Monatshefte für Chemie - Chemical Monthly (2024) 155:309–312
https://doi.org/10.1007/s00706-024-03184-6

ORIGINAL PAPER

Lithium-ion (LCO/NMC, NMC, LFP) battery recycling: partial LCA study

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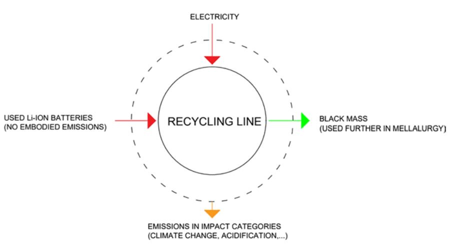
Received: 2 October 2023 / Accepted: 12 February 2024 / Published online: 5 March 2024

Abstract

Recycling lithium-ion batteries (LIBs) have become increasingly important in response to expanding electromobility. This paper is focused on evaluating the environmental impacts (EIs) of recycling pre-treatment of three types of LIBs with black mass as its product. A detailed gate-to-gate Life Cycle Assessment study was conducted to obtain EIs of the recycling process. The benefits of LIBs recycling pre-treatment and significant recovery of secondary aluminum for compared battery types are highlighted in the analysis. This paper points out that the varying chemistry of the compared LIBs does not affect the resulting EIs of the recycling pre-treatment procedures.

Graphical abstract



Keywords Material science · Ecology · Metals · Electrotechnology · Battery · Recycling

Introduction

The expansion of electromobility, especially in the automotive industry, leads to an increasing number of waste electric vehicles and their battery systems. Thus, the necessity of end-of-life (EOL) lithium-ion batteries (LIBs) treatment is set down; valuable materials such as cobalt, nickel, manganese, and lithium, and other essential metals such as aluminum, copper, or iron can be obtained from the recycling of waste batteries.

Reusing secondary materials in new products mitigates the environmental impacts of the sectors within the vehicle industry supply chain. That means, for example, less emission from mining ores and minerals and less energy demand to produce primary materials used in batteries.

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This paper presents the partial gate-to-gate Life Cycle Assessment (LCA) analysis focused on the LIBs recycling pre-treatment evaluation. The environmental impacts (EIs) of recycling three different types of LIBs: lithium cobalt oxide/lithium nickel manganese cobalt oxide (LCO/NMC), lithium nickel manganese cobalt oxide (NMC), and lithium iron phosphate (LFP) were compared. Each battery type contains different inner materials: cathode active materials, electrolyte, separator, cathode aluminum foil, anode copper foil, anode active materials, and housing [1]. The battery recycling pre-treatment process included the following steps: discharging, dismantling, crushing, milling, sieve separation, magnetic separation, and a high-temperature furnace for thermal treatment [2].

The performed study focuses on the recycling pre-treatment procedure, considering black mass as the final output under the conditions of the plant located in the Czech Republic. Black mass (BM) represents shredded materials with a significant valuable metal content (such as cobalt,

Table 1 Environmental impacts of battery recycling

Impact category	Unit	LCO/NMC	NMC	LFP
Climate change	kg CO_2 eq	– 12.882	– 12.861	– 12.859
Particulate matter	Disease inc	– 0.0014	– 0.0014	– 0.0014
Acidification	mol H^+ eq	– 168.588	– 168.503	– 168.494
Resource use, fossils	MJ	– 136.205	– 135.869	– 135.832

manganese, or nickel); it is typically used for further specialized metal recovery based on pyro-/hydro-metallurgy recycling methods [3]. This paper points out that the varying chemistry of the compared LIBs does not affect the resulting EIs of the recycling pre-treatment procedures.

Results and discussion

The functional unit of the LCA study is one ton of produced black mass (BM). To this referring amount, the EIs were counted. In the normalization and weighing phase of the LCA study, the most important impact categories of the Environmental Footprint 3.0 (EF 3.0) method were named. The significant normalized impacts of the recycling process, summarized in Table 1, are in EF 3.0 impact categories:

- Climate change (kg CO_2 eq);
- Acidification (disease inc.);
- Particulate matter (mol H^+ eq);
- Resource use—fossil (MJ).

The total EIs are negative, which signifies the battery recycling benefits. Although the composition of LIBs is different for each battery type, the EIs of their recycling route are nearly equal. There is a maximum of 0.3% nuance between the EIs of each battery type. It comes from the different compositions of each battery type and generated shares of black mass and secondary aluminum. The chemical composition of selected LIBs has a negligible effect on EIs considering recycling pre-treatment.

However, the main advantages of battery recycling are set for obtaining secondary aluminum as it goes with nearly 96% of total EIs. This is due to that recycled aluminum can save up to 95% of energy compared to primary aluminum. The rest comes from obtaining secondary graphite and steel. The production of primary aluminum is highly demanding on electrical energy and ores. Electricity used in the production stage comes in the Czech Republic mainly from fossil fuels [4]. In a nutshell, recovery of secondary aluminum and its further usage can decrease the EIs of this heavy industry.

Conclusion

According to the performed study, the crucial benefit of recycling pre-treatment of different LIBs was determined in gaining secondary aluminum. The main advantage is preventing primary aluminum production, which is highly demanding on energy and metal ores. The negative EIs coming from obtaining secondary aluminum denote the benefits of the recycling stage of LIBs.

This paper points out that the varying chemistry of the compared LIBs does not affect the resulting EIs of the recycling pre-treatment procedures. The follow-up work

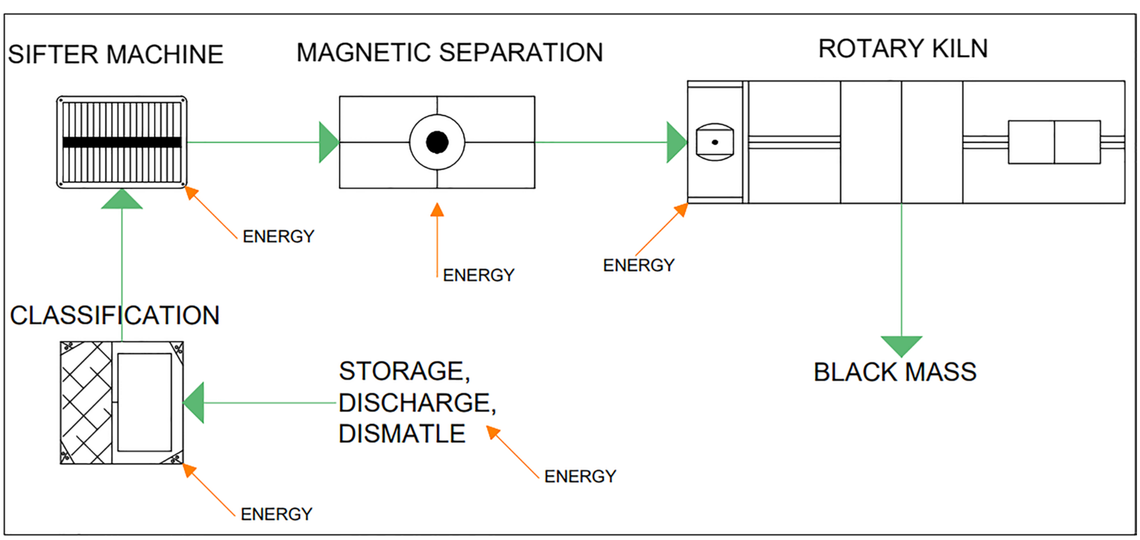

Fig. 1 Recycling pre-treatment process scheme

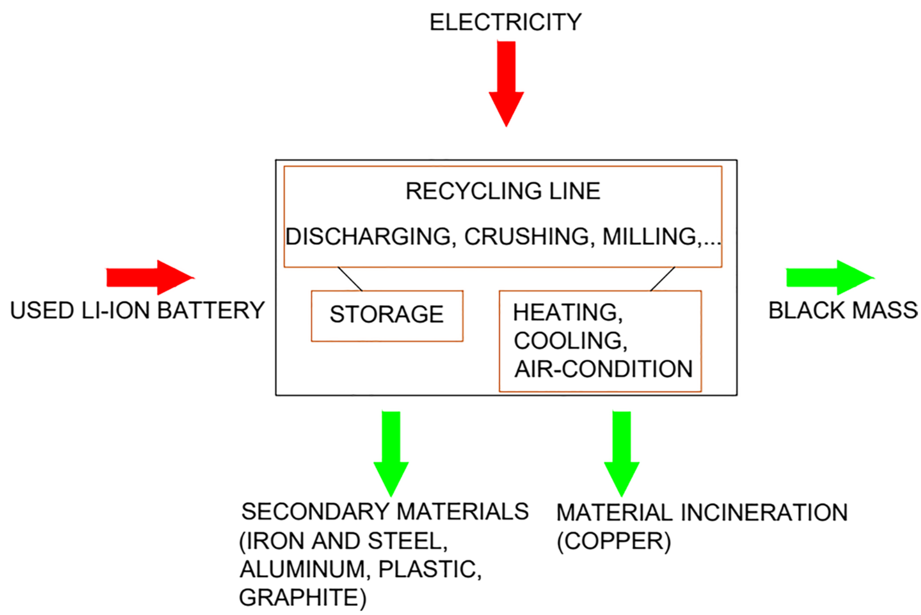

Fig. 2 LCA boundaries and material flows

will focus on the full LCA study comparing recycling pre-treatment routes of consumer electronic batteries to electric vehicle battery packs.

Experimental

The battery recycling pre-treatment process, outlined in Fig. 1, included the following steps: discharging, dismantling, crushing, milling, sieve separation, magnetic separation, and a high-temperature furnace for thermal treatment

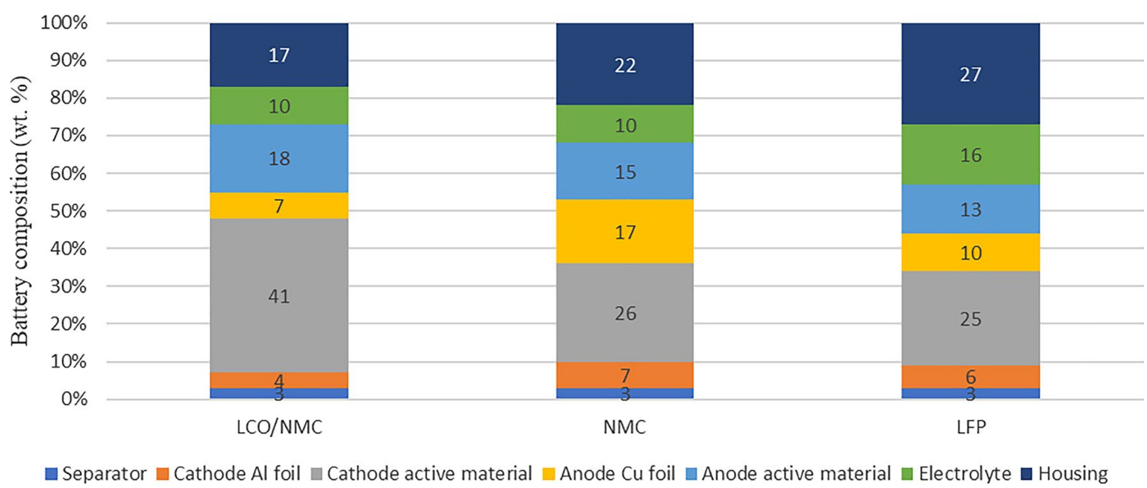

Fig. 3 Material composition of studied battery types

Table 2 Material inventory of recycling pre-treatment process

(In tonnes)	Milling	Sifter machine	Magnetic separator		Rotary Kiln		
Compound	Plastic	Iron/steel	Cu	Al	Electrolyte	Graphite	BM
Treatment	R	R	I	R	I	R	–
LCO/NMC	15.75	89.25	36.75	21.00	52.50	94.50	215.15
NMC	15.75	115.50	89.25	36.75	52.50	78.25	136.50
LFP	15.75	141.75	52.50	31.50	84.00	68.25	131.25

R Recycling, *I* incineration, *BM* black mass

[2]. The evaluated EIs, by a detailed gate-to-gate LCA study, were examined within systems boundaries illustrated in Fig. 2.

Three different types of LIBs for recycling were compared in this work. An annual battery mass of each battery type is considered 525 tons. This refers to the exemplary recycling plant already in operation but with reduced operating shifts [5]. Their material shares (within anode/cathode active materials, electrolyte, separator, copper (Cu)/aluminum (Al) foils, and housing) are specified in detail in Fig. 3 [1] and are used for computation of material inventory in Table 2. As an input, the used LIBs are considered to be with zero embodied emissions.

A detailed gate-to-gate LCA study was conducted via 9.5.0.0 version of SimaPro modeling software using the Ecoinvent 3.9. database with a Cut-off (U) modeling access. The results were evaluated by Environmental Footprint 3.0 (EF 3.0) life cycle impact assessment method.

Acknowledgements This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS23/058/OHK3/1T/13.

Funding Open access publishing supported by the National Technical Library in Prague. This article is funded by České Vysoké Učení Technické v Praze, SGS23/058/OHK3/1T/13, Michael Fridrich.

Data availability The core data for this study were sourced from the licensed Ecoinvent 3.9 database and were transformed based on information from references [1–5].

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