Quantitative Modelling and LCA for Sustainable Lithium-Ion Battery Recycling: Indicators, Bottlenecks, and Policy Implications

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The transition towards a circular economy for lithium-ion batteries (LIBs) requires robust tools to evaluate and guide recycling technologies. This study combines process modelling and environmental assessment to compare pyrometallurgical and hydrometallurgical recycling routes. A quantitative model developed in Python enables a detailed representation of mass and energy flows of two selected processes, while a Life Cycle Assessment (LCA) quantifies environmental impacts. Together, these tools allow a consistent evaluation of technical performance and sustainability trade-offs of recycling LIBs.

The analysis introduces recycling performance indicators (RPIs) and material purity levels to assess the effective recovery of critical elements. These metrics, applied to a range of feed chemistries and formats, reveal significant variations in efficiency and environmental burden. Results highlight the influence of input characteristics on process performance and demonstrate how inconsistent definitions of recycled flows can lead to overestimations in reported recovery rates.

By identifying both technical and environmental bottlenecks, the study outlines key areas for improvement in process design and data reporting. Furthermore, it proposes harmonized criteria for classifying output streams, aiming to support comparability across technologies and regulatory frameworks. This integrated approach provides a replicable methodology for evaluating LIB recycling processes and contributes to the development of more sustainable practices. It also offers decision-making support for industry stakeholders and policymakers engaged in shaping the future of battery value chains.

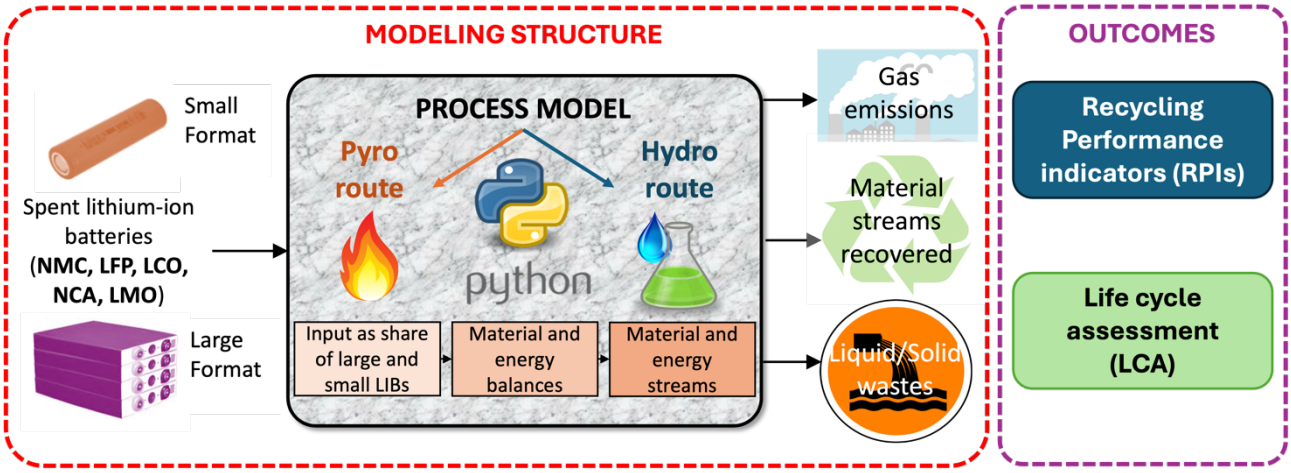

Figure 1 Conceptual diagram of the proposed approach

Keywords: *Lithium-ion battery recycling; Process modelling; Life Cycle Assessment; Pyrometallurgy; Hydrometallurgy; Recycling performance indicators*