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Renewable Paradox in Sustainable Battery Energy

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Abstract

Introduction/Main Objectives: Explores life cycle assessment (LCA) environmental impact arising growth renewable energy and electric vehicles, increasing battery waste and associated threat of heavy metal (cadmium, lead, mercury) pollution to ecosystems and natural resources.

Background Problems: Intersection renewable energy development and battery waste management problem of hazardous heavy metal contamination. Addresses research question: “How can advanced battery recycling strategies prevent environmental contamination and enhance energy sector sustainability—transforming a potential ‘renewable paradox’ into a systemic solution?

Research Methods: Life cycle assessment (LCA), regulatory review, and analysis of industry recycling practices in both Asia and Africa to comprehensively evaluate

Finding/Results: Reveal that discarded batteries can raise soil and water heavy metal concentrations up to 50-fold, while robust recycling measures substantially decrease carbon emissions and mitigate ecosystem toxicity.

Conclusion: Integrating renewable energy expansion with sustainable battery waste management is critical to ecosystem health. Adoption of circular economy principles and national policy frameworks is shown to significantly reduce environmental risks while supporting a resilient green energy transition.

Keywords: Renewable energy, Battery waste management, Life cycle assessment (LCA), Urban waste, Circular economy

Introduction

Global acceleration of electrification and renewable energy integration has catalyzed an unprecedented reliance on rechargeable batteries, notably lithium-ion architectures, underpinning critical infrastructure in energy storage and electric mobility sectors. The escalating deployment of electric vehicles and large-scale storage arrays has correspondingly precipitated exponential growth of end-of-life battery inventories, intensifying environmental and societal concerns surrounding critical material depletion, waste management, and hazardous emissions. Life cycle assessment (LCA) offers a comprehensive framework to quantify environmental impacts throughout production, utilization, and recycling phases, ensuring the net benefits from recycling and reuse exceed the externalized costs to ecosystems and communities (Au et al., 2025). Global need reflected in the 12 sustainability principles adopted for modern battery development.Leading-edge research underscores that advanced recycling modalities—including direct cathode healing, hydrometallurgical leaching, pyrometallurgical processing, and black mass valorization—substantially enhance the circularity of high-value metals while lowering the lifecycle carbon footprint and diminishing ecosystem toxicity.

Emergent innovations transcend conventional lithium-based chemistries, facilitating the incorporation of bio-derived or polymeric feedstocks, enabling organic battery systems with favorable electro-chemo-mechanical characteristics and diminished reliance on conflict or non-renewable metals (Yang et al., 2022). Persistent barriers include insufficient real-time health data, conservative safety protocols, and systematic underutilization of battery modules during operational use (Gervillié-Mouravieff et al., 2024) Sophisticated diagnostic and state-of-health monitoring technologies, including real-time impedance spectroscopy and machine learning-driven prognostics, optimize operational lifespan and facilitate process-efficient sorting and refurbishment. Nevertheless, the field confronts persistent barriers: economic viability of secondary resource valorization, heterogeneity of spent battery streams, evolving regulatory landscapes, and safety risks associated with hazardous constituents and incomplete data streams (Asakuma, 2023). Conquering these issues necessitates harmonized international policy, integration of multi-sectoral expertise, and deployment of modular, scalable recycling infrastructures to sustainably manage resource circularity, environmental stewardship, and energy system resilience through 2050.

Battery technologies such as lithium-ion and emerging organic systems increasingly utilize recycled inputs, directly reducing dependence on extracted metals and fostering circular economy models in the energy sector. Waste generated by end-of-life batteries poses significant environmental challenges, with polymeric components now forming a major target for advanced recycling and recovery processes. Jeong et al. (2024) demonstrate that recycling methods for polymers—including depolymerization, reprocessing, and upcycling—can be integrated with existing infrastructure, enhancing sustainability throughout the battery lifecycle (Durowoju & Salaudeen, 2022). Addressing these multifaceted challenges requires a multidisciplinary approach, bridging materials science, environmental engineering, and technological innovation, as proposed by Grey et al. (2016). Critically, our understanding of battery health relies on limited operational metrics (current, voltage, temperature, impedance), often resulting in conservative safety thresholds and systematic underutilization of modules, an issue highlighted by Gervillié-Mouravieff et al. (2024). The overarching goal is to develop batteries that remain efficient and sustainable across all lifecycle stages, responding to technical, environmental, and economic imperatives.

Research Methods

Research methods section should present the content analysis procedure for environmental regulation studies in detail and systematically so that it can be reproduced by other researchers and produce consistent findings. This procedure includes the following steps:

1. **Data Collection**: Collect official regulatory documents such as laws, government regulations, policies, and supporting documents related to environmental management from official sources. It may also include relevant news, reports, scientific articles, or other documents.
2. **Data Selection and Screening**: Choose documents that meet the study criteria, for example focusing on specific environmental regulations, a certain time period, or particular geographic area.
3. **Categories and Coding Scheme:** Define the main categories for analysis, such as type of regulation, policy goals, types of sanctions, supervision mechanisms, or environmental impacts regulated. Then develop coding schemes to label each relevant text segment according to these categories.
4. **Data Analysis:**
   - Quantitative analysis involves counting the frequency of codes to identify dominant themes and regulation focuses.
   - Qualitative analysis interprets meanings, relationships between categories, and provides in-depth description of the regulatory content and context.
   - Validation and Triangulation: To minimize bias, conduct intercoder reliability tests involving multiple researchers and triangulate findings with other sources like interviews or different documents.
5. **Reporting:** Compile the analysis results using narratives, tables, and charts to present a comprehensive picture of the content and implications of the environmental regulations.

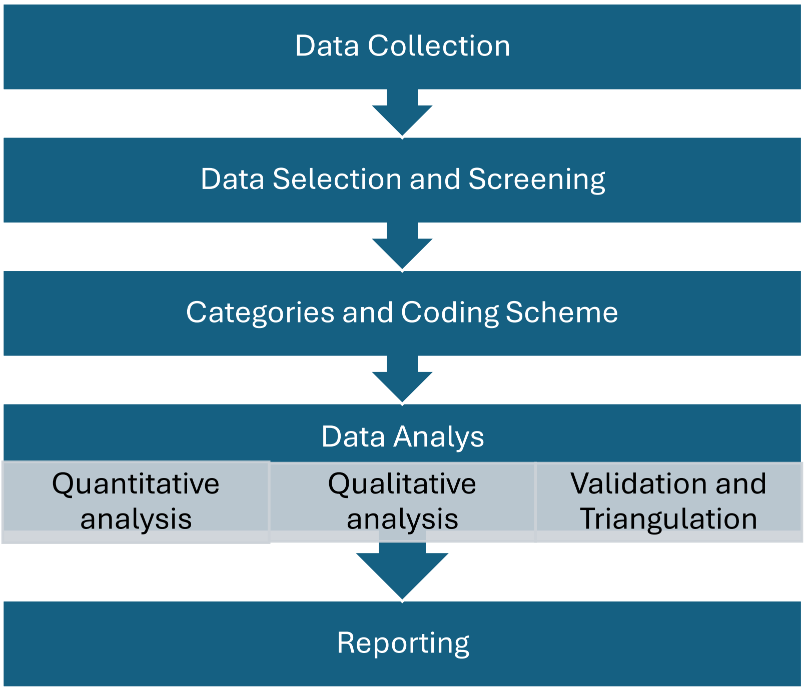

Figure1 Reseach Flow Design
Source: Author's Data, 2025

Discussion

Rapid growth of electrification and renewable integration has made batteries a critical node in global energy systems, but has simultaneously amplified concerns over critical-material depletion, hazardous waste, and lifecycle emissions (Au et al., 2025). Life cycle assessment (LCA) provides a robust framework to evaluate whether advanced recycling routes and reuse strategies genuinely deliver net environmental benefits once upstream extraction, manufacturing, and downstream recovery are accounted for. In this context, Tables 1 and 2 of the EU Battery Regulation operationalize LCA principles at the legal level: Table 1 codifies requirements along each life-cycle stage (from raw material acquisition to end-of-life and recycling), while substance restrictions for mercury, cadmium, and lead in Table 2 directly target high-impact pollutants, constraining their presence in batteries and thereby internalizing part of the environmental externalities.

Table 1 Life cycle stages and the processes system

Life cycle stage	Processes involved
Raw material acquisition and pre-processing	Includes mining and other relevant sourcing, preprocessing and transport of active materials, up to the manufacturing of battery cells and battery components (active materials, separator, electrolyte, casings, active and passive battery components), and electric or electronic components.
Main product production	Assembly of battery cells and assembly of batteries with the battery cells and the electric or electronic components
Distribution	Transport to the point of sale
End of life and recycling	Collection, dismantling and recycling

Source : https://eur-lex.europa.eu, 2025

Table 2 Restriction On Substances

Column 1 Designation of the substance or group of substances	Column 2 Conditions of restriction
1. Mercury CAS No 7439-97-6 EC No 231-106-7 and its compounds	Batteries, whether or not incorporated into appliances, light means of transport or other vehicles, shall not contain more than 0,0005 % of mercury (expressed as mercury metal) by weight.
2. Cadmium CAS No 7440-43-9 EC No 231-152-8 and its compounds	Portable batteries, whether or not incorporated into appliances, light means of transport or other vehicles, shall not contain more than 0,002 % of cadmium (expressed as cadmium metal) by weight.
3. Lead CAS No 7439-92-1 EC No 231-100-4 and its compounds	1. From 18 August 2024, portable batteries, whether or not incorporated into appliances, shall not contain more than 0,01 % of lead (expressed as lead metal) by weight. 2. The restriction set out in point 1 shall not apply to portable zinc-air button cells until 18 August 2028.

Source : https://eur-lex.europa.eu, 2025

Emerging recycling and materials innovations discussed in the literature—such as hydrometallurgical and pyrometallurgical recovery, direct cathode relithiation, polymer depolymerization, and black-mass valorization—find clear regulatory touchpoints in the EU framework. For instance, Jeong et al. (2024) show that polymer recycling streams can be integrated into existing infrastructures, complementing metal-focused recovery and supporting the end-of-life processes mandated in Table 1. At the same time, the calculation of collection rates for portable and LMT batteries (Table 3) translates circular-economy ambitions into enforceable performance metrics, creating incentives for higher return flows of spent batteries and more predictable feedstock for recycling facilities. These mechanisms collectively underpin a shift from linear “take-make-dispose” paradigms toward regulated circular loops (Olusesan et al., 2025).

Labelling, Marking And Information Requirements

Part A: General information on batteries Information on the label of a battery shall comprise the following information regarding the battery: 1. information identifying the manufacturer in accordance with Article 38(7); 2. the battery category and information identifying the battery in accordance with Article 38(6); 3. the place of manufacture (geographical location of a battery manufacturing plant); 4. the date of manufacture (month and year); 5. the weight; 6. the capacity; 7. the chemistry; 8. the hazardous substances present in the battery, other than mercury, cadmium or lead; 9. usable extinguishing agent; 10. critical raw materials present in the battery in a concentration of more than 0,1 % weight by weight.

Part B: Symbol for separate collection of batteries

Part C: QR code The QR code shall be in high contrast to the background colour and of a size that is easily readable by a commonly available QR reader, such as those integrated in hand-held communication

Content-analysis coding framework (Tables 3 and 4) reveals how the regulation embeds multiple governance dimensions beyond purely technical standards. Codes REG01 and REG02 highlight that Regulation (EU) 2023/1542 is not only a product-specific instrument but also a strategic policy tool that formalizes life-cycle and sustainability objectives across the battery value chain. REG03 and REG04 emphasize enforcement architecture: monitoring obligations, collection-rate formulas, and substance limits are paired with the possibility of administrative or financial sanctions at the member-state level, addressing persistent barriers around incomplete data, safety risks, and under-enforced waste rules noted by Gervillié-Mouravieff et al. (2024). REG05–REG07 capture how environmental impacts, public participation, and supporting instruments intersect through labelling, QR-code battery passports, and information duties, which improve traceability, inform consumers, and support market surveillance.

Table 3 Calculation Of Collection Rates For Waste Portable Batteries And LMT Batteries

Year	Data Collection		Calculation	Reporting Requirement
Year 1	Sales In Year 1 (S1)			
Year 2	Sales In Year 2 (S2)			
Year 3	Sales In Year 3 (S3)			
Year 4	Sales In Year 4 (S4)	Collection In Year 4 (C4)	Collection Rate (CR4) = 3*C4/(S1+S2+S3)	(CR4)
Year 5	Sales In Year 5 (S5)	Collection In Year 5 (C5)	Collection Rate (CR5) = 3*C5/(S2+S3+S4) CR5	(CR5)
Etc.	Etc.	Etc.	Etc.	

Source : https://eur-lex.europa.eu, 2025

Table 4. Codes and definitions for content analysis of environmental regulations

Code	Category	Definition
REG01	Type of Regulation	The form of the regulation such as law, government regulation, ministerial decree, etc.
REG02	Policy Objectives	The main goals of the regulation, e.g., emission reduction, waste management, water conservation
REG03	Enforcement Mechanism	Methods for monitoring and enforcing compliance like inspections, penalties, or audits
REG04	Sanctions	Types of sanctions for violations, e.g., fines, license suspension, administrative actions
REG05	Environmental Impact	Specific environmental issues addressed, such as hazardous waste, air pollution, noise control
REG06	Public Participation	Levels and methods of public involvement in the policy-making and implementation process
REG07	Supporting Instruments	Supporting policies or technologies like economic incentives or public education

Source : Reseacher, 2025

Table 4 Integrated framework for content analysis of battery regulation

Code	Category	Example regulatory element (EU Battery Regulation)
REG01	Type of Regulation	Regulation (EU) 2023/1542 on batteries and waste batteries.
REG02	Policy Objectives	Life-cycle approach in Table 1 (from raw material acquisition to end-of-life and recycling).
REG03	Enforcement Mechanism	Calculation and reporting of collection rates for waste portable and LMT batteries in Table 4.
REG04	Sanctions	Non-compliance with substance restrictions for mercury, cadmium, and lead in Table 2 may trigger administrative or financial penalties under national law.
REG05	Environmental Impact	Limits on mercury, cadmium, and lead content in batteries in Table 2; requirements for collection, dismantling, and recycling in the end-of-life stage in Table 1.
REG06	Public Participation	Consumer information via labelling, marking, and QR codes (Part A–C: label content, separate collection symbol, QR code).
REG07	Supporting Instruments	Digital battery passport/QR code, information duties, and traceability tools that support compliance and market surveillance.

Source : Reseacher, 2025

Renewable paradox in sustainable battery energy systems captures the tension between accelerating renewable energy deployment and managing the environmental and social externalities of battery production, particularly lithium extraction (Gurram et al., 2025). This paradox is reinforced by market structures that still privilege fossil fuels, creating situations where the success of renewables can undermine their own long-term growth if supporting institutions and supply chains lag behind (Blazquez et al., 2018; Munonye et al., 2025)). Underlying drivers include liberalized power markets that emphasize short-run marginal costs, environmentally and socially disruptive lithium mining in producing regions (Wolters & Brusselaers, 2024), and climate policies that may inadvertently lock in fossil-fuel extraction pathways (Nachtigall & Rübbelke, 2014). Mitigation therefore requires a multifaceted strategy: circular-economy approaches that prioritize lithium recovery and high-quality recycling streams (Wolters & Brusselaers, 2024); accelerated development of alternative, less resource-intensive battery chemistries (Wilamowska-Zawłocka, 2025); and integrated policy frameworks that align renewable expansion with sustainable resource governance across the value chain (Au et al., 2025). Experiences from environmental management accounting and community-based waste-to-energy projects demonstrate how local governance innovations can complement these macro-level strategies and strengthen accountability for material and energy flows (Junus et al., 2025; Putra et al., 2025; Yang et al., 2022). At the organizational level, robust information systems and asset-management practices are equally critical to monitor lifecycle performance and financial implications of low-carbon technologies (Maharani & Putra, 2024; Putra, 2022, 2024). Together, these strands of evidence suggest that resolving the renewable paradox will depend on tightly coupling technological innovation, circular resource management, and integrative policy design so that economic growth, environmental integrity, and social equity are advanced simultaneously rather than traded off against one another.the introduction.

Combined LCA-based regulatory architecture and the coded content-analysis framework provide a transferable template for other jurisdictions seeking to align battery policy with climate, resource, and industrial strategies. By mapping each article and annex of the EU Battery Regulation onto REG01–REG07 and the life-cycle stages, researchers can systematically compare how different legal regimes approach similar risks, identify gaps (e.g., weak public-participation mechanisms or absent collection-rate targets), and propose evidence-based reforms. This discussion positions the present study within international debates on sustainable battery governance and demonstrates that effective regulation must be co-designed with advances in materials science, diagnostic technologies, and circular-business models to ensure that battery systems remain environmentally sound, socially acceptable, and economically resilient throughout their lifecycle

Conclusion

Reseach is not a magic socket that solves every energy headache. Currently available policy texts and secondary data, which means rapid regulatory changes or proprietary industrial practices may still be hiding offstage. Future work will need to plug into more granular operational data, explore social-justice impacts in mining regions, and test how digital battery passports perform in real supply chains rather than in neat diagrams. Nudge regulators to write smarter rules, firms to treat waste as a resource, and researchers to share better data, then this paper has done its job—quietly helping batteries be a little cleaner, a little fairer, and a lot less paradoxical. Sustainable battery regulation, technological innovation, and circular-economy practices can peacefully coexist without giving policymakers or engineers a nervous breakdown. Well designed rules on hazardous substances, clear life-cycle responsibilities, and transparent labelling can genuinely reduce environmental risks, particularly when combined with advanced recycling technologies and better battery health monitoring. At the same time, the study confirms that the “renewable paradox” is real: pushing for more clean energy while ignoring extraction impacts, data gaps, and skewed market incentives simply moves the problem from smokestacks to mine pits and waste yards.

References

Asakuma, M. (2023). The Paradox of Green Growth: Challenges and Opportunities in Decarbonizing the Lithium-Ion Supply Chain. Archimedes, 107–123. https://doi.org/10.1007/978-3-031-25577-9_6

Au, H., Crespo Ribadeneyra, M., Edge, J., Lander, L., Kendrick, E., & Titirici, M. (2025). Rethinking Sustainable Batteries. Advanced Energy Materials. https://doi.org/10.1002/aenm.202502829

Blazquez, J., Fuentes-Bracamontes, R., Bollino, C. A., & Nezamuddin, N. (2018). The renewable energy policy Paradox. Renewable & Sustainable Energy Reviews, 82(1), 1–5. https://doi.org/10.1016/J.RSER.2017.09.002

Durowoju, E. S., & Salaudeen, H. D. (2022). Advancing lifecycle-aware battery architectures with embedded self-healing and recyclability for sustainable high-density renewable energy storage applications. World Journal Of Advanced Research and Reviews, 14(2), 744–765. https://doi.org/10.30574/wjarr.2022.14.2.0439

Gervillié-Mouravieff, C., Bao, W., Steingart, D.A., & Meng, Y.S. (2024). Non-destructive characterization techniques for battery performance and life-cycle assessment. Nature Reviews Electrical Engineering, 1, 547 - 558. DOI:10.1038/s44287-024-00069-y

Grey, C.P., & Tarascon, J.M. (2016). Sustainability and in situ monitoring in battery development. Nature materials, 16 1, 45-56 . https://doi.org/10.1038/nmat4777

Gurram, S., Seelaboyina, R., & Adarapu, S. (2025). The Double-Edged Sword of Sustainability: Lithium-ion Batteries, Environmental Impacts and Opportunities for Improvement. E3S Web of Conferences, 648, 02003. https://doi.org/10.1051/e3sconf/202564802003

Jeong, D., Kwon, D., Won, G., Kim, S., Bang, J., & Shim, J.-Y. (2024). Toward Sustainable Polymer Materials for Rechargeable Batteries: Utilizing Natural Feedstocks and Recycling/Upcycling of Polymer Waste. Chemsuschem. https://doi.org/10.1002/cssc.202401010

Junus, M., Mustain, A., Putra, I. L., Afrizal, D., Bintang, Z., Rizky, M. A., … Herdiana. (2025). Technology-Driven Community Waste Management Model: Transforming Organic Waste into Renewable Energy. Jurnal Pengabdian Masyarakat, 6(2), 800–807. https://doi.org/10.32815/jpm.v6i2.2834

Manthiram, A., Lutkenhaus, J. L., Fu, Y., Bai, P., Kim, B. G., Lee, S.-W., Okonkwo, E., & Penner, R. M. (2022). Technological pathways toward sustainable batteries. One Earth, 5(3), 203–206. https://doi.org/10.1016/j.oneear.2022.02.010

Maharani, A. S., & Putra, I. L. (2024). Analysis of The Influence of System Quality, Information Quality, Service Quality on Net Benefits in The Finance Billing Management System (FBMS). Journal of Applied Accounting and Taxation, 9(2), 216–223. https://doi.org/10.30871/jaat.v9i2.7412

Munonye, W. C., Ajonye, G. O., Ahonsi, S. O., Munonye, D. I., Chukwuemeka, I. C., & Akinloye, O. A. (2025). Advancing Circularity in Battery Systems for Renewable Energy: Technologies, Barriers, and Future Directions. Advanced Energy and Sustainability Research. https://doi.org/10.1002/aesr.202500255

Nachtigall, D., & Rübbelke, D. T. G. (2014). The Green Paradox and Learning-by-Doing in the Renewable Energy Sector. Social Science Research Network. https://doi.org/10.2139/SSRN.2469746

Olusesan, O. O., Nasir, F. O., Atumah, P. E., Akinlabi, M. A., Olayiwola, D. E., Thanni, A. A., & Adeniyi, S. A. (2025). Life cycle assessment of lithium-ion batteries in utility-scale applications: Impacts on power supply sustainability and grid decarbonization. Global Journal of Engineering and Technology Advances, 24(3), 165–190. https://doi.org/10.30574/gjeta.2025.24.3.0262

Putra, I. L. (2022). Manajemen Pemasaran Dilengkapi Studi Kasus Dan Video Pembelajaran. CV. ALPHA ROCKET NUSANTARA.

Putra, I. L. (2024). Manajemen Aset. CV. Dewa Publishing.

Putra, I. L., Junus, M., Imam, M. K., Rachmah, S., Risdiana, D. M., & Khoiriyah, R. (2025). Environmental Management Accounting Assistance at TPST 3R Mulyoagung Bersatu. Jurnal Pengabdian Masyarakat, 6(2), 410–420. https://doi.org/10.32815/jpm.v6i2.2670

Wilamowska-Zawłocka, M. (2025). Radiochemia na Uniwersytecie Gdańskim. Wiadomości Chemiczne, 79(7–8), 457–484. https://doi.org/10.53584/wiadchem.2025.07.1

Wolters, L., & Brusselaers, J. (2024). The energy transition paradox: How lithium extraction puts pressure on environment, society, and politics. The Extractive Industries and Society, 19, 101498. https://doi.org/10.1016/j.exis.2024.101498

Yang, Z., Huang, H., & Lin, F. (2022). Sustainable Electric Vehicle Batteries for a Sustainable World: Perspectives on Battery Cathodes, Environment, Supply Chain, Manufacturing, Life Cycle, and Policy. Advanced Energy Materials, 12(26), 2200383. https://doi.org/10.1002/aenm.202200383