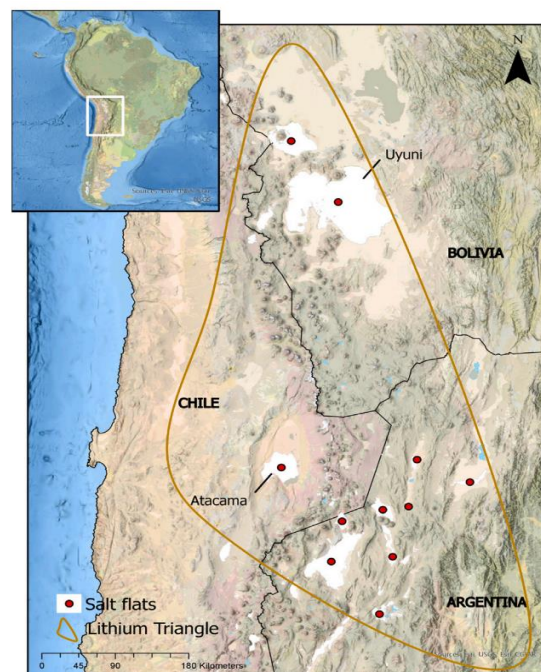


Figure 26: The Lithium Triangle and the location of salt flats in the Andean Altiplano (Rentier et al., 2024).

Recycling of used LIBs offers a promising solution to reduce reliance on primary lithium extraction and to mitigate its environmental footprint. Advanced recycling technologies, such as hydrometallurgical processes, have shown significant potential for recovering lithium, cobalt, and nickel from used batteries. These methods not only reduce GHG emissions but also contribute to a CE by reintegrating recovered materials into the supply chain (Wang et al., 2024). Recent innovations, such as the use of alginate hydrogels as recyclable extracting media, have improved the efficiency and sustainability of lithium recovery, achieving high recovery rates with reduced environmental impacts (Wang et al., 2023). Furthermore, low-temperature fluorination roasting has emerged as an effective method for the regenerating carbon residues and recovering high-purity materials, further enhancing the environmental benefits of LIBs recycling (Zhu et al., 2022). Such advancements highlight the importance of scaling up recycling technologies to sustainably address future lithium demand.

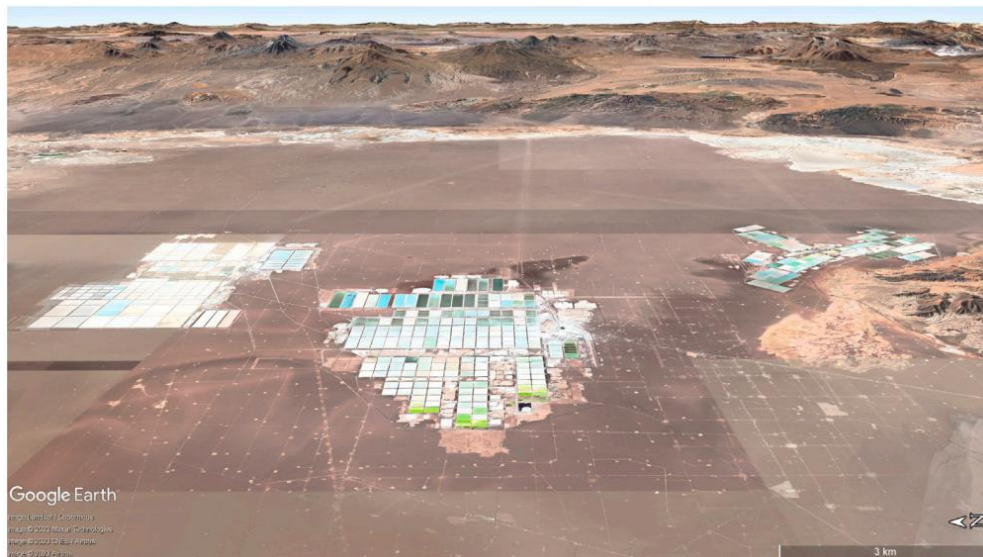


Figure 27: Snapshot of an oblique aerial photo composition of a lithium brine mining site in the Salar de Atacama in Northern Chile (Rentier et al., 2024)³.

Global policy frameworks have also recognized the strategic importance of lithium in the transition to a LE. Initiatives such as the EU's CRMs Act and Battery Regulation aim to strengthen domestic supply chains, promote recycling, and reduce dependence on imported lithium (Valero et al., 2018). These policies are crucial for ensuring a sustainable and resilient lithium

³ The squared fields are evaporation ponds, and their colour reflects the mineral concentration of the water. The mixing zones are depicted in white at the transition towards the Andean Mountain range. The squared pattern in the front is caused by roads and the white dots are pumping stations and monitoring wells (Rentier et al., 2024).

supply, while supporting broader decarbonization efforts. For example, the EU Battery Regulation imposes string recycling targets and reporting of battery carbon footprints, aligning industrial practices with global climate goals (Wang et al., 2024).

Technological advancements in LIBs production further complement these efforts, reducing material intensity and improving battery performance. Solid-state batteries and new cathode materials are being developed to improve energy efficiency while reducing reliance on CRMs. Such innovations, coupled with advances in recycling methods, promise to minimize the environmental footprint of LIBs throughout their lifecycle, contributing to a more sustainable energy ecosystem (Zhu et al., 2022).

A comparative analysis of physical exploitation versus recycling reinforces the environmental benefits of CE practices. Wang et al. (2024) demonstrate in their study that recycling spent LIBs can achieve significantly lower carbon emissions and energy consumption than traditional mining. For instance, recycling processes for lithium carbonate reduce carbon emissions by 41% compared to primary production using mass-based allocation methods. Such findings highlight the necessity of moving to closed-loop systems, where materials are continuously reused, reducing waste and conserving resources.

3.2.2 Low - carbon economy and Cobalt

The transition to a LE is a critical component of global strategies to mitigate climate change and promote sustainable industrial practices. Central to this shift is the effective management of CRMs, which are essential for renewable energy technologies and energy storage systems. However, the extraction, processing, and use of these materials are inherently carbon-intensive, requiring innovative approaches to reduce environmental impacts while meeting growing demand.

Recycling plays a pivotal role in this transformation, offering a path to significantly lower GHG emissions compared to primary material extraction. Ali et al. (2024) highlights in their study that recycling processes for NCM based batteries can reduce the carbon footprint of secondary materials such as cobalt sulphate by 73.5% and nickel sulphate by 57.4% compared to their primary counterparts. In contrast, recycling lithium carbonate presents challenges, presenting a 20.8% higher carbon footprint than its primary production under some scenarios. These findings highlight the importance of promoting recycling technologies and improving recovery efficiency to meet the carbon reduction targets imposed by the EU's Battery Regulation, which requires detailed carbon footprint reporting and strict recycling targets.

The escalating demand for CRMs is another dimension of the LE. As Laing and Pinto (2023) emphasize in their study, renewable energy technologies require a greater quantity and variety of materials compared to traditional energy systems. For instance, EVs use significantly more lithium, cobalt and nickel than internal combustion vehicles. This surge in demand places immense pressure on global supply chains, particularly in regions such as the DRC, which supplies over 70% of the world's cobalt. ASM is critical to meeting this demand but is often associated with environmental degradation, unsafe labour practices, and social challenges. Consequently, the integration of recycling and circular supply chain practices is imperative to mitigate these issues while reducing carbon emissions.

Technological innovations and policy frameworks are instrumental for addressing the carbon impacts of CRMs supply chains. Nguyen et al. (2021) discuss in their study, the importance of recycling and reducing reliance on primary materials to stabilize supply chains and mitigate environmental impacts. Zhang et al. (2022) further elaborate in their study, on the potential of advanced hydrometallurgical recycling methods to recover valuable metals from used LIBs, significantly reducing carbon emissions associated with primary mining. These innovations align with policy measures such as the EU's CE action plan, which provides incentives for lower carbon footprints and promotes sustainable industrial practices.

3.2.3 Low - carbon economy and Rare Earth Elements

The transition to an LE is fundamentally based on REEs, which serve as critical enablers for renewable energy technologies GHG emissions reduction. Among them, NdFeB permanent magnets, composed of neodymium, praseodymium, and dysprosium, are essential for technologies such as wind turbines and EVs due to their superior magnetic properties. These magnets directly contribute to the energy efficiency of renewable systems and the decarbonization of transport, in line with global climate goals such as those outlined in the Paris Agreement. Bonfante et al. (2021) emphasize in their study the alignment of these advancements with SDGs, particularly SDG 7, which supports affordable and clean energy, and SDG 13, which focuses on climate action.

However, the production and use of REEs presents significant challenges. REEs mining involves energy-intensive processes that rely on hazardous chemicals such as sulfuric acid, generating toxic waste streams and radioactive byproducts, including thorium and uranium (Bonfante et al., 2021). Furthermore, the global REEs supply chain is highly concentrated in China,

which processes over 90% of the world's REEs. This geographical concentration raises concerns about supply chain resilience and geopolitical risks (Borra et al., 2024). The combination of environmental degradation and resource dependency highlights the urgent need for more sustainable supply chain practices.

A key strategy for addressing these challenges lies in the adoption of CE principles. Mejame et al. (2022) in their study propose a CE model that focuses on enhancing resource efficiency and recycling, particularly for NdFeB magnets, which can recover up to 95% of valuable REEs such as neodymium and dysprosium. This approach not only reduces the dependence on primary resource mining, but also mitigates the environmental impacts associated with mining. Similarly, Zhao et al. (2024) highlight in their study urban mining as a complementary strategy, emphasizing the recovery of REEs from EoL products such as EVs and wind turbines. Urban mining, especially in regions with substantial industrial and economic activity, offers significant potential for waste reduction and diversification of supply sources.

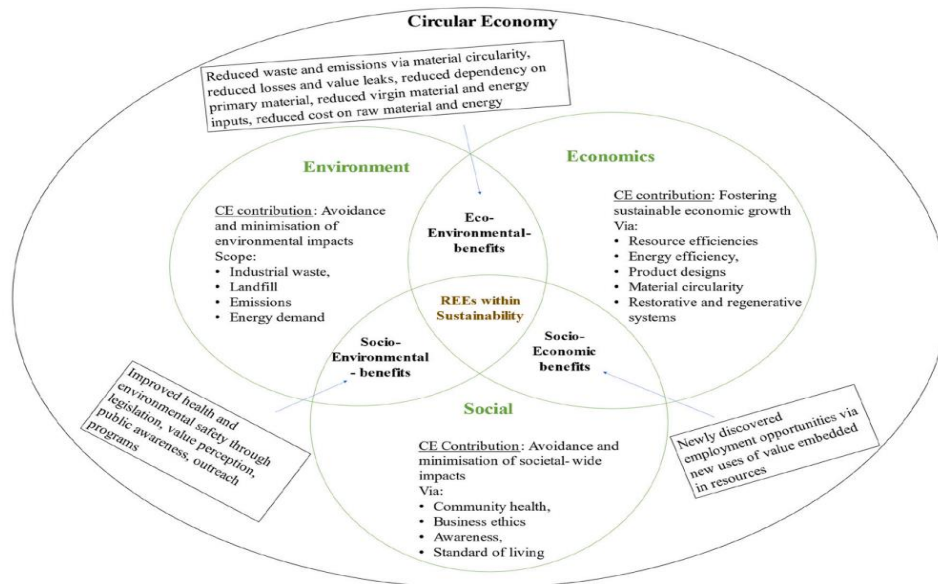


Figure 28: A comprehensive Circular Economy Scheme (Mejame et al., 2022)⁴.

The ethical and geopolitical dimensions of REEs production add further complexity to their role in a LE. Brown et al. (2024) in their study discusses the concept of "sacrifice zones," where marginalized communities in mining regions disproportionately bear the environmental and

⁴ REEs within the framework of sustainable development. Sustainability in REEs consumption from a Circular Economy perspective contributes to all the three pillars of sustainable development (Economics, Environmental and social) (Mejame et al., 2022).

social costs of extraction. These inequities call for stronger governance mechanisms and international cooperation to ensure that the transition to cleaner energy does not exacerbate social and environmental injustices. Integrating environmental justice into supply chain management and regulatory frameworks is essential for creating a fair and sustainable system.

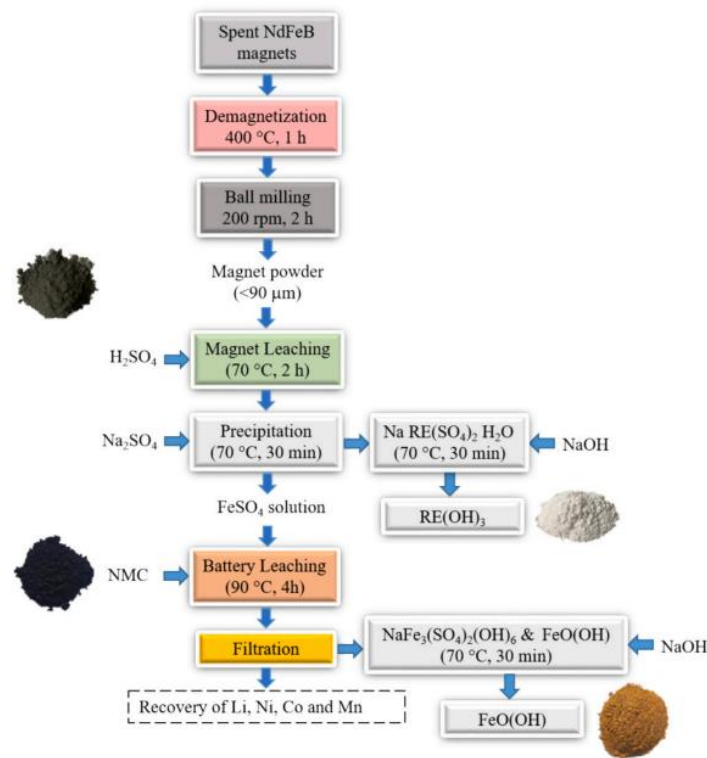


Figure 29: Simultaneous recovery of critical elements from NdFeB magnets and LIBs - The schematic flowsheet of the overall process (Borra et al., 2024).

Advancements in recycling technologies provide promising pathways for aligning REEs supply chains with sustainability objectives. Borra et al. (2024) in their study propose a synergetic recycling methodology that minimizes waste generation and reagent consumption during the recovery of REEs from NdFeB magnets and LIBs. Such innovations exemplify the potential of technological progress to address both environmental and supply chain challenges while adhering to CE principles.

3.3 Energy Transition Metals and Supply Chain

The global transition to renewable energy and low-carbon technologies has brought energy transition metals to the forefront of sustainability discussions. These critical metals, including NCM, and REEs, are indispensable for the development of clean energy technologies (Kamran et al., 2023). Their unique properties enable the efficient operation of these technologies, which

are crucial for achieving carbon neutrality. However, the supply chains of these metals face significant challenges, such as growing demand, regional dependencies, environmental degradation, and geopolitical risks. Addressing these challenges requires a comprehensive understanding of the supply chain dynamics, environmental trade-offs, and policy frameworks that underpin and support the sustainable management of these resources.

The demand for energy transition metals is projected to increase dramatically in the coming decades as countries strive to meet their decarbonization goals. LIBs, essential for EVs and renewable energy storage systems, are driving demand for NCM. By 2050, the annual demand for these metals is expected to increase by six to nine times from current levels (Yuan et al., 2024). Similarly, REEs such as neodymium and dysprosium, which are crucial for the production of high-performance magnets in wind turbines and electric motors, are projected to experience a threefold increase in demand by 2040 (Kamran et al., 2023). This surging demand is placing unprecedented pressure on supply chains, which are often concentrated in specific regions. For instance, the DRC accounts for over 60% of global cobalt production, while China dominates REEs processing, controlling approximately 85% of the global supply (Golroudbary et al., 2022; Yuan et al., 2024). Additionally, underexplored regions such as Central Asia hold vast CRMs reserves that could alleviate supply pressures if logistical and geopolitical barriers are addressed (Vakulchuk & Overland, 2021).

The environmental and ethical challenges associated with the mining and processing of these metals further complicate their supply chains. Mining activities often result in significant environmental degradation, including habitat destruction, water pollution, and GHG emissions. For instance, the lithium extraction from brine in South America's "Lithium Triangle" is associated with extensive water use, leading to conflicts with local communities over water rights (Weinand et al., 2023). Similarly, cobalt mining in the DRC has raised concerns about child labour, unsafe working conditions, and broader social inequities (Golroudbary et al., 2022). These issues are exacerbated by limited governance in resource-rich areas, highlighting the need for stricter environmental and labour standards in mining operations (Watari et al., 2021).

CE strategies and technological innovations offer promising pathways to mitigate the environmental and social impacts of energy transition metals supply chains. Recycling critical metals from EoL products, can significantly reduce the dependency on primary extraction. For instance, recycling cobalt from batteries could reduce GHG emissions by up to 59% and reduce water usage by 40% compared to primary production (Golroudbary et al., 2022). Similarly, DLE from geothermal brines presents a sustainable alternative to conventional mining, with

lower environmental impacts and the potential for integration into renewable energy systems (Weinand et al., 2023). Furthermore, creating recycling hubs close to production centers could optimize the use of resources and create more resilient supply chains (Calderon et al., 2020). These innovations highlight the importance of integrating CE principles into resource management to create more sustainable supply chains.

Effective governance and policy frameworks are essential for ensuring the resilience and sustainability of energy transition metal supply chains. Enhanced resource governance, including stricter environmental regulations and international partnerships, can address the socio-environmental risks associated with mining in regions with weak institutional frameworks (Watari et al., 2021). Policies that promote material efficiency, such as extending products lifespans and promoting recycling initiatives, are also critical for reducing demand pressures on primary resources. Furthermore, regional diversification of supply chains, as seen in emerging mineral-rich areas such as Central Asia, could mitigate geopolitical risks associated with overreliance on a few dominant suppliers (Vakulchuk & Overland, 2021). Collaborative efforts between producing and consuming countries, including strategic stockpiling and early warning mechanisms, are necessary to stabilize markets and reduce vulnerabilities (Yuan et al., 2024).

By integrating CE practices, fostering innovation in mining and recycling technologies, and strengthening governance frameworks, stakeholders can address the complex challenges associated with energy transition metals. These strategies not only address the immediate concerns of supply chain resilience and environmental sustainability but also pave the way for a more equitable distribution of resources necessary for a carbon-neutral future.

3.4 Key Materials in Electric Vehicle Supply Chains: Lithium and Cobalt

3.4.1 Electric Vehicles Supply Chain and Lithium

The rapid global shift toward EVs has underscored the importance of lithium as a cornerstone material in the energy transition. Valued for their high energy density, efficiency, and longevity, LIBs dominate the EVs market, acting as a critical enabler of decarbonization goals. Global EVs sales are projected to grow tenfold by 2030, leading to a significant increase in lithium demand (Wesselkämper et al., 2024). This growing demand introduces significant challenges, ranging from environmental degradation to geopolitical dependencies, technological barriers, and the need for sustainable transformation of lithium supply chains (Weinand et al., 2023; Toba et al., 2021).

Traditional lithium extraction methods, such as brine evaporation and hard rock mining, impose significant environmental costs. Brine extraction, prevalent in the Lithium Triangle of South America, involves pumping lithium-rich brine to the surface and evaporating it. While energy-efficient, this process depletes local water resources, exacerbating ecological pressure in arid regions and threatening the livelihoods of surrounding communities. Hard rock mining, concentrated in Australia, relies on high-temperature processes that emit significant GHGs. Ren et al. (2023) in their study emphasize that these mining practices highlight the urgency of advancing sustainable mining technologies.

Technological bottlenecks further complicate the lithium supply chain. Innovations such as DLE offer potential solutions, enabling lithium recovery with reduced environmental impact. However, DLE is not yet widely scalable while the recycling of LIBs is critical to ensure resource efficiency. Current recycling technologies, including hydrometallurgical and pyrometallurgical methods, achieve recovery rates of up to 95%, particularly for lithium, cobalt, and nickel. Despite these advances, logistical and economic barriers hinder widespread adoption (Vaccari et al., 2024).

Lithium's production is geographically concentrated, with more than 80% of it sourced from Australia, Chile, and Argentina. In refining, however, China dominates, controlling almost 90% of global capacity. This geographic imbalance intensifies supply chain vulnerabilities and exposes nations to geopolitical risks. Trade restrictions and regional conflicts could disrupt global access to lithium, creating price volatility and market uncertainty (Yan et al., 2020).

Diversifying supply sources is crucial to mitigate these risks. Investments in domestic refining capability, particularly in Europe and North America, aim to reduce dependence on Chinese facilities and enhance supply chain resilience (Yuan et al., 2024). The development of alternative battery chemistries, such as solid-state batteries, further reduces dependence on lithium while enhancing energy efficiency.

Integrating CE principles is crucial for addressing environmental and supply chain challenges. LIBs recycling offers a sustainable path to reduce dependence on primary lithium sources. Studies indicate that substituting 30% of primary lithium with recycled material could reduce GHG emissions and water use by more than 10% (Alessia et al., 2021). Emerging technologies such as automated disassembly and AI-driven sorting promise to improve recycling efficiency, overcome technical challenges, and enhance scalability.

Advanced policies, such as the EU Battery Regulation, mandate a minimum recycled content in new batteries, 12% for lithium by 2036 and promote life - cycle accountability. These measures complement innovations in near-zero-waste processing technologies, which minimize emissions while maximizing material recovery (Zhou et al., 2024).

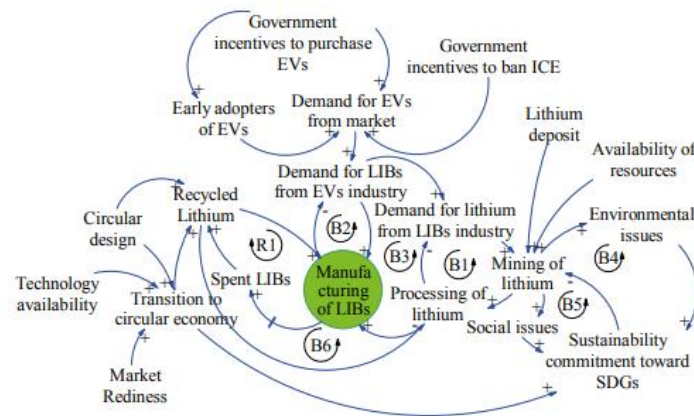


Figure 30: Causal Loop Diagram of LIBs supply chain (Quinteros-Condorett et al., 2021)

Figure 30, depicting a causal loop diagram of the LIBs supply chain (Quinteros-Condorett et al., 2021), visualizes the interconnected challenges. Figure G.1, which illustrates a closed-loop recycling system for LIBs (Kunz, 2019), is included in Appendix G, as its technical details complement the broader discussion without disrupting the narrative flow.

3.4.2 Electric Vehicles Supply Chain and Cobalt

Cobalt is indispensable in LIBs and critical for EVs. However, its supply chain presents significant environmental, social, and geopolitical challenges. Over 70% of global cobalt mining occurs in the DRC, where unethical labour practices, including child labour, and environmental degradation are widespread (Brink et al., 2020). Refining operations, primarily concentrated in China, add to the carbon footprint due to their reliance on coal - fired power (Zeng & Li, 2015).

The surging demand for cobalt, driven by the adoption of EVs, is illustrated in Figure 31, which projects a sharp increase in global cobalt requirements by 2030 (Jones et al., 2020). While demand pressures are increasing, the supply chain faces vulnerabilities, including geopolitical dependencies and limited diversification of supply sources. Recycling is emerging as a key mitigation strategy, offering the potential to reduce dependence on primary mining. Hydro-metallurgical and pyrometallurgical methods achieve high recovery rates but remain energy - intensive and hindered by inefficient collection systems (Golroudbary et al., 2019; Nguyen et al., 2021).

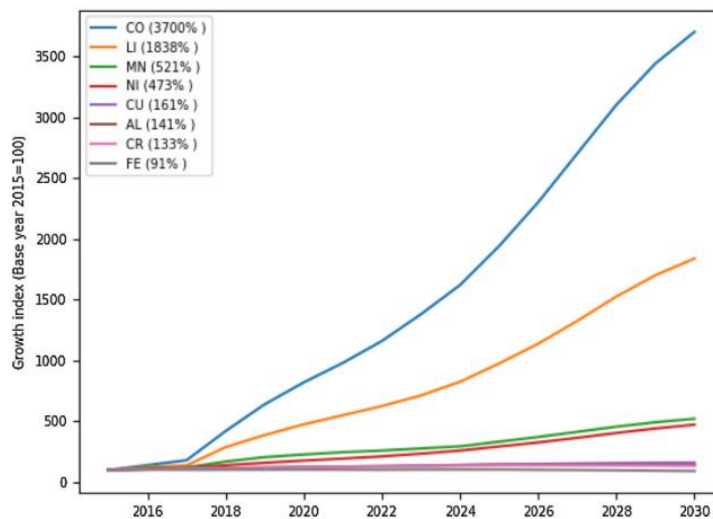


Figure 31: The growth of metal demand for vehicles. Figures in brackets indicate projected growth indices of metal demands in 2030 in comparison with base year 2015 (set at 100) (Jones et al., 2020).

CE principles are increasingly being applied to enhance the sustainability of the cobalt supply chain. Policies such as the EU Battery Regulation mandate recycled content quotas for LIBs, aiming to reduce dependency on primary resource and improve resource efficiency (Zhou et al., 2024). Technological advancements, such as solid-state batteries, could reduce cobalt usage while maintaining high battery performance (Severson et al., 2023). In addition, blockchain technology is being used to improve monitoring and ensure compliance with ethical and environmental standards (Thies et al., 2019).

The logistical and geopolitical challenges of cobalt transportation and refining are further explored by Niri et al. (2024), who emphasize the need for regional supply chain integration to minimize emissions and enhance resilience. Furthermore, the role of initiatives such as the Fair Cobalt Alliance in promoting fair labour practices and community development in mining regions cannot be overstated (Deberdt & Billon, 2021).

Addressing these challenges requires collaborative global effort between governments, industries, and research institutions. The integration of advanced recycling systems and the adoption of cleaner refining technologies are crucial. Studies also show that closed-loop systems could significantly stabilize markets and reduce environmental impacts (Wesselkämper et al., 2024). Achieving a sustainable and carbon-neutral cobalt supply chain will depend on the implementation of these multifaceted strategies (Brink et al., 2020; Zhou et al., 2024; Golroudbary et al., 2019). Figure H.1 provides a detailed overview of the cobalt life cycle in China, illustrating the interconnected stages of mining, refining, and recycling. It is included in Appendix H, as technical details complement the broader discussion without disrupting the narrative flow.

4. European Union Frameworks and Strategies for Sustainable Management of Critical Raw Materials

4.1 European Union Policies and Critical Raw Materials

The EU's reliance on CRMs for the renewable energy, digital, and mobility sectors highlights the urgency of policies that promote sustainability and strategic autonomy. The CRM Act, introduced in 2024, serves as a cornerstone of these efforts, establishing benchmarks for CRM management. By 2030, the CRM Act aims for at least 10% of annual consumption to come from domestic extraction, 40% from local processing, and 15% from recycling, while limiting dependence on any single non-EU country to 65% of total imports (Distefano et al., 2024). These targets are designed to mitigate supply risks, strengthen domestic resource capabilities, and enhance the EU's resilience to global market fluctuations.

In parallel, the Circular Economy Action Plan (CEAP) provides the structural framework for integrating circularity into CRM supply chains. The CE principles focus on minimizing resource waste by extending the lifecycle of products through repair, reuse, and recycling. This strategy is aligned with the broader goals of the European Green Deal, which aims to achieve carbon neutrality by 2050. For instance, LIB recycling has become a key point for keeping valuable materials domestically while reducing dependence on imports from countries such as China and the DRC. By keeping resources "in the loop", the EU can address supply chain vulnerabilities while promoting environmental and economic sustainability (Baldassarre, 2025).

Despite these ambitious initiatives, significant obstacles remain to achieving these goals. The regulatory landscape across member states remains complex, creating inconsistencies in the implementation and enforcement of policies. Furthermore, scaling up recycling infrastructure and its economic viability are ongoing challenges. For instance, while recycling processes for materials such as cobalt and REEs have advanced, the high costs associated with these technologies often deter investment. Addressing these issues requires integrated policy frameworks that combine financial incentives, public-private collaboration, and technological innovation (Halkos and Aslanidis, 2024).

Geopolitical concerns further complicate the EU's CRM strategy. Dependence on non-EU countries for materials such as REEs and cobalt has exposed industries to risks arising from market concentration and geopolitical tensions. The CRM Act explicitly seeks to mitigate these vulnerabilities by diversifying import sources and strengthening strategic partnerships with re-

source-rich countries. However, import dependency cannot be eliminated. Strengthening domestic capabilities, such as recycling and secondary production, is therefore crucial. For instance, recent advances in recycling technologies for rare earth magnets and e-waste have demonstrated the potential to reduce external dependencies while contributing to a more sustainable material flow within the EU (Distefano et al., 2024; Cole et al., 2019).

The integration of CE practices into CRM policy is exemplified by the WEEE Directive. This directive improved material recovery rates, particularly for electrical and electronic equipment, by prioritizing higher levels of the waste hierarchy, such as repair and reuse, over recycling. However, broader CRM strategies need to go beyond recycling - focused approaches to include systemic changes in product design, manufacturing, and consumption. Such measures are crucial to achieving a fully circular system that reduces environmental impacts while enhancing resource efficiency (Cole et al., 2019).

The EU's CRM policies reflect a broader commitment to systems thinking in resource management. Recognizing the interconnected environmental, economic, and social dimensions of resource use, these policies aim to create a sustainable balance between production and consumption. The alignment of the CRM Act and CEAP with the objectives of the European Green Deal is an example of the EU's ambition to lead on climate action and sustainable development. However, achieving these objectives requires overcoming systemic barriers, promoting innovation, and strengthening governance frameworks that encourage collaboration between member states and international partners (Baldassarre, 2025).

Implementing these policies is crucial not only to reduce the EU's environmental footprint but also to strengthen its competitive advantage in global markets. By addressing challenges such as regulatory fragmentation and technological constraints, the EU can build a resilient supply chain that supports its energy transition and economic objectives. As the CRM Act and CEAP continue to evolve, their success will depend on a concerted effort to align policy with practice, ensuring that the EU remains at the forefront of sustainable resource management (Distefano et al., 2024; Halkos and Aslanidis, 2024).

4.2 European Green Deal and Critical Materials

The European Green Deal, as the cornerstone of the EU's environmental strategy, aims to achieve climate neutrality by 2050. Central to this vision is the sustainable management of CRMs and REEs, which are essential for renewable energy technologies, EVs, and energy

storage systems. These materials enable the transition to a LE while posing significant challenges related to supply chain vulnerabilities, environmental impacts, and social issues. Addressing these complexities is essential for the EU to ensure sustainable integration of these materials into its supply chains.

A key element of the Green Deal is the CEAP, which emphasizes reducing dependency on primary materials through recycling, reuse, and remanufacturing. For CRMs, this approach has been transformative. Advanced recycling technologies, such as hydrometallurgical methods for LIBs, allow the recovery of valuable materials like lithium and cobalt. These technologies enhance resource efficiency while significantly reducing the environmental impacts of primary mining operations (Thompson et al., 2021). The Circular Input Rate (CIR) indicator has emerged as a critical tool for monitoring material circularity across sectors, including REEs used in electric vehicles and wind turbines. Through the adoption of these practices, the EU is expected to reduce its dependence on primary resources by 2030 (Bobba et al., 2023).

Supply chain vulnerabilities for critical materials, particularly REEs, are a major challenge for the EU. China's dominance in REEs production and refining raises geopolitical risks and highlights the need to diversify sources of supply. The Green Deal addresses these risks through investments in urban mining and recycling technologies, enabling the recovery of critical materials from EoL products like wind turbine magnets and EVs motors. Such efforts strengthen the EU's strategic autonomy and align with its broader decarbonization goals (Silvestri et al., 2021).

Digital innovation plays a vital role in achieving the Green Deal's objectives. The EU Battery Regulation introduces Digital Product Passports (DPP), which provide comprehensive information about the composition, origin, and lifecycle of batteries. This facilitates recycling, enhances transparency, and reduces waste across the supply chain (Rizos and Urban, 2024). Such developments are essential to optimise the recovery of critical materials and strengthen CE.



Figure 32: Types of data that should go into a digital product passport (Tian., 2024)

Technological innovation is vital to address the projected growth in demand for CRMs. By 2050, global demand for lithium, cobalt, and REEs is expected to increase substantially, driven by the widespread adoption of renewable energy systems and EVs (Watari et al., 2020). Urban mining, second-life batteries applications, and advancements in recycling technologies are key to reducing environmental and social impacts while meeting future demand (Crespo et al., 2022).

4.3 EU Battery Regulation and Lithium Recycling

The EU Battery Regulation, the cornerstone of the Green Deal and the CE Action Plan, sets a framework for sustainable LIB management. As LIBs support the EU's renewable energy and mobility strategies, this regulation addresses growing demand and its environmental and social impacts. By imposing strict recycling targets, the regulation aims to achieve near – total recovery of critical materials like lithium and cobalt by 2030, reducing dependency on primary resources and strengthening the EU's strategic autonomy (Wolters & Brusselsaers, 2024).

Traditional recycling methods, such as hydrometallurgy and pyrometallurgy, are effective but have environmental trade-offs. The high energy requirements of pyrometallurgy result in significant carbon emissions, while hydrometallurgy, although less carbon-intensive, involves hazardous chemicals that require robust waste management (Wu et al., 2022). Emerging technologies, such as cathode-healing, offer promising alternatives by preserving cathode structures for direct reuse, reducing GHG emissions by 50–70% compared to conventional methods.

These innovations align with the EU's goals to reduce environmental impacts and increase recycling efficiency (Xu et al., 2020).

The regulation also addresses challenges in scaling up recycling infrastructure. High purity recycled lithium often fails to meet standards for high-performance applications, maintaining dependence on primary lithium sources, primarily from regions such as South America. To overcome this, the EU invests in research to improve recycling efficiency and material quality while also incentivizing advanced recycling technologies (Ziemann et al., 2018).

The environmental benefits of improved LIBs recycling include significant reductions in habitat destruction, water depletion, and carbon footprints. Switching from traditional methods to innovative approaches such as cathode-healing could prevent millions of metric tons of CO₂ emissions annually (Wu et al., 2022). These advancements support the EU's decarbonization objectives and contribute to the global CE.

In addition to the environmental benefits, the regulation mitigates social and geopolitical risks by reducing dependence on imported lithium and promoting ethical sourcing. The establishment of a robust recycling system strengthens the EU's strategic autonomy while maintaining high labour and environmental standards (Wolters & Brusselaers, 2024).

Figures I.1 and I.2 provide critical insights into the advancements in LIBs recycling technologies and their contributions to reducing GHG emission. These figures are included in Appendix I for reference.

5. Sustainable Management of Critical Raw Materials through Circular Economy and Recycling Strategies.

5.1 Circular Economy and Critical Raw Materials

The transition towards a CE represents a pivotal strategy in mitigating the environmental and supply chain challenges associated with CRMs. By emphasizing closed-loop systems and reducing dependency on finite resources, the CE directly addresses issues such as resource scarcity, supply chain vulnerabilities, and environmental degradation. Zhou et al. (2024) highlight in their study that recycling and repurposing initiatives not only reduce extraction pressures but also create more resilient supply chain networks by diversifying material sources and minimizing geopolitical dependencies. A CE emphasizes waste reduction, materials reuse, and EoL product recycling to minimize reliance on primary resource extraction. This model is particularly important for materials such as lithium, cobalt, and REEs, which are integral to the

EU's renewable energy and digital transitions. The growing demand for these materials, driven by technologies like LIBs and EVs, highlights the urgent need to adopt circular practices (Wesselkämper et al., 2024).

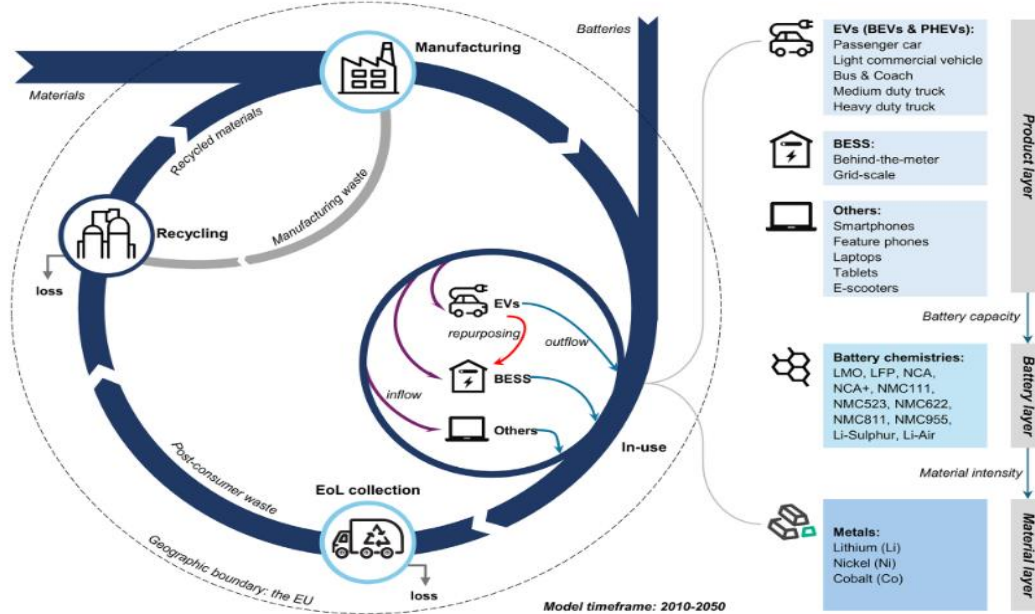


Figure 33: The framework of a dynamic Material Flow Analysis (MFA) model for the EU's LIBs (Zhou et al., 2024).

The EU has set ambitious targets for integrating recycled content in new batteries to enhance sustainability and reduce dependence on mining. However, the feasibility of achieving these targets remains contested. Research by Zhou et al. (2024) demonstrates that while the EU's recycled content mandates for lithium, cobalt, and nickel aim to enhance materials circularity, they could inadvertently compromise other sustainability metrics. In particular, mandates may require early battery to meet recycling quotas, thereby reducing their operational lifespan, and increasing the overall environmental costs. Furthermore, these stringent requirements could reduce opportunities for batteries reuse, limiting their potential use in secondary applications and conflicting with the broader objectives of the CE. For instance, stringent requirements may require early battery retirement and reduced opportunities for reuse, thereby undermining the broader goals of the CE. This highlights the need for flexible policies that balance recycling objectives with other circular strategies, such as reuse and remanufacturing.

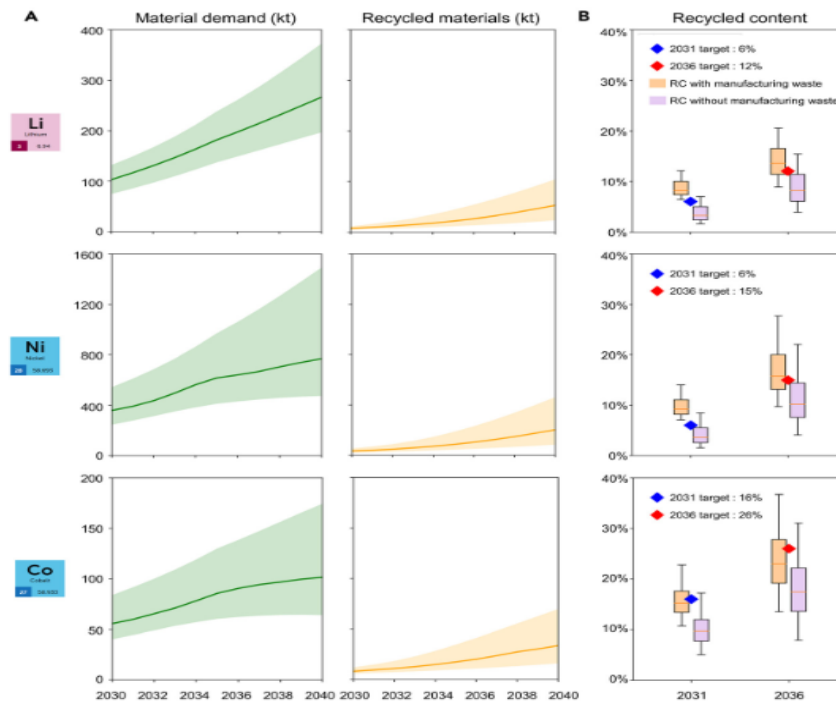


Figure 34: Material demand, available recycled materials, and potential recycled content for EU's LIBs during 2030–2040 (Zhou et al., 2024)⁵.

Urban mining emerges as a critical component of CE practices, offering a sustainable solution to reduce dependency on primary resource extraction. Xavier et al. (2023) highlight this in their study by referring to methodologies such as the recovery of lithium and cobalt from e-waste through advanced sorting and chemical treatment techniques. For instance, case studies demonstrate the successful application of bioleaching to recover REEs from discarded electronic components, achieving high recovery rates while reducing environmental impacts. These practices demonstrate how urban mining can effectively transform waste streams into valuable resources, thereby supporting the goals of the CE. By leveraging secondary resources from anthropogenic deposits, urban mining not only alleviates supply constraints but also addresses environmental concerns associated with traditional mining practices. However, the successful implementation of urban mining depends on harmonized regulatory frameworks and advancements in recycling technologies.

⁵ (A) The EU's material demand and the availability of recycled materials for lithium-ion batteries (LIBs). The lines represent the estimated median values across 108 scenarios, while the shaded areas illustrate the potential ranges. (B) Potential recycling contributions (RCs) for the EU's LIBs. The box plot highlights significant uncertainties in RCs (with or without battery manufacturing waste) and compares them to the EU's RC targets. The upper and lower edges of the box correspond to the third and first quartiles of potential RCs, respectively, with the line inside the box denoting the median. The whiskers extend to the minimum and maximum values, excluding outliers (Zhou et al., 2024).

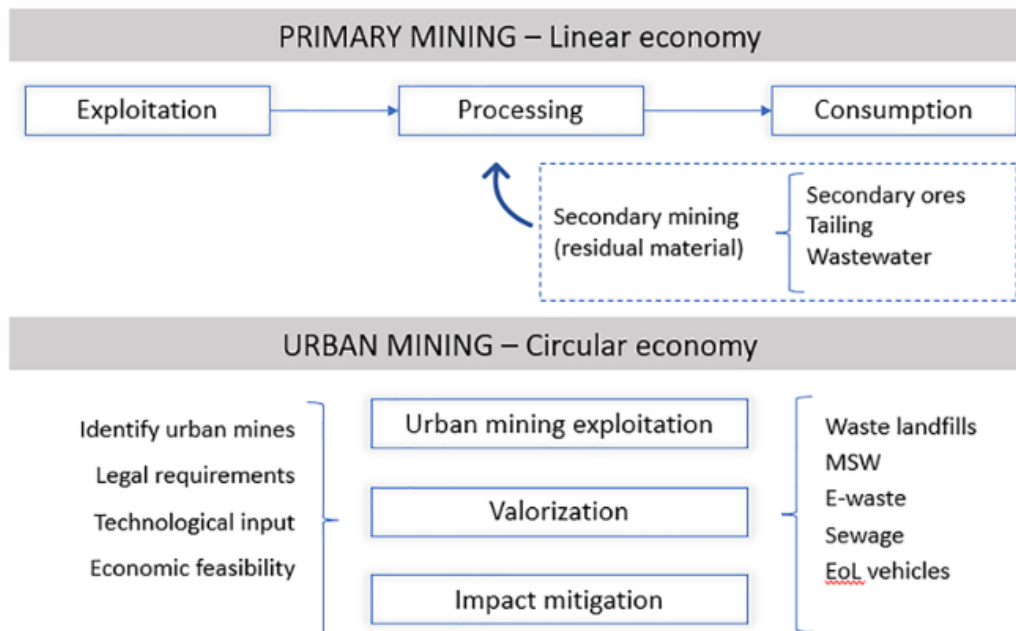


Figure 35: Primary and urban mining concepts according to the circularity approach (Xavier et al., 2023).

In addition to recycling and urban mining, the integration of CE and LE is essential for achieving sustainability objectives. Xie et al. (2023) highlights in their study the synergies between these two, emphasizing the importance of prioritizing strategies beyond EoL. Examples in practice include the remanufacturing of components from EoL products, such as EVs batteries, which can be refurbished and reused to maintain functionality and reduce waste. Initiatives like modular product design facilitate repairs and upgrades, further extending product lifespan while minimizing the need for primary raw material.

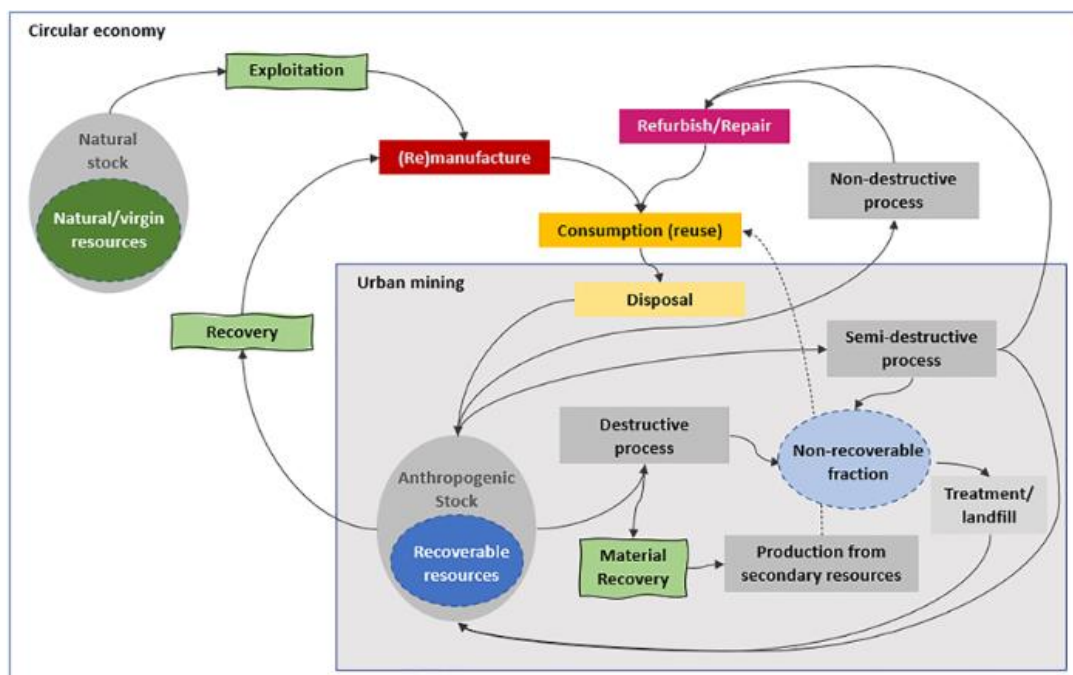


Figure 36: Circularity pathways and urban mining focus (Xavier et al., 2023).

These approaches not only conserve critical materials but also significantly reduce GHG emissions, demonstrating their dual impact on material conservation and carbon reduction. For instance, extending the lifespan of products and components through reuse and remanufacturing can significantly reduce GHG emissions while conserving critical materials. This integrated approach requires a systemic transformation in both industrial practices and policymaking to maximize resource efficiency and minimize environmental impacts.

The adoption of innovative recycling technologies further enhances the potential of the CE. Wesselkämper et al. (2024) in their study identify hydrometallurgical and direct recycling methods as particularly effective for LIBs, allowing high recovery rates of lithium, cobalt, and nickel. Despite expectations, these technologies face challenges related to economic viability and adaptation to multiple battery chemistries. Addressing these obstacles requires targeted investments in R&D, as well as supportive regulatory frameworks.

Moving towards a CE for CRMs requires a multifaceted approach that integrates advanced recycling technologies, urban mining initiatives, and coherent policy frameworks. By aligning circular practices with low-carbon objectives, the EU can enhance its resilience against supply chain disruptions while minimizing the environmental and social costs of resource extraction. However, achieving this vision necessitates coordinated efforts across stakeholders, robust governance, and continuous innovation to overcome existing obstacles.

5.2 Lithium-ion Batteries Recycling and Sustainable Supply Chain

The increasing global demand for LIBs, fuelled by the rapid adoption of EVs and renewable energy systems, has intensified the pressure on CRMs. LIBs recycling is increasingly recognized as a cornerstone for achieving a sustainable supply chain, offering solutions to the challenges of resource depletion and environmental degradation (Miao et al., 2022; Srivastava et al., 2023).

LIBs recycling significantly reduces reliance on primary resource mining, which is often associated with severe environmental and social costs. Lithium mining in arid regions, for instance, disrupts local ecosystems and depletes vital water resources, while cobalt extraction, mainly in the DRC, is associated with unethical labour practices and socio-environmental challenges. By recycling LIBs, hazardous leaching of heavy metals and organic electrolytes into soil and water systems is minimized, mitigating long-term contamination risks (Srivastava et al., 2023).

Technological advancements in LIBs recycling have introduced various methods, each with explicit advantages and limitations. Pyrometallurgical processes, which rely on high-temperature smelting, effectively recover valuable metals like cobalt and nickel but are energy-intensive and generate significant GHG emissions. Hydrometallurgical processes, in contrast, use chemical leaching to extract critical materials with recovery rates approaching 100%. These processes are less energy-intensive and align with low-carbon objectives. Emerging direct recycling methods preserve the structure of battery components, such as cathodes, without extensive chemical processing (Gebhardt et al., 2022), offering significant potential for cost and energy savings. However, these methods require further development to accommodate diverse battery chemistries and designs (Wesselkämper et al., 2024).

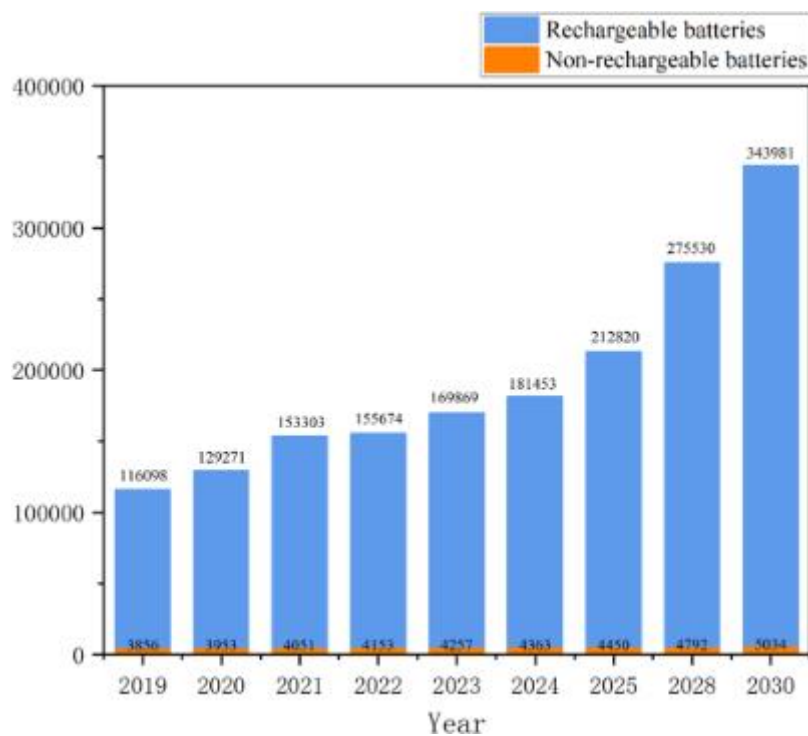


Figure 37: Global projection of lithium demand for batteries, by type (2019-2030) (Miao et al., 2022).

Integrating CE principles into LIBs recycling is essential for creating a sustainable supply chain. Recycling allows recovered materials to be re-integrated into the production of new batteries, reducing waste and conserving natural resources. For instance, replacing 30% of primary sourced lithium with recycled material can reduce carbon emissions and water usage by more than 10%. Policies such as the EU Battery Regulation, which mandates recycled content in new batteries, are critical in driving the adoption of CE practices (Mas-Fons et al., 2024; Dunn et al., 2022).

Despite these advances, widespread adoption of LIBs recycling faces significant challenges. The lack of robust collection and sorting infrastructure limits the availability of recyclable materials. Furthermore, the economic viability of recycling technologies is often limited by high operational costs and variable recovery rates of critical materials. Variability in battery chemistries and design further complicates recycling efforts. Addressing these challenges requires investments in R&D, as well as supportive regulatory frameworks that incentivize innovation and market adoption (Zhou et al., 2024).

The environmental benefits of LIBs recycling are significant. Studies show that recycling lithium carbonate generates 41% fewer GHG emissions compared to primary production. Hydro-metallurgical methods consume less energy and produce fewer emissions, supporting global decarbonization goals. Recycling also reduces the environmental burden associated with mining, such as habitat destruction and water pollution. By promoting the recovery and reuse of CRMs, LIBs recycling contributes to the transition toward a more sustainable energy future (Wang et al., 2024).

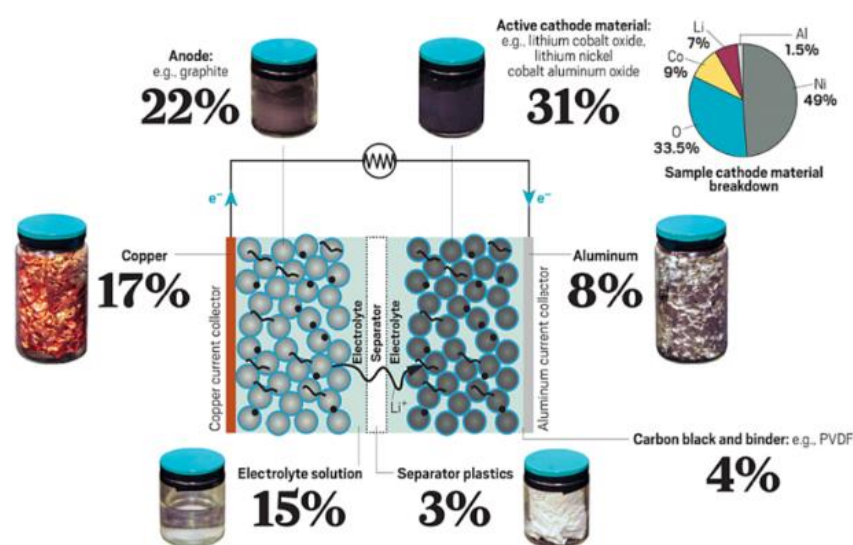


Figure 38: Composition of LIB cell (Srivastava et al., 2023).

The financial implications of LIBs recycling are equally significant. Recycling reduces supply chain vulnerabilities by diversifying material sources, thereby decreasing dependency on geopolitically unstable regions. This is important for the EU, which heavily relies on imported lithium and cobalt. By strengthening domestic recycling capabilities, regions can enhance strategic autonomy and resilience in their supply chains. Furthermore, recycling creates financial opportunities through the development of new technologies and industries, aligning environmental sustainability with economic growth (Dunn et al., 2022).

Figures 37 and 38 are integral to understanding the context of LIBs recycling. Figure 37 illustrates global projections of lithium demand for batteries by type from 2019 to 2030, highlighting the growing necessity for recycling. Figure 38 details the lifecycle of LIBs recycling technologies, showcasing advancements and the potential for scalability. These visual aids highlight the importance of integrating recycling practices into supply chain strategies. Figure J.1, which provides a detailed schematic representation of the hydrometallurgical recycling process, is presented in Appendix J to provide further technical insights.

5.3 Recycling Technologies and Critical Materials

The increasing reliance on LIBs for various applications, has highlighted the urgent need for effective recycling technologies to recover critical materials. Current advancements in recycling technologies aim to address environmental and economic concerns while enhancing the efficiency of material recovery processes. These advancements are critical for ensuring a sustainable supply chain and reducing dependency on virgin raw materials (Yoo et al., 2023).

Emerging recycling technologies have shown significant potential for improving the recovery efficiency and environmental performance of LIBs recycling. Among them, ultrasonic-assisted leaching and microwave irradiation are noteworthy innovations. These methods not only enhance the dissolution rates of critical metals but also reduce the energy and reagent consumption compared to conventional approaches (Milian et al., 2024). For instance, studies have shown that microwave-assisted techniques significantly improve lithium and cobalt recovery rates while minimizing processing times, offering a promising alternative to energy-intensive methods such as pyrometallurgy (Fan et al., 2023). A feature that significantly enhances the scalability of these methods in industrial applications is the ability to target critical materials during the process without compromising the stability of the surrounding components (Yoo et al., 2023).

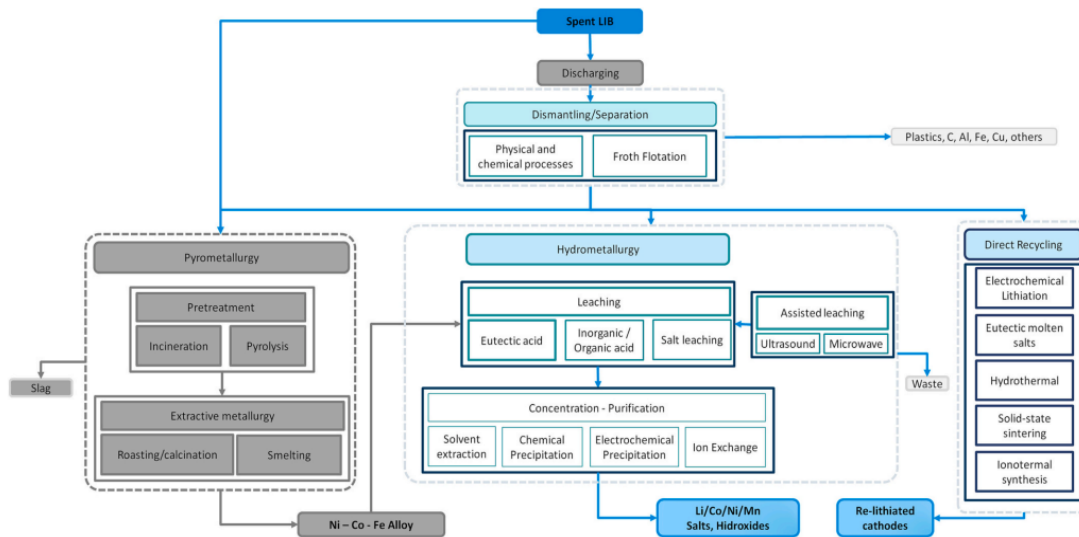


Figure 39: Emerging technologies for critical materials recovery via spent-LIB recycling processes (Milian et al., 2024).

Direct recycling methods have emerged as a viable approach for recovering cathode materials with minimal environmental impact. Unlike traditional hydrometallurgical and pyrometallurgical techniques, direct recycling involves the regeneration of spent cathode materials without extensive chemical processing. This approach reduces the number of processing stages and reduces reagents consumption, aligning with the principles of a CE (Mossali et al., 2020). Research shows that direct recycling processes can achieve high recovery efficiencies for valuable metals while maintaining the structural integrity of cathode materials, thereby reducing the need for energy-intensive resynthesis steps (Milian et al., 2024). Furthermore, the application of direct recycling methods provides an opportunity to address the increasing volumes of EoL LIBs by creating closed-loop systems that integrate recovered materials back into the production process, thereby reducing the dependence on primary materials (Fan et al., 2023).

Advanced hydrometallurgical methods also play a vital role in LIBs recycling, particularly for the selective recovery of critical metals. Innovations such as solvent extraction, ion exchange, and selective precipitation have enhanced the purification and recovery rates of metals such as lithium, cobalt, and nickel (Zheng et al., 2018). The use of novel green solvents, including deep eutectic solvents, has further minimized the environmental footprint of these processes. These solvents provide high selectivity and efficiency in extracting critical metals while reducing the production of hazardous waste, making them a viable alternative to traditional acidic reagents (Fan et al., 2023). Furthermore, the development of fluidized hydrometallurgical processes has demonstrated significant improvements in lithium recovery rates, offering lower GHG

emissions and operating costs compared to conventional methods (Yoo et al., 2023). These advancements highlight the potential of hydrometallurgical techniques not only for recovering materials efficiently but also for meeting stringent environmental standards, critical in global efforts to achieve sustainability (Mossali et al., 2020).

The recovery of REEs from e-waste products and LIBs components has attracted significant attention due to their criticality in high-tech and renewable energy applications. Techniques using ion-imprinted materials and dual-template mesoporous membranes have shown remarkable selectivity in recovering REEs such as neodymium and dysprosium (Zheng et al., 2018). These innovative materials enable the simultaneous recovery of multiple REEs, demonstrating high adsorption capacities and reuse (Fan et al., 2023). Such advancements represent an important step toward addressing the challenges of REEs recycling and ensuring a sustainable supply for emerging technologies (Milian et al., 2024). Moreover, the integration of these techniques with other recycling methods could further optimize recovery efficiency, thereby supporting the growing demand for REEs in technologies such as wind turbines and EVs (Yoo et al., 2023).

Despite these advancements, recycling technologies face several challenges that hinder their widespread adoption. Pyrometallurgical methods, while reliable for large-scale operations, are associated with high energy consumption and significant GHG emissions (Mossali et al., 2020). Similarly, hydrometallurgical processes, although less energy-intensive, often struggle with issues related to waste management and the scalability of innovative approaches (Fan et al., 2023). The financial viability of emerging technologies remains a critical obstacle, particularly for processes requiring specialized equipment. Addressing these challenges necessitates continuous R&D to optimize operational parameters and reduce costs (Milian et al., 2024; Yoo et al., 2023). Moreover, the lack of standardization across all recycling processes creates an additional obstacle, necessitating collaboration between industry and policymakers to establish consistent protocols and quality standards (Zheng et al., 2018).

Process	Pros	Cons
<i>Pyrometallurgy</i>	Easiness of procedure; No necessity of passivation steps; Optimal technology readiness; Generation of exothermic reaction reducing energy consumption.	High energy consumption; Hazardous gaseous emissions; Material loss (Li in the slag); Need of Co LIBs chemistries (pre-sorting); High capital costs.
<i>Hydrometallurgy</i>	High recovery efficiency; High quality outputs; Good technology readiness; Moderated energy consumption; No gaseous emissions; Recovery of all LIBs cathodic metals; Mild reaction conditions.	Wastewater productions; Incomplete binder/ electrolyte recycling; Complexity of procedure; Need of pre-treatments; Selectivity of reagents.

Table 5: Comparison between pyro- and hydrometallurgical LIBs recycling processes (Mossali et al., 2020).

Future perspectives in recycling technologies emphasize the integration of hybrid approaches that combine the strengths of pyrometallurgical and hydrometallurgical methods (Fan et al., 2023). This integration aims to improve overall efficiency while reducing the environmental impact of recycling processes. In addition, policy interventions and industry partnerships are crucial to promote the adoption of sustainable recycling technologies. By establishing robust regulatory frameworks and financial incentives, stakeholders can drive the transition toward a CE, ensuring the sustainable management of critical materials in the supply chain (Yoo et al., 2023). Furthermore, promoting public-private partnerships could accelerate innovation and investment in recycling infrastructure, facilitating the transition from laboratory developments to large-scale applications. (Milian et al., 2024).

5.4 Circular Supply Chain and Critical Materials

The transition to a CE has emerged as a critical pathway for addressing the challenges associated with the supply chain of CRMs. The economic model of "take, make, and dispose" is no longer sustainable given the growing global demand for these materials and the environmental and geopolitical risks associated with their extraction and processing. By integrating the principles of circularity, the supply chain can mitigate resource scarcity, reduce environmental impacts, and enhance resilience.

The recycling and recovery of materials, particularly LIBs, is the cornerstone of the circular supply chain. Ali et al. (2022) emphasize in their study that advanced preprocessing methods

for EoL LIBs, including sorting, disassembly, and separation, can achieve recovery efficiencies of more than 90%. These methods, when compared to hydrometallurgical and pyrometallurgical techniques, show significant improvements in efficiency and environmental impact (Ali et al., 2022). These processes not only reduce energy requirements compared to traditional pyrometallurgical methods but also significantly reduce GHG emissions. For instance, using recycled materials can reduce production costs by 40% and decrease emissions by more than 91%, highlighting the financial and ecological advantages of LIB recycling.

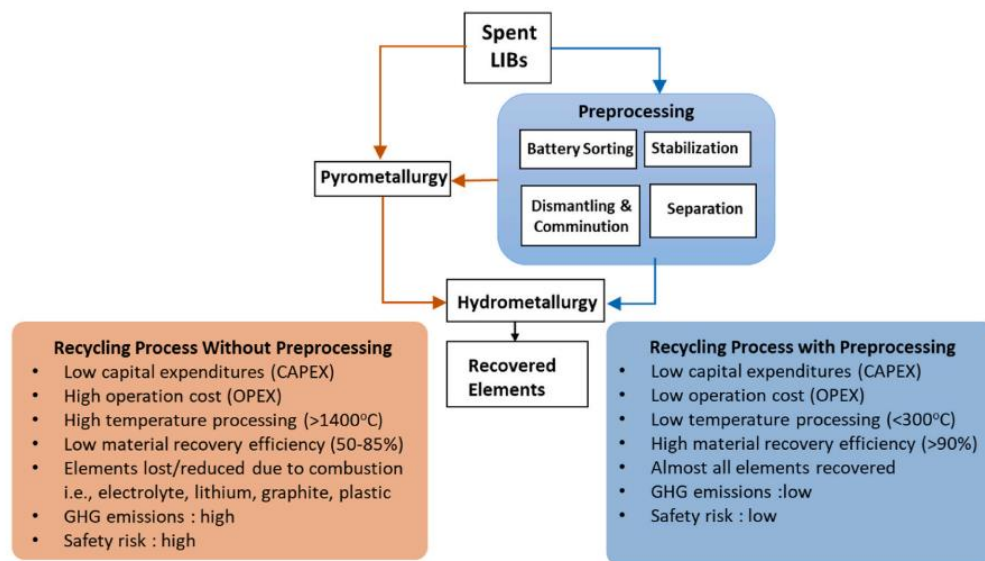


Figure 40: Comparison of LIB recycling processes with and without preprocessing (Ali et al., 2022).

The product design phase also plays a crucial role in circularity. As Babbitt et al. (2021) discuss in their study, products containing critical materials are often not designed for disassembly or recycling, which limits the potential for material recovery. They emphasize the need for modular design strategies, such as standardized components and easily separable connections, to facilitate disassembly. For instance, adopting snap-fit assemblies instead of adhesives can significantly improve recyclability, as observed in studies of modular electronic devices and automotive components (Babbitt et al., 2021). Case studies in the electronics and automotive sectors demonstrate how such design changes enable higher recovery rates of critical materials, reducing reliance on primary resources and aligning with CE targets.

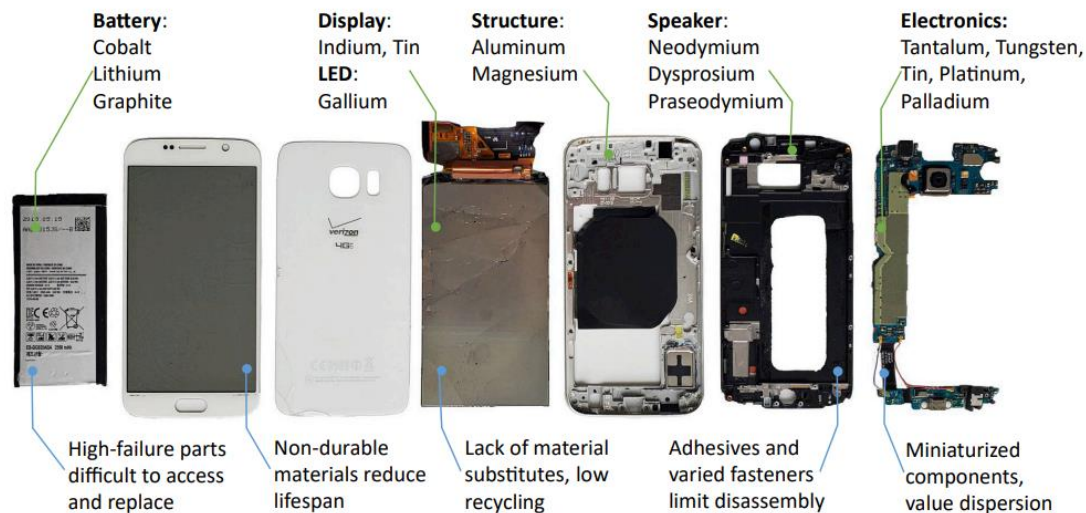


Figure 41: Illustration of critical material use in a smartphone and the design challenges that limit circular economy strategies that may slow and close resource loops for these materials (Babbitt et al., 2021).

EVs provide a unique case study for implementing CE strategies. Deng et al. (2022) highlight in their study, the importance of establishing a robust EoL infrastructure to recover and reuse critical materials from EVs batteries and components. Their simulations further show that such systems can substantially improve supply chain resilience by reducing material reliance by more than 30% in certain scenarios (Deng et al., 2022). Their model shows how a well-structured EoL system, incorporating efficient collection and centralized disassembly hubs, can optimize material recovery. For instance, streamlining the logistics network for used batteries can reduce costs by 15% while improving recycling efficiency by 20%. This strategy not only reduces supply chain risks but also improve the economic competitiveness of EVs by reducing dependence on primary resources. Mathur et al. (2019) further extend this discussion in their study, by proposing IS strategies where degraded EVs batteries are reused to store energy for renewable systems, demonstrating a practical application of CE principles.

Cobalt, a key component of LIBs, is an example of the environmental benefits of a CE approach. Golroudbary et al. (2022) demonstrate in their study that recycling cobalt can lead to a 46% reduction in energy consumption and a 59% decrease in GHG emissions compared to primary production. Furthermore, regional analyses indicate that integrating recycling facilities near production hubs could reduce transportation-related emissions by 10% (Golroudbary et al., 2022). However, achieving these recycling rates poses significant technological and logistical challenges. Cobalt separation and purification processes often require advanced infrastructure and consistent feedstock quality, which are not available globally. Moreover, logistical issues such as the collection, transportation, and sorting of EoL

products containing cobalt can hinder the efficiency of recycling and increase costs. Addressing these obstacles is necessary to realize the full potential of cobalt recycling in CE. Furthermore, by 2050, approximately 25% of cobalt demand could be met through recycling. This highlights the potential for recycling to mitigate supply risks while contributing to global sustainability goals.

Policy frameworks and standards are crucial for the adoption of CE practices. Dunn et al. (2022) analyse in their study, the role of recycled content standards (RCSs) in fostering a circular battery ecosystem. They highlight that by mandating a certain percentage of recovered materials in new products, they create a steady demand for recycled content, driving investment in recycling technologies. For instance, the revised EU battery regulations set ambitious recycled content targets, positioning the region as a leader in policy-driven circularity. Comparatively, countries like the US are still exploring similar standards, with state-level initiatives such as California's advisory group discussing optimal RCS levels. Lehtimäki et al. (2024) emphasize in their study that such policies are crucial to address systemic obstacles in recycling, particularly low material recovery rates, currently less than 1% for lithium and cobalt in some regions. These comparisons highlight the importance of harmonized policies to accelerate global adoption of CE practices.

REEs also present significant opportunities for circularity. Maani et al. (2023) estimates in their study that recycling neodymium, a critical REE, can meet up to 12% of U.S. demand by 2050. Furthermore, their analysis highlights the role of improved collection rates and processing technologies in achieving higher recovery levels, suggesting that the rate could increase to 20% under optimal conditions (Maani et al., 2023). Li et al. (2024) further discusses in their study the challenges of recycling rare earth magnets used in EV motors, emphasizing the potential carbon savings and supply chain benefits of hydrogen processing techniques for magnet recovery. Adopting CE strategies for REEs not only addresses supply chain vulnerabilities but also reduces dependence on geopolitically concentrated sources of these materials. Incorporating circular principles into the REE supply chain is essential to sustaining technological progress in clean energy and electric mobility.

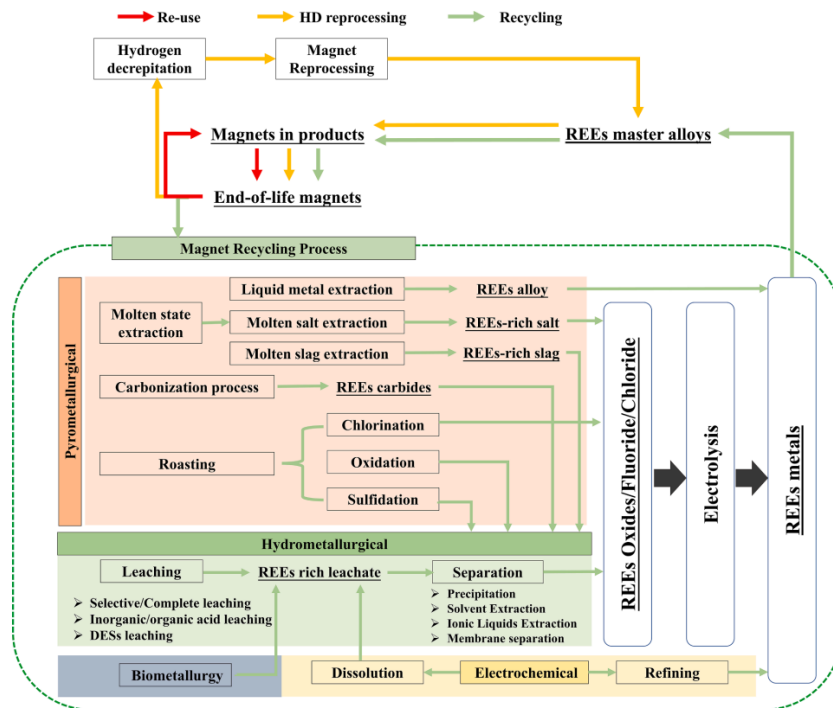


Figure 42: Overview of recycling processes for permanent magnets (Li et al., 2024).

Integrating CE principles into the supply chain for CRMs requires a multi-faceted approach that includes technological innovation, policy support, and systemic changes in product design and resource management. By transitioning to a circular supply chain, industries can ensure the sustainable use of critical materials while minimizing environmental impacts and strengthening financial resilience.

6. Sustainable Practices and Environmental Impacts in Critical Raw Material Mining

6.1 Sustainable Mining and Sourcing of Critical Raw Materials

The sustainable management of CRMs requires a comprehensive approach that integrates responsible mining practices with ethical and environmentally conscious sourcing strategies. The mining and sourcing of CRMs, present significant environmental and social challenges. Mining operations often lead to habitat destruction, soil erosion, and water contamination (Barakos et al., 2016; Pell et al., 2019). The energy-intensive nature of mining and refining processes further contributes to GHG emissions, exacerbating climate change. For instance, the use of fossil fuels in refining and transportation processes increases the carbon footprint of CRMs (Mas-Fons et al., 2024).

Social issues also play a vital role, particularly in regions where ASM dominates. Practices in these areas are often associated with human rights violations, including child labour and unsafe working conditions (Thies et al., 2019). These challenges highlight the need for stringent environmental and social governance (ESG) practices in mining and sourcing operations.

Innovative approaches to mining operations can mitigate the environmental impact of CRMs extraction. Green mining technologies, such as the adoption of near-zero-waste processes and renewable energy sources, can significantly reduce waste and emissions (Spooren et al., 2020). Process optimization through advanced metallurgical techniques, such as acid regeneration systems and closed-loop recycling, improve material recovery and minimizes environmental degradation (Pell et al., 2019). IS which involves collaborations between industries to reuse waste materials, promotes resource efficiency and reduces ecological footprints (Leigh & Li, 2015).

Sustainable sourcing focuses on fair and ethical sourcing of CRMs. Transparency and traceability can be achieved through blockchain technology, ensuring compliance with ethical standards (Wang et al., 2025). Social responsibility initiatives, such as the Fair Cobalt Alliance, promote fair labour practices and community development in mining regions (Deberdt & Billion, 2021). Diversification of sources, by reducing dependence on geopolitically sensitive regions through alternative sourcing or increased recycling, improves supply chain resilience (Yan et al., 2020).

CE practices are vital in addressing both environmental and supply chain challenges. Recycling EoL products and recovering valuable materials minimize waste and reduce reliance on primary resources. Advanced recycling technologies, such as hydrometallurgical processes, achieve high recovery rates for lithium, cobalt, and rare earth elements (Lehtimäki et al., 2024). Urban mining, which involves extracting materials from e-waste, reduces environmental damage and diversifies CRMs sources, making supply chains more resilient (Xie et al., 2023).

Strong regulatory frameworks, such as the European Green Deal and the CRM Act, play a crucial role in promoting sustainable practices. These policies encourage investment in clean technologies, set recycling targets, and mandate lifecycle accountability for CRM usage (Zhou et al., 2024; Baldassarre, 2025). Financial incentives, such as subsidies for green technologies, further support the transition to sustainable mining and sourcing practices (Ghadimi et al., 2019).

A visual representation of the proportion of the material footprint due to imports from non-EU countries highlights the significance of regional dependencies and the need for diversification. Figure 43 illustrates the "Business-as-usual (BAU) Scenario (2030)," which shows the share of the material footprint for each material category associated with imports from each of the 27 EU member states from the rest of the world (Distefano et al., 2024). This figure highlights the urgent need to address import dependencies through strategies such as urban mining and recycling.

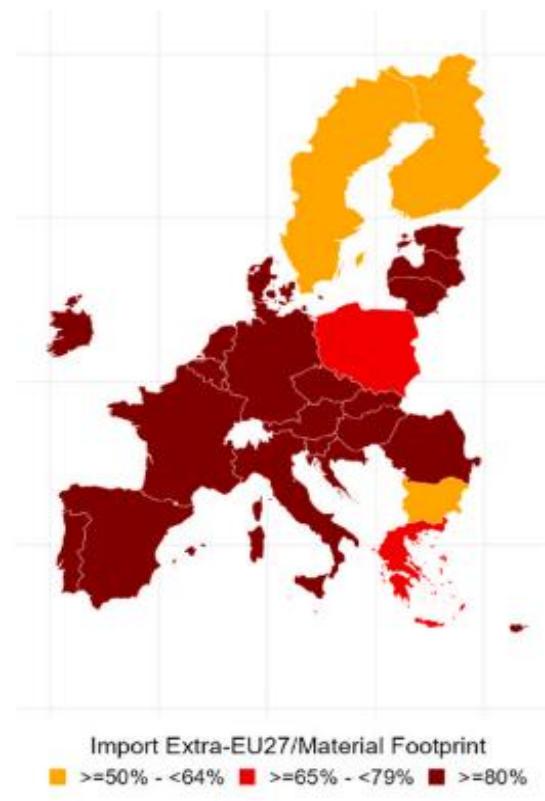


Figure 43: Business-as-usual (BAU) Scenario (2030): Percentage of Material Footprint Due to Imports from Non-EU Countries. The maps show the share of material footprint for each category of materials related to imports from each of the 27 EU member states from the rest of the world⁶ (Distefano et al., 2024)

Sustainable mining and sourcing of CRMs requires a balanced approach that addresses environmental, social, and economic dimensions. By integrating advanced technologies, ethical practices, and CE principles, stakeholders can build resilient and sustainable CRMs supply chains. Collaborative efforts between governments, industries, and communities are essential to achieve these goals, ensuring equitable access to resources while minimizing environmental impacts.

⁶ Countries exceeding the CRM target of 65% import dependency are coloured in red, with darker shades indicating higher dependency. Countries that meet the target are coloured green (Distefano et al., 2024).

6.2 Environmental Impact and Critical Material Mining

The environmental impact of mining critical materials has become a major concern as global efforts move towards carbon neutrality. As advanced technologies become increasingly dependent on CRMs such as lithium, cobalt and REEs, the extraction and processing of these materials is associated with significant ecological degradation and social challenges. This subchapter explores the environmental consequences of CRM mining and examines the broader implications for sustainable supply chains.

The extraction of CRMs is associated with local environmental degradation, particularly in regions that host abundant mineral reserves. Berthet et al. (2024) emphasize in their study that mining activities often lead to severe water and soil contamination. This issue is emerging in areas such as Chile and South Africa, where mining operations take place in water-scarce basins, affecting local ecosystems. The mining processes for materials such as lithium and cobalt are resource-intensive, requiring large amounts of water and energy, which further increases their environmental footprint. Furthermore, mining activities release toxic chemicals into nearby areas, contributing to pollution and biodiversity loss.

The environmental consequences of critical mineral extraction are not limited to localized damage. They are expanding globally, a phenomenon described as the “decarbonization divide” (Berthet et al., 2024). This divide highlights the difference between developed nations, which benefit from cleaner technologies, and developing countries, which bear the environmental and social burdens of mining. The extraction of these materials often involves regions in Africa and South America, where environmental regulations may be less stringent. Consequently, the global supply chain for critical materials perpetuates environmental degradation in resource-rich but vulnerable regions.

Soeteman-Hernández et al. (2023) underscore in their study the environmental risks associated with lithium and cobalt mining, noting their harmful impacts on both ecosystems and human health. These risks have driven policy innovation and technological advancements aimed at reducing their impact. For instance, stricter environmental regulations and the development of less resource-intensive mining technologies are being explored to mitigate these impacts. In addition, sustainable supply chain frameworks encourage collaboration between industry stakeholders to prioritize environmental stewardship while ensuring resource availability. Soeteman-Hernández et al. (2023) identify in their study toxic emissions and ecosystem disruption as direct results of these mining activities. For instance, lithium mining in the Atacama Desert has led to significant water depletion, negatively impacting local communities

and biodiversity. Similarly, cobalt mining in the DRC contributes to environmental pollution, including heavy metal contamination of soil and water.

Policy responses have begun to address these environmental challenges by promoting sustainability throughout the supply chain. For instance, the European Green Deal outlines specific measures, such as stricter emission standards for mining operations and ensuring sustainable sourcing of critical materials. Furthermore, the EU Battery Regulation includes provisions for recycling targets as well as the use of recycled content in new batteries, which have shown a reduction in resource depletion. These policies aim not only to mitigate environmental impacts but also to promote innovation in resource management and CE practices. The European Green Deal and related frameworks emphasize the need for stricter environmental standards and the adoption of CE principles. According to Soeteman-Hernández et al. (2023), strategies like the “safe and sustainable by design” approach integrate environmental considerations throughout the life cycle of critical materials, from extraction to EoL management. These frameworks are aimed at mitigating the negative impacts of mining while ensuring the availability of critical materials for clean energy technologies.

Efforts to reduce the environmental footprint of mining also include innovations in material recycling and resource efficiency. Berthet et al. (2024) in their study suggests that diversification of supply chains and the adoption of advanced recycling technologies can mitigate the ecological pressures associated with primary extraction. These strategies are aligned with broader goals of balancing the demands of a carbon-neutral economy with the imperative to protect ecosystems and communities affected by mining operations.

The environmental challenges associated with CRMs mining highlight the need for comprehensive and integrated approaches to sustainability. As demand for these materials increases, the environmental and social risks of mining must be addressed through robust policy measures, innovative technologies, and a commitment to equitable resource management.

7. Conclusions and Future Research Directions

This thesis examined the challenges and opportunities for ensuring sustainable access to CRMs such as lithium, cobalt, and REEs within the context of a carbon-neutral European supply chain. By addressing environmental, financial, and social dimensions, this study highlights the essential role of sustainable supply chains in supporting a low-carbon economy.

Key findings highlight the critical importance of adopting CE principles, promoting recycling technologies, and diversifying sourcing strategies. Lithium, cobalt and REEs are vital for renewable energy technologies and EVs, but their supply chains face significant sustainability challenges, including high carbon footprints, environmental degradation, and geopolitical dependencies. Innovative approaches such as direct lithium mining, hydrometallurgical recycling, and urban mining present reduced environmental impacts while at the same time enhancing resource efficiency.

The EU's regulatory frameworks, including the Green Deal and the Battery Regulation, play an important role in promoting and reinforcing sustainable practices, imposing quotas on the use of recycled CRMs as well as encouraging innovative technologies. Efforts for further collaboration among stakeholders, alongside the necessary investments in research and development, are essential to harmonize policies and accelerate the adoption of sustainable technologies.

This thesis highlights the need for integrated strategies that align environmental stewardship, economic growth, and social responsibility. Stakeholders should prioritize ethical sourcing, reduce dependence on primary resources, and promote technological developments to create resilient CRM supply chains capable of meeting the demands of a carbon-free future.

A promising area for future exploration is the advancement of recycling technologies, particularly the development of more efficient and cost-effective methods, such as direct cathode recovery for lithium-ion batteries, which could significantly reduce dependence on primary resources. Research into material substitution and innovation is another critical area, as alternatives to CRMs, such as cobalt-free batteries, have the potential to reduce environmental impacts and mitigate geopolitical dependencies.

The digital transformation of supply chains represents a promising area for further study. Technologies such as blockchain and AI have significant potential to enhance transparency, optimize efficiency, and promote sustainability. Future research could focus on leveraging these

tools to address persistent challenges in traceability and coordination among the stakeholders, which are critical for effectively managing the complex networks of CRM supply chains.

Urban mining and resource recovery offer opportunities to diversify material sources while reducing environmental impacts. Expanding research in this area could transform waste streams into useful resources, enhancing in that way supply chain resilience.

By addressing these areas of research, future studies can build on the foundations established by this thesis, contributing to the resilience and adaptability of CRM supply chains, while ensuring their alignment with global sustainability goals.

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Appendices

Appendix A: Detailed Analysis and Visuals for Lithium Extraction Methods

A.1 Overview of Lithium Extraction Methods

Lithium mining is vital for the production of LIBs, which play a key role in achieving global decarbonization goals. The two main lithium mining methods, brine extraction and hard-rock mining, differ significantly in their environmental impacts and resource requirements. Brine extraction involves mining lithium from saline water in arid regions, while hard-rock mining relies on extracting lithium from spodumene ores. Each method presents unique challenges, such as water consumption, carbon emissions, and energy intensity, making a comprehensive analysis of processes and their impacts crucial (Mas-Fons et al., 2024; Kallitsis et al., 2024).

A.2 Brine Extraction

Brine extraction is mainly used in areas such as the Salar de Atacama in Chile, where lithium-rich saline water is pumped to the surface and evaporated, leaving lithium salts. This process consumes substantial amounts of water, up to 7.7 m³ per kilogram of lithium carbonate equivalent (Li₂CO₃) and has a relatively low carbon footprint of 5.0 to 25.0 kg CO₂-eq per kilogram. The efficiency of this method depends on environmental conditions such as evaporation and groundwater recharge rates (Mas-Fons et al., 2024).

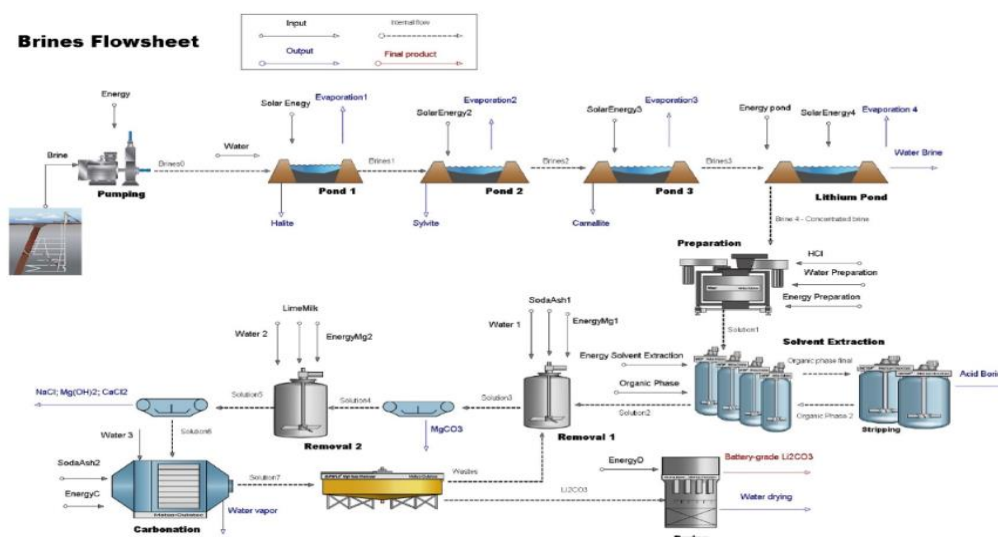


Figure A. 1: Simplified process flowsheet in USC Sim for the production route of lithium carbonate from brine (Mas-Fons et al., 2024).

The above figure illustrates the brine mining process, highlighting the key stages and resource requirements of the process. This figure helps to understand the environmental impacts and operational specifics of brine-based lithium production (Mas-Fons et al., 2024).

A.3 Hard-Rock Mining

Hard-rock mining, mainly carried out in Australia, involves extracting lithium from spodumene ores through energy-intensive refining processes, including roasting and chemical treatments. While it uses significantly less water compared to brine extraction (0.2 to 0.5 m³ per kilogram of Li₂CO₃), its carbon footprint is higher, ranging from 17.1 to 22.3 kg CO₂-eq per kilogram. The emissions of this method are significantly higher due to its reliance on fossil fuels during refining (Mas-Fons et al., 2024; Mas-Fons et al., 2024).

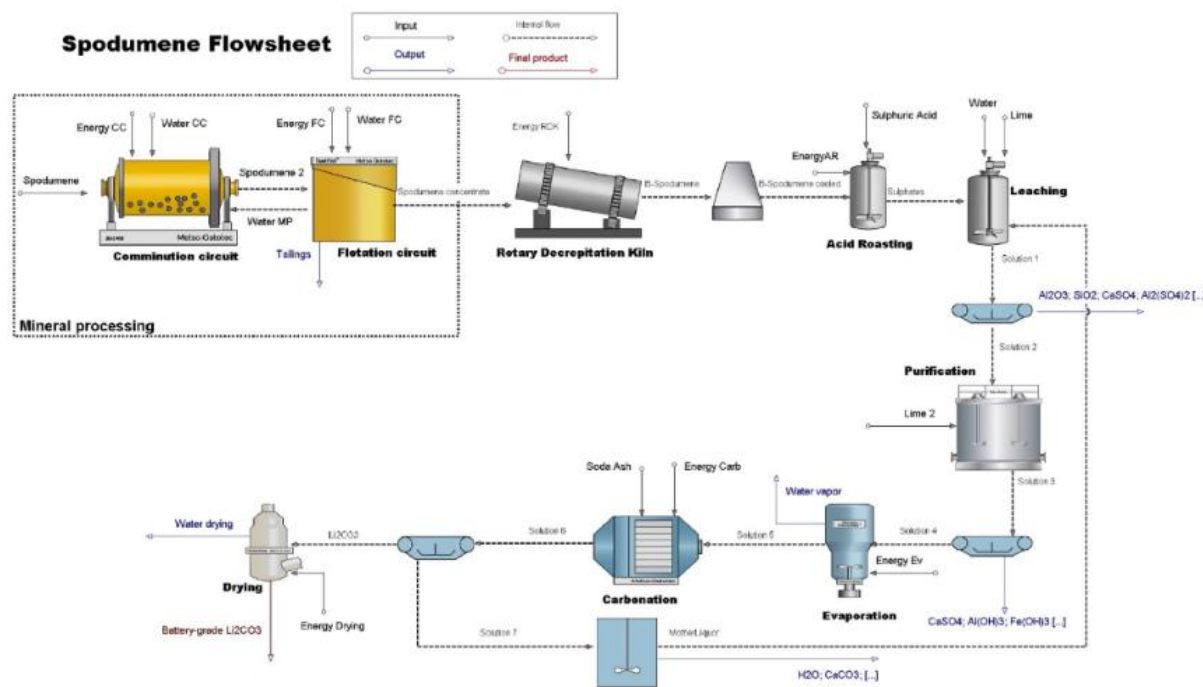


Figure A. 2: Process flowsheet in HSC Sim for the flotation circuit in the spodumene pathway (Mas-Fons et al., 2024).

The above figure provides a detailed view of the hard rock mining process, showcasing the steps involved and their environmental impacts (Mas-Fons et al., 2024).

A.4 Lifecycle Analysis Comparisons

Life cycle analyses (LCA) reveal significant variations in carbon emissions during the lithium production process. Facilities in Europe and North America benefit from cleaner energy grids, leading to lower emissions. In contrast, regions such as China, which rely heavily on fossil

fuels, result in higher carbon emissions, except for Sichuan Province, where hydropower reduces carbon intensity to levels comparable to Europe (Kallitsis et al., 2024).

This comparative analysis highlights the importance of regional energy sources in determining the environmental impacts of lithium production. These insights guide strategic decisions for lithium sourcing and refining to minimize carbon footprints (Kallitsis et al., 2024).

A.5 Emerging Technologies

Emerging technologies, such as Direct Lithium Extraction (DLE), promise to revolutionize lithium production by significantly reducing water use and emissions. DLE uses advanced filtration techniques to isolate lithium directly from brine, bypassing the need for extensive evaporation ponds. While promising, scalability and economic feasibility remain significant barriers to widespread adoption (Mas-Fons et al., 2024).

By integrating renewable energy into extraction processes and investing in innovations like DLE, the industry can align lithium production with global sustainability goals. These technologies represent critical steps toward reducing the environmental impacts of lithium supply chains while ensuring their scalability to meet growing global demand (Mas-Fons et al., 2024; Kallitsis et al., 2024).

Appendix B: Technical Insights into Recycling Processes and Regional Frameworks

Hydrometallurgical recycling, a widely accepted method for LIB recycling, involves dissolving battery components in acids to recover materials such as lithium, cobalt, and nickel. This process achieves recovery rates exceeding 95% but requires significant energy inputs, which can vary depending on the specific chemical agents used and the operation scale (Vaccari et al., 2024; Liu et al., 2024). In contrast, direct recycling preserves the cathode materials without extensive chemical or thermal processing, providing a cost-effective and energy-efficient alternative. However, challenges such as the diverse designs of LIBs and a lack of standardized recycling procedures complicate the widespread adoption of both methods (Quinteros-Condoretti et al., 2021; Yuan et al., 2024).

Regionally, Europe has been established as a leader in LIB recycling infrastructure, supported by policies like the EU Battery Regulation, which mandates specific recycled content targets and lifecycle accountability (Zhou et al., 2024). Decentralized facilities across the EU reduce transportation emissions and foster localized circular economies. In contrast, North America and parts of Asia face fragmented regulatory frameworks and underinvestment in advanced recycling technologies, which hinder the scalability and efficiency of their recycling processes (Dunn et al., 2022; Mayyas et al., 2023).

Technological advancements play a crucial role in improving recycling efficiency and sustainability. Automated disassembly systems simplify the breakdown of used batteries, while AI-driven sorting mechanisms optimize material recovery rates by accurately identifying and separating components (Gebhardt et al., 2022; Niri et al., 2024). Modular battery construction, which allows for easier disassembly and reuse of components, is increasingly being adopted to facilitate recycling processes. These innovations, combined with policies supporting R&D in recycling technologies, create opportunities to overcome existing challenges and promote the circularity of lithium supply chains (Mas-Fons et al., 2024; Tang et al., 2023).

LCA studies further highlight the environmental benefits of integrating recycled lithium into new production cycles, particularly in reducing GHG and water usage. These assessments reinforce the critical role of advanced recycling methods in achieving sustainability goals and mitigating the ecological impact of LIBs supply chains (Alessia et al., 2021; Zhou et al., 2024).

Appendix C: Technical Insights into Policy Frameworks and Technological Innovations

The EU Battery Regulation represents one of the most comprehensive policy frameworks aimed at ensuring sustainability in lithium supply chains. The regulation mandates lifecycle accountability, requiring transparency in carbon footprints, resource efficiency metrics, and the use of recycled content in new batteries. By 2036, at least 12% of lithium in new produced batteries must come from recycled sources, encouraging CE practices across the EU (Dunn et al., 2022; Zhou et al., 2024). The regulation also includes stringent standards for EoL battery collection and recycling efficiency, providing a robust policy for supply chain sustainability.

Comparative analysis of global regulatory frameworks reveals significant disparities. While the EU imposes mandatory recycling and carbon footprint targets, the United States adopts a more decentralized approach, with voluntary recycling standards and limited federal oversight (Vaccari et al., 2024; Niri et al., 2024). Emerging economies, key players in lithium extraction, often lack robust regulatory frameworks, resulting in environmental degradation and social inequities. Initiatives such as the Responsible Lithium Partnership aim to bridge these gaps by strengthening collaboration among governments, industries, and communities, particularly in South America and Australia (Slattery et al., 2023; Thies et al., 2019).

Technological innovations play a vital role in aligning policy frameworks with sustainability goals. DLE is a transformative technology that reduces water and carbon footprints compared to traditional mining methods. By isolating lithium from brine without extensive evaporation processes, DLE integrates efficiency with environmental sustainability. Pilot projects in areas such as the Upper Rhine Graben in Germany and the Salton Sea in California have demonstrated their potential, although scalability remains a challenge (Schenker et al., 2024; Weinand et al., 2023).

Geothermal lithium extraction represents another promising advancement. This method combines renewable energy generation with lithium recovery, minimizing the environmental impact while diversifying supply sources. Countries such as Germany and the US have invested in geothermal mining, with the aim of creating domestic lithium production hubs that align with decarbonization goals (Weinand et al., 2023).

The GBA promotes international collaboration to harmonize policies and create common standards for battery lifecycle management. These efforts address fragmented regulations and ensure best practices are adopted globally, promoting sustainability in lithium extraction, recycling, and reuse (Niri et al., 2024).

Appendix D: Supplementary Details for Critical Raw Materials and Sustainable Sourcing

D.1 Environmental and Geographical Insights into CRM Sourcing

Manjong et al. (2024) assess in their study the environmental performance of CRM sourcing regions. Figure D.1 presents the relative environmental scores, while Figure D.2 highlights variability within regions, driven by governance and technological factors.

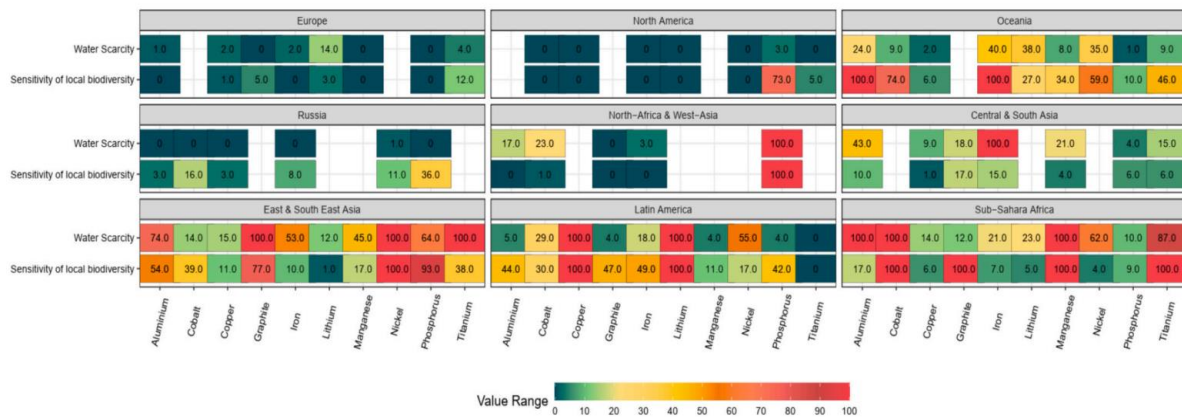


Figure D. 1: Relative environmental scores [0–100] per raw material and region (Manjong et al. 2024).

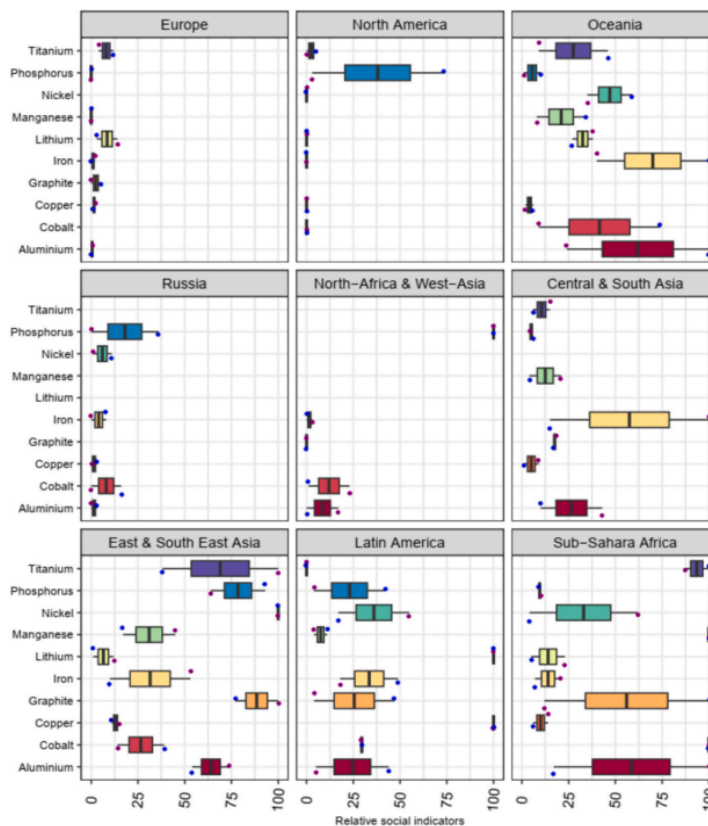


Figure D. 2: Spread in relative environmental scores across sourcing regions (Manjong et al. 2024).

D.2 Recycling Technologies and Their Role in Sustainability

Recycling is integral part of CRM sustainability. Hydrometallurgical and pyrometallurgical recycling processes recover critical materials such as lithium, cobalt, and nickel from used batteries. Figure D.3, presented below, provides a schematic representation of LIBs recycling stages, showcasing the potential for high-purity material recovery (Sultana et al., 2022).

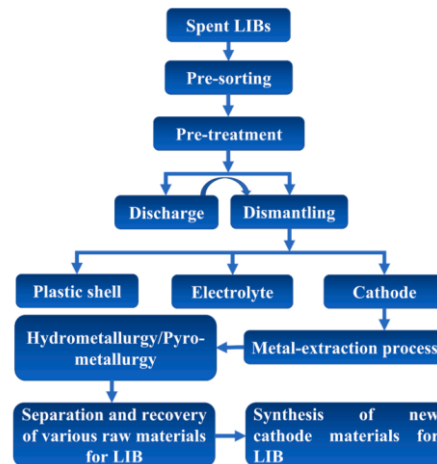


Figure D. 3: A schematic diagram of recycling stages of spent LIBs (Sultana et al., 2022).

LIBs recycling involves stages such as collection, disassembly, separation, and material recovery. Collection ensures a steady supply of EoL batteries, while disassembly, increasingly automated, prepares components for processing. During separation, physical methods like shredding and sieving isolate materials for recovery. Hydrometallurgical processes recover more than 95% of lithium, cobalt, and nickel through acid dissolution, while pyrometallurgical methods use high temperatures to extract metals but are more energy intensive. Emerging direct recycling techniques retain cathode materials in their original form, reducing chemical use and enhancing efficiency (Sultana et al., 2022; Lehtimäki et al., 2024).

Recycling decreases dependency on primary resources and mitigates environmental impacts. For instance, substituting 30% of primary lithium with recycled material reduces emissions and water use by more than 10%, aligning with CE goals (Sultana et al., 2022). These processes are crucial for creating sustainable supply chains for CRMs.

D.3 Methodological Frameworks for Sustainable Sourcing

The ESSENZ method evaluates the sustainability of CRM sourcing by integrating environmental, social, and economic dimensions. Environmental criteria assess impacts like emissions and water use, while social aspects focus on labour conditions and community health. Financial

indicators take into account resource availability and trade dependencies, offering a balanced view of sourcing challenges (Schneider et al., 2021).

D.4 Policy Frameworks and Regional Comparisons

Global policy frameworks play a vital role in ensuring the sustainable management of CRMs. The European Union is leading the way with comprehensive regulations such as the EU Battery Regulation, which mandates a 12% recycled lithium content in new batteries by 2036, promotes lifecycle accountability, and supports CE principles. These policies encourage investment in recycling infrastructure and encourage innovation in material recovery, setting a global benchmark for sustainability (Dunn et al., 2022).

In contrast, regulatory approaches in North America and parts of Asia remain fragmented. The United States relies on voluntary guidelines and decentralized policies, which often lack the stringency of EU regulations. Emerging economies, while rich in CRM resources, frequently face gaps in governance, leading to issues like environmental degradation and ethical concerns in sourcing practices (Yan et al., 2020). This lack of harmonization presents challenges for global CRM supply chains, particularly in aligning sustainability goals.

To address these disparities, international collaboration is essential. Initiatives such as the Global Battery Alliance aim to create standardized policies for CRM management, enhance transparency and accountability across supply chains. By integrating robust policies with technological advancements, regions can reduce their environmental footprints and mitigate geopolitical risks, ensuring a more sustainable and resilient global CRM supply chain (Zhou et al., 2024).

Appendix E: Supplementary Details on Supply Chain Risks for Critical Raw Materials

E.1 Quantitative Data on CRM Risks

Table E.1 categorizes the risks in CRM supply chains into three primary dimensions: geopolitical, environmental, and social. These risks demonstrate the complexity of ensuring sustainable and resilient CRM supply chains, particularly for Europe's transition to carbon neutrality (Kamran et al., 2023; Rizos et al., 2024).

Category	Description
Geological availability risk	Issues related to the global supply of the elements (resource & reserve base).
Geopolitical/regional risk	Issues related to the element supply chain, its geographic distribution, and potential disruptions; vulnerability concerns for meeting demand in specific regions (also affected by price fluctuations).
Environmental risk	Issues related to associated air emissions and pollution to water and land.
Social risk	Issues related to miners and local communities (including: health & safety, financial risk).

Table E. 1: Four main categories of risk associated with critical elements for the energy transition (Kamran et al., 2023).

E.2 Case Studies on Environmental and Social Risks

Lithium mining in Chile: Lithium extraction in the Atacama Desert consumes vast amounts of water, exacerbating water scarcity in one of the driest regions on Earth. This has led to tensions between local communities and mining companies, as agricultural and indigenous livelihoods are directly impacted. Furthermore, the extraction process disrupts ecosystems, threatening native species and biodiversity (Wesselkämper et al., 2024).

Cobalt mining in the DRC: The DRC accounts for over 70% of global cobalt supply, much of it from artisanal and small-scale mining (ASM). Environmental risks include severe soil contamination and habitat destruction, while social risks involve exploitative labour practices such as child labour and unsafe working conditions. Advocacy groups and regulatory bodies have called for stricter sourcing standards, leading to potential disruptions in the supply chain (Zhou et al., 2024).

E.3 Future Mitigation Strategies

Efforts to mitigate CRM risks include the development of CE practices, such as recycling and urban mining, which can reduce dependence on primary resources. However, these solutions face challenges like low material recovery rates and high costs associated with advanced recycling technologies. Policy frameworks, such as the EU Battery Regulation, aim to address these issues by mandating recycled content and improving traceability across the supply chain (Dunn et al., 2022).

Appendix F: Supplementary Details on Decarbonization and Critical Raw Materials

F.1 Quantitative Data on CRM Requirements

Material requirements for renewable energy technologies vary significantly depending on the type and scale of the installation. Table F.1 presents a detailed breakdown of CRM needs for key technologies, including EVs, wind turbines, and energy storage systems. This data underscores the material intensity of transitioning to renewable energy infrastructure, particularly for lithium, cobalt, and REEs (Cristóbal et al., 2020).

Material requirements by type of turbine and installation (in kg/MW).

	Model 1		Model 2	
	On shore	Off shore	On shore	Off shore
Al	840	840	560	560
Cu	2700	11,500	7000	15,800
Fe	172,100	292,100	112,670	232,670
Nd	60.92	60.92	182.75	182.75
Dy	4.86	4.86	14.58	14.58
Ni	111	111	111	111

Table F. 1: Material requirements by type of turbine and installation (in kg/MW)

For solar thermal power systems, Table F.2 details the specific materials required, emphasizing their reliance on rare and high-value elements. Solar thermal systems, which are critical for large-scale energy production, depend heavily on materials like gallium and indium, further intensifying the pressure on CRM supply chains (Valero et al., 2018).

Material	PT (ton/GW)	CRS (ton/GW)
Ag	13	16
Al	740	23,000
Cr	2200	3700
Cu	3200	1400
Fe	650,000	393,000
Mn	2000	5700
Mo	200	56
Ni	940	1800
Ti	25	0
V	2	2
Zn	650	1400

Table F. 2: List of materials used in Solar Thermal Power installations (in ton/GW)

F.2 Lithium Demand and Recycling Challenges

The demand for lithium is projected to rise exponentially, with forecasts suggesting a 700% increase by 2050. However, recycling rates for lithium remain extremely low, at only 1%, posing a significant challenge to supply chain sustainability. Figure F.1 illustrates the projected lithium demand and supply gaps, highlighting the urgency of developing effective recycling and recovery technologies. These gaps demonstrate the critical need for scaling up CE practices to mitigate resource scarcity and reduce environmental impacts (Valero et al., 2018).

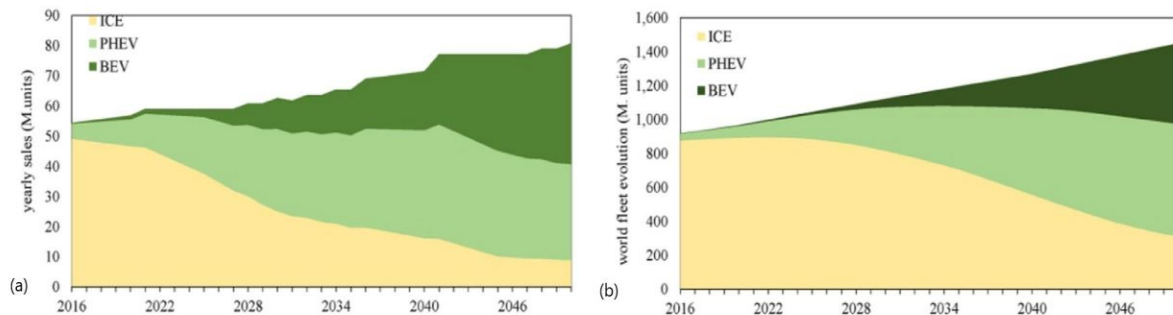


Figure F. 1: (a) yearly sale of vehicles and (b) world fleet evolution for ICEV, PHEV and BEV (Valero et al., 2018).

F.3 Case Study: Barroso Mine in Portugal

The proposed Barroso Mine in Portugal represents Europe's attempt to secure domestic lithium supplies for the decarbonization transition. However, the project has faced strong resistance from local communities due to its potential ecological and cultural impacts. Critics argue that the mine threatens agricultural heritage and ecosystems while offering limited benefits to local populations. This case highlights the tension between global decarbonization goals and local socio-environmental priorities, emphasizing the importance of equitable and transparent decision-making processes (Dunlap and Riquito, 2023).

Appendix G: Supporting Figures and Technical Details

Figure G.1 provides an in-depth representation of the processes involved in a closed-loop recycling system for LIBs. It demonstrates the recovery and reuse of critical materials, including lithium, cobalt, and nickel, which are vital for battery production. This system ensures that EoL batteries are not discarded as waste but instead are dismantled, processed, and reintegrated into the supply chain. Kunz (2019) emphasizes that such systems significantly reduce environmental impacts by minimizing reliance on primary material extraction and lowering greenhouse gas emissions associated with traditional mining and refining methods.



Figure G. 1: Closed loop recycling system of lithium batteries (Kunz., 2019).

The closed-loop recycling framework is particularly important in addressing the challenges posed by the geographic concentration of lithium refining and the environmental degradation linked to conventional extraction techniques. By recovering materials from used batteries, regions can reduce their dependency on imports from areas such as China, which currently dominates the global lithium refining capacity (Yuan et al., 2024). This approach not only enhances the resilience of supply chains but also contributes to the CE by extending the lifecycle of critical materials and reducing waste generation.

Appendix H: Supporting Data and Visuals

Figure H.1, sourced from Qiao et al. (2024) study, provides a detailed overview of the cobalt life cycle in China, illustrating the interconnected stages of mining, refining, and recycling. The figure highlights the inefficiencies in refining operations, which are highly energy-intensive and dependent on fossil fuels, contributing significantly to greenhouse gas emissions. Qiao et al. (2024) highlight in their study the urgent need to transition to renewable energy sources in refining processes to reduce the environmental impact.

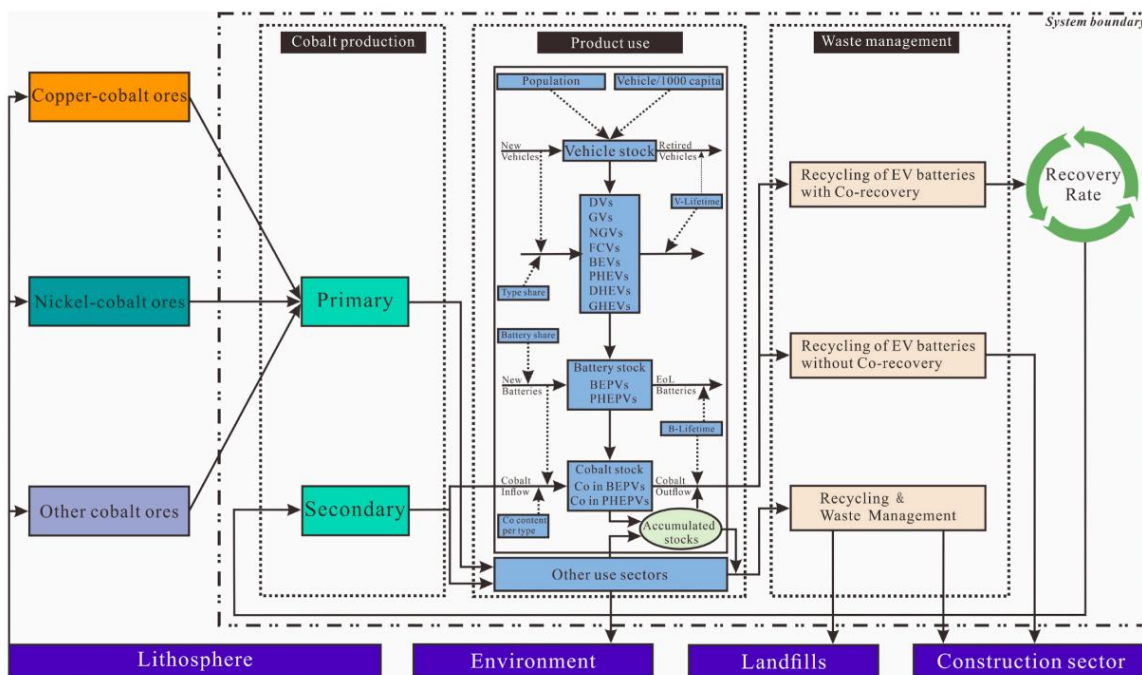


Figure H. 1: The process and material flow of the cobalt life cycle in China (Qiao et al., 2024).

Integrating recycling into the cobalt supply chain is also critical. Wesselkämper et al. (2024) highlight in their study that closed-loop systems can reduce dependency on primary resources while stabilizing market supply. These systems align with EU policies that mandate minimum recycled content in new batteries. However, scaling recycling systems globally requires addressing logistical barriers and technological inefficiencies (Nguyen et al., 2021).

Additionally, Niri et al. (2024) explores in their study the importance of regional supply chain optimization to reduce transportation emissions. By localizing refining and recycling operations, regions can decrease their carbon footprint and enhance resilience against geopolitical risks. Such strategies are essential for meeting growing cobalt demands while ensuring sustainability and reducing environmental degradation.

Appendix I: Technological Advances in Lithium-Ion Battery Recycling

Figures I.1 and I.2 provide critical insights into the advancements in LIBs recycling technologies and their contributions to GHG emission reductions. Figure I.1 showcases the cumulative GHG flow network, highlighting the substantial reduction potentials achieved by transitioning from stepwise to direct recycling methods. This transition underscores the importance of technological innovation in achieving the EU's decarbonization goals (Wu et al., 2022).

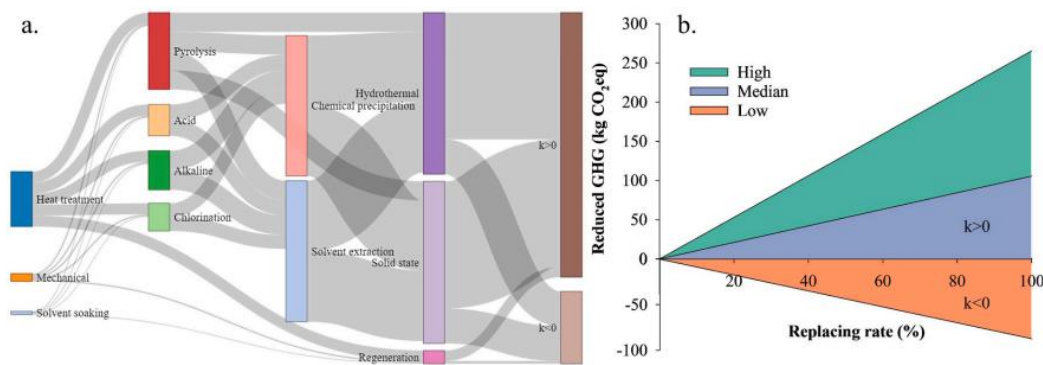


Figure I. 1 a) Cumulative GHG flow network and probability of achieving carbon remission by replacing stepwise with direct recycling. b) Prediction of GHG remission by replacing stepwise with direct recycling with changing adaption rates (Wu et al., 2022).

Figure I.2 delves into the efficiency of cathode-healing processes, emphasizing its ability to preserve cathode structures for direct reuse. This not only enhances material recovery rates but also significantly reduce energy consumption and GHG emissions compared to traditional methods. Such innovations align directly with the EU's CE Action Plan, paving the way for more sustainable supply chains (Xu et al., 2020).

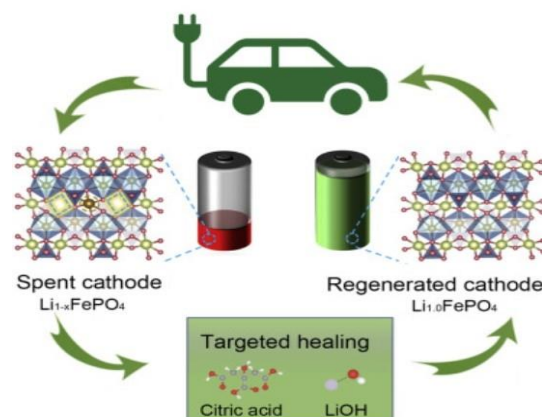


Figure I. 2: Efficient Direct Recycling of Lithium-Ion Battery Cathodes by Targeted Healing (Xu et al., 2020)

These figures collectively emphasize the transformative impact of integrating cutting-edge recycling technologies within the regulatory framework. They serve as visual evidence of how targeted strategies can address environmental challenges while supporting the EU's broader objectives for sustainability and resource efficiency.

Figures I.1 and I.2, illustrating GHG reduction potentials and cathode-healing processes, are relocated here for detailed reference. These visuals provide comprehensive insights into technological advancements and their impacts on recycling efficiency (Wu et al., 2022; Xu et al., 2020).

Appendix J: Supplementary Information on LIB Recycling

Figure J.1 provides a detailed schematic of the hydrometallurgical recycling process, emphasizing its key steps and efficiencies in recovering critical materials like lithium, cobalt, and nickel. This process utilizes chemical leaching to dissolve battery components and achieve high recovery rates, typically 100%. The method aligns with global decarbonization goals by consuming less energy and producing fewer emissions compared to traditional pyrometallurgical processes (Wesselkämper et al., 2024).

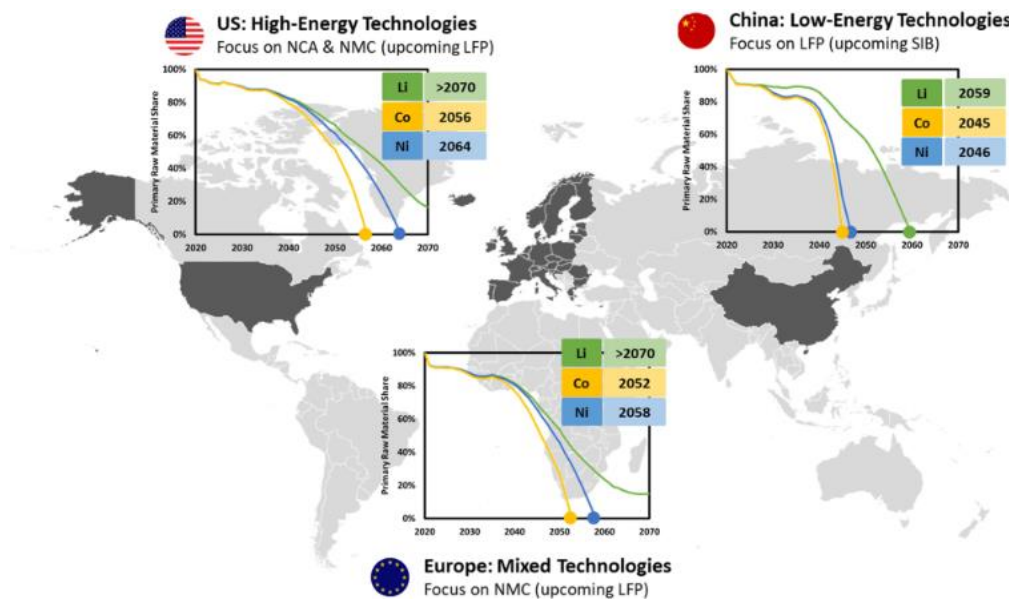


Figure J. 1: Forecasted break-even points (BEPs) of full demand coverage by secondary supply for lithium, cobalt and nickel in China, US, and Europe (Wesselkämper et al., 2024).

This appendix also delves into direct recycling, a promising approach that preserves the structural integrity of battery components such as cathodes. By reducing the need for extensive chemical processing, direct recycling offers potential cost and energy savings. However, the method faces challenges in scalability and requires technological advancements to accommodate the diversity of LIBs chemistries (Gebhardt et al., 2022). Emerging innovations, including modular battery designs and automated disassembly systems, are pivotal for addressing these limitations and enhancing recycling efficiency.

Author's Statement:

I hereby expressly declare that, according to the article 8 of Law 1559/1986, this dissertation is solely the product of my personal work, does not infringe any intellectual property, personality and personal data rights of third parties, does not contain works/contributions from third parties for which the permission of the authors/beneficiaries is required, is not the product of partial or total plagiarism, and that the sources used are limited to the literature references alone and meet the rules of scientific citations.