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RESEARCH ARTICLE

Can circular economy strategies address resource constraints for lithium-ion batteries?

A comprehensive dynamic material flow analysis of lithium flows in China's battery sector

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Abstract

The low-carbon transition requires widespread adoption of lithium-ion batteries (LIBs), which rely on critical raw materials. Lithium (Li) demand is expected to increase 10-fold by 2050 globally, raising concerns over the sustainability of future supply. As one of the world's largest producers and consumers of LIBs, China's role is pivotal in addressing resource constraints, enhancing circularity, and enabling global climate commitments. This paper uses a dynamic material flow analysis model to trace Li flows and stocks in China's LIBs system, taking 2021 as the base year and designing scenarios to 2050 to assess the potential role of circular economy (CE) strategies in addressing primary lithium constraints. While previous studies have concentrated on electric vehicle (EVs) LIBs, this research provides more comprehensive coverage of Li chemicals and products, assesses future Li demand considering saturation curves across different applications/groups, and provides a broader overview of policy interventions to align with CE strategies. Results illustrate that Li cumulative demand in China's LIBs sector is expected to reach 6.65 Mt from 2022 to 2050 under the business-as-usual (BAU) scenario. In parallel, there is a significant potential for addressing primary Li constraints through different combinations of circularity strategies, with a reduction of 60%–100% by 2050 compared to the BAU. The contribution of recycled Li is highly dependent on the strategies adopted to optimize end-of-life (EOL) LIBs management and battery chemistry innovation. Policies to address this are discussed including waste regulatory instruments, new remanufacturing business models, and continuous support to research and development activities to help close the loop of lithium and ease Li constraints.

KEYWORDS
China, circularity strategy, dynamic material flow analysis, industrial ecology, life cycle stages, lithium-ion batteries

1 | INTRODUCTION

In response to the climate change emergency and low-carbon transition commitments, clean energy technologies and green mobility have been developed rapidly and shown the potential to bring down emissions (UNEP, 2021). Such radical transformation implies a profound restructuring of industry transformation to supply chains and the adoption of new technologies to reduce reliance on fossil fuels. Substantial amounts of high-importance metals, also referred to as "critical raw materials" (CRMs), are required for low-carbon technologies (Sovacool et al., 2020). Global CRMs consumption is expected to increase by almost 40% by 2030 compared to 2010, reaching 100 Gt/a (OECD, 2019; UNEP, 2017).

Simultaneous transitions toward clean energy technologies and decarbonization, green mobility, and digitalization are likely to pull the demand for lithium-ion batteries (LIBs) (Vinayak et al., 2024). The LIBs market is projected to grow across all ranges of applications from electric vehicles (EVs) and their batteries to other energy storage systems (ESS). It is expected that global LIBs demand will increase from 960 GWh in 2022 to 5 TWh in 2030, with 38 million EVs on the road and 1 TWh of battery storage (IEA, 2023).

As one of the world's largest producers and consumers of LIBs, China's LIBs production reached 750 GWh in 2022, a 130% increase from 325 GWh in 2021, which accounted for 70% of the global share, followed by the United States (9%) (CNMN, 2023; MIIT, 2023). China is also the largest LIBs exporter, making up half of global LIBs exports. In 2022, around 35% of China's LIBs exports were absorbed by Europe, for example, where China's LIBs made up 65% of the EU total LIBs imports (UN Comtrade Database).

Accelerated growth of LIBs has attracted attention due to concentrated supply and resource problems associated with extraction and beneficiation processes of CRMs, where lithium (Li) has been identified at the highest risk of supply shortage in China's LIBs industry (Sun et al., 2023; Zhang et al., 2022). Although Li reserves are relatively abundant in China, with 2 Mt in 2022, 70% of them are salt-lake lithium reserves (Hao et al., 2017; USGS, 2023). Owing to low lithium levels and high extraction costs, domestic lithium production capacity is limited. In 2022, Li consumption in China drove to 0.1 Mt and is projected to grow three to five times by 2030, which surpasses the expected supply from China's existing mines and projects under construction (Ambrose & Kendall, 2020; Li et al., 2022). As a result, China relies heavily on imported lithium raw materials. In 2022, China imported 2.84 Mt of lithium ores with an external dependence of 80%, resulting in lithium supply security concerns (NBSC National Database).

In parallel, end-of-life (EOL) batteries are expected to significantly increase. Lithium stored in products is either collected and recovered or is lost or disposed of. While batteries' lifespans and exports justify some of the divergence between products put on the market and waste arisings, improper disposal or inadequate reprocessing of waste LIBs is the cause of severe CRMs losses and Li is one of the least recycled metals owing to its high solubility and low concentration (Richa et al., 2017; Yan et al., 2023). China's current waste LIBs management is suboptimal with low collection and recycling rates. In 2022, only 0.4 Mt of EOL batteries were recycled by the formal recycling sector, less than half of the total installed recycling capacity (EVTank, 2023). Most EOL batteries were either lost or treated by informal enterprises, where waste often ends up in landfills even when collected (Teng, 2024). The volume of recycled Li contributes only about 5% of domestic demand, making it insufficient to address future Li supply shortages (EVTank, 2023).

The use of material flow analysis (MFA) in the literature to better understand CRMs requirements is not new. Several studies have adapted specific MFA models to examine CRMs flows through LIBs life cycle (S-1 Table S1). Ziemann et al. (2012) developed a global lithium MFA model to evaluate Li supply and demand and outflows to the environment. Hao et al. (2017) developed the first lithium MFA within the Chinese context and estimated that China's total Li consumption was 87 kt (Li_2CO_3eq) in 2015, accounting for half of the global total. Lu et al. (2017) assessed lithium material flows in China from 2007 to 2014 and emphasized how despite the continuous growth of lithium stock, its use as a secondary material has been limited due to an ineffective waste management system. Song et al. (2019) and Liu et al. (2021a) focused their MFA analysis on China's LIBs sector and highlighted how flaws and limitations of the current battery collection and recycling system negatively impact domestic Li supply security.

In these studies, circular economy (CE) is identified as a potential strategy to address the above issues and ease bottlenecks toward the green transition. Previous literature focused on EOL battery management to identify the potential for lithium recovery (Neumann et al., 2022). More recently dynamic MFA has been employed to represent future Li flows. Ziemann et al. (2018) and Lähdesmäki et al. (2023) assessed global Li demand as a response to EVs penetration and highlighted the importance of multiple complementary circular strategies to maintain lithium sustainable supply. Watari et al. (2019) and Zhang et al. (2023) assessed the impacts of EOL recycling for future projected use in EVs on a global basis. Other studies focused on a national scale, such as the United States and the EU, and modeled future lithium demand for LIBs use (Kastanaki & Giannis, 2023; Miatto et al., 2021). Specific to the Chinese context, Wu et al. (2020) and Guo et al. (2021) calculated China's future obsolete power battery generation by 2030 and highlighted the huge increase of potentially recyclable lithium resources in the short term. Qiao et al. (2021) and Liu et al. (2023) estimated future waste LIBs arisings from EVs and indicated that recycled lithium could potentially reduce primary Li consumption in the range of 30%–60% by 2050 if adequate EOL management is introduced.

In summary, much research has highlighted resource concerns caused by China's rapid LIBs development and potential opportunities that CE strategies present. However, most existing literature focuses on EVs batteries. The relevance of the consumer electronics market and, more recently, ESS, justifies the adoption of a broader scope when examining long-term CRMs requirements in China, which is an under-researched area. Furthermore, the literature has mostly focused on CE directed toward closing the loop strategies, mainly related to adoption of advanced battery waste recycling. However, a broader set of CE strategies that cover slowing and narrowing resource flows, such as changes in battery materials and lifespan due to chemistry innovations, as well as the repurposing of EOL batteries before entering the waste stream as ESS have been mainly overlooked in current literature.

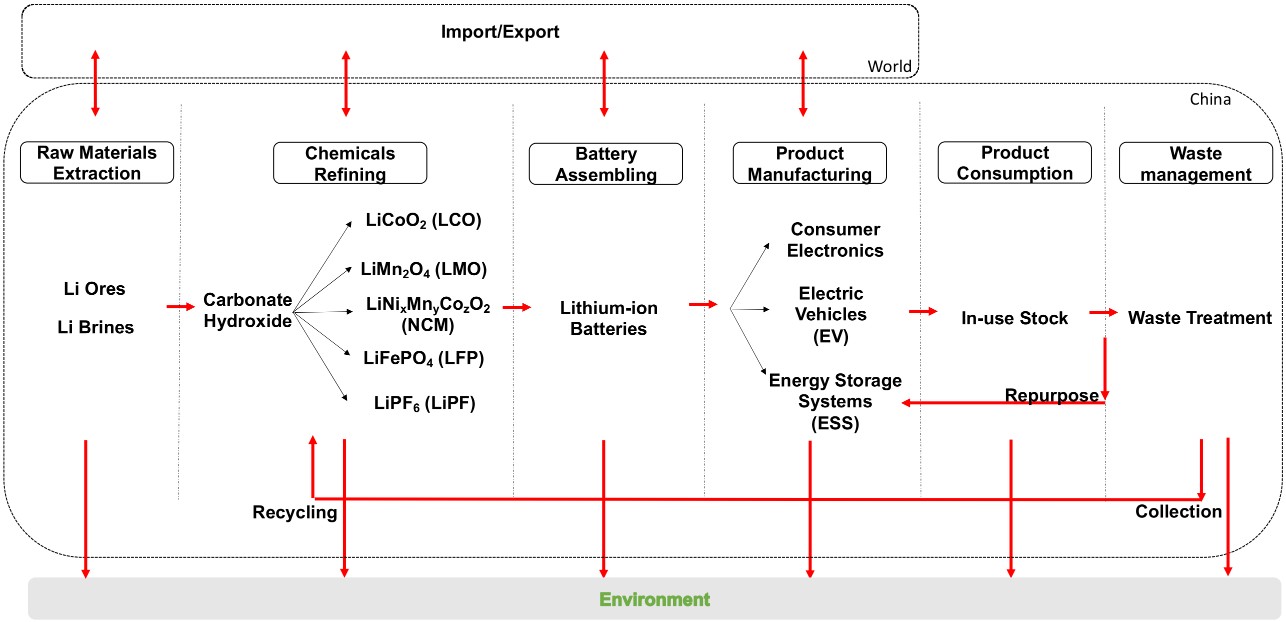


FIGURE 1 Lithium-ion batteries' (LIBs') industrial lithium processing stages and activities.

This study focuses on shedding light on lithium material flows embedded in batteries through their whole life cycle from extraction to EOL in China, to provide an accurate understanding of the potential to optimize lithium use and assess the potential of circular pathways to achieve a more sustainable Li supply chain management. This study extends current knowledge by providing: (1) a broader coverage of main LIBs-powered products; (2) a more accurate representation of future demand considering market saturation effects; (3) a detailed description of circularity scenarios up to 2050, considering a broader set of CE strategies; and (4) extending and enhancing previous partial representations of whole lithium supply chain to provide a broader overview of circularity pathways impacts, rather than focusing on individual areas of policy intervention.

This paper is divided into five sections. Section 2 describes the methodological approach, and Section 3 presents the main findings. Section 4 discusses the main implications derived from the findings and explores circular pathways for addressing lithium supply constraints. Section 5 presents conclusions and future outlooks.

2 | METHODS

2.1 | Dynamic MFA model

This study uses a dynamic MFA model to assess current and future lithium flows and stocks in China's LIBs system, which can help better understand the main bottlenecks in the system and quantify the potential effects of different circularity strategies (Müller et al., 2014).

Mainland China is the spatial boundary, where Hong Kong, Taiwan, and Macau are not included. The baseline year is 2021 but the dynamic analysis will cover the period up to 2050 to capture China's rapidly developing market of EVs and ESS. The analysis covers all stages of LIBs' life cycle, including six main phases (Figure 1).

Due to different chemistries and varying levels of concentration, Li content within batteries may vary substantially across battery types. This study sets corresponding Li content for different commodities based on Hao et al. (2017) and Sun et al. (2018) (S-1 Table S2). Total Li mass in commodities at one stage defined as A_{Li} is:

$$A_{Li} = \sum_{p=1}^{n} A_{Li,p} = \sum_{p=1}^{n} C_p * R_{Li,p} \tag{1}$$

where p represents different commodities at one stage, $A_{Li,p}$ represents Li mass in one commodity p, C_p represents the mass of commodity p, and $R_{Li,\,p}$ represents Li content in commodity p.

The relationship in each stage follows the material balance principle, where total inputs equal total outputs plus net accumulation.

Data on primary lithium and chemicals come from the US Geological Survey (USGS, 2023) and the China Nonferrous Metals Industry Association (CNMIA, 2022). Data on the production and sales of LIBs and battery-powered products come from the China National Bureau of Statistics (NBSC National Database) and the China Association of Automobile Manufacturers (CAAM, 2022). Trade data relies mainly on the UN Comtrade database

TABLE 1 List of key parameters of the model.

Analysis layer	Parameters	References
Market level	Population	NBSC National Database
	Gross domestic product (GDP)	NBSC National Database
	Product ownership per capita	Pauliuk et al. (2012)
Products level	Products category	Sun et al. (2019)
	Products sales	CAAM (2022) and IEA (2023)
	Market share of each product	Hsieh et al. (2020) and ICET (2021)
LIBs level	Battery capacity	Hao et al. (2019)
	Battery chemistry	Zhang et al. (2023)
Li level	Lithium intensity	Xu et al. (2020) and Lopez et al. (2023)

and China Customs Statistics. Data, such as battery lifetime and EOL LIBs management, are obtained from the Ministry of Industry and Information Technology of China and other relevant literature sources (Qiao et al., 2021; Wang & Yu, 2020a; Ziemann et al., 2018). A detailed list is shown in S-1 (Table S3).

2.2 | Model structure

2.2.1 | Demand forecast

This study uses a logistic model to forecast product inflows over the next 30 years in China. The logistic function (S-shaped growth) is usually used to model resource consumption (Houari et al., 2014). It allows for estimating trends of natural resources consumption by industry and anticipating future demand to adjust production volumes (Guo et al., 2021). Following Guo et al. (2021), this study estimates future Li demand based on the following function:

$$D_p\ (t) = \frac{D_{max-p}}{1 + \exp\left\{-g_p\,(t - t_h)\right\}} \tag{2}$$

where $D_p(t)$ represents the demand for commodity p in year t, D_{max-p} represents maximum demand of commodity p, g_p represents a forecasted growth rate of demand for commodity p, t_h represents the year when forecasted demand reaches half of the maximum demand. Key parameters for simulating stocks and flows of LIBs-powered products and associated lithium requirements are listed in Table 1. Changes to each of the parameters are explained in detail in S-1 (Table S5-S7).

Given mineral resource reserves are finite and technology changes over time, demand for lithium-containing products may plateau when reaching a near-saturated state (Wang et al., 2017). The concept of "apparent domestic consumption" (ADC) is used to map the trajectory of China's lithium demand over time. Following Bleischwitz et al. (2018), total demand D for commodity p is calculated by adding net import from finished goods $D^t_{tr,p}$ and output of transformative industries $D^t_{pr,p}$ (Equation (3)). ADC values of Li embodied in commodities are determined by applying specific $R_{Li,p}$ to each commodity (Equation (4)).

$$D^t_p = \sum \left(D^t_{pr,p} + D^t_{tr,p}\right) \tag{3}$$

$$\mathrm{ADC}^t_p = D^t_p \times R_{\mathrm{Li,p}} \tag{4}$$

ADC per capita and GDP per capita are employed to determine the extent to which industrialized economies reach material-specific saturation. Detailed calculations are explained in S-1 (Figure S1).

2.2.2 | Battery lifespan distribution

This study applies Weibull distribution to simulate battery life distribution and forecast future waste arisings of battery materials (Guo et al., 2021; Yao et al., 2021). To simplify the calculation, this study makes following assumptions adapted from Xu et al. (2020), Guo et al. (2021), and Zhang et al. (2023): (1) one product uses one battery pack at a time; (2) products of consumer electronics will be scraped directly when battery reaches EOL;

(3) for products of EVs and ESS, the study assumes that battery will be replaced and the products continue to be used until reaching the expected lifespan of the product. In the case of repurposed batteries for ESS, the batteries will be used until exhaustion, and for EVs, the replaced battery will reach EOL directly when the product reaches its lifetime. The formula is defined as:

$$F\ (t) = \frac{\alpha}{\beta} \times \left(\frac{t}{\beta}\right)^{(\alpha-1)} \times e^{-(t/\beta)\alpha} \tag{5}$$

where $F(t)$ is a probability density function of the standard Weibull distribution that presents the obsolete rate of LIBs after use in year t. $\alpha$and β represent shape and scale parameters, respectively.

The scale parameter represents the battery life cycle, which is equal to the average battery lifetime. The shape parameter represents battery quality and varies according to its function, size, and technical lifespan (Wu et al., 2020). In this study, the former is adapted from Song et al. (2019), Sun et al. (2018), and Liu et al. (2021a), while the latter is adapted from Guo et al. (2021) (see results in S-1 Figure S2).

2.2.3 | Waste arisings estimation

Combining product demand and battery lifetime distribution, total lithium demand and associated waste arisings are estimated following Qiao et al. (2021). Total lithium inflows of LIBs in year t are calculated as:

$$M_t = N_t + E_t \tag{6}$$

$$E_t = \sum_L F\ (t) \times (N_{t-L} + E_{t-L}) \tag{7}$$

where L is the product lifespan, M_t indicates lithium inflows in year t, N_t indicates lithium demand for new items purchased in year t, and E_t indicates lithium demand for in-use products that need to replace batteries in year t.

Theoretical lithium outflows of the economy entering EOL in year t defined as S_t is measured as:

$$S_t = \sum_L F\ (t) \times M_{t-L} \tag{8}$$

2.2.4 | Scenario modeling

This study models different forecasting scenarios to assess the potential impacts of different pathways combining circularity strategies to decrease primary lithium requirements for China's LIBs sector. Each of the scenarios focuses on a specific type of circular strategy, while there is one ambitious sustainability scenario that combines all strategies. Five future scenarios are modeled to assess key opportunities and challenges associated with circularity pathways, which are described in Table 2. The business-as-usual (BAU) scenario provides a baseline representation of China's current situation, where lithium iron phosphates (LFP) and various LiNixMnyCozO2 (NCM) dominate the market of battery chemistry and EOL LIBs are largely entering the waste management stage without secondary use. Although Li consumption is less relevant in consumer electronics and, thus, changes in battery types may be delayed beyond the timeline of the scenarios, this study assumes that the adoption of new batteries in this sector follows the development plans for EVs batteries. In the improved waste management (IWM) scenario, EOL EVs batteries are expected to be repurposed as ESS first before entering the waste stream. The lifetime of repurposed batteries is 10 years (Rossi et al., 2023). As for the waste treatment stage, this scenario assumes all waste batteries will be collected and treated by the formal recycling sector, with a 92% technical maximum of Li recycling efficiency (GEM, 2022). New battery chemistries with little or no lithium are progressively adopted in the new battery chemistry (NBC) scenario, where batteries are expected to be all-solid-state batteries from 2030 and sodium-ion (Na-ion) batteries from 2040. The policy-driven vision (PDV) scenario and the sustainability-driven (SDV) scenario are a combination of the above CE strategies. The former is driven by China's "The 14th Five-Year Plan and Vision 2035" (GOVCN, 2021) and the latter sets out the strongest ambition towards sustainable development, combining strategies from all other scenarios.

2.3 | Data uncertainty analysis

The construction of the MFA and scenario 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. This study adopts the uncertainty analysis framework developed by

TABLE 2 Scenario assumption.

Strategy			BAU	IWM	NBC	PDV	SDV
Scenario narrative			Product sales continue to grow but EOL practices remain the same	Introduce EOL battery repurpose and improve waste battery management	Mass production of new battery chemistry, achieving high battery capacity and long battery lifespan	Develop new energy technologies under China's 14th Five-Year Plan	Achieve high-performance battery management toward sustainable development
Battery Lifetime	Consumer electronics	Mobile phones	4	4	6	5	6
		Laptops/tablets	5	5	10	8	10
		Digital cameras	5	5	10	8	10
		Wearable electronics	6	6	10	8	10
	EV	Passenger vehicles—battery electric	10	10	16	12	16
		Passenger vehicles—plug-in hybrid electric	10	10	16	12	16
		Buses—battery electric	8	8	12	10	12
		Buses—plug-in hybrid electric	8	8	12	10	12
		Special vehicles—battery electric	8	8	12	10	12
		Electric two/three wheelers	6	6	10	8	10
	ESS	Energy storage system	15	15	25	20	25
Secondary use of LFP batteries from EV to ESS before going to waste			0%	100%	0%	50%	100%

(Continues)

TABLE 2 (Continued)

Strategy			BAU	IWM	NBC	PDV	SDV
Waste collection rate	Consumer electronics	Mobile phones	30% in 2021 (Growth of 10%/a)	Reaching 100% by 2050	30% in 2021 (Growth of 10%/a)	Reaching 80% by 2050	Reaching 100% by 2050
		Laptops/tablets					
		Digital cameras					
		Wearable electronics					
	EV	Passenger vehicles—battery electric	50% in 2021 (Growth of 10%/a)	Reaching 100% by 2050	50% in 2021 (Growth of 10%/a)	Reaching 100% by 2050	Reaching 100% by 2050
		Passenger vehicles—plug-in hybrid electric					
		Buses—battery electric					
		Buses—plug-in hybrid electric					
		Special vehicles—battery electric					
		Electric two/three wheelers	30% in 2021 (Growth of 10%/a)	Reaching 100% by 2050	30% in 2021 (Growth of 10%/a)	Reaching 80% by 2050	Reaching 100% by 2050
	ESS	Energy storage system	50% in 2021 (Growth of 10%/a)	Reaching 100% by 2050	50% in 2021 (Growth of 10%/a)	Reaching 100% by 2050	Reaching 100% by 2050
Li recovery process efficiency			Reaching 80% by 2050	Reaching 92% by 2050	Reaching 80% by 2050	Reaching 85% by 2050	Reaching 92% by 2050
New chemistry adoption			LFP (70%) and NCM811 (25%) dominate, reaching 350 Wh/kg by 2050	LFP (70%) and NCM811 (25%) dominate, reaching 350 Wh/kg by 2050	New batteries with less or no lithium, reaching 500 Wh/kg by 2050.	New batteries with less or no lithium, reaching 500 Wh/kg by 2050.	New batteries with less or no lithium, reaching 500 Wh/kg by 2050.

Abbreviations: BAU, business-as-usual; IWM, improved waste management; NBC, new battery chemistry; PDV, policy-driven vision; SDV, sustainability-driven; EOL, end-of-life; LFP, lithium iron phosphates; NCM, various $LiNi_xMn_yCo_zO_2$; EV, electric vehicle; ESS, energy storage system.

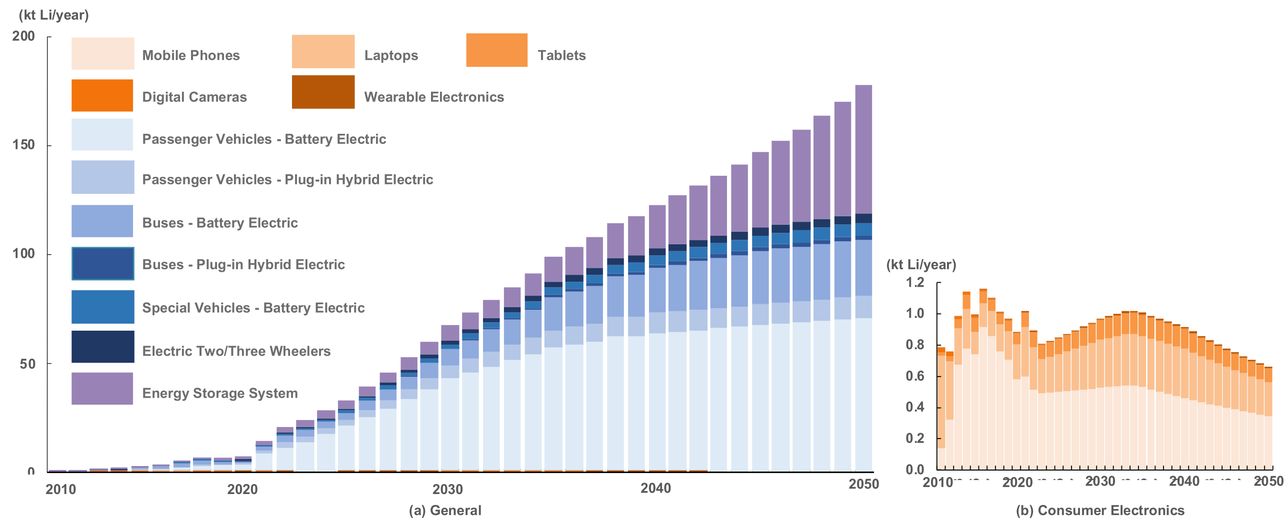


FIGURE 2 Projected Li annual inflows of lithium-ion batteries (LIBs)-powered products in China under the business-as-usual (BAU) scenario, 2010–2050 (underlying data are available in S-2 Table S1).

Laner et al. (2014), which specifically applies to MFA. This approach qualitatively assesses each data input based on data quality criteria. The main areas of uncertainty in this study are the mass of Li-containing commodities and Li content in commodities. The method considers five indicators (source reliability, completeness, temporal correlation, geographical correlation, and other correlation), which are then calculated to derive uncertainty ranges (Hsu et al., 2021). The criteria on which each indicator is based are described by Laner et al. (2016). Complementary to the uncertainty analysis, we use data reconciliation processes assisted by STAN software (Cencic & Rechberger, 2008). The main core equation of MFA is based on the mass conservation law. However, in some cases, there may be a contradiction between the expected values and the given data. The reconciliation process aims to solve these incongruences in the data by altering the mean values of uncertain data to ensure alignment with the model equations (Cencic, 2016). More detailed explanations are shown in S-1 (Table S8-S10).

3 | RESULTS

3.1 | Future Li sales growth in China's LIBs market

Annual inflows of Li embedded in LIBs-powered products are predicted to considerably increase from 15 kt Li/a in 2021 to 178 kt Li/a in 2050 under the BAU scenario (Figure 2).

Sales of consumer batteries in China boomed from 2010 to 2018, followed by a gentle decline indicating that the market of consumer electronics is nearing saturation. Future sales of consumer batteries are expected to reach the peak during 2030–2035 (1 kt Li/a) and then decline to 0.65 kt Li/a by 2050. Mobile phones and laptops with high Li intensity are expected to remain dominant Li-consuming products in this market.

Sales of power batteries are expected to surge driven by the fast adoption of EVs, increasing from 12 kt Li/a in 2021 to 102 kt Li/a in 2040. As the country progresses from industrialization into maturity, the model has estimated that the ADC Li per capita of China's EVs market is expected to reach saturation stage at a level of 2.5-3 g/capita when a threshold of $40,000 GDP/capita is exceeded. Future sales of power batteries in China are expected to slow down from 2040 and reach 118 kt Li/a in 2050, with battery electric passenger vehicles accounting for 60% of total sales.

Sales of storage batteries are estimated to remain in the growth stage in the next decades with a rapid increase pace. In response to the fast deployment of energy storage and 5G base stations, sales of ESS in China are expected to increase from 2 kt Li/a in 2021 to 60 kt Li/a in 2050, becoming the second largest Li demand segment after battery electric passenger vehicles.

There are high uncertainties with regard to the level of product ownership per capita, market penetration of LIBs-powered products, and shifts across product categories and types of products (e.g., from plug-in hybrid EVs to pure battery EVs). To account for these, this study performs sensitivity analysis for: (1) the market demand for LIBs-powered products with/without the saturation stage, (2) the market penetration rate of different types of EVs, and (3) the future adoption of different advanced battery chemistries. These provide an overview of how changes in assumptions impact results, which is presented in S-1 (Figures S3-S4).

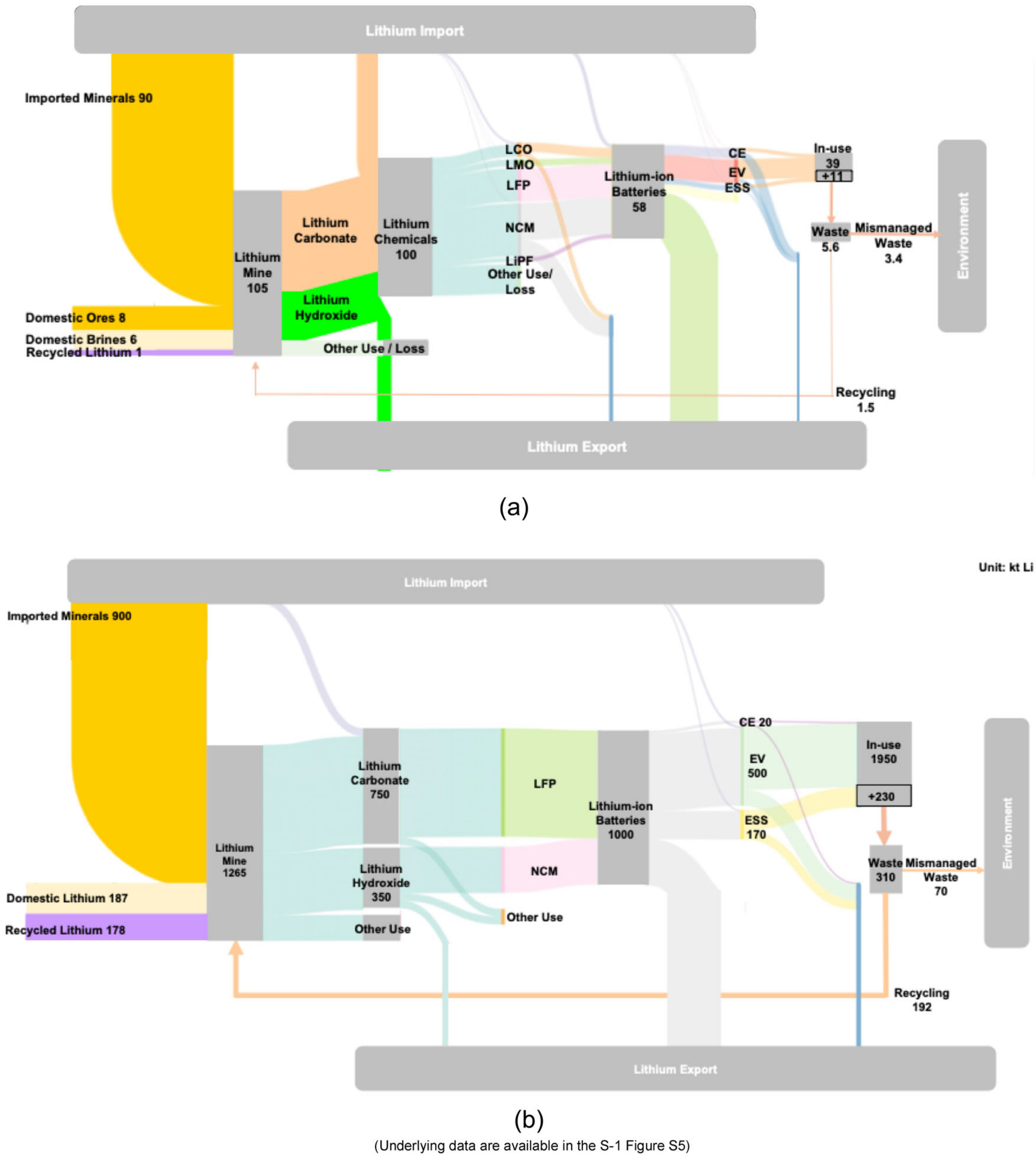


FIGURE 3 Sankey diagram of lithium material flows in China's lithium-ion batteries (LIBs) industry: (a) 2021 and (b) 2050 under the business-as-usual (BAU) scenario (underlying data are available in S-1 Figure S5). CE, consumer electronics; LCO, lithium cobalt oxide; LMO, lithium manganese oxide; LFP, lithium iron phosphates; NCM, various $LiNi_xMn_yCo_zO_2$; LiPF, lithium hexafluorophosphate; EV, electric vehicle; ESS, energy storage system.

3.2 | Li flows and stocks in China's LIBs sector

Figure 3 depicts lithium flows and stocks within China's LIBs system in 2021 and 2050 under the BAU. All units of values are lithium metal equivalents unless otherwise stated.

In 2021, China's domestic Li production was 14 kt (USGS, 2023). Although China has large reserves of lithium brines, raw lithium is primarily extracted and produced from ore-based deposits. Total Li flow into the chemical refining stage was 105 kt in 2021, which was mainly supported by imports. Domestic production of lithium carbonate and lithium hydroxide was 56 and 30 kt, respectively, in 2021, accounting for 53% and 27%, respectively, of total Li chemicals. About 80% of the above chemicals were used as battery pre-materials, particularly for NCM (33 kt) and

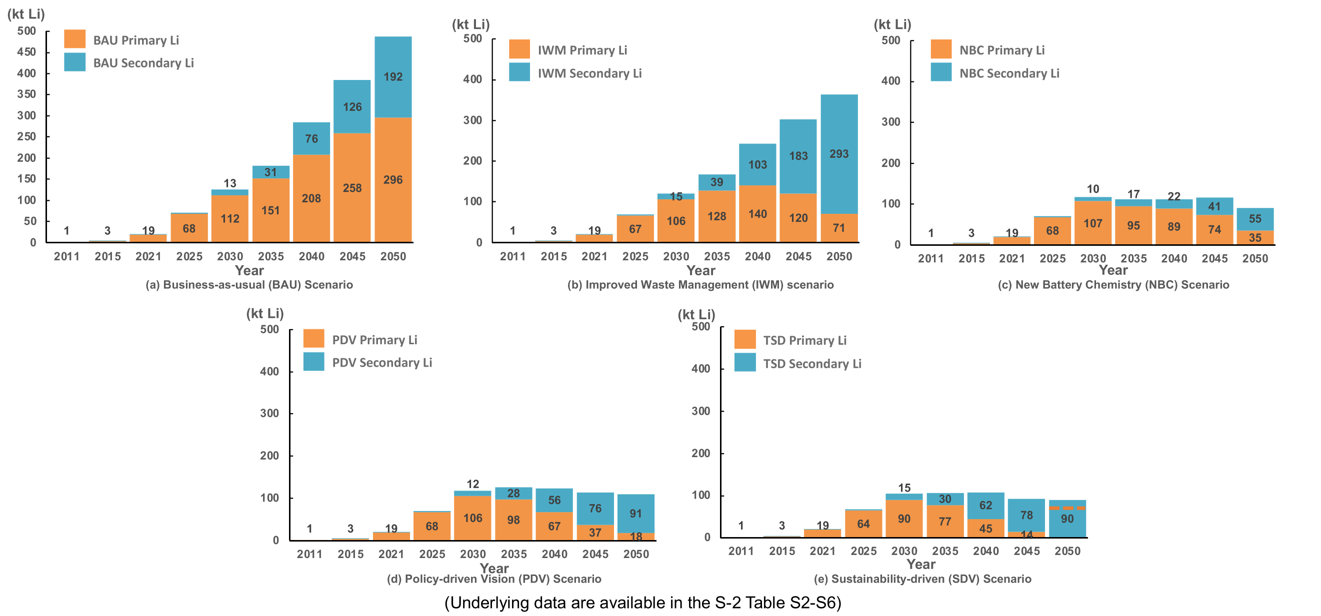


FIGURE 4 Annual Li demand for lithium-ion batteries (LIBs) in China under different scenarios (underlying data are available in S-2 Table S2-S6).

LFP (21 kt). To be noted is that a third of NCM and half of LiOH, which is used only for high-nickel NCM processing, were exported abroad for the automotive sector, while China relies mainly on LFP for domestic consumption (SMM, 2021).

China's domestic LIBs production reached 56 kt in 2021 and nearly half of all LIBs were exported. Li contained in final products at the domestic use stage was 27 kt in 2021. Sixty percent of domestic in-use LIBs were used for EVs, led by battery electric passenger vehicles (10 kt). The consumer electronics sector was another important user of LIBs (5.6 kt), while ESS production was 3.2 kt. There was also a significant Li export flow of final products, with consumer electronics accounting for the largest share (55%).

The model estimates that 5.6 kt Li contained in LIBs entered EOL in 2021. However, only 2.2 kt of EOL batteries are currently collected by the formal recycling sector, leaving 55% of spent LIBs unaccounted for and potentially mismanaged, treated by the informal sector, or leaked into the environment (SMM, 2022). 1.5 kt of Li was recovered from the waste in 2021, representing only 6% of lithium demand for domestic LIBs-powered products' use.

Driven by the imperative of mobility electrification and the low-carbon and digital transition, global LIBs demand is expected to sharply grow and China is expected to dominate around 60% of the global LIBs market by 2050 (CEA, 2022). This shows a slight decline from 2021 as new regulations in the EU and the United States are expected to ramp up domestic LIBs production, while there is also a rapid consolidation of the sectors in other parts of Asia. Considering the national strategic policy, this study predicted that the amount of Li flows through each stage of China's LIBs sector in 2050 will increase 13–18 times compared to 2021 under the BAU. Data uncertainty results are reported in S-1 (Figure S5), and the main parameters affecting model predictions include the decline in ore grades over time, the time needed for new ore extraction, and changes in global international trade structure.

Total Li flow into the chemical refining stage in China is projected to reach 1265 kt in 2050, nearly 13 times larger than in 2021. Although primary lithium imports are still expected to dominate raw Li supply, the import rate is expected to decline from 85% in 2021 to 70% in 2050. This is because China's domestic lithium supply is expected to increase by more than 15-fold of 2021 by 2050, and the secondary lithium supply is also expected to grow due to advances in recycling technology.

Total LIBs in manufacturing in China are expected to concentrate 1000 kt of Li in 2050, with an 18-fold increase compared to 2021. This is despite an expected increase in LIBs production capacity in the EU and the United States to reduce dependency on Chinese imports, which would represent a decrease in China's LIBs export rate from 52% of domestic production in 2021 to 30% in 2050. Total Li contained in LIBs at China's domestic use stage is expected to reach 490 kt in 2050, of which consumption in EVs and ESS is expected to account for 80% and 15%, respectively.

In-use lithium stock is estimated to reach 2.2 Mt in 2050, representing 115% of China's current Li reserves. 310 kt of Li contained in LIBs is expected to enter EOL in China in 2050. Since technologies are likely to improve in efficiency of lithium recycling, secondary lithium is projected to reach 192 kt in 2050, representing 39% of Li demand for domestic LIBs use. Even though an improved recovery rate is assumed, the contribution of recycled lithium is still insufficient to meet the Li surge in demand under the BAU.

3.3 | Circular pathways for lithium resources

To explore the potential of CE strategies in securing and addressing domestic Li supply constraints, this research quantifies changes to the BAU through scenarios that depict different circularity pathways. The scenarios provide an estimation of the extent to which changes in battery chemistries, policies, and waste management could help to reduce primary Li dependency in China's LIBs sector (Figure 4).

The IWM scenario focuses on effective and efficient waste management. In this scenario, EOL EVs batteries are repurposed to ESS before entering waste recycling, leading to Li demand decreasing to 365 kt in 2050, a 25% reduction compared to the BAU. Meanwhile, rapid improvements in waste collection and recycling efficiency lead to a significant share of Li recovery, making up to 80% of Li demand in 2050.

The NBC scenario assumes strategic support in research and development (R&D) activities leading to rapid adoption of Li-free battery chemistries and longer battery life spans. In this scenario, Li demand is predicted to remain stable at 100–120 kt between 2030 and 2040 and then decline to 90 kt in 2050, which is about 20% of that under the BAU. Although most of the lithium demand still relies on primary Li due to remaining inefficiencies in the waste management system, Li demand is expected to be reduced to the projected domestic primary Li supply.

The PDV scenario combines a range of circular strategies based on policy instruments and targets defined in "the 14th Five-Year Plan and Vision 2035" (GOVCN, 2021). Li demand is expected to peak in 2035 at 125 kt and then decline and remain constant at around 110 kt after 2045, a decline of 78% compared to the BAU. Secondary lithium is expected to grow and fulfill up to 83% of Li demand in 2050.

The SDV scenario is the most ambitious, simultaneously combining improvements in battery chemistry innovation, waste management, and policy support mechanisms. Here, Li demand is predicted to reach a peak of 107 kt in 2040, and then decrease to 84 kt in 2050. There is a delay in the peak Li inflow time compared to the previous PDV scenario, due to the assumed longer battery lifetime and higher rate of EOL repurposing. Secondary lithium is expected to exceed Li demand in 2050, creating a surplus of 6 kt Li, which could be exported or utilized in other industrial applications.

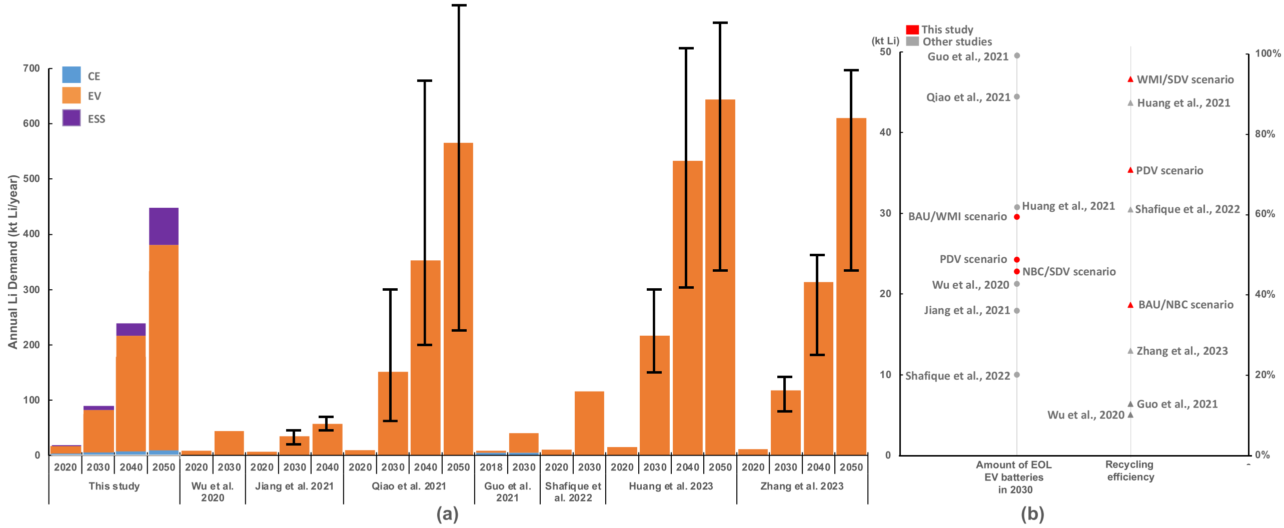
4 | DISCUSSION

4.1 | Comparison with previous literature

This study has provided an overview of future Li flows and stocks in China's LIBs sector. While there are some previous studies that cover Li flows and projections to 2050, this study has adopted a whole supply chain approach and includes other key application sectors. Despite the differences in system boundary, the comparison of the study results with those of previous studies identifies three main areas that justify deviations from results in previous studies: (1) differences in the selection of LIBs-powered products and main areas of application; (2) improvement in the estimation method of future demand and waste arisings; (3) assumptions around estimation of waste captured through the formal waste management system. Overall, the results of this study align with previous partial contributions, with some variations originating from these disparities noted above in modeling assumptions and approaches (Figure 5).

This study estimates lithium flows covering all LIBs-powered products and generates scenarios up to 2050 to describe different pathways for more circular and sustainable lithium use. The wider scope of this study and the improvement in the method for lithium demand forecast allows for a better representation of China's market saturation in the battery sector, which was not considered in previous studies. Li demand for power batteries alone, predicted in studies by Guo et al. (2021), Jiang et al. (2021), Wu et al. (2020), and Shafique et al. (2022) are comparatively smaller than in our study. The difference though is explained by the broader scope of EVs types considered in this study compared to previous ones. The predicted Li demand for power batteries in Huang et al. (2023), Qiao et al. (2021), and Zhang et al. (2023) are larger than in our study. In particular, Li demand for EVs in China in Huang et al. (2023) is projected to reach 611 kt in 2050, nearly twice as much as in our study, as it assumes the same growth pathway for all types of EVs and relatively short battery lifetime, just 8 years. Previous studies do not consider the effects of new battery development on total battery weight and Li intensity or EVs market saturation effects, which explains the larger estimates compared to our study.

As for the predicted waste arisings and the proportion of secondary lithium use, our results are in line although slightly smaller than for most other studies. The differences stem from the following: (1) former studies assume a high-growth assumption in battery-containing product demand, while this study assumes stock saturation in consumer electronics and EVs markets, with different electrification pathways for different types of vehicles by 2050 in line with ICET (2020); (2) former studies assume a high-efficiency EOL management; however, this study departs from the current limitations in the waste collection and recycling systems, as well as challenges for EOL batteries repurposing; (3) former studies assume a short average battery lifespan, but this study assumes a relative longer battery lifespan and a reduction of Li content in batteries as technology advances, in accordance with latest developments.



(Underlying literatures are available in the S-1 Table S11)

FIGURE 5 Comparisons for the amount of Li demand (a), the number of end-of-life (EOL) electric vehicle (EV) batteries in 2030 (b, left), and waste Li recycling efficiency (b, right) in China across studies (underlying literatures are available in S-1 Table S11). BAU, business-as-usual; IWM, improved waste management; NBC, new battery chemistry; PDV, policy-driven vision; SDV, sustainability-driven vision; CE, consumer electronics; ESS, energy storage system.

4.2 | Changes in trade dynamics and geopolitical considerations

One of the most prominent areas of uncertainty in this analysis stems from the assumptions around the evolution of global trade dynamics in the LIBs market. In the current context, China's current dominance of Li processing and battery manufacturing, supported by foreign investment in mining countries, has sparked concerns over the resilience of the EU and the US positions and led to policy responses to promote domestic Li mining and battery manufacturing and increase recycling capacity, which may affect future global trade of Li and secondary Li, but also distribution of production capacity. The EU's new "Critical Raw Materials Act" (EC, 2023) aims to support domestic Li mining, LIBs manufacturing, and the developing of recycling to reduce imports' dependence and enhance domestic supply chain resilience. While China's domestic LIBs demand remains strong, it is likely that global battery chemicals processing and battery manufacturing will be more geographically distributed in the coming decades. Currently, the EU represents 35% of total exports of LIBs from China and the United States 20% (UN Comtrade Database). If benchmarks for the EU and the United States are achieved, the role of China may significantly change. This creates a global context of uncertainty around the distribution of extraction, manufacturing, and demand, fueled by more restrictive trade policies. Even in this scenario of increased trade tensions, China's strong domestic demand would help to secure a relevant position of China in the global market.

Secondary material distribution is also highly dependent on domestic battery consumption and installed recycling capacity. While there are inefficiencies in China's collection and recycling systems, this situation is changing rapidly due to the accelerated expansion of the battery recycling sector in China and other regions of Asia. Connections between recyclers and manufacturers are helping to smooth some of the obstacles traditionally affecting Li recovery from LIBs. Globally, changes in the legislation both in the EU and the United States, such as the new "Regulation (EU) 2023/1542," are also leading to a rapid expansion of the installed capacity and providing an industry push for more efficient systems, which includes Li recovery rate target of up to 80% of LIBs by 2031. Recent estimates indicate that recycling capacity in Europe may increase from 160 kt in 2023 to 400 kt in 2025, across all battery materials (Saatkamp, 2023). Under this rapidly changing context, uncertainties arise associated with new trade dynamics and complex geographical restructuring of the whole supply chain, resulting in higher possible variation in the trajectory of the projected exports. The surge in demand for LIBs globally though makes it unlikely for China's major role to drastically change.

4.3 | Circular policy recommendations and research implications

Despite major changes in the global context of lithium processing and battery manufacturing, as described above, China is likely to maintain a dominating global position in LIBs and LIBs-powered products trade, supported by well-established LIBs whole supply chain and rapid expansion of production and recycling capacity, and increase Li production in mining regions globally. This study has comprehensively explored Li flows and stocks across all main sectors of application in China's LIBs sector and has identified potential future domestic lithium constraints, which will require adjustments on both Li supply and Li demand for final products. The results have highlighted the importance of CE strategies to enhance Li supply security and enable sustainable low-carbon transition. However, this requires addressing current bottlenecks and defining supporting policy frameworks in at least four areas, especially in light of the changing global landscape.

(a) Support innovation to optimize primary material extraction.

One of the high-risk areas in China's LIBs supply chain is lithium imports reliance. Our study shows that China's imports reliance is expected to remain above 70% in the next few decades. While China has some domestic reserves, their exploitation is restricted. Identified lithium resources in China increased to 6.8 Mt in 2022, but the high magnesium-to-lithium ratio and harsh geographical conditions constrain the mining due to the poor economic feasibility of Li extraction and beneficiation, as well as high costs of water and waste treatment during mining (Sun et al., 2024). According to the report of Qinghai Salt Lake Industry (2023), costs of lithium extraction from salt lakes and pegmatites in China are 30,000 and 55,000 RMB/t respectively, compared to more competitive global prices such as that for Chile with around 16,000–20,000 RMB/t.

New mining technologies can help promote domestic Li production by reducing extraction costs and environmental impacts during mining. These may include technologies such as advanced sensing and ore extraction, dehydrating, mineral extraction from tailings, and electrification of extractive actives, which may be supported by R&D policies and investment and strategic investment and stricter cleaner production policies to ensure the adoption of advanced technologies and best practices (CCSI, 2023). This is of critical importance given the ore quality of Chinese reserves. This may also lead to scope 3 emission reductions of primary mining.

On the other hand, China, as the main lithium importer and dominating position in global trade, can help to strengthen global mining standards through international commitments and policies, following other regions such as the EU.

(b) Further policy support and public-private investment for new chemistries R&D.

Recent studies (Dai et al., 2019; Liu et al., 2021b; Wang and Yu, 2020b) point to the manufacturing phase as one of the main hot spots in batteries' environmental life cycle impacts. Exploring new more efficient manufacturing processes, increasing renewable energy use in production processes, and promoting R&D for the development of lower-impact battery chemistries and binders may help to reduce the overall footprint. This study has explored that the uptake of new battery chemistries is expected to help reduce annual Li demand by 20%–80%. The uptake of new battery chemistries at different levels of maturity is still uncertain but is likely to contribute to impact reduction. While some timid steps have been taken in this direction in China, through a new series of battery management measures (e.g., "GB 31241–2022" and "GB 40165–2021") to promote the technological transformation of LIBs production processes and R&D of substitute battery materials, there is room for more ambitious policies to reduce risks of adoption and then dissemination at a larger scale (SAC Platform, 2024).

(c) Stringent waste management targets and supporting mechanisms for industrial symbiosis.

Considering the current limitations of China's current EOL management system, increasing the waste collection rate should be given priority. This study shows that 70 kt of Li contained in spent LIBs may be lost due to an ineffective collection system, causing a significant resource loss for China's secondary Li market. While most attention has been drawn to EVs batteries, cumulative lithium concentrations in consumer batteries are also relevant, and the current level of recovery through recycling is very low. Besides, as China is expected to remain a net exporter of LIBs and products, in the absence of new business models, large flows of lithium will leave the Chinese system boundary and enter the EOL stage abroad. Results indicate that recyclable Li contained in exported commodities is expected to increase from 30 kt in 2021 to 450 kt in 2050. That may limit the capacity of secondary Li recovery in China, though it may result in a more developed secondary trade of Li globally. Results also suggest the untapped potential of lithium recovery in other industrial applications beyond batteries. In 2021, 35.5 kt of Li was used for other Li-containing applications, accounting for 34% of Li mine outputs. While it is beyond the scope of this paper, levels of recovery are not reported but are expected to be even lower as no formal systems for collection and recovery are in place (Sun et al., 2024).

The root cause of these inefficiencies is the lack of stringent sets of regulations and targets for the collection and treatment of LIBs in China across application sectors. The extended producer responsibility policies are still largely absent in the Chinese policy landscape, creating a lack of coordination between producers and treatment operators. The concentration of both manufacturing and recycling capacity in China creates opportunities to develop an industrial eco-system based on industrial symbiosis with close interaction between manufacturers and recyclers to optimize secondary material use. This also needs to be accompanied by policies that promote secondary Li use in LIBs manufacturing, such as setting recycled content minimum targets and the use of taxes and economic instruments to provide economic incentives for secondary materials.

(d) Policies and regulatory instruments to promote material traceability and new business models.

The new "Regulation (EU) 2023/1542" has introduced instruments such as battery passports to enhance the transparency and traceability of batteries by providing digital identifiers that detail battery materials, their origin, and the carbon intensity of battery manufacturing. This is already an incentive to improve the traceability of exported LIBs to the EU. This type of policies could be used domestically to increase the traceability of all battery materials and, potentially, promote the adoption of new business models, such as battery leasing and reverse logistics. Interventions focusing on life extension through modular design, and business models based on selling performance rather than products, could help to address current circularity gaps. Systems of enhanced traceability and digital technologies, such as sensors in the Internet of Things, can also help to develop advanced systems of planned maintenance and repair, which can improve performance, extend batteries' lifetime, and facilitate the introduction of performance and leasing models for batteries (see, e.g., the use of manufacturing execution system for real-time data collection and quality control in battery production at CATL) (CATL, 2024).

5 | CONCLUSION

With the rapid development of China's LIBs industry in recent years and predicted future growth, concerns around domestic primary Li constraints have been raised, which may become a potential bottleneck compromising the low-carbon transition. A comprehensive bottom-up dynamic MFA model of current and future lithium flows and stocks in China's LIBs system has been undertaken in this study. Results show that from 2021 to 2050, LIBs production and consumption in China are expected to continue to grow as EVs become more widespread and ESS develops. Cumulative lithium demand is expected to reach 6.65Mt in China's LIBs market in the period 2021–2050 under the BAU, which is nearly equal to China's currently measured Li reserves. However, over 70% of primary lithium in China is still expected to rely on imports, raising issues of future lithium supply constraints and risks of import security. In parallel, EOL batteries are expected to significantly increase from 4 kt in 2021 to 310 kt in 2050. Departing from the current context of China's EOL management system, unless measures are taken, less than half of waste LIBs may be collected in 2050, leading to a relatively modest contribution of recovered Li, which may be around 39% of lithium demand for domestic LIBs in 2050 under the BAU. Four different circularity strategies have been developed as future scenarios and compared against the BAU. Despite current challenges, the analysis shows that the potential of new chemistry innovation and improving waste management is promising for a more circular and sustainable lithium supply in China's LIBs sector, with implications for primary raw material extraction and reduction of associated environmental impacts. Four areas of policy intervention are proposed based on the results to accelerate the transition toward a more circular lithium use in China's battery sector.

CONFLICT OF INTEREST STATEMENT

All of the authors declare that they have no conflicts of interest. The authors confirm that this is an original submission that has not been published previously or submitted to any other journal.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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