A Framework for Sustainable Lithium-Ion Battery Recycling Facilities, Vol 1

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ABSTRACT

Addressing the dual challenges of escalating demand for Lithium-Ion Batteries (LIBs) and the critical need for sustainable end-of-life management, this study proposes a novel framework for the design, construction, and operation of LIB recycling facilities grounded in circular economy principles. Through an integrative approach that combines life cycle analysis, sustainable architectural practices, and innovative recycling technologies, we offer a comprehensive solution to enhance the environmental, economic, and social sustainability of LIB recycling. Our framework emphasizes the importance of advanced material recovery techniques, the application of green building standards, and the integration of stakeholder engagement processes to ensure operational transparency and community involvement. By synthesizing insights from multiple disciplines, this research underscores the potential of sustainable LIB recycling facilities to contribute significantly to resource conservation, pollution reduction, and the transition towards a more sustainable and circular global economy. The findings highlight the pivotal role of policy support, technological innovation, and cross-sector collaboration in realizing the full potential of LIB recycling as a key component of sustainable development and environmental stewardship.

Keywords Circular Economy, Sustainable Recycling, Lithium-Ion Batteries, Facility Design, Environmental Impact, Resource Efficiency, Life Cycle Analysis, Green Building Practices, Battery recycling facilities.

“We are all living together on a single planet, which is threatened by our own actions. And if you don't have some kind of global cooperation, nationalism is just not on the right level to tackle the problems, whether it's climate change or whether it's technological disruption.”
Yuval Noah Harari

INTRODUCTION

The advent of Lithium-Ion Batteries (LIBs) has been a cornerstone in the march towards electrification and decarbonization of the global economy. LIBs have become the hub of modern technology, powering everything from portable electronics to electric vehicles (EVs) and stabilizing renewable energy grids. However, the swift rise in LIB usage has precipitated an unprecedented demand for lithium, cobalt, nickel, and other critical raw materials, intensifying the need for efficient recycling methods to mitigate the environmental impact of their disposal and ensure a sustainable supply chain.

The environmental implications of LIB disposal are multifaceted, holding not only the loss of valuable materials but also the risk of hazardous waste generation. Economically, the increasing demand threatens to outstrip the supply of critical minerals, highlighting the necessity of recycling to reduce dependence on virgin materials. Socially, the lifecycle of LIBs encompasses issues ranging from labor practices in mineral extraction to health and safety concerns in waste management. Our paper sets out to bridge the gap between the burgeoning demand for LIBs and the sustainable management of their end-of-life. By articulating a comprehensive framework for the design, construction, and operation of LIB recycling facilities, it aims to demonstrate how sustainability principles can be integrated into every stage of the recycling process.

The objectives of this research are to evaluate the current landscape of LIB recycling practices, to propose a sustainable framework that encompasses environmental, economic, and social dimensions, and to explore the implications of this framework for the future of LIB recycling. Through this study, we seek to inform and inspire stakeholders across the value chain, from policymakers to industry leaders and consumers, to adopt and advocate for sustainable practices in LIB recycling.

BACKGROUND AND LITERATURE REVIEW

The imperative to recycle Lithium-Ion Batteries (LIBs) arises from both an environmental stewardship perspective and a strategic material recovery viewpoint. Current LIB recycling technologies predominantly fall into three categories: pyrometallurgical, hydrometallurgical, and direct physical processes. Pyrometallurgical methods involve high-temperature processes to smelt batteries and recover metals, whereas hydrometallurgical processes use aqueous solutions to dissolve and selectively recover battery materials. Direct physical recycling methods focus on disassembling and directly recovering and refurbishing battery components.

A review of existing LIB recycling facilities reveals a heavy reliance on pyrometallurgical processes, given their relative simplicity and the maturity of the technology. However, these methods often result in lower recovery rates for critical materials such as lithium and can have a higher environmental footprint due to the energy-intensive nature of smelting operations. Hydrometallurgical and direct recycling methods, while more complex, offer the potential for higher material recovery efficiencies and less environmental impact, but they are less widely adopted due to technological and economic barriers.

Currently, there are several gaps and challenges in present LIB recycling practices. Primary among these is the economic viability of recycling operations, heavily influenced by the fluctuating prices of raw materials and the cost of recycling processes. Additionally, the lack of standardization in LIB designs complicates recycling efforts, as does the safe handling of batteries, which can pose fire and explosion risks. From an environmental perspective, current recycling methods can generate significant waste and emissions, underscoring the need for more sustainable practices.

Remarkably, sustainability frameworks in similar industries, such as the electronics recycling sector, offer valuable lessons for LIB recycling. These frameworks emphasize the importance of designing products for recyclability, establishing robust collection, and recycling networks, and adopting closed-loop recycling processes to minimize waste and maximize material recovery.

THEORETICAL FRAMEWORK FOR SUSTAINABLE LIB RECYCLING FACILITIES

To address the challenges identified in the literature and harness the lessons from similar industries, this paper proposes a theoretical framework for sustainable LIB recycling facilities grounded in the principles of the circular economy. This framework is built on three pillars: sustainable design and construction practices, operational sustainability in recycling processes, and the integration of circular economy principles.

Sustainable Design and Construction Practices: The framework advocates for the sustainable design and construction of recycling facilities, incorporating green building materials, renewable energy sources, and energy-efficient designs. Facilities should be strategically located to minimize transportation emissions and designed to optimize material flow and recycling efficiency. Water management systems, waste reduction measures, and emissions control technologies are also critical components of sustainable facility design.

Operational Sustainability in Recycling Processes: Balancing economic viability with environmental and social considerations in the adoption of recycling methods is vital. This includes prioritizing hydrometallurgical and direct recycling processes where feasible, implementing safe handling and storage practices for batteries, and ensuring transparency and fairness in labor practices. Additionally, the framework highlights the importance of continuous improvement and innovation in recycling technologies and processes, as well as the engagement of stakeholders across the recycling value chain to promote shared accountability for sustainability.

Circular Economy Principles Applied to LIB Recycling: At the center of the framework is the application of circular economy principles, which advocate for the minimization of waste and the maximization of resource efficiency. This involves designing recycling processes that enable the highest possible recovery rates of critical materials, promoting the use of recycled materials in new batteries, and fostering innovation in recycling technologies to improve efficiency and reduce environmental impact.

By synthesizing these elements into a cohesive framework, this paper aims to chart a course toward more sustainable LIB recycling facilities that not only contribute to the conservation of critical materials but also align with broader environmental and social sustainability goals.

DESIGN CONSIDERATIONS FOR LIB RECYCLING FACILITIES

The architecture and design of Lithium-Ion Battery (LIB) Recycling Facilities are pivotal in realizing sustainability goals. These facilities require meticulous planning and strategic design considerations to minimize environmental impacts, enhance energy efficiency, and promote resource conservation. The following sections outline key design considerations:

Site Selection and Facility Layout for Optimal Environmental Impact:
When selecting a site for a lithium-ion battery (LIB) recycling facility, it is crucial to prioritize locations that minimize environmental and social impacts while enhancing logistical efficiency. Ideal sites are those close to LIB supply sources, such as urban centers or manufacturing hubs, to cut down on transportation emissions, thereby contributing to the reduction of the facility's overall carbon footprint. Additionally, it is essential to assess the environmental sensitivity of potential locations, steering clear of areas rich in biodiversity or high ecological value to avoid disrupting natural habitats. Comprehensive risk assessments are vital to identify and tone down potential hazards inherent in battery recycling, like fire risks and chemical spills, ensuring both community safety and environmental preservation. Moreover, the facility's layout should be meticulously planned to streamline material flow, decrease energy consumption, and promote safe and efficient recycling operations. This involves optimizing the arrangement of processing stages to reduce transit distances within the facility and incorporating designated safety zones, thereby enhancing operational efficacy and safeguarding both workers and the surrounding environment.

Utilization of Green Building Materials and Technologies:
In constructing lithium-ion battery (LIB) recycling facilities, prioritizing the utilization of green building materials and technologies is essential for minimizing environmental impact. This involves selecting sustainable building materials like recycled steel, sustainably sourced timber, and low-emission concrete alternatives, alongside embracing innovative bio-based materials for insulation and mycelium-based products for packaging and interior applications. Such materials are chosen for their low environmental footprint, including those with recycled content, rapidly renewable resources, and those sourced from sustainably managed forests. Furthermore, integrating architectural designs that enhance the use of natural light and promote effective natural ventilation plays a crucial role in reducing the reliance on artificial lighting and mechanical ventilation systems. This holistic approach not only underscores a commitment to environmental sustainability but also contributes to the creation of healthier, more energy-efficient recycling facilities.

Traditional Material	Proposed New Material	Benefits
Steel	Recycled Steel	Lower carbon footprint, reduced waste
Convention Timber	Sustainably sourced Timber	Reduces deforestation, biodegradable
Concrete	Low-emission Concrete Alternatives	Reduced CO2 emissions during production

Energy Efficiency and Renewable Energy Integration:
Adopting energy-efficient design principles is essential in the development of lithium-ion battery (LIB) recycling facilities, with strategies including the use of high-performance insulation, windows engineered for energy savings, and reflective roofing materials that substantially reduce the need for heating and cooling. Furthermore, the integration of renewable energy sources, exemplified by the installation of solar photovoltaic panels on rooftops or wind turbines nearby, ensures the facility's operations are powered in an eco-friendly manner. Solar parking canopies offer a dual benefit of vehicle protection while generating clean energy. Moreover, the application of smart building technologies exemplifies modern energy management, employing systems such as automated controls for lighting, heating, ventilation, and air conditioning (HVAC), alongside energy monitoring systems. These smart technologies not only optimize energy consumption across the facility but also pave the way for a more sustainable and efficient operational model.

Water Management and Waste Reduction Strategies:
Designing Lithium-Ion Battery (LIB) Recycling Facilities with sustainability at the forefront necessitates a comprehensive strategy that spans across water efficiency, waste management, and the safe handling of hazardous materials. Integrating water-efficient technologies such as rainwater harvesting systems for non-potable purposes, employing water-saving landscaping practices, and incorporating closed-loop water recycling within the manufacturing processes exemplify a commitment to conserving water resources. Additionally, minimizing waste through the thoughtful design of facilities that promote the segregation and recycling of waste materials plays a critical role in reducing landfill dependency. Strategies focused on the reduction, reuse, and recycling of operational waste further underscore this commitment. Moreover,

addressing the challenge of hazardous waste generated during the recycling process is paramount; developing designated areas equipped for the safe storage and handling of such materials is essential in preventing environmental contamination.

CONSTRUCTION STRATEGIES FOR SUSTAINABILITY

Minimizing Carbon Footprint During Construction and workers well-being:
Employing energy-efficient machinery and electric-powered tools, alongside solar-powered temporary structures, and LED lighting, is essential for reducing emissions. Meticulous planning and the utilization of software for optimized material layout and design are instrumental in diminishing waste and excess materials. Moreover, investing in carbon offset projects, like reforestation or renewable energy initiatives, addresses unavoidable emissions, fostering environmental restoration.

Concurrently, prioritizing worker safety and well-being through comprehensive training in safety protocols, regular health and fatigue monitoring via wearable technology, and providing mental health support, ensures a safe and supportive work environment. These combined efforts in resource optimization, carbon offsetting, and the holistic care of workers encapsulate a commitment to sustainability and well-being in the construction phase of LIB recycling facilities, embodying a model for responsible and conscious construction practices in the industry.

COMPLIANCE WITH ENVIRONMENTAL REGULATIONS AND CERTIFICATIONS

In constructing Lithium-Ion Battery (LIB) recycling facilities, a steadfast commitment to environmental stewardship is demonstrated by rigorous adherence to both local and international environmental standards, going beyond mere compliance to embrace best practices that exceed statutory requirements. The pursuit of recognized sustainability certifications, such as LEED, BREEAM, or WELL, plays a pivotal role in not only validating the environmental performance and sustainability of the projects but also in driving the wider construction industry towards greener practices.
Moreover, the establishment of mechanisms for continuous feedback and improvement, complemented by regular audits, assessments, and the renewal of certifications, ensures that sustainability practices are not static but evolve to reflect the latest advancements and insights in sustainable construction. This comprehensive approach underscores a deep-rooted commitment to environmental excellence and the promotion of a culture of continuous enhancement in sustainability efforts.

Operational Sustainability Framework:
Theoperational sustainability framework for Lithium-Ion Battery (LIB) recycling processes encompasses a comprehensive approach aimed at enhancing environmental performance, resource efficiency, safety, and societal impact throughout the battery's life cycle. Here's a detailed overview:

Lifecycle Analysis of LIB Recycling Processes:
Comprehensive Lifecycle Assessment (LCA): Conduct LCAs to identify environmental impacts associated with each stage of the LIB recycling process, from collection to material recovery and reintegration into the production cycle. This assessment should consider energy consumption, emissions, water usage, and potential pollution.

Benchmarking and Improvement: Use LCA results to benchmark against best practices and identify areas for improvement. Prioritize actions that significantly reduce the environmental footprint, such as adopting cleaner technologies or improving logistics to minimize transportation impacts.

Optimizing Resource Efficiency and Recovery Rates:
Advanced Separation Technologies: Implement advanced physical and chemical separation techniques that enhance the purity and yield of recovered materials. Techniques such as hydrometallurgical and bio-hydrometallurgical processes can increase the efficiency of metal recovery while minimizing environmental impact.

Design for Recycling: Advocate for and collaborate on the design of LIBs that facilitate easier disassembly and higher recovery rates of valuable materials. Engage with battery manufacturers to promote design changes that simplify recycling without compromising battery performance.

Resource Recovery Optimization: Develop and utilize software tools and algorithms to optimize resource recovery processes. These tools can help in decision-making related to material sorting, processing pathways, and the allocation of resources to maximize efficiency and economic returns.

Hazardous Waste Management and Safety Protocols:
Hazardous Material Handling: Establish strict protocols for handling hazardous materials found in LIBs, such as lithium, cobalt, and electrolyte solvents. This includes specialized training for workers, the use of appropriate personal protective equipment (PPE), and the implementation of containment measures to prevent environmental contamination.

Emergency Response Plans: Develop and regularly update comprehensive emergency response plans to address potential incidents, including fires, chemical spills, and worker exposure to toxic substances. Conduct regular drills to ensure readiness and efficacy of the response measures.

Regulatory Compliance: Ensure that all operations comply with local and international regulations concerning hazardous waste management. Regular audits and certifications can help maintain high standards of safety and environmental protection.

Community Engagement and Transparency:
Stakeholder Communication: Maintain open lines of communication with stakeholders, including local communities, environmental groups, and regulatory bodies. Share information about recycling processes, environmental and safety measures, and the benefits of LIB recycling.

Public Education and Awareness: Implement programs to educate the public and industry stakeholders about the importance of LIB recycling, how individuals and organizations can contribute to the recycling effort, and the environmental and economic benefits of recovering valuable materials.

Transparency and Reporting: Commit to transparency in operations by regularly publishing reports on recycling rates, environmental impacts, safety incidents, and progress towards sustainability goals. This transparency builds trust with stakeholders and can foster collaborative efforts to improve the sustainability of LIB recycling.

Challenges and Opportunities:
The landscape of Lithium-Ion Battery (LIB) recycling is rapidly evolving, driven by the dual imperatives of environmental stewardship and the efficient use of resources. The economic viability, regulatory frameworks, and technological innovations are pivotal factors that will determine the success and scalability of sustainable LIB recycling facilities. Here's a comprehensive analysis:

Economic Viability and Scalability of Sustainable LIB Recycling Facilities
Economic Viability: The sustainability of LIB recycling hinges on its economic feasibility. Factors such as the market value of recovered materials, the cost efficiency of recycling processes, and the scale of operations significantly influence profitability. Economies of scale can be achieved by expanding recycling capacity, which, in turn, reduces per-unit costs and enhances economic viability.

Scalability: For LIB recycling to be scalable, it must adapt to the growing volume of end-of-life batteries. This requires investments in technology to improve processing efficiency and capacity. Partnerships between battery manufacturers, recyclers, and automotive companies can facilitate a steady supply of recyclable materials and ensure a closed-loop supply chain, contributing to scalability and sustainability.

Regulatory and Policy Implications
Regulatory Frameworks: Effective regulatory frameworks are crucial for fostering a conducive environment for LIB recycling. Policies that mandate battery recycling, extended producer responsibility, and standards for recycled content in new batteries can drive the industry forward.

Incentives and Subsidies: Government incentives and subsidies for sustainable recycling practices can lower the entry barriers and stimulate market growth. Financial incentives for R&D in recycling technologies, tax breaks for recycling facilities, and subsidies for using recycled materials can encourage investment in this sector.

International Collaboration: Given the global nature of the battery supply chain, international collaboration on regulations and standards can help harmonize efforts and ensure efficient recycling practices worldwide.

The Role of Innovation and Technology in Enhancing Sustainability
Innovation in Recycling Processes: Technological innovation is the backbone of sustainable LIB recycling. Advances in separation technologies, material recovery processes, and purification techniques can enhance efficiency, reduce costs, and minimize environmental impacts.

Battery Design for Recycling: Innovation isn't limited to recycling processes; it also extends to battery design. Developing batteries with recycling in mind can simplify disassembly, improve recovery rates, and reduce recycling costs, significantly impacting sustainability.

Digitalization and Data Analytics: Leveraging digital tools, IoT devices, and data analytics can optimize recycling operations, improve material traceability, and enhance decision-making processes, leading to more sustainable outcomes.

Future Directions for Research and Development

Advanced Material Recovery: Future R&D should focus on improving the recovery rates and purity of recycled materials, reducing the dependency on virgin resources, and closing the loop on battery materials.

Environmentally Friendly Recycling Methods: There's a need for research into less energy-intensive and more environmentally friendly recycling methods. This includes developing non-toxic solvents and processes that have minimal water and air pollution impacts.

Lifecycle Assessments (LCA): Continued research into the lifecycle environmental impacts of various recycling technologies can help identify the most sustainable options and guide industry practices.

Integration with Renewable Energy: Exploring how LIB recycling facilities can be powered by renewable energy sources will further enhance the sustainability profile of the recycling process.

CONCLUSION

The economic landscape of LIB recycling is intricately tied to the development and enforcement of regulatory frameworks that incentivize material recovery and sustainable design. Establishing robust policies that promote recyclability and set global standards for recycled content is paramount. This would not only enhance the economic appeal of LIB recycling operations but also drive the industry towards greater environmental responsibility and social accountability.Technological innovation stands at the core of advancing LIB recycling processes. Our investigation highlights the need for ongoing research and development to refine recycling technologies, improve material recovery rates, and devise battery designs that facilitate easier recycling. Furthermore, employing life cycle analysis tools can offer critical insights into the environmental impacts of various recycling methodologies, guiding industry practices and policy decisions towards more sustainable outcomes.

The role of infrastructure design in enhancing the sustainability of LIB recycling facilities cannot be overstated. By incorporating green building materials, energy-efficient layouts, and leveraging advanced technologies like Building Information Modeling (BIM), these facilities can significantly reduce their carbon footprint and operational waste, setting new standards for industrial sustainability.Engaging stakeholders, including policymakers, industry leaders, and the general public, in the narrative of LIB recycling is essential. Communicating the economic opportunities, environmental benefits, and societal impacts of sustainable recycling practices will foster a broader understanding and support for the circular economy. This collective effort is crucial not only for addressing the immediate challenges associated with battery disposal and recycling but also for contributing to the overarching goal of sustainable development.

In conclusion, the path to sustainable LIB recycling encompasses a collaborative approach across disciplines, emphasizing the importance of innovation, supportive policies, and public engagement. As we navigate forward, embracing the principles of the circular economy will be instrumental in establishing a more sustainable, economically viable, and environmentally friendly framework for managing the lifecycle of lithium-ion batteries. This endeavor is pivotal not only for the LIB recycling sector but also as a model for sustainable practices across industries, paving the way for a future where economic growth and environmental preservation go hand in hand, ensuring a livable planet for future generations.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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