



## Assessing the global sustainability implications of China's lithium-ion battery sector using value chain analysis

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### ABSTRACT

Sustainable supply chain management (SSCM) of critical raw materials (CRMs) is instrumental for the low-carbon transitions. Recent literature has emerged mapping CRMs' physical flows and analysing their current degree of circularity. However, limited research has focused on the understanding of the patterns of value-added creation along the supply chain, as a critical step in assessing long-term sustainability through rethinking how value is retained and created in circular loops. This paper develops a value chain analysis (VCA) model, with a consideration of value retaining processes (VRPs), which combines physical and monetary value flows of lithium (Li) for China's lithium-ion batteries (LIBs) sector. The results indicate that the largest stages of value creation in China's LIBs supply chain are Li chemicals refining and LIBs-powered products production, while an estimated economic loss happens at end-of-life (EOL). Results also highlight three main issues that affect value addition in the whole chain, including: (1) price volatility of upstream raw materials; (2) VRPs conducted at EOL; (3) international trade dynamics in the downstream LIBs and LIBs-powered products. Therefore, targeted policies to enhance CRMs traceability along LIBs value chain and stringent regulatory requirements for EOL recovery are needed to enhance resilience, maintain value, and sustainability. These need to be accompanied by international cooperation to globally address lithium supply chain risks and reduce associated impacts.

### 1. Introduction

The transformation of supply chain management (SCM) towards sustainability is critical and it entails addressing its environmental, social, and economic dimensions (Theeraworawit et al., 2022). A new strand of the literature has looked at the integration of circular economy (CE) strategies and SCM, especially from a triple bottom line (TBL) perspective to improve the sustainability along the supply chain (Carter and Roger, 2008; Seuring and Müller, 2008). Sustainable supply chain management (SSCM) thus is defined as a creation of coordinated actions across supply chains through voluntary integration of economic, environmental, and social considerations to efficiently and effectively manage resource and capital flows associated with the products or services to improve the profitability, competitiveness, and resilience of the organization over the short- and long-term (Ahi and Searcy, 2013). SSCM places the attention not only on how materials are sourced,

transformed through manufacturing processes, used, and then recovered or managed at the end-of-life (EOL), but also on the economic dimensions that motivate and shape material flows towards minimizing potential negative impacts to the environment and society.

Minerals, as inputs to virtually all supply chains (Sauer and Seuring, 2017), and, specifically, critical raw materials (CRMs) are at the core of the green energy and digital transitions. Lithium (Li), in particular, is included in the list of CRMs across regions, such as China, the U.S., and the EU, given its high economic importance and the supply risks associated with the limited reserves, difficulties of substitution and growing demand to fulfil requirements of new green technologies (OECD 2019). In 2023, global Li consumption was estimated to be 180kt and 87 % of Li was used in lithium-ion batteries (LIBs) (USGS, 2024). Global Li demand is expected to increase sharply to 1.3–3 Mt by 2050 to enable the green transition, where electric vehicles (EVs) batteries are the main lithium application (Lähdesmäki et al., 2023). This has raised concerns over the

*Abbreviations:* BEPVs, Battery Electric Passenger Vehicles; CRMs, Critical Raw Materials; EOL, End-of-life; ESS, Energy Storage System; ETW, Electric Two/Three Wheelers; EVs, Electric Vehicles; LCE, Lithium Carbonate Equivalent; LCO, Lithium Cobalt Oxide, LiCoO<sub>2</sub>; LFP, Lithium iron phosphates, LiFePO<sub>4</sub>; LIBs, Lithium-ion Batteries; LMO, Lithium Manganese Oxide, LiMn<sub>2</sub>O<sub>4</sub>; MFA, Material Flow Analysis; NCM, various LiNi<sub>x</sub>Mn<sub>y</sub>Co<sub>z</sub>O<sub>2</sub>; SSCM, Sustainable Supply Chain Management; VCA, Value Chain Analysis; NPs, Net Profits; VRPs, Value retaining processes.

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resilience of Li supply chain, environmental implications of mining and refining stages, as well as the increasing volumes of waste.

Despite recent focus on supply chain evaluation, integrative analyses considering the interdependencies between material and monetary flows from a supply chain perspective are limited. One of the few contributions that provide an integrated assessment of physical flows and value is [Dahlström and Ekins \(2006\)](#), which combined material flow analysis (MFA) with a value chain analysis (VCA) of the UK iron/steel sector. The concept of “value chain” was first introduced by [Porter \(1985\)](#) as a business model to describe integrated activities required to add value in creating a product or service. While earlier literature focused solely on examining how the interaction among different firms and sectors contributed to value added, the use of value chain analysis has broadened significantly to include aspects around material traceability, resilience, governance, and sustainability ([Elvira, 2016](#)).

Only recently, focus has been placed on analysing downstream activities that contribute to preserve value or recover value of products and materials. [The International Resource Pane \(IRP\) \(2018\)](#) defines value retaining processes (VRPs) as activities that aim to preserve the resource value at the end of the first life of a product, including direct reuse, repair, (comprehensive) refurbishment, and remanufacturing. The role of VRPs in moving towards circular flows has been identified as an effective pathway to reduce raw materials requirements through the collection and recovery of valuable products or materials, and, thus, the retention of their embodied and inherent value ([IRP, 2018](#)).

In summary, there is insufficient understanding of CRMs’ circular flows from a whole life cycle perspective combined physical and monetary flows. Therefore, this study aims to fill this gap and contribute to the understanding of the interlinkages between physical and monetary flows in complex CRMs supply chains. Main areas of novelty of the paper are the following: 1) integrating value retaining processes (VRPs) into VCA modelling framework to identify the role of VRPs in promoting effective functioning of secondary markets; 2) creating new datasets, combining both secondary and primary data sources, to be first, to our knowledge, to quantitatively assess both material and monetary value flows of Li in China’s LIBs industry; 3) understanding value variations across the whole life cycle and identifying strategies to maintain or recover resource value at the use and EOL phases; and 4) understanding the physical and value dynamics to design interventions towards enhancing resource supply resilience.

This paper is divided into six sections. [Section 2](#) summarizes the background of LIBs supply chain management and Li value chain mapping in China. [Section 3](#) describes the methodological approach adopted; [Section 4](#) presents findings; and [Section 5](#) discusses main implications derived from findings and explores different policy interventions for addressing challenges associated with SSCM of CRMs. [Section 6](#) presents conclusions and outlook.

## 2. LIBs value chain management from lithium perspective

LIBs are now widely used as clean energy technologies for green mobility. [Fig. 1](#) presents the LIBs value chain from a whole life cycle perspective with a focus on lithium, divided into upstream, production, and downstream processes. In the upstream process, primary lithium minerals are sourced from both domestic deposits and imports. Lithium is then refined into battery chemicals and processed at a large scale, especially lithium carbonate and lithium hydroxide as main battery cathode materials. The next stage is that of production and manufacturing processes focusing on LIBs assembling. The downstream processes cover the end of first life of LIBs-powered products, including consumer electronics, EVs, and energy storage systems (ESS).

Due to the unbalanced geological distribution of lithium reserves, primary mineral supply concentrates mainly in Australia, Chile, and China ([USGS, 2023](#)). In the stages of chemicals refining and battery manufacturing, China plays the dominating role in the supply structure, accounting for two-thirds of global capacity ([GBA, 2023](#)). In the downstream processes, China is also the main player, contributing to half of global EVs production and sales in 2021 ([CAAM, 2023](#); [NBSC, 2023](#)). Since China has formed an integrated supply chain that covers the stages of processing and battery manufacturing and become the world’s largest producer and consumer of LIBs, global Li sustainable supply is highly dependent on disruptions in China ([Cheng et al., 2024](#)).

Prices of materials in the upstream process of China’s LIBs value chain have become increasingly sensitive due to the imbalance of supply and demand associated with risks of Li mineral supply security ([Mauler et al., 2022](#)). The adoption of electric mobility has made lithium prices soar since 2015. Prices for lithium ore, lithium carbonate, and lithium hydroxide showed a significant increase from 2021, after the covid, with their per tonne prices increased nearly ten-fold from \$400, \$8200, and \$7300 respectively in Jan. 2021 to \$5525, \$89,500, and \$86,500 respectively in Dec. 2022. The rising prices of Li chemicals and soaring inflation contributed to raising LIBs manufacturing costs ([Sun et al., 2022](#)). The price of China’s LIBs packs increased from 111 \$/kWh in 2021 to 127 \$/kWh in 2022. The rising costs, however, also led to a sharp decline of battery pre-materials production in 2023 due to the moderate growth and stabilisation of downstream products demand ([Li et al., 2019](#)). Consequently, prices of upstream materials started to decrease. By 1st Jan 2025, price of Li ore has dropped to 840 \$/t, an 85 % drop from its peak, while prices of Li chemicals and battery pre-materials have also fallen by >65 % from their peaks.

Historic price peaks and extreme volatility can massively affect the economic viability of the LIBs supply chain. Shrinking margins could also make some green applications far less attractive than they were previously, which would delay much-needed attempts to accelerate decarbonization ([GBA, 2023](#)). Among the methods used to assess the

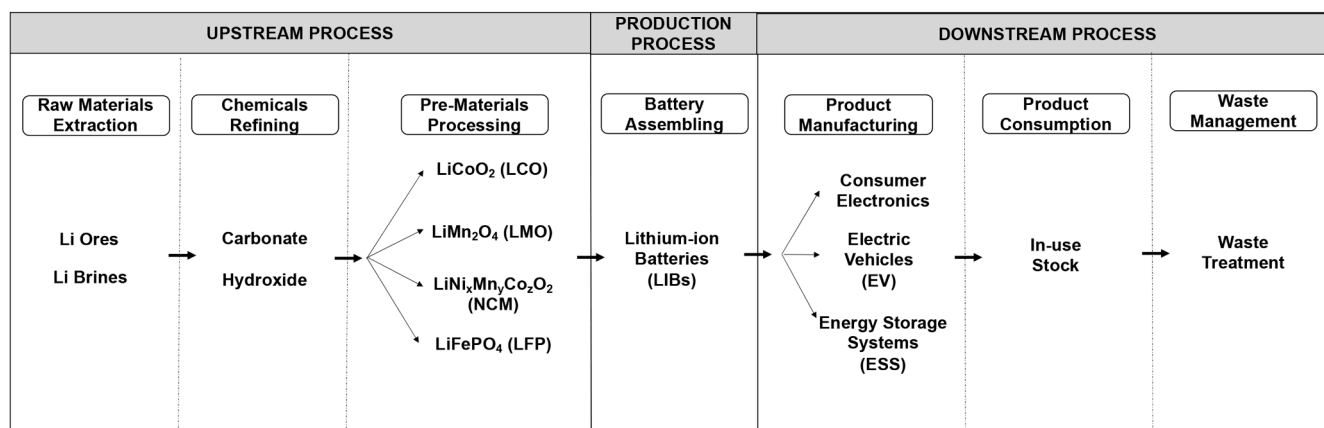


Fig. 1. LIBs value chain from lithium perspective.

resilience of current and future configurations of CRMs supply chains, a widespread one consists in the use of index-based analysis, considering supply risk, economic importance, and environmental risk separately (Dou and Xu, 2022). A large body of literature employs different indicators to evaluate security risks or price volatility of Li supply in primary acquisition stage (SI Table S1). Zhang et al. (2022) and Sun et al. (2023) developed a global supply risk assessment framework for metals used in clean energy technologies, considering technological and economic factors, social and regulatory factors, and other geopolitical factors. Results highlighted that lithium has the highest risk of supply shortage globally and China has the largest supply risk associated to mining governance and policy. Yan et al. (2020) and Yu et al. (2021) used multi-criteria analysis to evaluate Chinese supply resilience of critical metals considering resources availability, economic fluctuations, technology innovation, and import instability, and found that China's Li supply security is moving towards to a higher level of criticality or lower resilience.

Recent studies have also used a combination of supply chain and complex network theory to map supply chain structure and identify potential disruptions in global minerals value chains associated with supply concentration and trade networking (Bam and De Bruyne, 2017; Van den Brink et al., 2020). Shao and Jin (2020) used system dynamic modelling to evaluate China's Li supply-chain resilience, indicating that Li supply is less resilient because of EVs demand growth but pointing to recycling as an optimal strategy to address Li supply risks. Jin et al. (2023) employed an attack model to examine network resilience dynamics of China's Li supply chain, concluding that there has been a stable Li network efficiency from 2017 to 2021 but its resilience will decline. Material flow analysis (MFA) is another important tool in CRMs value chain assessment, which has been widely applied across various resources and countries (Dou and Xu, 2022). Hao et al. (2017) developed the first lithium MFA within the Chinese context. Song et al. (2019) and Liu et al. (2021) developed MFA models of China's LIBs sector and suggested that raw Li supply relies heavily on imports to satisfy LIBs demand and that potentially recyclable Li is found in stocks, while the system exhibits low recycling rates at the EOL stage.

However, analyse of the linkage between material and economic dimensions of resource flows are limited. Following Dahlström and Ekins (2006), Yan and Wang (2014) and Dong et al. (2019) conducted mapping exercises of China's iron and magnesium systems respectively, considering both material and monetary flows, and concluded that material recycling could contribute to resource preservation and value retention. Yu et al. (2019) employed a VCA perspective to analyse the value flow of China's lead-acid battery system, concluding that reducing environmental impacts requires improving battery manufacturing process and increasing recovery rate of secondary lead. Similarly, VCA modelling approaches have been applied to map international trade flows of specific materials, such as iron-containing commodities (Chen et al., 2020) and tungsten-containing commodities (Tang et al., 2022). These studies all point to the need of promoting cooperative approaches between trade partners and to globally improve material management to reduce dissipative losses and pollution.

Despite all these relevant contributions, there is insufficient understanding of CRMs' flows from a combined physical and monetary perspective, adopting the whole life cycle. This study aims to develop a value chain analysis modelling framework, which combines value chain mapping and monetary analysis, to discuss structural changes of value added, detraction, and retaining processes in CRMs' whole supply chain and then identify areas where value dynamics need to be modified towards greater value chain sustainability.

### 3. Methodology

#### 3.1. Value chain analysis (VCA) model

MFA is widely used to assess materials flows and stock changes

within a system defined in space and time (Brunner and Rechberger, 2016). MFA generally records flows in physical units, but a critical element in the transition towards circularity is to be able to generate value from circular loops. Building on MFA, Mao and Lu (2003) proposed the concept of "value level" to identify value-variations of specific elements along a value chain. Combining material and economic dimensions of resource flows into a VCA model is used in this study, to better understand leverage points contributing to value retention from a whole life cycle perspective (Dahlström and Ekins, 2006).

Building on the classical VCA model, this study selects Mainland China as the system boundary, where Hong Kong, Taiwan, and Macau are not included. The baseline year is 2021 when China's economy started to recover from the covid. The analysis tracks material flows across seven stages (Fig. 1), considering lithium density contained in chemicals and products at different stages, which produces variations along value levels at different processing stages. The model therefore enables tracking down the value level of Li along the value chain.

Following Mao and Lu (2003), the analysis departs from the calculation of the assigned monetary value of Li per unit in one commodity  $p$  defined as  $V_{M,p}$  in:

$$V_{M,p} = \frac{V_p}{A_{M,p}} = \frac{V_p}{C_p * R_{M,p}} \quad (1)$$

Where  $V_p$  represents the monetary value of the commodity  $p$ ,  $A_{M,p}$  represents the mass of Li in one commodity  $p$ ,  $C_p$  represents total mass of commodity  $p$ , and  $R_{M,p}$  represents lithium intensity in commodity  $p$ .

Net profits (NPs) per unit in one commodity  $p$ , in terms of Li value level, is defined as  $NP_{M,p}$  in:

$$NP_{M,p} = R_{M,p} - C_{M,p} \quad (2)$$

Where  $R_{M,p}$  and  $C_{M,p}$  represent total revenues and operating costs of one commodity  $p$  respectively.

Given the scope of the study and its focus on Li, the calculation of NPs does not consider further taxes from product dealings and company operations. Subsidy received from the government is also excluded from the scope. This decision has been adopted to minimise the distortion of taxes and subsidy in the calculation of the unit price of the substance Li.

The monetary value of Li reflects variations across product categories and aggregately defines the monetary value flows in the model. To evaluate variations of value along the value chain, the model uses the concept of the incremental value of the whole supply chain ( $\Delta V$ ), following Yu et al. (2019), which is defined as the sum of monetary increase at each stage ( $\Delta V_s$ ). Aggregated value addition of each stage is calculated as the sum of monetary value of the output (including production and exports) minus the monetary value of the input, as shown in Eq. (3) and (4).

$$\Delta V_s = V_{s,pro} + V_{s,ex} - V_{s,im} \quad (3)$$

$$\Delta V = \sum_{s=1}^n (\Delta V_s - \Delta V_{s-1}) \quad (4)$$

Where  $V_{s,pro}$ ,  $V_{s,ex}$ , and  $V_{s,im}$  represent total monetary value of production, export, and import at one stage  $s$  respectively.

This analysis is the first to include value retaining processes (VRPs) in the VCA model to assess their contribution by dividing China's waste LIBs treatment process into three flows. These include: 1) battery repurposing as energy storage; 2) battery recycling and Li recovery, or 3) disposal to the environment. On the basis of this analysis, the study develops different scenarios to estimate the EOL pathways under different assumptions, including changing in collection rates and treatment options, to assess the potential resource and economic benefits associated to VRPs (Table 1). The model assumes no other exogenous losses that are not captured in the model (e.g. dissipative waste from the in-use stock stage) and that all repurposed products or recovered materials meet the necessary quality standards for VRPs. Detailed

**Table 1**  
Scenario description of different VRP applications.

| Scenarios  | BAU<br>Base Condition<br>in 2021 | Scenario 1<br>Decrease Waste<br>Transportation and Disposal<br>Cost | Scenario 2<br>Increase Waste<br>Collection Rate | Scenario 3<br>Improve Waste<br>Recycling Technology | Scenario 4<br>Introduce Waste<br>Repurpose Technology | Scenario 5<br>Best<br>Performance |
|--|----------------------------------|---|---|---|---|-----------------------------------|
| Disposal Rate  | 70 %                             | 70 %  | 0 %   | 70 %  | 70 %  | 0 %                               |
| Landfill Rate  | 50 %                             | 50 %  | 50 %  | 50 %  | 50 %  | 50 %                              |
| Incineration Rate  | 50 %                             | 50 %  | 50 %  | 50 %  | 50 %  | 50 %                              |
| Reduction Rate of Waste<br>Transportation and Disposal<br>Cost | 0 %                              | 52 %  | 0 %   | 0 %   | 0 %   | 52 %                              |
| Collection Rate  | 30 %                             | 30 %  | 100 %   | 30 %  | 30 %  | 100 %                             |
| Repurpose Rate Before Recycling<br>Process                     | 0 %                              | 0 %   | 0 %   | 0 %   | 40 %  | 40 %                              |
| Reduction Rate of Waste<br>Recycling Cost                      | 0 %                              | 0 %   | 0 %   | 25 %  | 0 %   | 25 %                              |
| Li Recycling Efficiency  | 75 %                             | 75 %  | 75 %  | 90 %  | 75 %  | 90 %                              |

description of each scenario is explained in the SI.

The scope of the analysis is mainly concerned with the values of the principal material categories of Li and Li contained products and does not consider costs associated with ancillary and energy inputs or residual output treatments (Dahlström and Ekins, 2006). Overall, by combining material and monetary flows, the study enables the identification of the value variations (creation and detraction) along China's LIBs supply chain and how VRPs could contribute to value retention through different loops of Li repurposing and recovery.

### 3.2. Data collection and data harmonisation

Data for the VCA model is taken from different secondary data sources in both physical (weight in kg) and value (unit in U.S. dollars) for all Li products and Li containing products at each stage of the value chain from mining to disposal. This includes LIBs collection and disposal costs at the EOL (SI Table S2). All monetary data is in nominal terms for the year 2021. Li monetary values are estimated by using lithium metallic content and Li intensity of each product along the value chain (SI Table S3).

Trade data in both physical and monetary terms are collected from the UN Comtrade Database. All trade flows reported by Mainland China (as both importer or exporter) based on 17 Harmonized System six-digit codes (SI Table S3) are included in the model. Unitary trade prices of each commodity are then calculated by dividing total value (\$) by trade quantity (in tonnes).

As for domestic production and sales of different Li products and Li containing commodities, physical data mainly comes from China Nonferrous Metals Yearbook, the U.S. Geological Survey (USGS), and China National Bureau of Statistics. Value data is derived mainly from Shanghai Metals Market (SMM), London Metal Exchange (LME), and China Industrial Statistic Yearbook. As there were no official fixed sales prices of related commodities along the LIBs supply chain in China, this study has developed a dataset collecting primary data from Chinese companies' annual reports. For each products category, product prices are estimated based on published data for 3–10 leading companies selected along China's LIBs value chain, which are representative of the product sector of production scale, market share, and sales stability. Most of the selected companies are listed companies which guarantee a level of accuracy and completeness of the data they present, which has been audited by third parties. Production mass, sales mass, production costs, and sales values of main commodities from each company's 2021 annual report are collected and processed to calculate the unit price/cost of each commodity at each stage of the value chain.

As for the waste battery treatment stage, some adjustments are required due to the availability of data. Values of EOL LIBs treatment collected from Chinese companies include not only recovered Li but revenues from all recycled CRMs. Based on the data collected from the

selected companies' annual reports, more than half of the economic benefits come from cobalt (Co) recovery, a quarter from nickel (Ni) recovery, while Li recovery accounts for a relatively small proportion of <20 %. There is also limited data for the specific waste LIBs collection and disposal costs in China at present and, thus, this study uses average costs of electronic waste disposal as a proxy, as it's not expected that CRMs contained in EOL products which are not segregated will vary significantly from other types of mixed electronic waste collection and disposal costs.

Moreover, this study uses the average price of LIBs-related products over the course of the year 2021 as a stable price to avoid the impact of extreme short-term price spikes on the model. This approach can help to better analyse the overall structure and focus on the value distribution across the whole battery supply chain, without distortion from transient market fluctuations.

A summary of the primary datasets created in this study is shown in the Appendices.

### 3.3. Data uncertainty and sensitivity analysis

The construction of the VCA model requires gathering and harmonizing data from different sources, and thus reconciliation processes have been undertaken. Given that different sources vary in terms of data comprehensiveness and quality, data limitations and analytical uncertainties are inevitable and have been assessed as part of data uncertainty analysis. Following Liu and Domenech (2024), this study adopts the uncertainty analysis framework to qualitatively assess each data input based on the following five indicators: source reliability, completeness, temporal correlation, geographical correlation, and other correlation. Each individual indicator is calculated to derive uncertainty ranges (Laner et al., 2014). The criteria for each indicator is described by Laner et al. (2016), as shown in SI Table S4. The result, as illustrated in SI Table S5, shows that uncertainties affecting commodity cost/prices come from three main areas: market price volatility of upstream primary lithium and Li chemicals, dynamic markets of LIBs-powered products consumption, as well as uncertainties arising from gaps in spent battery traceability and EOL treatment.

To reflect the volatility of Li prices, this study also performs sensitivity analysis to assess how changes in Li prices could affect the value addition/reduction across the whole life cycle of LIBs sector, considering (a) changes of market prices of upstream raw materials; (b) impacts of external costs/benefits to products; and (c) international trade risks of LIBs and downstream products. Detailed explanations and description of the findings are shown in the SI, and results (SI Table S9) will be further discussed in the following sections.

### 4. Results

The primary aim of this paper is to look in more detail at the evolution of Li along the value chain and identify ways to preserve value associated with CE strategies. All units of value are expressed as lithium metal equivalents unless otherwise specified.

#### 4.1. Li value level across China's LIBs value chain

Using the concept of the value level, value levels of Li within principal Li-containing commodities in 2021 were calculated for China's domestic market (a) and trade (b). Generally, as Li moves along the value chain, being refined and further processed, its value level increases. Fig. 2 presents the unit value calculated as the value of Li embodied in Li-containing commodities. In 2021, domestic value levels of Li in Li-containing commodities increased from 17–28 \$/kg at the raw material extraction stage to 1500–8500 \$/kg at the final product consumption stage, indicating a significant value-addition along the value chain. As one would expect, as the technical properties of the material and the complexity of the products increases, the value level of lithium in those commodities also increases. At the waste management stage, however, the value level of the material drops sharply due to the associated costs of collection and treatment at the EOL. Waste batteries that are not collected by recycling companies would enter landfill or incineration routes, resulting in a negative Li value level (−26 \$/kg in 2021) due to the additional disposal costs. For those EOL LIBs following formal recycling processes, the value level of Li at this stage could increase to 230 \$/kg through CRMs recovery and product repurposing.

From the value analysis of international trade, China's imports of Li-containing products showed a very high Li value level. On the other hand, the average export Li value level is relatively low (Fig. 2(b)). This is evident in the EVs segment, where the value level of imports is substantially higher than the unit level of exports. In 2021, the average unit

value of EVs imports was 6230 \$/kg, but that of exports was only 2431 \$/kg, accounting for <40 % of imports. The disparity may be related to the brand, technical specifications, and added-value processes (including design), which forms the basis of the global market. Another factor may be the adjustment for export subsidies applied in China. In 2020, the State Taxation Administration of China increased the export tax rebate rate for products to promote the stability of international trade. According to the latest "Export Tax Refund Rates Library Version" (STAC, 2023A), the export tax rebate rate for LIBs and LIBs-related chemicals increased to 13 % and 16 % respectively to reduce relative export costs from China to the rest of the world, which in turn led to a decrease of the exports unit price.

#### 4.2. Value-added analysis along China's LIBs supply chain

Based on the analysis of main public companies for each value chain stage, the results show significant variations in net profits (NPs) of lithium and lithium contained products across the value chain in China. Fig. 3 shows the NPs of key commodities manufactured and sold in China across the LIBs value chain in 2021, in terms of Li value level.

The lowest positive NPs (around 1.33 \$/kg) in 2021 happened at the raw lithium production stage in China. This is mainly explained by the nature of the reserves and the high cost of current predominant extraction methods based on crushing, roasting and sulfuric acid leaching for extracting Li from ores (Gao et al., 2023), resulting in energy costs which accounted for half of total costs. The NPs at the chemical refining stage are higher, since most leading companies have integrated advanced refining technologies with associated lower labour and energy cost. Variations in NPs at this stage depend heavily on material sourcing and the types of Li reserves used. The lowest NPs (6.75 \$/kg in 2021) are recorded for a company that acquired raw materials from spodumene in Sichuan, while the highest NPs (72.48 \$/kg in 2021) are obtained when using Li from brines in Qinghai, reaching a gross

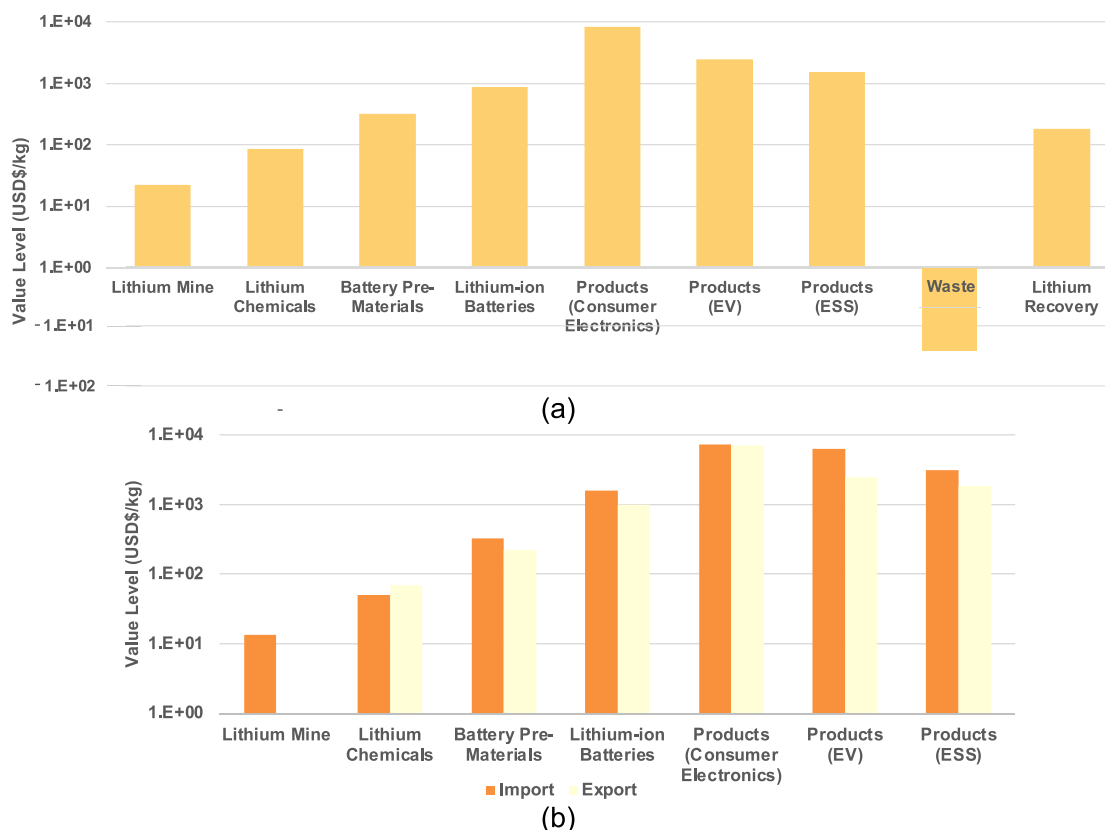


Fig. 2. Li Value level across China's LIBs value chain in (a) domestic and (b) international trade situation, 2021.

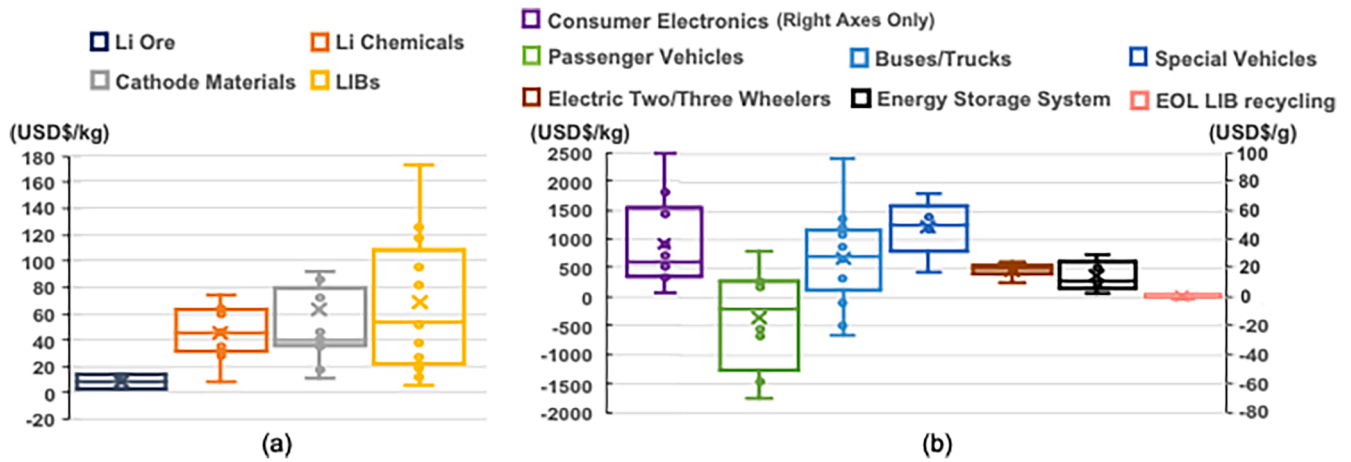


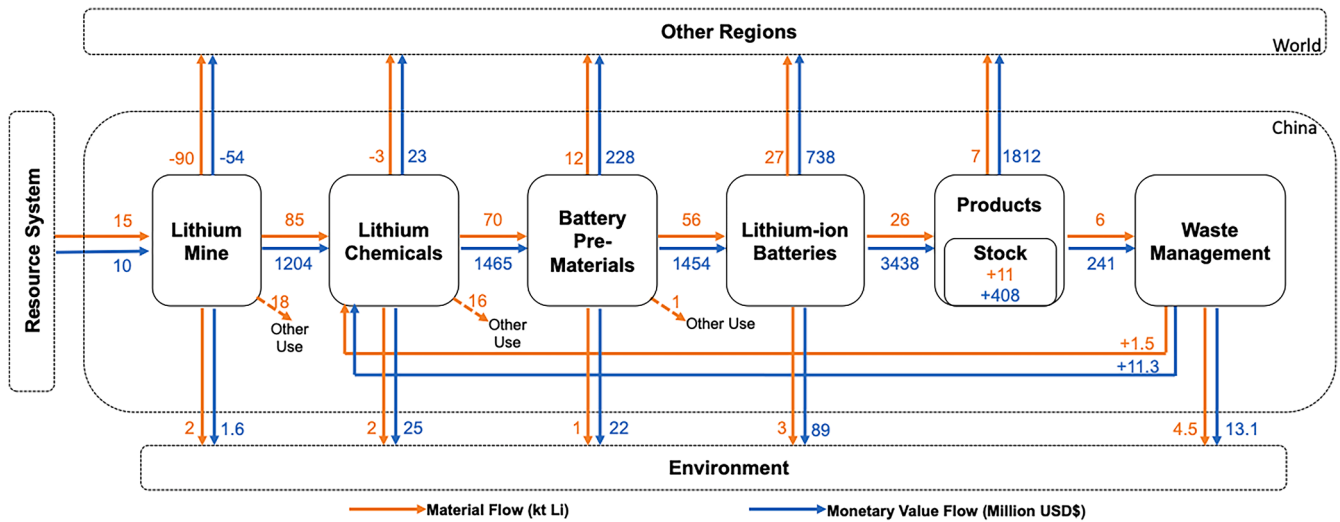
Fig. 3. Range of value-added at each stage in (a) upstream and (b) downstream processes of China's LIBs value chain, 2021.

margin of 70 %.

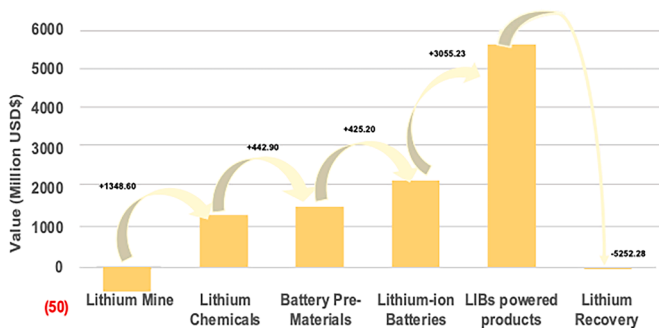
The level of NPs at the cathode materials production stage provides a gross margin of around 10–15 %, as current production in China concentrates on LCO and LFP batteries. The production of high-Ni NCM cathode shows the highest NPs (90.93 \$/kg in 2021), indicating the potential of new battery chemistries for increasing profit levels at this stage. Competition in China's LIBs industry has increased, especially in the production of power batteries, with a large disparity in net profit among existing companies. In particular, the highest NPs of NCM batteries were 170.92 \$/kg higher than that of smaller manufacturers in

2021. Consumption of batteries used in emerging fields, such as energy storage and true wireless stereo (TWS) technology, also provided higher NPs at this stage.

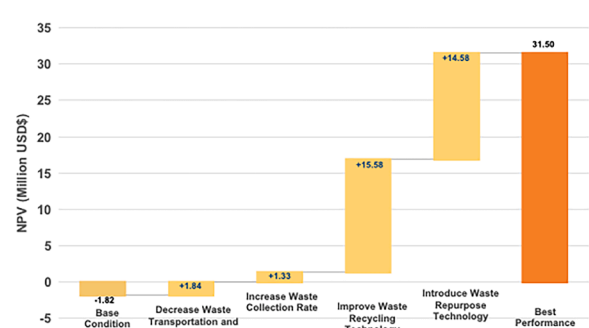
The NPs at the final product consumption stage vary greatly across market segments, but are, in general, at a low margin stage given the intense competition across Chinese brands in a highly globalized market. For example, the highest NPs for Chinese brands in the consumer electronics segment were 98.62 \$/g in 2021, but only a third of Apple's NPs in China (378 \$/g). In China's EVs market, similarly, the NPs of the top-selling Chinese brands were relatively low (782.98 \$/kg) in 2021,



(a) Results for Li material and value flows in China's LIBs sector, 2021



(b) Value addition and detraction of Li in China's LIBs sector, 2021



(c) Cost-benefit analysis of waste battery treatment, 2021

Fig. 4. Li value chain mapping of China's LIBs sector, 2021.

especially when compared to Tesla's NPs (4950 \$/kg) in China. New Chinese EVs brands with low sales even had negative net profits (around –1500 \$/kg) in 2021 due to the high operating and R&D costs. In the energy storage market, average NPs were around 352.91 \$/kg in 2021, constrained by the limited production capacity, which are expected to increase as economies of scale in the production are realised and accompanied by technological upgrading in the next decades.

The NPs corresponding to lithium recovery in China are also relatively low, with an average of 23.68 \$/kg in 2021, due to China's current inefficient waste treatment technologies. One of the largest companies in this segment, GEM Co., Ltd., is China's largest formal battery recycling company, which only collected and recycled 8.4 kt of EOL power batteries in 2021, accounting for <10 % of its recycling capacity (CNINF Database). Moreover, even when EOL batteries are treated by the formal recycling sector, Li is still one of the least recycled metals owing to its high solubility and low concentration (Yan et al., 2023). As current revenues from secondary lithium account for <20 % of the total value from waste batteries recycling processed, this analysis indicates a significant potential for achieving higher economic benefits from Li recovery in the future if advanced EOL battery management system would allow an economically feasible way to recover secondary lithium.

#### 4.3. Li value chain mapping of China's LIBs supply chain

Both material and value flows of lithium in China's LIBs sector in 2021 are presented in Fig. 4(a). The detailed analysis and discussion of Li material flows have been documented elsewhere (Liu and Domenech, 2025) and the focus of this section is on value chain mapping associated with monetary flows of key Li-containing materials.

China relies heavily on Li ore imports, and in 2021, the value of imports was \$54 million. Combined with domestic extraction of Li ore and Li brine, the 2021 raw Li trade in China exceeded \$64 million in the domestic market. China plays a leading global role in lithium chemicals and battery pre-materials processing with a total trade value of \$1.2 billion and \$1.5 billion respectively in the domestic market in 2021. Although China is a net importer of lithium chemicals in physical terms, the value of exports is larger than imports in monetary terms, due to value added activities at the stage of Li chemicals processing in China. In 2021, the value of net exports of lithium chemicals and battery pre-materials was \$23 million and \$228 million, respectively.

At the battery manufacturing stage, the total output value of LIBs in China was \$1.5 billions in 2021, with a substantial positive trade balance of \$738 millions. Total output value of LIBs-powered products in China was \$3.4 billion in 2021, of which 34 % and 21 % came from mobile phones and battery electric passenger vehicles (BEPVs) respectively. The export value of LIBs-powered products was also considerable with \$1.8 billion in 2021, indicating a high domestic value added in gross exports that flowed out of the system boundary.

Finally, this model estimates that a total of 1.5 Mt of Li could be recycled in 2021 at the EOL across all product categories, with a potential \$0.9 million of net-savings, compared to the options of disposal as unrecovered waste. However, more than two-thirds of Li embedded in EOL batteries (3.4Mt) ended up in landfills or incineration due to gaps in the collection system, resulting in an extra estimated disposal cost of \$2.7 million in 2021.

In summary, the LIBs sector in China is experiencing, both in material and monetary flows, a rapid growth period (Fig. 4(b)). From the analysis, the most significant stage of value addition is at the LIBs-powered products consumption stage, reaching \$5.2 billion of total revenues in 2021, with a total of \$3.1 billion of value addition. The stages from Li extraction to Li chemicals refining also provides relevant value addition (\$1.3 billion). The reliance on Li imports led to a negative trade value at the raw materials extraction stage but this was then compensated by the chemicals refining processing which generated a high value-added.

While this is not generally considered in conventional VCA model,

this research extends the value chain analysis to assess the detracting of value associated with the waste stage and quantifies the economic potential of circular economy approaches to recover and retain value through VRPs such as recovery associated with batteries and battery remanufacturing, repurpose, and materials recovery. According to the analysis, significant value detracting happens at the stage of waste management, with a loss of about \$1.8 million, explained by the current limited lithium recovery rate and high transportation and disposal costs of waste.

The profitability of EOL LIBs treatment depends on many factors which shape the economic viability of circular economy strategies (Fig. 4(c)). Among key factors are: landfill taxes set at adequate levels; the improvement of waste treatment technology and infrastructure; efficient collection systems and stringent recycling targets set by regulations such as Extended Producer Responsibility (EPR) schemes. The analysis identified transportation cost as one of the biggest cost categories, accounting for 40 % of waste disposal costs. To ensure that loss of value is minimised or even retained, transportation and disposal costs would need to decrease substantially by 52 % or be internalised by manufacturers and importers using EPR or similar policy instruments. Efforts are also needed to improve the waste collection networks and availability of advanced waste treatment technologies. Increasing Li recycling efficiency to 90 % could increase net profit by \$16 million, while introducing EOL LIBs repurpose as ESS before entering recycling stream could generate up to \$15 million in additional net profits. If all these strategies are combined, as described as the "Best Performance", the overall net profit at the EOL stage could be \$32 million higher compared to the "Base Condition" in 2021.

## 5. Discussion and policy implications

The previous analysis illustrates that potential to increase or maintain the value of Li resources is significant at the raw materials extraction and the waste management stages of the value chain of Li in China's LIBs sector. In this section, the focus is placed on both mining and waste disposal as key areas where value dynamics could be enhanced to support circularity and promote value creation and retention.

### 5.1. Towards enhanced Li sustainable supply

The extraction of lithium is unevenly distributed globally, which has led to trade tensions and the advance of resource nationalism policies. The analysis of the value chain from a combined material and monetary perspective has indicated that spodumene-based routes to be appear significantly more costly than brine routes and China has the highest raw Li extraction cost for both routes (Fig. 5). South America, on the other hand, has the lowest Li extraction costs, where the brine deposits are the world's highest lithium occurrences (Tabelin et al., 2021). The high altitude also promotes faster evaporation making the extraction of Li from salt lakes in Chile and Argentina easier, leading to a relatively lower extraction cost of around 3000–3500 \$/t lithium carbonate equivalent (LCE) in 2021 (CNINF Database). Apart from South America, China has the second-largest Li-brine deposits in the regions of Qinghai and Tibet, which have been considered as the most promising potential for exploration (CNMIA, 2023), but Li extraction costs are substantially higher at about 5500–6000 \$/t LCE in 2021.

As for Li production from spodumene, Australia has the world's largest spodumene deposits (USGS, 2023). The lowest Li extraction cost from hard-rock pegmatites was 7360 \$/t LCE in 2021, because of a high average ore grade (2.4 % Li) in Greenbushes, Australia (IGO, 2023). The largest pegmatite deposit in Asia is in Sichuan, China, with 0.76 Mt of Li reserves at an average ore grade of 1.4 % Li (Huang et al., 2020). However, given the high Li extraction cost (9413 \$/t LCE in 2021), due to the conditions of the exploration at high altitude and in a rugged terrain-region, there is limited production capacity. Li extraction from Li-rich lepidolite in Jiangxi is another strategy area for China to increase

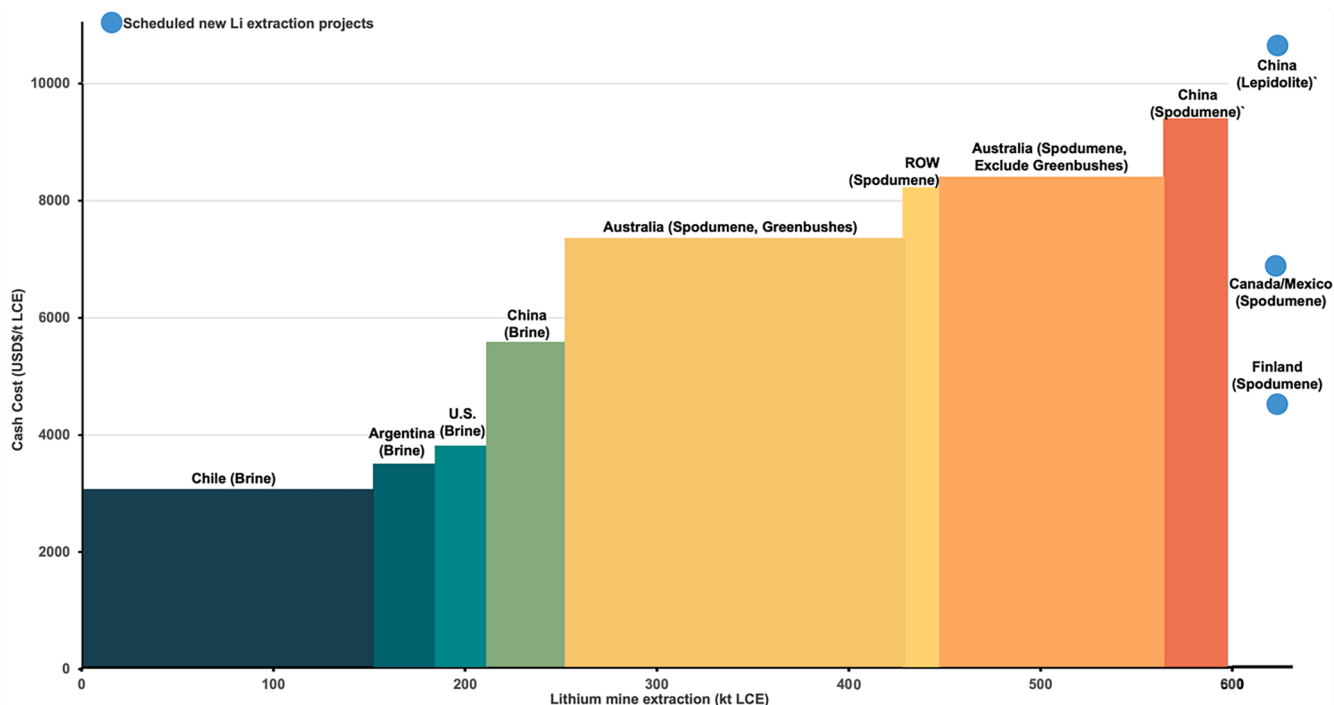


Fig. 5. Comparison of lithium extraction costs among global leading lithium mining companies, 2021.

domestic lithium extraction, but the processing cost is expected to be much higher (12,000 \$/t LCE) compared to other new mining projects in Finland and Canada, where Li processing cost is expected to be equivalent to that of the upper range of projects in Argentina (Sterba et al., 2019; Sebastián et al., 2021; Gao et al., 2023).

As the result of the higher extraction and processing costs, China's efforts to reduce the import reliance on foreign lithium resources are limited, leaving China subjected to a higher degree of vulnerability giving the price volatility of Li materials. As illustrated in SI Table S9, sharp fluctuations in market prices of upstream raw materials, both upward and downward, would contribute to negative impacts on the value-added of the battery production process. On the one hand, in the case of price soaring, the increase rate of upstream material costs is often faster than that of downstream product prices, especially for manufacturers with long-term fixed-price supply contracts. On the other hand, when Li prices fall sharply, this may result in substantial losses in accumulated product stocks. The above impacts, however, are also affected by non-powertrain and assembly costs, which have a large contribution to the overall costs, as well as the costs of other controllers and modules.

To increase Li supply resilience in China, the government has promoted Chinese domestic and foreign investments in mining activities both in China and globally (SI Table S11). Scheduled extraction capacity of primary Li in China is expected to grow significantly from 53.4 kt LCE in 2021 to 490 kt LCE, especially in Jiangxi and Tibet. As the US and Canada have adopted protective measures through royalties and increase in tax rates on Chinese investors mining projects (Qiu and Gong, 2021), China, while insisting on promoting domestic self-sufficiency, has focused on cooperation and alliances with South Africa to guarantee a stable CRMs supply at stable price points from these regions, such as in Mali and Zimbabwe. These initiatives make it unlikely for China's major role in the global lithium supply chain to change drastically over the next decades, although this will depend on continuous adequate R&D investments and introduction of new regulations to support new exploration and mine development.

## 5.2. Towards international supply chain resilience for Chinese products

As mentioned in Section 4.3, China acts as the leading global trade partner within LIBs supply chain with a high domestic value-added ratio in exports, especially at the product consumption stage. Key product groups where there is a clear Chinese dominance include battery packs, consumer electronics, and electric two/three wheelers (ETW), which rank as the top three lithium-containing commodities in the EU and the U.S.

Despite the reliance of the Chinese manufactured power batteries, the penetration of Chinese EVs is relatively low for both the EU and the U.S. Belgium and Germany are the main importers of China's EVs exports, although their share in the total EVs imports for the EU is small. For example, China exported \$2.5 billion of BEPVs to Belgium in 2021, accounting for 30 % of China's total BEPVs exports, but that value contributed to only 6 % of Belgium's total BEPVs imports. As for the U. S., the share of BEPVs imports from China is <5 %, while Germany and Mexico are the main importers. Results indicate a lack of market presence of Chinese EVs brands in the global market, which is consistent with the low NPs at this stage demonstrated in Section 4.1, although this may be rapidly changing.

The perceived risks associated with the bottlenecks of the current configuration of the LIBs supply chain, for both the EU and the U.S., heavily reliant on imports from China, have been at the basis of the introduced new trade protection measures, leading to the inflation act (the U.S. IRA, 2022) and Raw Materials Acts (the EU CRMs Act, 2023). In particular, the EU has raised the tariff rate on Chinese brands of electric cars sharply from 10 % to a maximum of 45.3 %, while the U.S. and Canada have even raised the tariffs on China's LIBs and EVs from 7.5 % and 25 % respectively to 25 % and 100 % respectively (EC, 2024). These actions also impose trade restrictions on the related upstream materials and intermediate inputs in the whole battery value chain.

This study has defined two scenarios to assess the impacts of tariff increases on the value addition of products in the chain (SI Table S9). The reduction of value addition in the value chain ranges from 6 % to 89 % under a conservative scenario, and these effects are expected to be amplified by a factor of 4–6 under the aggressive protectionist scenario.

The EVs market, in particular, would be negatively impacted by the tariffs due to a reduction rate in NPs of 223 % and 185 % for light-duty and heavy-duty electric vehicles respectively under the aggressive scenario. These findings raise concerns around the escalation of international trade tensions and have encouraged actions from China to increase the security and reliance of the battery value chain.

Despite this international context, Chinese domestic market is still fuelled by a strong domestic demand and effective vertical integration, which enables the achievement of economies of scale unlikely to be matched in other regions. This may contribute to securing a relevant position of China in the future global market. This study also illustrates that continued subsidies from the government would significantly increase the value addition of the chain, especially for the BEPVs (a 35 % growth as shown in Si Table S9).

Overall, the study highlights the potential role of the Chinese government's continuous investment support to companies in all stages of the LIBs value chain and R&D in technologies and products to increase brand recognition and global competitiveness.

### 5.3. Towards enhanced LI circularity

Improvement of waste LIBs management is also important for increasing LIBs industry sustainability and key value retaining processes (VRPs) are identified in this study to help promote economic benefits by reducing value detracting and loss at the EOL. The recycling capacity of waste LIBs in China is expected to increase from 2.4 MT in 2022 to 8.1 Mt by 2028, which is aligned with the projected growth of waste LIBs generation (EVTank, 2023). China has also established a National Traceability Platform for Power Batteries since August 2018, which has recorded a cumulative total of 12 million EVs by the end of 2022, accounting for 90 % of the total ownership (TBRAT, 2023). This initiative may help to close the loop of batteries and, specifically lithium, as it requires more stringent regulations and targets to enhance the cooperation among key stakeholders to enable compliance.

But several concerns need to be addressed. EOL LIBs are defined as 'Class IX' based on the 'the List of Dangerous Goods (GB 12268-2012)', with high standards for handling and transportation across provinces. In fact, the inter-provincial transportation of waste batteries faces cumbersome administrative procedures and high costs. Small and medium enterprises (SMEs), which do not have effective local waste treatment capacity, may face short-term challenges associated to financial burdens in improving EOL products collection and the recovery of materials embedded in them. Therefore, targeted policies, aligned with ESG requirements and with the principles outlined in the Responsible Minerals Initiative (RMI), should be enhance traceability and transparency and improve the inclusion of sustainability considerations along the value chain. Investment in infrastructures also needs to be accompanied with the set of waste recovery and recycling targets and the policy enforcement which enables the development of secondary markets. An effective way to do this is through extended producer responsibility (EPR) schemes, which internalise financial costs of EOL management of products to producers and importers. However, buffer mechanisms, such as flexible compliance timelines, public-private partnerships, and other cost-sharing initiatives targeted at different scales of enterprises, may also need to be considered to overcome constraints associated with high upfront costs to meet the EPR requirements. A detailed assessment of recycling efficiencies which accounts for disparities across technologies and provinces would also be desirable to understand variations in recycling rates across provinces.

Another concern is the losses of CRMs embedded in batteries that are exported, as they reduce domestic capacity to recover lithium. This study estimates 35 kt Li of potential losses associated with exports of LIBs and downstream products in 2021. Adoption of global material traceability and new business models, such as battery leasing and reverse logistics, could help to address current circularity gaps in this

sector. If lithium processing and battery manufacturing remains concentrated in China, secondary trade may also play an important role and may be subjected to trade tensions in the future. If EOL LIBs can be exported back to China, however, costs of treatment will increase. As China has effectively developed spatial approaches in industrial areas adopting industrial symbiosis approaches for clustering manufacturing and recycling activities to reduce the costs, increase the efficiency of CRMs recovery, and secondary materials re-integration back into the manufacturing process, a similar approach could be deployed internationally by establishing alliances between Chinese enterprises abroad and local producers and recyclers to build global resource recycling networks.

## 6. Conclusion

SSCM has raised attention to the required supply chain transformations to meet the material requirements towards the low-carbon transition. An increasing body of research has highlighted resource and environmental impacts of complex CRMs supply chains. However, integrated analyses that assess both material flows and monetary flows of CRMs supply chains are still limited, resulting in a lack of understanding of key leverage points to increase resilience and sustainability. This study develops a VCA model to provide another layer of understanding to complement existing research in SSCM. The concepts of value level and value creation are relevant to understand the economic motivation that shape physical flows and the required strategies to promote circularity. The study aims to contribute to the understanding of CRMs supply chains from a whole life cycle perspective and identify supply chain adjustments required to encourage a more sustainable and circular use of CRMs.

This study first quantitatively assesses both material flows and monetary value flows of China's LIBs supply chain taking lithium as a representative substance and quantifies value creation associated with Li along the whole chain and how the losses that occur at the EOL stage can be minimised or recovered through VRPs. The results indicate that as Li is refined and further processed along China's LIBs supply chain, the higher is its value, in consonance with its technical complexity and industrial added value. On the contrary, China's high imports reliance on primary lithium and low recovery of secondary lithium result in the decrease of the NPs. Despite the potential economic opportunities of CE strategies, recycling capacity is still limited, and important gaps are identified in the waste management system. Based on the results, this study proposes some key areas of focus towards greater sustainability: (i) to upgrade not only the technical capacity of lithium recycling but the technical requirements of materials and products throughout the whole LIBs supply chain increasing their traceability and ability to be recovered at the EOL, and (ii) to strengthen international cooperation to increase lithium secondary markets. A combination of policy instruments to enhance resilience would need to secure domestic Li supply while managing demand and EOL repurposing and recovery to ensure a more sustainable LIBs value chain.

### CRedit authorship contribution statement

**Haoning Liu:** Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Teresa Domenech Aparisi:** Writing – review & editing, Supervision, Methodology, Conceptualization.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2025.108452](https://doi.org/10.1016/j.resconrec.2025.108452).

## Appendices

### Appendix A. List of unit market revenues of lithium-containing commodities by Chinese companies, 2021

| Commodity                   |                           | Unit Market Revenues by Chinese Companies<br>(Ordered by Market Share) |         |        |        |            | Unit       | Market Concentration<br>(SMM Data) |
|-----------------------------|---------------------------|--|---------|--------|--------|------------|------------|------------------------------------|
|                             |                           | 1  | 2       | 3      | 4      | 5          |            |                                    |
| Minerals                    | Lithium Ore               | 743  | 566     | 1682   | –      | –          | USD\$/t    | CR3: 60 %                          |
| Chemicals                   | Lithium Carbonate         | 16,430   | 10,261  | 14,583 | 16,585 | 16,731     | USD\$/t    | CR5: 40 %                          |
|                             | Lithium Hydroxide         | 15,608   | 15,587  | 14,818 | 10,261 | 15,438     | USD\$/t    | CR5: 77 %                          |
| Battery Cathode Materials   | LCO                       | 39,420   | 35,660  | 39,131 | 37,915 | 42,223     | USD\$/t    | CR5: 83 %                          |
|                             | LMO                       | 7440   | 8862    | 12,034 | –      | –          | USD\$/t    | CR3: 48 %                          |
|                             | LFP                       | 8,931  | 8173    | 10,016 | 7853   | 9183       | USD\$/t    | CR5: 64 %                          |
|                             | NCM                       | 24,554   | 28,354  | 23,026 | 26,372 | 24,540     | USD\$/t    | CR5: 50 %                          |
| Lithium-ion Batteries       | Consumer Battery          | 4.09   | 5.38    | 5.61   | 7.01   | 5.83       | USD\$/item | CR5: 80 %                          |
|                             | Power Battery             | 122  | 102     | 96     | 93     | 129        | USD\$/kWh  | CR5: 86 %                          |
|                             | Storage Battery           | 126  | 102     | 112    | 132    | 199        | USD\$/kWh  | CR5: 42 %                          |
| Consumer Electronics        | Mobile Phones             | 170  | 665     | 310    | –      | –          | USD\$/item | CR3: 63 %                          |
|                             | Laptops/Tablets           | 447  | 809     | 526    | –      | –          | USD\$/item |                                    |
|                             | Wearable Electronics      | 66.4   | 226     | 201    | –      | –          | USD\$/item |                                    |
| Electric Vehicles           | Passenger Vehicles        | 15,801   | 14,678  | 22,180 | 17,155 | 17,360     | USD\$/item | CR10: 68 %                         |
|                             |                           | 43,321   | 20,506  | 33,143 | 61,262 | 46,264     |            |                                    |
|                             | Buses/Trucks              | 115,344  | 110,328 | 86,400 | 92,156 | 79,656     | USD\$/item | CR10: 88 %                         |
|                             |                           | 103,043  | 95,348  | 91,309 | 73,944 | 138,321    |            |                                    |
|                             | Light Commercial Vehicles | 23,723   | 49,039  | 32,680 | 22,176 | 22,475     | USD\$/item | CR5: 38 %                          |
| Electric Two/Three Wheelers | 196                       | 344  | 233     | –      | –      | USD\$/item | CR3: 67 %  |                                    |
| Energy Storage System       |                           | 126  | 102     | 112    | 132    | 199        | USD\$/kWh  | CR5: 42 %                          |
| Waste Battery Treatment     | Recycling & Recovery      | 7780   | 6386    | 6141   | 5857   | 7716       | USD\$/t    | CR5: 46 %                          |
| Waste Battery Treatment     | Repurpose                 | 111 USD\$/kWh  |         |        |        |            |            |                                    |

**References**  
Hua et al., 2021

### Appendix B. List of unit operating costs of lithium-containing commodities by Chinese companies, 2021

| Commodity                   |                             | Unit Operating Cost by Chinese Companies<br>(Ordered by Market Share) |        |        |        |            | Unit       | Market Concentration<br>(SMM Data) |
|-----------------------------|-----------------------------|---|--------|--------|--------|------------|------------|------------------------------------|
|                             |                             | 1   | 2      | 3      | 4      | 5          |            |                                    |
| Minerals                    | Lithium Ore                 | 163   | 231    | 1622   | –      | –          | USD\$/t    | CR3: 60 %                          |
| Chemicals                   | Lithium Carbonate           | 6912  | 6376   | 3711   | 9873   | 9996       | USD\$/t    | CR5: 40 %                          |
|                             | Lithium Hydroxide           | 8897  | 6287   | 8063   | 5596   | 14,491     | USD\$/t    | CR5: 77 %                          |
| Battery Cathode Materials   | LCO                         | 36,610  | 33,232 | 37,523 | 36,018 | 38,825     | USD\$/t    | CR5: 83 %                          |
|                             | LMO                         | 5260  | 6271   | 9224   | –      | –          | USD\$/t    | CR3: 48 %                          |
|                             | LFP                         | 6340  | 3468   | 7009   | 5618   | 6591       | USD\$/t    | CR5: 64 %                          |
|                             | NCM                         | 21,629  | 23,650 | 20,461 | 23,780 | 22,305     | USD\$/t    | CR5: 50 %                          |
| Lithium-ion Batteries       | Consumer Battery            | 2.39  | 2.97   | 4.73   | 5.47   | 4.78       | USD\$/item | CR5: 80 %                          |
|                             | Power Battery               | 93  | 97.6   | 92.1   | 92.1   | 77.5       | USD\$/kWh  | CR5: 86 %                          |
|                             | Storage Battery             | 77.5  | 93     | 108    | 109    | 127        | USD\$/kWh  | CR5: 42 %                          |
| Consumer Electronics        | Mobile Phones               | 150   | 424    | 268    | –      | –          | USD\$/item | CR3: 63 %                          |
|                             | Laptops/Tablets             | 281   | 566    | 316    | –      | –          | USD\$/item |                                    |
|                             | Wearable Electronics        | 57.7  | 170    | 133    | –      | –          | USD\$/item |                                    |
| Electric Vehicles           | Passenger Vehicles          | 14,998  | 12,389 | 21,434 | 16,687 | 14,472     | USD\$/item | CR10: 68 %                         |
|                             |                             | 44,996  | 17,338 | 43,502 | 69,978 | 48,269     |            |                                    |
|                             | Buses/Trucks                | 109,166   | 92,836 | 78,205 | 85,680 | 73,515     | USD\$/item | CR10: 88 %                         |
|                             |                             | 107,640   | 84,707 | 88,262 | 70,838 | 139,346    |            |                                    |
|                             | Light Commercial Vehicles   | 20,164  | 39,232 | 27,038 | 17,126 | 20,710     | USD\$/item | CR5: 38 %                          |
| Electric Two/Three Wheelers | 166                         | 295   | 209    | –      | –      | USD\$/item | CR3: 67 %  |                                    |
| Energy Storage System       |                             | 77.5  | 93     | 108    | 109    | 127        | USD\$/kWh  | CR5: 42 %                          |
| Waste Battery Treatment     | Recycling & Recovery        | 7221  | 5720   | 6749   | 3386   | 4963       | USD\$/t    | CR5: 46 %                          |
| Waste Battery Treatment     | Collection & Transportation | 2 CNY/kg  |        |        |        |            |            |                                    |
|                             | Landfill & Incineration     | 2560 CNY/t for landfill   |        |        |        |            |            |                                    |
|                             |                             | 3540 CNY/t for incineration   |        |        |        |            |            |                                    |
|                             | Repurpose                   | 44 USD\$/kWh  |        |        |        |            |            |                                    |

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## Data availability

Data will be made available on request.

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