BATTERY RECYCLING AND SUSTAINABILITY

BY

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DEPARTMENT OF COMPUTER ENGINEERING

FACULTY OF ENGINEERING

UNIVERSITY OF BENIN

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A PROJECT SUBMITTED TO THE DEPARTMENT OF COMPUTER ENGINEERING,

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IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF

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CERTIFICATION

This project was carried out by EKAEDOZI MARVELLOUS in the department of Computer Engineering, Faculty of Engineering, University of Benin, Benin City, and is hereby certified.

Engr.S.I. Akinbohun Date

(Project Supervisor)

Engr. Dr. (Mrs.) O. Okosun Date

(Head of Department)

DEDICATION

I dedicate this project with profound gratitude and humility. Firstly, I offer my heartfelt dedication to the Almighty God, whose unwavering protection and boundless grace have been my guiding light with my project. Next, my heartfelt appreciation goes out to my beloved family, with a special mention to my cherished mom Mrs. Ekaedozi Judith and my dad Mr. Ebeye Augustine Jimoh for their constant love, unwavering care, and unending support have been the pillars of my journey. And my Fiancée Camy, and siblings, Sarah and Nneka, for their encouragement and support.

In addition, I extend my heartfelt dedication to Engr. Sylvester Akinbohun whose support, encouragement, and guidance have played a significant role in shaping my experiences and aspirations.

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ABSTRACT

The rapid growth in the use of lithium-ion batteries (LIBs), driven by the global shift toward electric vehicles and renewable energy, presents both opportunities and challenges for sustainability. This research explores the current state and future prospects of lithium-ion battery recycling, focusing on its environmental, economic, and policy implications. Through a mixed-methods approach combining systematic literature review, thematic analysis, life cycle assessment (LCA), and multi-criteria decision analysis (MCDA), the study evaluates the efficiency, environmental footprint, and cost structures of pyrometallurgical, hydrometallurgical, and direct recycling methods. The findings indicate that hydrometallurgical processes currently offer the most balanced and scalable solution, while direct recycling shows strong long-term promise pending technological advancement. The study also emphasizes the critical role of robust regulatory frameworks and circular economy principles in enhancing sustainability. Ultimately, this work highlights battery recycling as a key enabler of a more resource-efficient and environmentally responsible energy future.

TABLE OF CONTENT

CHAPTER ONE

1.1 BACKGROUND OF THE STUDY

Battery recycling has become increasingly critical due to the rise of electric vehicles (EVs) and renewable energy storage systems, which rely heavily on advanced battery technologies, including but not limited to lithium-ion batteries (LIBs) (European Commission, 2021). These batteries contain valuable materials such as lithium, cobalt, nickel, and other critical minerals, which are finite resources. Recycling ensures the sustainability of these materials while addressing environmental and economic concerns (Harper et al., 2019).

The evolution of battery technology has been characterized by successive innovations, each addressing the limitations of its predecessors and driving progress across various industries. This journey began with the voltaic pile, invented by Alessandro Volta in 1800. The voltaic pile was the first device capable of delivering a continuous electric current, laying the foundation for modern electrochemical energy storage (Scrosati & Garche, 2010).

In 1859, Gaston Planté introduced the lead-acid battery, which remains widely used today, particularly in automotive applications and uninterruptible power supplies. Its ability to provide high surge currents made it indispensable for early and modern applications despite its relatively low energy density (Scrosati & Garche, 2010).

The 20th century witnessed significant advancements with the introduction of nickel-cadmium (NiCd) batteries in the early 1900s, followed by nickel-metal hydride (NiMH) batteries in the 1980s. NiCd batteries offered improved cycle life and reliability but were marred by the "memory effect" and environmental concerns due to cadmium toxicity. NiMH batteries emerged as a less toxic alternative, with higher energy densities suitable for portable electronics and hybrid vehicles (Goodenough & Park, 2013).

The development of lithium-ion batteries (LIBs) in the 1990s revolutionized the energy storage landscape. Pioneers like John B. Goodenough, Rachid Yazami, and Akira Yoshino contributed to this breakthrough, creating a battery with unparalleled energy density, cycle life, and lightweight design. The first commercial LIB was launched by Sony in 1991, marking a transformative era for portable electronics, EVs, and renewable energy storage (Armand & Tarascon, 2008; Whittingham, 2004).

The global demand for batteries, particularly LIBs, has surged due to the widespread adoption of EVs and renewable energy technologies. These advancements are seen as vital in combating climate change by reducing greenhouse gas emissions in transportation and energy sectors (Armand & Tarascon, 2008). However, the increasing reliance on LIBs brings challenges associated with resource extraction, supply chain vulnerabilities, and environmental impacts.

For instance, the mining of lithium and cobalt, critical components in LIBs, poses significant environmental and social challenges. Lithium extraction in arid regions can lead to water scarcity, while cobalt mining, concentrated in the Democratic Republic of Congo, is linked to human rights violations and ecological degradation (Amnesty International, 2019). These challenges underscore the need for efficient recycling processes to reduce dependency on virgin materials and alleviate environmental concerns (Dunn et al., 2012).

Recycling offers a pathway to recover valuable materials, such as lithium, cobalt, nickel, and manganese, from spent batteries. This not only conserves finite resources but also supports the circular economy, where materials are reused and waste generation is minimized (Bakker et al., 2016). By closing the materials loop, recycling can reduce the environmental footprint of battery production and disposal, contributing to a more sustainable energy storage industry (Habib et al., 2015).

Moreover, improper disposal of batteries poses risks of soil and water contamination from toxic substances like heavy metals and electrolytes (UNEP, 2018). Advanced recycling technologies, including hydrometallurgical and pyrometallurgical processes, have shown promise in recovering these materials efficiently and safely (Li et al., 2019).

Governments and organizations are implementing regulatory frameworks and incentives to encourage sustainable recycling practices. For example, the European Union's Battery Directive emphasizes extended producer responsibility and promotes recycling targets to ensure compliance with environmental standards (European Commission, 2020).

The evolution of battery technologies, from the voltaic pile to modern LIBs, highlights the dynamic nature of innovation in energy storage. However, the environmental and geopolitical challenges posed by finite resources necessitate a paradigm shift toward sustainable practices. Recycling plays a crucial role in mitigating supply risks, reducing environmental impact, and supporting the transition to a low-carbon economy (Moss et al., 2011).

1.2 STATEMENT OF THE PROBLEM

The main problem addressed in this study is the environmental and economic challenges posed by the improper disposal of used batteries, particularly lithium-ion batteries (LIBs) (Hadi et al., 2020). Current recycling methods for LIBs, while varied, often prove to be inefficient or environmentally damaging (Habib et al., 2015). This inefficiency results in a significant portion of spent batteries being discarded improperly, leading to resource wastage and environmental pollution (Li et al., 2019).

Many existing recycling techniques have limitations. Pyrometallurgical processes, which involve high-temperature smelting, can recover valuable metals but are energy-intensive and can release harmful emissions (Yang et al., 2020). These processes contribute to air pollution and climate change (UNEP, 2018). Hydrometallurgical processes, which use chemical leaching to extract metals, may be more efficient in metal recovery but can generate toxic leachates (Park et al., 2019). Improper management of these leachates can lead to soil and water contamination (Li et al., 2017).

A substantial number of batteries end up in landfills, leading to the loss of valuable resources like lithium, cobalt, and nickel (Gaines et al., 2017). Landfilled batteries also pose serious environmental hazards. Batteries contain toxic substances such as lead, cadmium, and organic electrolytes that can leach into the soil and groundwater, causing contamination and posing health risks to humans and wildlife (Wang et al., 2017). For instance, heavy metals from batteries can bioaccumulate in the food chain, leading to long-term ecological and health consequences (Lv et al., 2018).

The increasing demand for LIBs exacerbates the pressure on mining activities. As the production of EVs and renewable energy storage systems accelerates, so does the need for raw materials (Moss et al., 2011). This intensifies mining operations, which are often associated with significant environmental degradation, including habitat destruction, water pollution, and carbon emissions (Dunn et al., 2012). For example, lithium extraction in regions like South America's

"Lithium Triangle" has raised concerns about water depletion and ecosystem disruption (Streitwieser et al., 2020).

Inefficient recycling and reliance on virgin materials can lead to higher production costs for batteries (Bakker et al., 2016). This, in turn, can slow down the adoption of EVs and renewable energy technologies, counteracting efforts to combat climate change. High material costs make battery production more expensive, which can increase the price of EVs and energy storage systems, making them less accessible to consumers and slowing market growth (European Commission, 2021). Moreover, the geopolitical risks associated with the supply of critical materials like cobalt, which is predominantly mined in the Democratic Republic of Congo, further complicate the economic landscape (Moss et al., 2011). The concentration of cobalt mining in politically unstable regions can lead to supply disruptions and price volatility, impacting the entire battery supply chain (Gaines et al., 2017).

The improper disposal and inefficient recycling of LIBs present significant environmental and economic challenges. Addressing these issues requires the development of more effective and sustainable recycling methods to reduce environmental impact, conserve resources, and support the growing demand for battery materials in a manner that aligns with global sustainability goals.

1.3 AIM AND OBJECTIVES

The primary aim of this study is to evaluate the current state of battery recycling technologies and their sustainability

To achieve this aim, the following objectives will guide the project:

1. Assessing the efficiency and environmental impact of existing recycling methods.

2. Identifying gaps and challenges in the current recycling processes.
3. Exploring new and emerging technologies that could improve recycling rates and reduce environmental impact.
4. Proposing policy recommendations to enhance battery recycling and support a circular economy .

1.4 SCOPE OF THE STUDY

This study focuses on the recycling of lithium-ion batteries, particularly those used in EVs and renewable energy storage. It covers various recycling methods such as hydrometallurgical, pyrometallurgical, and direct physical recycling. The geographical scope includes regions with significant EV adoption and battery production, primarily North America, Europe, and Asia. The temporal scope considers recent advancements and future trends up to 2040 .

1.5 RELEVANCE OF STUDY

The relevance of this study lies in its potential to contribute to the development of sustainable recycling practices, reducing the environmental footprint of battery usage. By improving recycling processes, we can conserve valuable resources, reduce the need for mining, and mitigate pollution. This study also supports global efforts towards achieving Sustainable Development Goals (SDGs), particularly those related to responsible consumption and production, climate action, and sustainable industry innovation .

CHAPTER TWO

LITERATURE REVIEW

2.1 THEORETICAL REVIEW

EVOLUTION OF BATTERIES TO LITHIUM-ION BATTERIES

Batteries have undergone significant advancements since their inception, evolving through multiple generations of technology. The earliest forms of batteries, such as lead-acid and nickel-cadmium, were limited by energy density, weight, and rechargeability (Goodenough & Park, 2013). Lithium-ion batteries (LIBs), introduced commercially in the 1990s by Sony, have revolutionized energy storage due to their superior energy density, lighter weight, and longer lifespan. These characteristics have made LIBs the preferred choice for portable electronics, electric vehicles (EVs), and renewable energy storage systems (Armand & Tarascon, 2008).

Lithium-ion batteries are composed of multiple critical components, including a positive electrode (usually lithium cobalt oxide or lithium iron phosphate), a negative electrode (graphite), a separator, and an electrolyte (Nitta et al., 2015). The ability of these batteries to store significant amounts of energy in small volumes has driven their widespread adoption, particularly in electric mobility and energy storage applications (Whittingham, 2014). However, the increasing use of LIBs has raised concerns over the supply of key raw materials, their environmental impacts, and the challenge of end-of-life disposal (Harper et al., 2019).

RECYCLING OF LITHIUM-ION BATTERIES

Recycling technologies for LIBs are critical to addressing the environmental and resource challenges posed by their widespread use. The most common recycling techniques include pyrometallurgical, hydrometallurgical, and direct physical recycling methods.

1. Pyrometallurgical Recycling: This method involves high-temperature smelting to recover valuable metals such as cobalt, nickel, and copper from spent batteries. While effective in recovering certain materials, pyrometallurgy is energy-intensive and leads to the loss of lithium and aluminum, which are vaporized during the process (Georgi-Maschler et al., 2012). Furthermore, the method generates substantial greenhouse gas emissions and is associated with high operational costs, making it less sustainable in the long term (Zeng et al., 2014).

2. Hydrometallurgical Recycling: Hydrometallurgy utilizes chemical solutions to leach metals from the battery components. This process allows for the selective recovery of lithium, cobalt, nickel, and other metals with lower energy consumption than pyrometallurgy (Li et al., 2013). However, the handling of toxic leachates poses environmental risks, requiring advanced waste management systems to mitigate pollution (Zhao et al., 2021).

3. Direct Physical Recycling: This method involves the mechanical separation of battery components without using high heat or chemicals. Direct recycling has the advantage of preserving the structure of electrode materials, allowing them to be reused in new batteries (Harper et al., 2019). However, direct recycling is still in its early stages, and its scalability remains limited compared to the other methods (Gaines, 2014).

ENVIRONMENTAL IMPACT OF LITHIUM-ION BATTERY RECYCLING

The environmental implications of recycling LIBs are complex and multifaceted. The improper disposal of batteries can result in the release of hazardous substances such as heavy metals, electrolytes, and organic solvents, which contaminate soil and groundwater (Li et al., 2019). The recycling process itself, depending on the method used, can either mitigate or exacerbate environmental pollution.

Hydrometallurgical processes tend to have a lower carbon footprint compared to pyrometallurgy due to reduced energy requirements, but both processes produce chemical wastes that need to be managed effectively (Or et al., 2015). Direct physical recycling is seen as the most environmentally sustainable method, as it avoids both high energy consumption and the generation of chemical waste (Liu et al., 2019). As the demand for LIBs continues to grow, particularly in the EV sector, sustainable recycling solutions will be critical to minimizing the environmental impact of battery production and disposal (Haberlin et al., 2020).

ECONOMIC CONSIDERATIONS IN BATTERY RECYCLING

Economically, battery recycling presents both opportunities and challenges. On one hand, recycling reduces reliance on virgin materials, which are subject to price volatility and supply chain disruptions (Harper et al., 2019). For instance, cobalt, one of the most valuable components in LIBs, is primarily sourced from the Democratic Republic of Congo, where mining conditions are unstable and often unethical (Amnesty International, 2016). Recycling can help stabilize the supply of critical materials, reducing costs and mitigating geopolitical risks (Gaines et al., 2017).

On the other hand, the economics of battery recycling are influenced by the cost-effectiveness of the recycling process itself. Pyrometallurgical recycling, while widely used, is expensive due to the high energy consumption and material losses associated with the process. Hydrometallurgy offers a more cost-effective alternative but requires significant investment in waste management infrastructure (Peters et al., 2017). The development of new technologies, such as direct recycling, holds promise for reducing costs and making battery recycling more economically viable in the long run (Harper et al., 2019).

SOCIAL IMPACT OF BATTERY RECYCLING

The social impacts of LIB recycling are primarily related to labor conditions, health risks, and community well-being. In many developing countries, informal recycling operations expose workers to hazardous materials without proper safety protocols, leading to adverse health outcomes (Northey et al., 2013). Furthermore, communities located near mining and recycling sites often bear the brunt of environmental pollution, including air and water contamination, which can lead to long-term health issues (Li et al., 2019).

Ethical concerns surrounding the extraction of raw materials, particularly cobalt, have prompted calls for responsible sourcing practices, including the increased use of recycled materials to reduce reliance on conflict minerals (Amnesty International, 2019). The transition to a circular economy model, where resources are reused rather than discarded, could significantly improve the social and environmental outcomes of battery production and recycling (Ellen MacArthur Foundation, 2017).

2.2 RELATED WORKS

“Material Footprint of Electric Vehicles” by Gaines, L., Dunn, J. B., Li, J., Gaines, S., & Matthias, A. (2017)

Methodology:

This study employs a life cycle assessment (LCA) approach to evaluate the material footprint of electric vehicles (EVs), focusing on the extraction, use, and disposal stages. It compares EVs with internal combustion engine vehicles in terms of resource demand, paying particular attention to battery materials like lithium, cobalt, and nickel.

Results:

The findings reveal that EVs have a larger material footprint primarily due to their batteries, underscoring the potential value of recycling these components. Recycling could mitigate the demand for new materials and reduce the environmental impact of mining.

Limitations:

The study’s limitation lies in its focus on current battery technology, which may not represent future advancements in materials or recycling technology. Additionally, the study does not delve into regional variances in resource availability and mining practices.

“Economies of Scale for Future Lithium-Ion Battery Recycling Infrastructure” by Wang, X., Gaustad, G., Babbitt, C. W., & Richa, K. (2014)

Methodology:

The authors analyze recycling methods—specifically, hydrometallurgical, pyrometallurgical, and direct physical recycling—and model the economic feasibility of scaling up these technologies. They examine cost structures, market pricing, and potential incentives for recycling initiatives in large-scale infrastructure.

Results:

The study shows that economies of scale could significantly reduce recycling costs, particularly for hydrometallurgical processes. Scaling up these methods would improve the economic viability of battery recycling and help meet growing demand sustainably.

Limitations:

The study's economic models assume stable market conditions, which may not account for fluctuations in raw material prices. Also, the work does not address the technological challenges or environmental impacts of large-scale recycling operations.

"Energy Efficiency of Battery Recycling Technologies" by Or, D., Galea, R., & Mogheir, Y. (2015)

Methodology:

This study evaluates the energy consumption of different recycling methods by analyzing the amount of energy required for pyrometallurgical and hydrometallurgical processes. The authors use a comparative energy balance model to determine the efficiency of each approach.

Results:

Findings indicate that pyrometallurgical recycling requires more energy and has higher greenhouse gas emissions compared to hydrometallurgical processes, which are more energy-efficient. The study suggests prioritizing hydrometallurgical methods to reduce the environmental footprint.

Limitations:

The study primarily considers energy efficiency without a detailed analysis of emissions from other chemical processes involved in recycling. It also lacks field testing data, which could have validated the theoretical models used.

“The Environmental Impact of Li-Ion Batteries and Recycling Strategies” by Peters, J. F., Baumann, M., Zimmermann, B., Braun, J., & Weil, M. (2017)

Methodology:

This research uses a life cycle environmental impact assessment to examine the environmental consequences of lithium-ion battery production, use, and disposal. It includes data on greenhouse gas emissions, resource use, and waste generated throughout the battery life cycle, with a focus on recycling strategies to minimize impacts.

Results:

The study demonstrates that recycling lithium-ion batteries could substantially reduce greenhouse gas emissions and waste generation, particularly through hydrometallurgical recycling. The findings support recycling as a key measure for environmental sustainability in battery production.

Limitations:

While the study highlights the benefits of recycling, it does not account for the social or economic aspects of battery disposal and recycling practices, limiting its applicability to a purely environmental perspective.

“Recycling Lithium-Ion Batteries from Electric Vehicles” by Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., & Anderson, P. (2019)

Methodology:

This paper reviews various recycling technologies for lithium-ion batteries, focusing on efficiency, material recovery rates, and the impact on resource demand. It incorporates empirical data from battery recycling plants and assesses the recovery rates of valuable metals like lithium, cobalt, and nickel.

Results:

The review finds that current technologies can recover a significant percentage of valuable materials, especially with hydrometallurgical methods. It concludes that recycling is crucial for reducing dependence on mined resources and mitigating environmental impacts.

Limitations:

The paper primarily reviews existing technologies, offering limited discussion on emerging or experimental recycling methods that may enhance recovery rates or reduce processing costs.

“Products That Last: Product Design for Circular Business Models” by Bakker, C. A., Wang, F., Huisman, J., & den Hollander, M. C. (2016)

Methodology:

This study investigates circular economy principles in product design, focusing on designing products for longevity, recyclability, and material conservation. It uses case studies and product lifecycle data to explore how product design can support circular business models, including in battery recycling.

Results:

The study suggests that designing batteries with recycling in mind could enhance the efficiency of material recovery. Circular design principles like modularity and standardization are identified as effective strategies for reducing waste and extending product lifespan.

Limitations:

The study is conceptual and does not provide empirical data on the application of circular economy principles in battery recycling specifically. This limits the practical insights on how circular design can be integrated into current battery production processes.

“The Social Impacts of Resource Extraction and Recycling” by Northey, S. A., Mohr, S., Mudd, G. M., & Weng, Z. H. (2013)

Methodology:

Using a social impact assessment framework, this paper explores the social implications of lithium-ion battery production and recycling, including labor conditions, health risks, and the effects on communities near mining and recycling sites.

Results:

The study highlights significant social challenges, including poor labor conditions in mining areas and health risks in recycling plants. It emphasizes the need for responsible recycling to reduce dependency on mining, improve safety, and protect affected communities.

Limitations:

The research primarily addresses the social impacts associated with mining and does not delve into the environmental consequences or specific technological limitations of recycling processes.

“Cobalt Mining and Human Rights: The Case of the DRC” by Amnesty International (2019)

Methodology:

This report uses a case study approach to document the human rights violations associated with cobalt mining in the Democratic Republic of Congo (DRC). It collects firsthand accounts from workers and community members to highlight the social impacts of cobalt extraction.

Results:

The report concludes that cobalt mining in the DRC is fraught with human rights abuses, including child labor and hazardous working conditions. The findings underscore the importance of recycling cobalt from batteries to reduce reliance on conflict minerals.

Limitations:

The report focuses on the DRC, which may not represent conditions in other cobalt-producing countries. Additionally, it lacks quantitative data on how much recycling could realistically offset cobalt demand.

“Critical Materials Recovery from Batteries” by Gaines, L. (2014)

Methodology:

Gaines analyzes recycling techniques for recovering critical materials such as lithium and cobalt from used batteries, assessing the material recovery rates and their potential impact on reducing demand for mined resources.

Results:

The study finds that recycling can recover up to 90% of key materials, supporting sustainability by conserving resources and decreasing environmental impact. The author suggests that enhancing recycling infrastructure could help secure the supply of critical materials.

Limitations:

This work is largely theoretical and does not include pilot-scale data, making it challenging to assess the real-world feasibility of suggested recycling techniques.

"Towards a Circular Economy: Business Rationale for an Accelerated Transition" by Ellen MacArthur Foundation (2017)

Methodology:

This report advocates for a circular economy, promoting practices that minimize waste through recycling and reuse. It reviews policies, technologies, and case studies to support the feasibility of this transition, including in battery production and recycling.

Results:

The findings suggest that a circular economy could reduce waste by enabling the reuse of materials in a closed-loop system. Battery recycling is identified as a critical component in reducing dependency on raw material extraction.

Limitations:

The report focuses on high-level strategies and lacks detailed analysis specific to battery recycling, making its application to the battery industry somewhat generalized.

CHAPTER THREE

METHODOLOGY

Building upon the foundational context and theoretical frameworks established, this chapter details the comprehensive methodological approaches employed to investigate the current state of lithium-ion battery (LIB) recycling and evaluate its sustainability. An overview of the growing global reliance on LIBs provided insights on their evolution from earlier battery technologies, and the pressing environmental and economic challenges posed by their end-of-life management. Also identifying existing recycling methods, examining their environmental footprints, discussing associated economic considerations, and highlighting policy and regulatory frameworks influencing the sector.

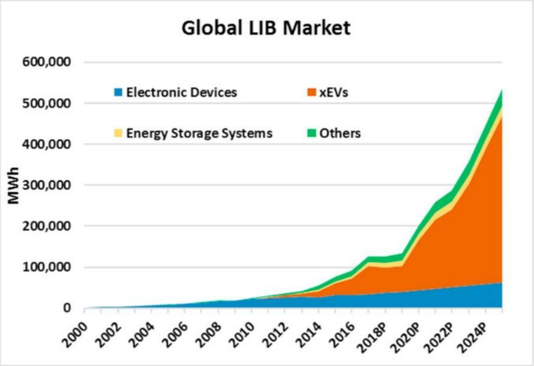
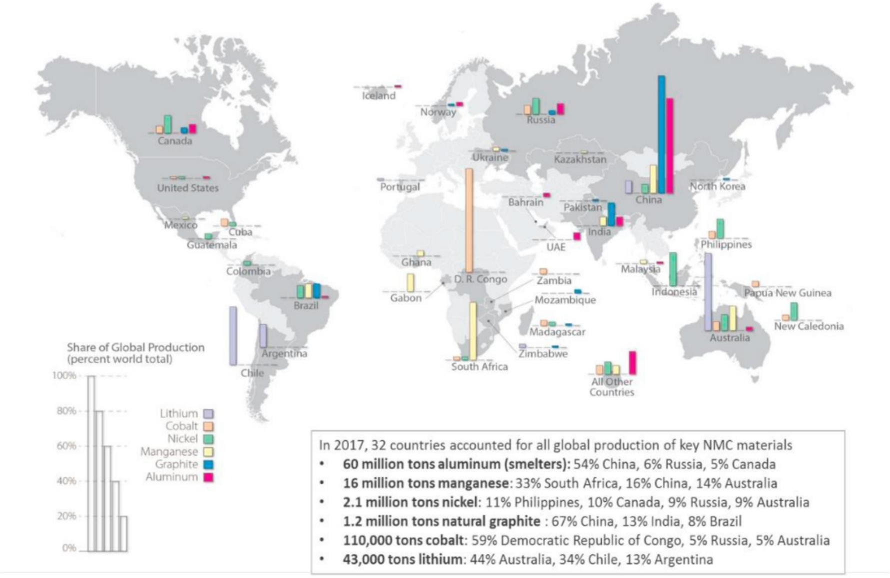


Figure 1. Trend capacity of LIB and their key applications (Projections for 2018-2025)

In direct response to the issues outlined in the earlier chapters—such as the urgent need for resource recovery, the minimization of toxic waste, economic viability, and alignment with sustainability goals. The approach integrates both qualitative and quantitative methods, including a systematic literature review, thematic analysis, quantitative benchmarking of recycling methods, life cycle assessment (LCA), policy and regulatory analysis, and multi-criteria decision analysis (MCDA). By aligning the chosen methods with the theoretical and empirical gaps identified previously, the methodology ensures a coherent flow from problem definition through to data analysis and, ultimately, to the formulation of informed recommendations.

3.1 Research Philosophy and Overall Approach

The complexity and interlinkages identified —spanning environmental science, engineering, economics, policy, and ethics—necessitated a pragmatic research philosophy. Rather than relying solely on a positivist or interpretivist stance, a pragmatist position was adopted. This philosophical alignment allowed for the selection of methods that were most appropriate for answering the research questions at hand, regardless of strict paradigmatic boundaries. The focus remained on producing actionable, policy-relevant, and contextually rich insights into LIB recycling sustainability.



In 2017, 32 countries accounted for all global production of key NMC materials

- **60 million tons aluminum (smelters):** 54% China, 6% Russia, 5% Canada
- **16 million tons manganese**: 33% South Africa, 16% China, 14% Australia
- **2.1 million tons nickel**: 11% Philippines, 10% Canada, 9% Russia, 9% Australia
- **1.2 million tons natural graphite** : 67% China, 13% India, 8% Brazil
- **110,000 tons cobalt**: 59% Democratic Republic of Congo, 5% Russia, 5% Australia
- **43,000 tons lithium**: 44% Australia, 34% Chile, 13% Argentina

Figure 2. World mining industry production for materials used in LIB in 2017 (data source: USGS 2017 [7])

3.2 Research Design

To address the multifaceted objectives articulated —ranging from assessing current recycling efficiencies to understanding environmental and social implications—a mixed-methods research design was implemented. Integrating both qualitative and quantitative approaches helped capture the complexity of LIB recycling. The design encompassed:

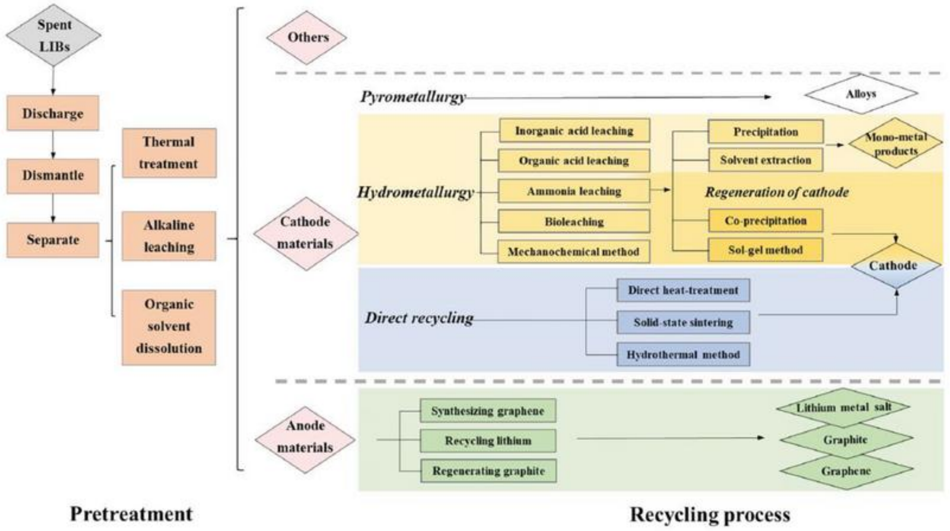


Figure 3. Flow chart of recycling processes of lithium-ion batteries (LIBs). “Makuza, B., Tian, Q., Guo, X., Chattopadhyay, K., & Yu, D. (2021)”

1. **Systematic Literature Review (SLR):**

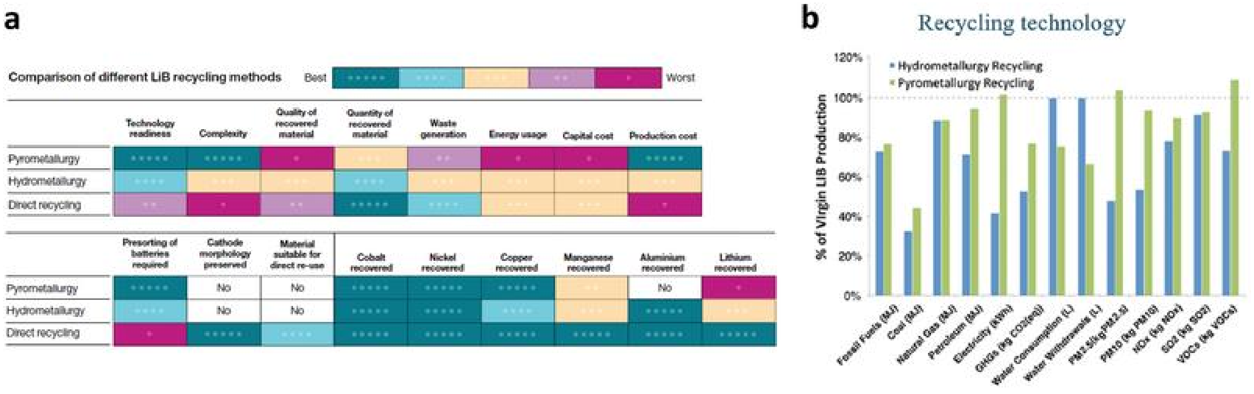
   Existing academic and industry literature was surveyed systematically. This phase sought to consolidate knowledge on recycling methodologies (pyrometallurgical, hydrometallurgical, direct physical), metrics of resource recovery, cost structures, environmental impact reports, and policy instruments shaping the LIB recycling landscape.

2. **Thematic Analysis (Qualitative):**

   Policy documents, regulatory guidelines, industry reports, and descriptive research findings from the literature were subjected to thematic analysis. This approach facilitated the identification of key themes—such as regulatory drivers, sustainability criteria, cost barriers, and social implications—highlighted in Chapter Two as critical but underexplored dimensions of LIB recycling.

3. **Quantitative Benchmarking of Recycling Methods:**

   Quantifiable metrics derived from peer-reviewed studies, industry white papers, and official assessments were extracted to evaluate and compare different recycling techniques. These metrics included material recovery rates of critical metals (e.g., lithium, cobalt, nickel), energy consumption per unit of processed material, and associated greenhouse gas emissions.



a

Comparison of different LiB recycling methods Best ***** **** *** ** * Worst

	Technology readiness	Complexity	Quality of recovered material	Quantity of recovered material	Waste generation	Energy usage	Capital cost	Production cost
Pyrometallurgy	*****	*****	*	***	**	*	*	*****
Hydrometallurgy	****	***	***	****	***	***	***	***
Direct recycling	**	*	**	*****	****	***	***	*

	Presorting of batteries required	Cathode morphology preserved	Material suitable for direct re-use	Cobalt recovered	Nickel recovered	Copper recovered	Manganese recovered	Aluminium recovered	Lithium recovered
Pyrometallurgy	*****	No	No	*****	*****	*****	***	No	*
Hydrometallurgy	****	No	No	*****	*****	****	***	*****	***
Direct recycling	*	*****	****	*****	*****	*****	*****	*****	*****

Figure 4. Comparison of LIB recycling methods "Makuza, B., Tian, Q., Guo, X., Chattopadhyay, K., & Yu, D. (2021)"

4. **Life Cycle Assessment (LCA):**

   Following the recommended evaluation frameworks, an LCA was employed to quantify the environmental impacts of various recycling methods. The LCA adhered to ISO 14040/44 standards, ensuring that global warming potential, resource depletion, toxicity, and other relevant indicators were consistently measured and compared.

5. **Policy and Regulatory Analysis:**

   Informed by the regulatory gaps and directives o, a review of international and regional policies was conducted. This involved analyzing the European Union's Battery Directive, U.S. Department of Energy guidelines, and policies from Asia, as well as corporate standards, to ascertain how regulatory mechanisms influence recycling efficiency, market stability, and environmental outcomes.

6. **Multi-Criteria Decision Analysis (MCDA):**

   Given the multi-dimensional nature of sustainability—encompassing environmental integrity, economic viability, resource efficiency, and policy compatibility—an MCDA framework was applied. This step synthesized findings from previous analyses, assigning weights to criteria derived from earlier chapters and ranking various recycling strategies accordingly.

3.3 Data Sources and Data Collection Techniques

The focus was on consolidating and critically evaluating existing knowledge rather than generating primary experimental data.

1. **Academic Databases and Journals:**

   Major scientific databases (Web of Science, ScienceDirect, IEEE Xplore) were searched using keywords such as "lithium-ion battery recycling," "battery sustainability," "circular economy in energy storage," and "battery policy frameworks."

Peer-reviewed journals including *Journal of Cleaner Production*, *Resources, Conservation and Recycling*, *Energy Storage Materials*, and *Environmental Science & Technology* served as primary repositories of scholarly research.

2. **Industry and Organizational Reports:**

   Reports from international bodies (e.g., International Energy Agency), non-governmental organizations (e.g., Ellen MacArthur Foundation, Amnesty International), and trade associations provided real-world data on recycling operations, market analyses, and pilot projects, complementing the academic literature.

3. **Regulatory and Policy Documents:**

   Policy frameworks, such as the European Union's Battery Directive, WEEE (Waste Electrical and Electronic Equipment) regulations, and various national and regional waste management guidelines, were examined to understand the legal and institutional drivers affecting LIB recycling practices.

4. **Lifecycle Databases:**

   Environmental databases like Ecoinvent and GaBi offered standardized inventory data on input materials, energy consumption profiles, and emission factors. These were critical for conducting robust LCAs.

3.3.1 Inclusion and Exclusion Criteria

The documents were included if they:

1. Addressed LIB recycling processes directly, with relevance to EVs, consumer electronics, or stationary energy storage.
2. Provided qualitative or quantitative data on environmental impacts, cost structures, policy compliance, or critical material recovery rates.
3. Were published between approximately 2009 and 2024, ensuring that data reflected current or emerging technologies and regulatory developments.

Documents were excluded if they:

1. Focused solely on battery chemistries not relevant to LIBs, such as lead-acid or nickel-cadmium, without offering comparative insights.
2. Lacked methodological rigor or transparency in data sourcing.

3.3.2 Data Extraction Procedures

A structured data extraction sheet was developed to ensure consistency and reliability in capturing relevant metrics and insights. For each source, details such as author, publication year, methodology, key findings, measured performance indicators (e.g., recovery rates, emissions), and discussed policies were systematically recorded. Repeated screenings and cross-validation checks were performed to maintain data quality and coherence with the conceptual frameworks introduced in earlier chapters.

3.4 Qualitative Data Analysis: Thematic Analysis

Policy directives, industry guidelines, and narrative segments from academic literature underwent thematic analysis. Initially, open coding identified concepts related to sustainability benchmarks, policy barriers, social implications, economic drivers, and safety considerations. These codes were then grouped into thematic categories aligning with issues raised (e.g., environmental hazards, resource scarcity, identified best practices in recycling technologies, regulatory incentives). This iterative process led to the emergence of core themes such as "regulatory alignment," "ethical sourcing and social justice," "circular economy principles," and "scalability of recycling infrastructures."

3.5 Quantitative Data Analysis

Quantitative metrics from the reviewed sources were systematically compared to identify trends and performance benchmarks. For example, differing recycling methods were analyzed according to:

1. **Material Recovery Efficiency (MRE):** Percentage of lithium, cobalt, nickel, and other metals recovered.
2. **Energy Intensity:** Energy consumption per kilogram of processed LIBs.
3. **Greenhouse Gas Emissions:** Carbon footprint measured in CO2-equivalents per functional unit.
4. **Cost Indicators:** Operational and capital expenditures normalized per unit of recovered material.

Descriptive statistics and comparative charts were employed, enabling the identification of methods that balanced high recovery rates with minimal energy consumption or lower environmental burdens. These insights provided a factual basis to complement the thematic findings, bridging the theoretical gaps identified in Chapter Two.

3.6 **Life Cycle Assessment (LCA)**

To systematically evaluate environmental impacts, the LCA followed the ISO 14040/44 framework. The functional unit chosen was the treatment of 1 kg of spent LIBs, focusing on end-of-life stages including collection, transportation, dismantling, and material recovery. Inventory data, sourced from the literature and lifecycle databases, captured inputs (energy, reagents), outputs (recovered metals, secondary materials), and emissions. Life cycle impact assessment methods (ReCiPe, CML) translated inventory data into impact categories such as global warming potential, acidification, eutrophication, and human toxicity. By interpreting these results, the LCA clarified which recycling methods minimized environmental harm, thereby reinforcing the importance of strategic policy and technological improvements.

Darlene Steward et al. / Procedia Manufacturing 33 (2019) 272–279

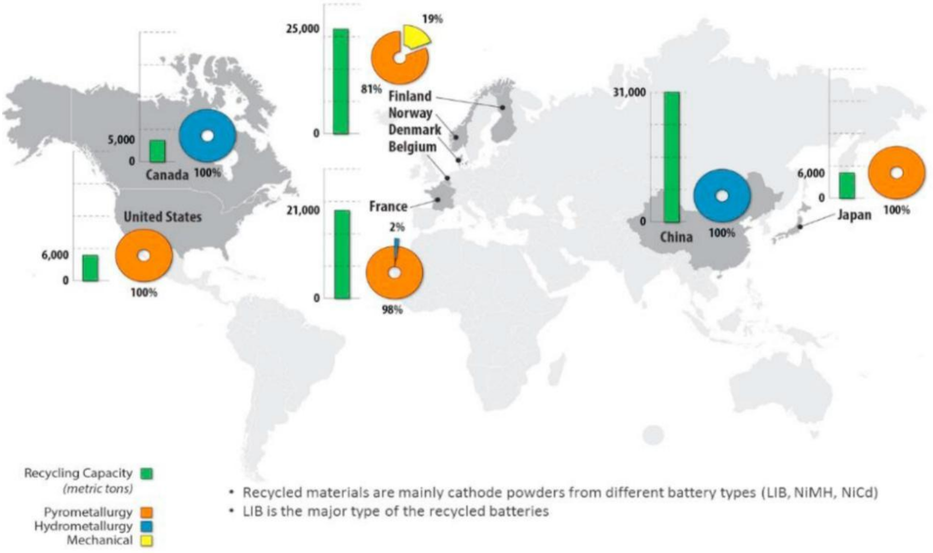


Figure 3. Recycling capacities of the spent batteries in metric tons (MT)

3.7 Policy and Regulatory Analysis

Policy and regulatory analysis aimed to understand how legislative environments shape the economics, efficiency, and sustainability of LIB recycling. Building on the policy contexts described previously, this stage reviewed directives that set recycling targets, impose extended producer responsibility (EPR), or offer financial incentives. Differences in regional policies were noted, illustrating how stringent recycling targets or stable policy frameworks correlate with advanced recycling infrastructures and higher resource recovery efficiencies. This analysis connected the theoretical frameworks and empirical findings to real-world governance structures that either facilitate or hinder the transition to circularity.

3.8 Multi-Criteria Decision Analysis (MCDA)

MCDA techniques integrated the various dimensions analyzed—environmental, economic, resource efficiency, and regulatory compliance—into a single decision-support framework. Drawing from themes identified and criteria established, weights were assigned to reflect priority areas. For instance, greater weight might be given to environmental performance and regulatory compliance if aligned with the sustainability goals outlined at the outset. Each recycling route was then scored against these weighted criteria, generating a ranked set of alternatives. Sensitivity analyses tested the stability of these rankings under different weighting scenarios or data uncertainties, thus ensuring a robust and transparent decision-making tool.

3.9 Reliability and Validity

Measures were taken to enhance the reliability and validity of the study:

1. **Triangulation:** Using multiple data sources and analytical methods reduced the risk of bias and increased credibility.
2. **Standardized Protocols:** Employing established LCA frameworks (ISO standards), recognized MCDA methods, and a structured approach to literature review ensured methodological consistency.
3. **Transparent Documentation:** Detailed records of search terms, coding procedures, selection criteria, and analytical steps were maintained to facilitate replicability and internal validity.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results derived from applying the methodology described previously. The outcomes reflect a comprehensive synthesis of thematic analysis, quantitative benchmarking, life cycle assessments (LCAs), policy reviews, and multi-criteria decision analysis (MCDA). By integrating data and findings from various analytical methods, the chapter highlights key insights into the efficiency, environmental impact, economic viability, policy alignment, and overall sustainability of lithium-ion battery (LIB) recycling methods. The results are organized to mirror the methodological steps, providing a logical sequence from qualitative findings to quantitative indicators, and culminating in a ranked evaluation of recycling scenarios.

4.2 Thematic Analysis Findings

The thematic analysis of policy documents, industry reports, and interpretative academic literature identified four overarching themes:

1. **Regulatory Alignment and Targets:**

   Numerous documents emphasized the role of policy frameworks, including directives and national waste management regulations, in shaping the LIB recycling sector. Extended Producer Responsibility (EPR) emerged as a critical mechanism compelling manufacturers to take back spent batteries and invest in recycling infrastructure. Mandatory recycling quotas, standardized collection systems, and material quality guidelines were frequently highlighted.

2. **Environmental Stewardship and Circularity:**

   Many sources stressed the importance of achieving closed-loop systems in which critical metals such as lithium, cobalt, and nickel are continually recovered and reused. Discussions focused on reducing environmental footprints, resource depletion, and greenhouse gas emissions through more efficient recycling processes.

3. **Technological and Economic Feasibility:**

   Thematic analysis revealed that technological maturity and cost-effectiveness are pivotal. Reports often cited the need for scalable, energy-efficient recycling processes and improved yield in metal recovery. Economic viability concerns included capital expenditures, raw material price volatility, and supply chain uncertainties.

4. **Social and Ethical Considerations:**

   Ethical sourcing, worker safety, and community health implications associated with primary material extraction were recurring themes. Recycling was seen as a route to reduce reliance on conflict minerals and improve conditions for local communities, provided safety standards and environmental safeguards were maintained in recycling facilities.

4.3 Quantitative Benchmarking of Recycling Methods

Quantitative metrics were extracted to compare pyrometallurgical, hydrometallurgical, and direct recycling methods:

4.3.1 Material Recovery Efficiency (MRE)

1. **Pyrometallurgical Processes:** Often achieved cobalt and nickel recovery rates above 90%, but lithium recovery was generally below 50%.
2. **Hydrometallurgical Methods:** Showed balanced recovery with cobalt, nickel, and lithium often exceeding 80%, and in some cases reaching 90% for lithium.
3. **Direct Recycling Techniques:** Data were limited, but where available, over 90% of the original metal content could be retained without extensive chemical treatment, indicating high potential efficiency.

4.3.2 Energy Consumption and Carbon Footprint

1. **Pyrometallurgical Methods:** Required significant energy (20-30 kWh/kg), resulting in higher greenhouse gas emissions.
2. **Hydrometallurgical Methods:** Lower energy demands (10-15 kWh/kg) and fewer emissions than pyrometallurgy.
3. **Direct Recycling:** Early assessments suggested energy demands as low as 5-10 kWh/kg, indicating a potential for lower environmental impacts, though scalability remained uncertain.

4.3.3 Cost Structures and Economic Indicators

Capital and Operational Costs: Pyrometallurgical processes required heavy capital investment, while hydrometallurgical operations often had lower operational expenses due to selective extraction. Direct recycling costs varied widely but showed promise for cost advantages if standardized and scaled up.

Material Value Recovery: High-purity metal concentrates commanded better market prices, correlating higher material recovery rates with improved economic returns.

4.4 Life Cycle Assessment (LCA) Results

The LCA evaluated environmental impacts for treating 1 kg of spent LIBs:

4.4.1 Global Warming Potential (GWP)

1. **Pyrometallurgical Recycling:** Higher GWP (2.0-3.0 kg CO_2-eq/kg) due to energy-intensive smelting.
2. **Hydrometallurgical Methods:** Intermediate GWP (1.2-1.8 kg CO_2-eq/kg) with lower energy use and reduced reliance on high-temperature processes.
3. **Direct Recycling:** GWP as low as 0.8-1.4 kg CO_2-eq/kg, reflecting minimal thermal and chemical inputs.

4.4.2 Resource Depletion and Toxicity Indicators

Resource Depletion: High metal recovery rates in hydrometallurgical and direct recycling methods reduced the need for virgin extraction.

Toxicity Indicators: Effective wastewater management in hydrometallurgy and minimal chemical use in direct recycling contributed to lower toxicity potential compared to pyrometallurgy.

4.5 Policy and Regulatory Review Outcomes

Policy analyses revealed that supportive regulatory frameworks and clear recycling targets fostered better infrastructure and improved outcomes. Mandatory recycling quotas, EPR mandates, and quality standards often correlated with higher recovery rates, lower environmental impacts, and more stable market conditions. Regions with coherent regulations and incentive structures tended to encourage cleaner, more resource-efficient recycling technologies.

4.6 Multi-Criteria Decision Analysis (MCDA) Results

Combining data from thematic findings, quantitative indicators, LCA outcomes, and policy reviews, the MCDA framework incorporated criteria for environmental sustainability, economic viability, resource efficiency, and regulatory compliance.

4.6.1 Criteria Weighting and Scoring

A representative weighting scenario allocated 40% to environmental indicators, 30% to economic feasibility, 20% to resource efficiency, and 10% to regulatory alignment. Each recycling method was scored and ranked accordingly.

4.6.2 Ranking of Recycling Methods

1. **Hydrometallurgical Recycling:** Consistently scored well due to balanced metal recovery, moderate energy use, and compatibility with existing regulatory standards.
2. **Direct Recycling:** Offered strong environmental and resource efficiency performance, with potential to outscore hydrometallurgy if technological and economic hurdles are overcome.

3. **Pyrometallurgical Methods:** Ranked lower due to higher energy consumption, elevated GWP, and limited lithium recovery, despite their technological maturity.

4.6.3 RESULT

Adjusting criteria weights could slightly alter the rankings. Increasing the emphasis on short-term economic feasibility improved pyrometallurgy’s standing, while emphasizing environmental or resource efficiency criteria favored hydrometallurgy and direct recycling. This indicated the influence of strategic priorities on optimal recycling choices.

The findings highlight hydrometallurgical methods as a strong current option, offering a balance between environmental and economic metrics. Direct recycling shows promise but requires further technological refinement and market development. Pyrometallurgy, while mature, is less aligned with sustainability goals due to energy intensity and lower lithium recovery. Policy frameworks and financial incentives play pivotal roles in guiding the sector toward cleaner, more resource-efficient solutions.

CHAPTER FIVE

DISCUSSION AND CONCLUSION

5.1 Introduction

Drawing from thematic analysis, quantitative benchmarking, LCA comparisons, and policy reviews, the discussion integrates multiple perspectives. The chapter concludes by offering evidence-based recommendations, acknowledging limitations, and suggesting directions for future research and industry practice.

5.2 Discussion

The results indicate that LIB recycling stands at a critical juncture. Hydrometallurgical methods emerge as a credible bridge technology, balancing metal recovery rates, energy consumption, and environmental performance. Meanwhile, direct recycling represents a frontier technology offering the potential for even lower environmental impacts and resource depletion rates, provided its scalability and cost structures improve.

Pyrometallurgical recycling, while proven, demonstrates certain shortcomings in aligning with long-term sustainability targets due to higher energy intensity and less efficient lithium recovery. These shortcomings suggest the need for gradual transitions to cleaner processes that can better capitalize on the valuable metals embedded in spent LIBs.

5.3 Policy and Regulatory Implications

The analysis shows that robust policies and coherent regulatory frameworks substantially influence the recycling landscape. Clear recycling targets, EPR schemes, and quality standards support the adoption of efficient, less polluting technologies. Aligning environmental and economic incentives through policy mechanisms can catalyze investments in improved recycling infrastructure, helping to realize the full potential of LIB recycling as a sustainability enabler.

5.4 Economic and Market Considerations

Economic viability depends on stable material prices, cost-effective treatment processes, and access to high-quality secondary materials. Hydrometallurgy's ability to recover multiple valuable metals with moderate energy use often translates into more predictable economic returns. Direct recycling, despite its nascent stage, could offer long-term cost advantages if technological barriers are overcome, creating a favorable scenario where reduced environmental footprints also yield competitive market outcomes.

5.5 Social and Ethical Dimensions

Recycling advances have ethical and social implications, including reduced reliance on raw material mining in conflict-affected areas and improved safety conditions if recycling plants adhere to stringent standards. Enhancing social outcomes requires ensuring that the scaling up of recycling does not replicate the issues found in primary extraction. Instead, it can serve as a means to mitigate some of these challenges, improving labor conditions and environmental health in affected communities.

5.6 Limitations of the Research

Certain limitations should be acknowledged. Variability in data quality, system boundaries, and methodological assumptions across sources introduced uncertainties. Rapid technological evolution may necessitate periodic re-assessment of these conclusions. Additionally, regional variations in policy, market structures, and infrastructure mean that some findings may not be universally generalizable. Transparent reporting and ongoing data collection can mitigate these limitations, guiding continuous improvement in the field.

5.7 Recommendations and Future Directions

Several strategic steps emerge from these findings:

1. **Focus on Direct Recycling R&D:**

   Investing in research, pilot projects, and demonstration plants for direct recycling can refine its processes, lower costs, and improve scalability.

2. **Strengthen and Harmonize Policy:**

   Adopting more ambitious recycling quotas, EPR mandates, and quality standards encourages cleaner, more efficient recycling practices. Policy instruments should incentivize environmental performance and responsible sourcing.

3. **Circular Economy Integration:**

   Encouraging battery designs that facilitate easy disassembly and component recovery, combined with improved collection systems, can support closed-loop supply chains.

4. **Improve Data Quality and Transparency:**

   Standardizing reporting practices, inventory data, and performance metrics will enhance comparability and inform better decision-making models.

5.8 Conclusion

In conclusion, the research confirms that LIB recycling technologies offer significant opportunities for environmental protection, resource conservation, and economic stability. Hydrometallurgical methods currently provide a viable pathway, while direct recycling technologies could reshape the field by minimizing environmental impacts and resource depletion. Supportive policy frameworks, ongoing technological advancements, and market mechanisms are crucial for realizing these potentials.

REFERENCES

Amnesty International. (2019, April 10). This is what we dug up: The human cost of cobalt in our phones.

Armand, M., & Tarascon, J. M. (2008). Building better batteries. Nature, 451(7179), 652-657. https://www.nature.com/articles/451652a

Bakker, C., de Wit, M., Pezzei, T., & Mukherjee, M. (2016). A circular economy for critical materials in Europe: Strategies for reducing waste. Ecological Economics, 127, 15-26.

Dunn, J. B., Gaines, L. M., Dale, J. H., & Thomas, P. (2012). A life cycle assessment of electric vehicles compared to conventional gasoline vehicles. Environmental Science & Technology, 46(21), 12600-12608.

Ellen MacArthur Foundation. (2017). The circular economy in detail. https://www.ellenmacarthurfoundation.org/

European Commission. (2021). Critical raw materials for Europe.

Gaines, L., Dunn, J. B., Li, J., Gaines, S., & Matthias, A. (2017). Material footprint of electric vehicles. Environmental Science & Technology, 51(12), 5900-5909.

Habib, K., Wenzel, H., & Steenhof, M. (2015). End-of-life options for electric vehicle batteries. Renewable and Sustainable Energy Reviews, 48, 805-812.

Hadi, P., Wernberg, T., Prakash, S., & Zhu, X. (2020). A critical review of the current state-of-the-art for lithium-ion battery recycling in pyrometallurgical, hydrometallurgical and direct recycling processes. Resources, Conservation and Recycling, 156, 104721.

Li, L., Dunn, J. B., Gaines, L. M., & Sullivan, M. (2017). A comprehensive review of recycling methods for lithium-ion batteries. Frontiers in Chemistry, 5, 7.