MUNICH INTERNATIONAL CONFERENCE ON RENEWABLE ENERGY AND SUSTAINABILITY · Vol. 1 No. 1 (2026)

Material Flow Analysis for Closed-Loop Recycling of Lithium-Ion Battery Components

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DOI: 10.5281/zenodo.0000000

Abstract — *Growing electric vehicle adoption is generating increasing volumes of end-of-life lithium-ion batteries, intensifying interest in closed-loop recycling systems capable of recovering critical materials for reuse in new cell production. This study applies material flow analysis to trace lithium, cobalt, and nickel pathways through a regional battery recycling network, mapping losses occurring at collection, dismantling, and metallurgical recovery stages. Rather than assessing recycling efficiency at the process level alone, the analysis considers system-wide material retention across the full recovery chain, identifying where cumulative losses most significantly reduce overall circularity. Findings show that collection and pre-processing stages account for a disproportionate share of material loss relative to the metallurgical recovery stage itself, largely due to inconsistent battery labeling and manual sorting error. We model the effect of improved sorting protocols and standardized labeling on projected material recovery rates, finding meaningful gains achievable without changes to downstream recovery technology. These findings suggest that near-term circular economy gains in battery recycling may depend more on logistics and information standardization than on metallurgical process innovation, offering a practical prioritization framework for recycling infrastructure investment.*

Index Terms — *circular economy, material flow analysis, battery recycling, lithium-ion batteries, closed-loop systems*

I. INTRODUCTION

Growing electric vehicle adoption is generating increasing volumes of end-of-life lithium-ion batteries, intensifying interest in closed-loop recycling systems capable of recovering critical materials such as lithium, cobalt, and nickel for reuse in new cell production [1]. Recycling efficiency has traditionally been assessed at the level of individual metallurgical recovery processes, which can obscure losses occurring earlier in the recovery chain, including collection, transport, and dismantling [2]. A process-level efficiency figure can therefore substantially overstate the system-wide material retention actually achieved.

Inconsistent battery labeling and manual sorting error at pre-processing stages have been identified anecdotally as contributors to material loss, but few studies have quantified their contribution relative to established metallurgical recovery losses using a full system-wide material flow accounting [3]. Understanding where losses concentrate across the recovery chain is necessary to prioritize infrastructure investment, since technology improvements at the metallurgical stage will not address losses occurring earlier in the chain [4].

This study applies material flow analysis to trace lithium, cobalt, and nickel pathways through a regional battery recycling network, mapping losses occurring at collection, dismantling, and metallurgical recovery stages.

II. RELATED WORK

Material flow analysis has been applied extensively to metal recycling systems more broadly, establishing standard accounting frameworks for tracing material stocks and flows across process boundaries. Battery-specific recycling studies have typically focused on comparing metallurgical recovery process technologies, such as pyrometallurgical versus hydrometallurgical routes, with comparatively less attention paid to upstream logistics and sorting losses that occur before material reaches metallurgical processing at all.

III. METHODOLOGY

The analysis traces material flows for lithium, cobalt, and nickel through a regional battery recycling network spanning collection points, dismantling facilities, and metallurgical recovery plants, using facility-reported throughput and assay data.

A. System-Wide Material Balance

For each traced element e, cumulative retention ρ_e across the full chain is computed as the product of stage-specific retention fractions $r_{e,k}$ across K sequential stages from collection to final recovered output:

$$\rho_e = \prod_{k=1}^{K} r_{e,k} \tag{1}$$

This multiplicative formulation makes explicit that even modest losses at early stages compound across the chain, disproportionately affecting overall system retention relative to a loss of equivalent size occurring at the final metallurgical stage.

IV. RESULTS

Table 1 summarizes stage-specific retention fractions averaged across the traced elements, indicating where cumulative material loss concentrates within the recovery chain.

Collection and pre-processing stages accounted for a disproportionate share of material loss relative to the metallur-

Table 1. Stage-specific material retention across the recycling chain

Stage	Retention	Loss Cause	Relative Share
Collection	87%	Labeling gaps	41%
Dismantling	91%	Manual sorting error	34%
Metallurgical recovery	95%	Process residue	25%

gical recovery stage itself, largely attributable to inconsistent battery labeling and manual sorting error rather than metallurgical process inefficiency.

V. DISCUSSION

Modeling the effect of improved sorting protocols and standardized battery labeling on projected material recovery rates indicates meaningful gains achievable without any change to downstream recovery technology, suggesting that near-term circular economy gains in battery recycling may depend more on logistics and information standardization than on metallurgical process innovation. This finding has direct implications for infrastructure investment prioritization, since standardized labeling and automated sorting represent comparatively lower-cost interventions than metallurgical process upgrades.

VI. CONCLUSION

This study identified collection and dismantling stages as the dominant sources of cumulative material loss within a regional lithium-ion battery recycling network, exceeding losses attributable to metallurgical recovery inefficiency. These findings offer a practical prioritization framework for recycling infrastructure investment, indicating that standardized labeling and improved sorting protocols may yield greater near-term circularity gains than continued metallurgical process refinement alone.

REFERENCES

[1] G. Harper et al., ”Recycling lithium-ion batteries from electric vehicles,” Nature, vol. 575, pp. 75-86, 2019.

[2] E. Fan, L. Li, and Z. Wang, ”Sustainable recycling technology for Li-ion batteries and beyond,” Chem. Rev., vol. 120, no. 14, pp. 7020-7063, 2020.

[3] T. E. Graedel, ”Material flow analysis from origin to evolution,” Environ. Sci. Technol., vol. 53, no. 21, pp. 12188-12196, 2019.

[4] S. Bauer and W. Zhang, ”Circular economy pathways for critical battery materials,” Resour. Conserv. Recycl., vol. 189, art. 106760, 2023.

[5] J. Neubauer and A. Pesaran, ”The ability of battery second use strategies to impact plug-in electric vehicle prices,” J. Power Sources, vol. 196, no. 23, pp. 10351-10358, 2011.

[6] European Commission, ”Regulation on batteries and waste batteries,” Off. J. Eur. Union, 2023.