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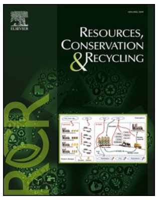

Full length article

Exploring the circular economy future of lithium-ion batteries in australia through comprehensive dynamic material flow analysis

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ABSTRACT

Despite its dominant role as a major supplier of battery materials, Australia faces significant challenges in managing end-of-life (EoL) lithium-ion batteries (LIBs). With growing interest in establishing a circular economy of LIBs in Australia, robust quantitative analysis is urgently needed to inform policy and industrial actions. This study develops a dynamic, regionally-resolved material flow analysis (MFA) model to project the future LIB demand, EoL arisings, battery repurposing, and material recycling potential (MRP) across electric vehicles (EVs), battery energy storage systems (BESS), and handheld products in Australia. Results underscore the challenges of collecting handheld devices and the regional heterogeneity in battery waste volumes and compositions. The repurposing potential of EV batteries is projected to remain limited in this decade, but could significantly reduce and potentially eliminate battery imports to meet domestic BESS demand as early as 2038. The cumulative MRP for EoL LIBs would reach 2481–4471 kt in Australia between 2025 and 2050, with an estimated economic value of 23–44 billion US dollars. These findings highlight the importance of effective collection systems and regional differentiated EoL policies for LIBs, as well as significant opportunities in developing onshore repurposing and recycling capabilities in Australia.

1. Introduction

Australia plays a key role in the global supply chain of lithium-ion batteries (LIBs), accounting for 48 % of global lithium mine production in 2023 (USGS, 2024). Despite its dominance in the upstream raw material market, Australia faces significant challenges in establishing a circular economy for LIBs, especially in their end-of-life (EoL) management. Only 10 % of EoL LIBs in Australia were collected for recycling in 2021 (CSIRO, 2024), while the majority ended up being stockpiled or landfilled, causing >10,000 fires in waste management trucks and facilities each year (Baker, 2024). In addition, the historically low volume of battery waste has discouraged the development of onshore recycling facilities in Australia (Furtado et al., 2024; King and Boxall, 2019). As a result, even the small fraction of LIBs that are collected can only be pre-processed within Australia before being exported as black mass to East Asia for further material recovery, resulting in substantial losses of valuable materials and economic value (Zhao et al., 2021).

While there is growing policy interest in the establishment of a circular economy of LIBs in Australia, there is still a lack of a uniform national regulatory framework and clear policy guidance. Currently, Australia's official battery stewardship relies on voluntary schemes like B-cycle, which only covers handheld batteries and lacks mandatory collection targets (Battery Stewardship Council, 2024; Boxall et al., 2018). In 2024, Australia introduced its National Battery Strategy which identifies establishing a circular economy as one of its five priorities, but concrete measures or roadmaps to achieve that goal are still in development (National Battery Strategy, 2024).

To better guide policymaking towards a circular economy, it's essential to identify key challenges and opportunities associated with EoL LIBs in Australia. This requires a comprehensive quantitative analysis of the future EoL LIB flows to explore the potential for different sustainable EoL options (e.g., battery repurposing and material recycling), a process often modelled through dynamic material flow analysis (MFA) (Brunner and Rechberger, 2016; Muller et al., 2014). While researchers have developed numerous MFA models for LIBs at different geographical scales, including global (Lopez et al., 2023; Maisel et al.,

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2023; Xu et al., 2020; Zeng et al., 2022) and regional levels (Ai et al., 2019; Baars et al., 2021; Bobba et al., 2019; Dunn et al., 2022; Liu et al., 2021; Shafique et al., 2022; Slotte et al., 2025; Song et al., 2019; Zhou et al., 2024), most of these studies have focused on electric vehicle (EV) batteries, particularly passenger cars, and neglected other LIB markets.

However, the growing LIB demand for consumer electronics and battery energy storage systems (BESS) necessitates the inclusion of a broader product scope in MFA models (Liu and Domenech Aparisi, 2024). This is particularly relevant in Australia, which has one of the fastest-growing BESS markets worldwide, driven by residential rooftop photovoltaic installations and grid-scale BESS deployment as renewable energy penetration rises (Clean Energy Council, 2023; Wood Mackenzie, 2023). Repurposing EV batteries for BESS applications presents a significant circular economy opportunity in Australia, which requires cross-sectoral modelling of upstream EoL flows from the EV sector and downstream BESS demand (Aguilar Lopez et al., 2024). In parallel, due to lagging EV adoption, handheld consumer electronics remain the dominant source of EoL LIB waste in Australia. Yet the absence of detailed modelling for this stream limits the understanding of policy levers for waste reduction. In addition, EoL LIB regulations vary across Australian jurisdictions (Furtado et al., 2024), making regional-level modelling essential for capturing spatial differences in battery waste generation, collection needs, recycling potential, and policy requirements. However, a comprehensive, cross-sectoral analysis of LIB flows with regional resolution in Australia remains absent. Existing reports only offer basic statistics on waste batteries without systematically evaluating repurposing or material recycling potential (MRP) (Energeia, 2019; Langdon et al., 2023). The lack of integrated analysis limits the development of effective policy frameworks to advance a circular economy for LIBs.

By developing a comprehensive dynamic MFA model that captures material flows across three major LIB markets (i.e., EV, BESS, and handheld products), this study addresses the critical need for an integrated understanding of EoL LIB management in Australia. The model projects future LIB demand, EoL LIB volumes, and their repurposing potential and MRP across eight Australian jurisdictions, considering variations in climate scenarios, battery lifespans, and battery chemistry mix. The cross-sectoral, regionally resolved approach not only fills the gap in literature but also enables targeted insights and circular economy levers. The findings contribute to the design of effective, context-sensitive policy strategies for advancing the circular economy for LIBs in Australia, with broader relevance to other markets facing similar challenges in developing collection systems and recycling infrastructure.

2. Methods

2.1. Model overview

Fig. 1 depicts the major battery life cycles in Australia and the system boundary for the MFA model. As Australia lacks domestic EV and battery manufacturing capacity, batteries are mostly imported and embedded within finished products, such as EVs and BESS units. After being put on the market, LIBs enter the in-use stage and stay for several years before reaching their EoL, the duration depending on the specific applications. Collection systems for LIBs are still in development in Australia, as a result, a proportion of EoL LIBs could remain uncollected, accumulating as obsolete stocks or ending up in scrap yards (Furtado et al., 2024). The rest of the EoL LIBs are collected for repurposing or recycling. For instance, EV batteries typically retire when their energy capacity drops to 70–80 % of their initial capacity, but some of them remain suitable for less-demanding applications, such as being repurposed as BESS (Prenner et al., 2024; Zhu et al., 2021). Another option for collected EoL batteries is recycling, which typically involves (1) a pre-processing treatment that turns EoL LIBs into the black mass, a powdered material containing valuable metals extracted from shredded LIBs, and (2) subsequent pyro- and hydro-metallurgical recycling processes for further material recovery (Fan et al., 2020; Neumann et al., 2022). Material losses occur during these processes due to limited processing efficiencies, as detailed in **SM-Table S10.**

In contrast to existing MFA models that often focus on passenger

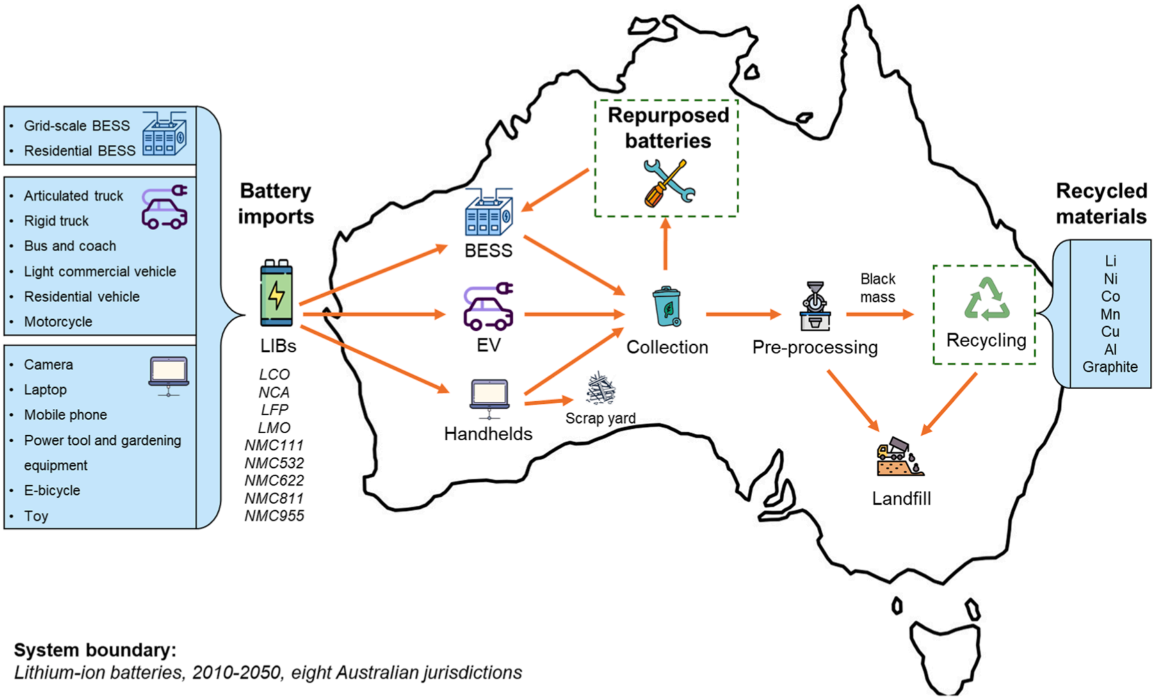

Fig. 1. Schematic diagram of the dynamic MFA model for LIBs in Australia. Note: LIB waste needs to be pre-processed domestically, which is then exported for further material recovery, given Australia's limited domestic recycling capacity. While not currently in place, onshore recycling may emerge in the future and is depicted using a dashed-line box. Spatial resolution is at the jurisdiction level. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

cars, our model covers the EV, BESS, and Handhelds markets, each including various and distinct LIB-containing products (Fig. 1). The EV market (including battery electric vehicles and plug-in electric vehicles) consists of six types of vehicles, namely buses, articulated trucks, rigid trucks, light commercial vehicles, passenger cars, and motorcycles. Each of these vehicle types has distinct usage patterns and battery pack sizes (more details are provided in the Supplementary Materials, **SM-Note S1, Table S2**). The BESS market includes both grid-scale BESS and residential BESS. The Handhelds market includes cameras, laptops, mobile phones, tablets, power tools and gardening equipment, E-bicycles and scooters, and toys.

To account for the varying implications of different battery chemistries, this study considers 9 types of widely used LIB chemistries, including lithium cobalt oxide (LCO), nickel-cobalt-aluminium oxide (NCA), lithium iron phosphate (LFP), lithium manganese oxide (LMO), and five variants of nickel-manganese-cobalt oxide (NMC) batteries (Grey and Hall, 2020; Houache et al., 2022). Other LIB chemistries are not included because of their minimal market shares (IEA, 2024a). Based on current recycling technologies (Neumann et al., 2022; Sommerville et al., 2021; Tian et al., 2024), we identify minerals recoverable from EoL LIBs and estimate the MRP for seven minerals listed on Australia's Critical and Strategic Mineral list (Department of Industry Science and Resources, 2024): lithium (Li), nickel (Ni), cobalt (Co), manganese (Mn), aluminium (Al), copper (Cu) and graphite. The rest of this section describes the calculation methods, data sources and key assumptions for the model.

2.2. *Quantifying the MFA system*

Product and battery pack inflows. The key task to quantify the MFA system defined in Fig. 1 is to calculate the flows and stocks of the in-use stage. For any given product, the stock-driven model calculates annual inflows based on prospective stocks and their lifetime distribution (Muller et al., 2014):

$$\mathrm{in}_{i,\, n}(t) = S_{i,\, n}(t) - S_{i,\, n}(t-1) + \sum_{s<t} \mathrm{in}_{i,\, n}(s) \times \mathrm{ltd}_i(t-s) \tag{1}$$

Where the subscript i denotes product category, and n indicates the n-th region; *in (t)* and *S (t)* represent the inflow and stock in the year of t, respectively, measured in units; *ltd* represents their lifetime distribution functions, which are assumed to be normal distribution in this study (Abdelbaky et al., 2021; Zeng et al., 2022; Zhou et al., 2024); *ltd (t-s)* indicates the probability that products/batteries sold in the year of s reach their EoL in the year of t. Therefore, the annual inflows are driven by both net stock growth (i.e., $S_{i,\, n}(t) - S_{i,\, n}(t-1)$) and the replacement of failed product or battery from earlier inflows (i.e., $\sum_{s<t} \mathrm{in}_{i,\, n}(s) \times \mathrm{ltd}_i(t-s)$).

Eq. (1) can also be applied to calculate battery pack inflows, assuming that each EV in the stock is equipped with one functioning battery pack of varying sizes (i.e., EV stock = battery pack stock). When battery lifespans are assumed to be shorter than those of EVs, Eq. (1) yields higher inflows for batteries than for EVs. This difference endogenously captures battery replacement demand for EVs without requiring additional assumptions about replacement timing.

Australian Energy Market Operator (AEMO) estimates future EV stocks by vehicle type across different states in Australia based on energy system models, which consider the impacts of various factors including future fuel costs, EV prices, transport demand, and demographic factors (AEMO, 2024a, 2024b; Graham, 2022). These EV stock projections are adopted to calculate the EV and battery pack inflows, with detailed descriptions provided in **SM-Note S1**. The historical and prospective sales for handheld LIBs are obtained from Langdon et al. (2023). Residential BESS stocks are also provided (AEMO, 2024a), however, the available data is not sufficiently disaggregated to identify grid-scale BESS. Accordingly, the following method is used to estimate stock levels for grid-scale BESS by state:

$$S_{\text{grid-scale BESS},\, n}(t) = PC_n(t) \times StG(t) \times SD(t) \tag{2}$$

where *PC* represents the power capacity of grid-scale wind and solar power stations in units of GW; *StG* denotes the storage-to-generation ratio, which is the required energy capacity of BESS relative to the power capacity of these stations; *SD* denotes the average storage duration of batteries, in the unit of hours. Data sources for these variables are provided in **SM-Note S2**. Recognising that future BESS demand may be partially met by non-LIB chemistries such as sodium-ion batteries, LIB demand for BESS is estimated by applying projected LIB market shares (see **SM-Table S4**) to total BESS demand.

Battery capacity and material inflows. With the product and battery pack inflows estimated using Eq. (1) and Eq. (2), battery and material inflows can be calculated as follows:

$$\mathrm{in}_{j,\, n}(t) = \sum_{i} \mathrm{in}_{i,\, n}(t) \times \mathrm{Cap}_i(t) \times \mathrm{MS}_{i,\, j}(t) \tag{3}$$

$$\mathrm{in}_{k,\, n}(t) = \sum_{j} \mathrm{in}_{j,\, n}(t) \times \mathrm{MI}_{j,\, k}(t) \tag{4}$$

where subscript j and k denotes battery chemistry and material type, respectively; Cap_i denotes the average energy capacity of LIB pack used in the i-type product, in the unit of kilowatt-hours (kWh); The average energy capacity of EV batteries has increased over the past decade (IEA, 2023) —a trend we assume will continue due to consumer preferences for longer driving range and larger vehicles (Baars et al., 2023) (see **SM-Note S3** and **SM-Table S2** for detailed assumptions). $\mathrm{MS}_{i,\, j}$ represents the market share of j-type battery chemistry used in the i-type product (see **SM-Table S3** and **Table S5**); $MI_{j,\, k}\ (t)$ represents the material intensity of k-type material in the j-type battery chemistry, in the unit of kg/kWh (**SM-Table S8**). As Australia heavily relies on battery imports from the global market, global average data are used for these data inputs.

EoL arisings of products, batteries, and materials. With the estimated inflows of different types of products, batteries, and materials, their EoL arisings, *out (t)*, could be calculated using the inflow-driven model (Muller et al., 2014):

$$\mathrm{out}_{i,\, j,\, k,\, n}(t) = \sum_{s<t} \mathrm{in}_{i,\, j,\, k,\, n}(s) \times \mathrm{ltd}_{i,\, j,\, k}(t-s) \tag{5}$$

Battery repurposing and material recycling potential. Battery repurposing potential and MRP are calculated using Eqs. (6) and (7), respectively:

$$\mathrm{BRC}_n(t) = \sum_{i,\, j} \mathrm{out}_{i,\, j,\, n}(s) \times 80\% \times \mathrm{CR}_{i,\, j,\, n}(t) \times \mathrm{RR}_{i,\, j,\, n}\ (t) \tag{6}$$

$$\mathrm{MRP}_{k,n}(t) = \sum_{i,\, j} \mathrm{out}_{i,\, j,\, k,\, n}(s) \times \mathrm{CR}_{i,\, j,\, n}(t) \times \mathrm{RE}_{i,\, j,\, k}\ (t) \tag{7}$$

Where *BRC* denotes the battery repurposing capacity from EV batteries; *CR* denotes the EoL collection rates of LIBs; We assume that large-format batteries from EVs, BESS, and e-scooters will all be adequately collected (i.e., *CR* reaches 99 % by 2040), following the global legislative trends (Niri et al., 2024). However, due to persistent challenges in shifting consumer behaviour, *CR* for handheld products is projected to increase gradually—from current levels to 45 % by 2030 and 73 % by 2040, as detailed in **SM-Table S6**. *RR* denotes the repurposing rate, i.e., the proportion of EoL EV batteries that are repurposed for a second life. *RE* denotes recycling efficiency, i.e., the proportion of materials that are recovered from recycling processes (**SM-Table S10**); MRP denotes material recycling potential, i.e., the amount of material that could be potentially recovered, which may exceed outcomes in real-world recycling systems.

Notably, repurposing and recycling are treated as mutually exclusive pathways to enable a clearer assessment of their respective upper-bound potentials in this study, which are not intended to be additive. For instance, the MRP is calculated without modelling a sequential flow where batteries are first repurposed and later recycled. A conservative stance is adopted in estimating BRC, reflecting the technical, operational, and economic challenges associated with second-life applications (Al-Alawi et al., 2022; Gu et al., 2024). In particular, repurposed batteries may struggle to compete with new ones in cost-effectiveness and performance, limiting their market attractiveness (Zhu et al., 2021). Accordingly, we assume a repurposing rate of 50 % for LFP batteries—due to their suitability for repurposing—and 0 % for NMC batteries, which are considered more suitable for direct recycling due to safety concerns and higher material value (Al-Alawi et al., 2022; Ma et al., 2024) (see **SM-Note S6**). The repurposed batteries are assumed to retain 80 % of their initial capacities (Xu et al., 2020; Zhou et al., 2024).

2.3. Scenarios design and key settings

MFA modelling results are subject to significant uncertainties arising from numerous data inputs and parameter assumptions, and scenario analysis is commonly used to incorporate these uncertainties (Shafique et al., 2022; Zhou et al., 2024). This study considers three highly uncertain and impactful factors, including climate scenarios, battery lifespans, and battery chemistry mix, and develops scenarios to analyse their impacts. Other sources of uncertainty are addressed in the Limitations section.

Climate scenarios. The future adoption of EVs and BESS in Australia is highly uncertain and significantly influenced by the nation's climate ambitions. We adopt two climate scenarios developed by AEMO, namely the Step Change (SC) scenario and the Progressive Change (PC) scenario. The SC scenario fulfils Australia's emission reduction commitments and anticipates a fast transition towards EVs and renewables, being viewed as the most likely scenario for Australia (AEMO, 2024a). On the other hand, the PC scenario reflects Australia's current policies and slower investment in clean energy transition, resulting in lower adoption rates of EVs and renewables (AEMO, 2024a).

Battery lifespan. Battery lifespan is an important parameter as there could be a mismatch between the lifespan of vehicles and batteries, resulting in substantial battery replacement demand (Baars et al., 2021). However, the actual lifespan of batteries is uncertain because it depends on multiple factors such as the ambient temperature, depth of discharge, road conditions, intensity of use (e.g., via shared ownership models), and drivers' driving habits (Han et al., 2019). While most EV manufacturers offer a warranty of eight years, the average lifespan of EV batteries is often assumed to be 10–15 years in the literature (Zhou et al., 2024). Therefore, the model adopts two EV battery lifespan scenarios: (1) the Short scenario assuming an average of 10 years and (2) the Long scenario assuming an average of 15 years. The average battery lifespan for other products is summarised in **SM-Table S7**.

Battery chemistry mix. As each battery chemistry has different performance and material compositions, future market shares of different chemistries (i.e., battery chemistry mix) could significantly impact battery repurposing potential and MRP. This study establishes two battery chemistry scenarios for the EV market: (1) the LFP scenario which represents a future with increasing market shares of LFP batteries; and (2) the NMC scenario assuming an increasing market share of NMC batteries, with detailed assumptions provided in **SM-Table S3**. The BESS and Handhelds market are assumed to adopt different future battery chemistry mixes due to their distinct performance and cost requirements (**SM-Table S5**).

The scenario design for these three key factors is summarised in Table 1. Scenario names for different factors can be combined for simplicity of expression. For example, the SC-Long-LFP represents the scenario where the adoption of EVs and renewables follows the SC scenario, the EV battery has an average lifespan of 15 years, and the future EV market is dominated by LFP batteries.

Table 1
Scenario design and assumptions for three key factors.

Factors	Scenario names	Brief descriptions
Climate scenarios	Progressive change (PC)	The PC scenario assumes moderate growth in EVs and renewables, following the historical trend (AEMO, 2024a).
	Step change (SC)	The SC scenario assumes higher climate ambition and a faster transition towards EVs and renewables, considered the most likely scenario (AEMO, 2024a).
EV Battery lifespan	Short	An average lifespan of 10 years, following the normal distribution.
	Long	An average lifespan of 15 years, following the normal distribution.
Battery chemistry mix	NMC	The NMC scenario assumes Australia will import more EVs with NMC batteries, with their market share rising from 54.5 % in 2022 to 82.0 % by 2050.
	LFP	The LFP scenario envisions a future where LFP-equipped EVs gain prominence in Australia, with their market share growing from 35.1 % in 2022 to 55 % by 2050.

3. Results and discussion

3.1. Rapid LIB demand growth driven by accelerated EV and BESS adoptions

Driven by rapid growth in EV adoption, the total LIB demand in Australia is projected to rise from 7 GWh in 2022 to 140–280 GWh by 2050 under different scenarios (Fig. 2). The SC-Short scenario, with a faster transition to EVs and renewables, projects the highest LIB demand (280 GWh), marking a 35-fold increase from 2022(Fig. 2b). This is 56 % higher than that of the PC-Short scenario, largely reflecting the difference in climate ambition and the associated decarbonisation trajectories. Extending the EV battery lifespan from 10 years to 15 years reduces the annual LIB demand by 22–26 % in 2050 under different climate scenarios (Fig. 2c-d).

EV adoption rates have been historically low in Australia, with a market share of 3.8 % in 2022 (Electric Vehicle Council, 2023), much lower than other developed economies such as the EU (21.0 %) (IEA, 2024b); however, Australia has seen accelerated EV adoptions in recent years, a trend that will last in the next decades (AEMO, 2024a). EV passenger cars will be the largest contributor to LIB demand growth and require 157 GWh of LIBs by 2050 under the SC-Short scenario, accounting for 56 % of the total LIB demand. Light commercial vehicles and rigid trucks are another two important contributors, requiring 65 GWh and 25 GWh of LIB by 2050, respectively. The LIB demand for articulated trucks and buses is projected to reach 5 GWh and 3 GWh in 2050, respectively. By 2050, Australia is projected to require a total of 16 GWh of LIBs for grid-scale and residential BESS annually under the SC-short scenario. While handheld devices represented over 80 % of total LIB demand in 2020, their share is projected to decline sharply to 10 % by 2030 and just 2 % by 2050, due to much slower demand growth compared to EVs and BESS.

While passenger cars will account for 55–59 % of Australia's total LIB demand by 2050 under different scenarios (Fig. 2), over 40 % of the demand will stem from other applications. This suggests MFA models for LIBs should not be limited to passenger cars but also include other EVs, BESS and handheld applications for a more complete picture of future LIB flows; otherwise, it would significantly underestimate the scales of future LIB demand, EoL arisings, and subsequently MRP of LIBs.

3.2. Rising EoL LIB volumes calling for effective collection systems

The volume of EoL LIBs will surge from 2 GWh in 2022 to 58–183 GWh by 2050, and the growth trajectory depends on climate scenarios and battery lifespan assumptions (Fig. 3a). The SC-Short scenario

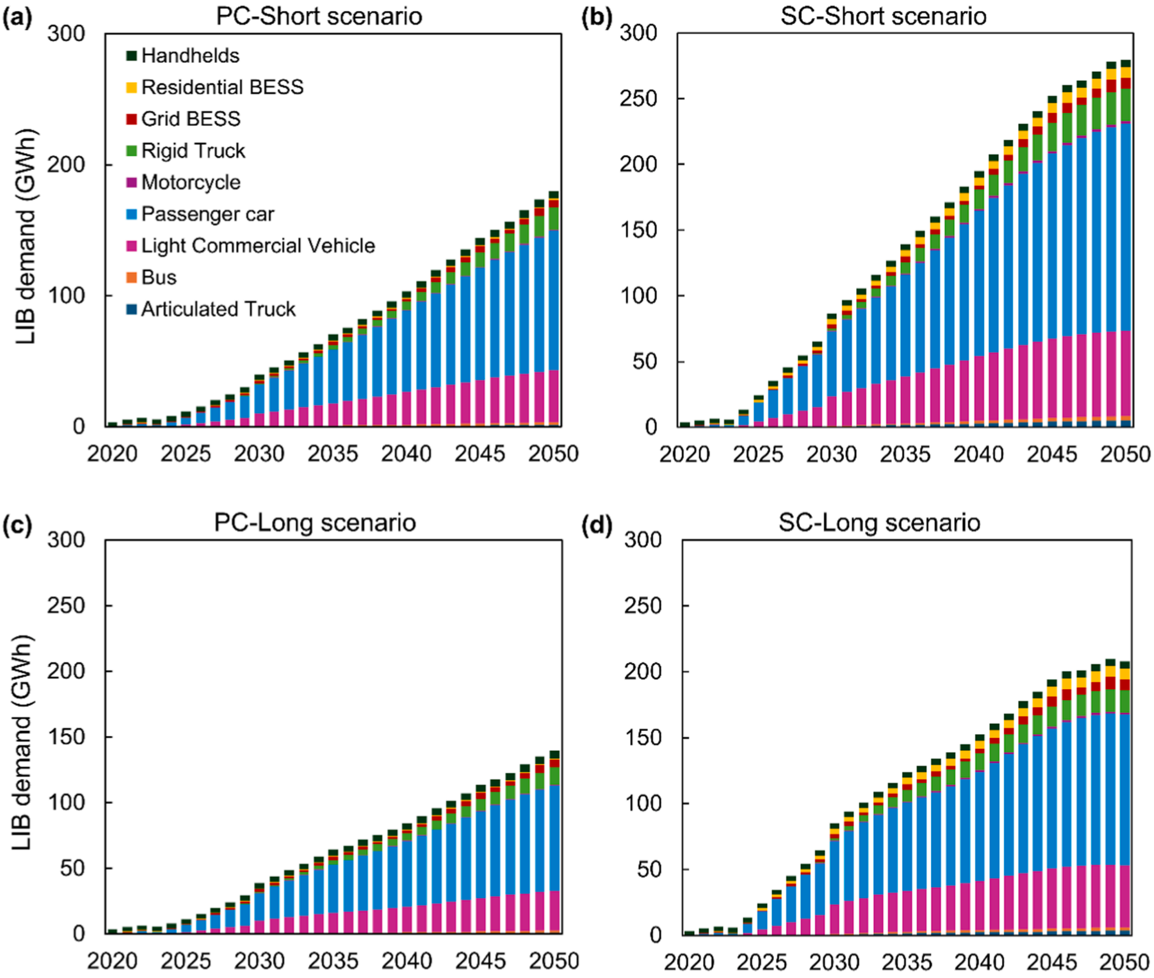

Fig. 2. LIB demand by product type in Australia during 2020–2050 under different scenarios. Note: (a–d) show results under four scenarios combining two climate scenarios (SC and PC) and two EV battery lifespan scenarios (Short and Long). The results for each vehicle type include the LIB demand for both battery electric vehicles and plug-in electric vehicles. The results for different handheld products are aggregated into one category because of their small shares.

anticipates 183 GWh of EoL LIBs by 2050, nearly double that of the PC-Short scenario. The SC-Long scenario projects 113 GWh of EoL LIBs in 2050, 38 % less than the SC-Short scenario, indicating substantial benefits of extended EV battery lifespan in reducing future EoL LIBs.

Due to the relatively small market, limited battery waste streams have been identified as a key factor incentivising the development of a circular economy for LIBs in Australia (Boxall et al., 2018; Furtado et al., 2024). However, the situation is likely to change over the next decade, posing major challenges in effectively collecting EoL LIBs. The model projects a 5–11 times surge in LIB waste between 2022 and 2035, reaching 10–23 GWh under the most likely SC scenario. This corresponds to 59–133 kilotons (kt) of battery waste by 2035, calculated based on energy densities (**SM- Table S12**) and market shares (**SM-Table S4**) of different battery chemistries. For comparison, recent statistics indicate that only 0.5 kt of EoL LIBs—equivalent to an estimated 15.3 % collection rate—were collected in Australia during the 2024 fiscal year (Battery Stewardship Council, 2024). The striking difference highlights an urgent need for expanding battery collection systems for LIBs. Moreover, since the direct export of battery waste overseas is restricted under the Basel Convention, collected EoL LIBs must be pre-processed into black mass domestically, necessitating the development of sufficient pre-processing capacity within Australia.

In 2022, handheld devices accounted for 99 % of Australia's total LIB waste; however, only 10 % of handheld batteries were collected for recycling as of 2021 (Zhao et al., 2021). Despite increasing adoption in EVs and BESS, handheld batteries would still account for 66–88 % of total EoL LIBs by 2030 (Fig. 3b). This highlights the importance of increasing collection rates of handheld batteries in the short term. In the medium run, the share of EoL LIBs from EVs will increase from 1 % in 2022 to 30–75 %, and BESS from 0 % in 2022 to 5–15 % by 2035 (Fig. 3b). In the long run, EVs will become the dominant source of LIB waste by 2050, accounting for 86–92 % of the total EoL LIBs under all scenarios (Fig. 3b). The medium and long-term trends underscore the need for a national regulatory framework for managing EoL LIBs that covers EV and BESS batteries, which is currently lacking in Australia.

3.3. Regionally differentiated EoL LIB flows and management priorities

Our results reveal substantial regional heterogeneity in projected EoL LIB volumes, reflecting differences in EV and BESS uptake, population, and local policies across jurisdictions. EoL LIBs will be predominantly concentrated in three eastern coastal states (Fig. 3c). The volume of EoL LIBs by 2035 is estimated to be 7.0 GWh for New South Wales (NSW), 5.8 GWh for Victoria (VIC), and 4.9 GWh for Queensland (QLD) under the SC-Short scenario (Fig. 3c). These three states collectively represent three-quarters of the nation's total EoL LIB arisings. This is followed by Western Australia (WA) and Southern Australia (SA), while the remaining three states only contribute minimal volumes (Fig. 3c). Interestingly, WA exhibits a distinctive product composition of EoL LIBs, with a significantly higher proportion originating from BESS compared to other regions. This trend is attributed to the state's extensive deployment of grid-scale wind and solar power installations and

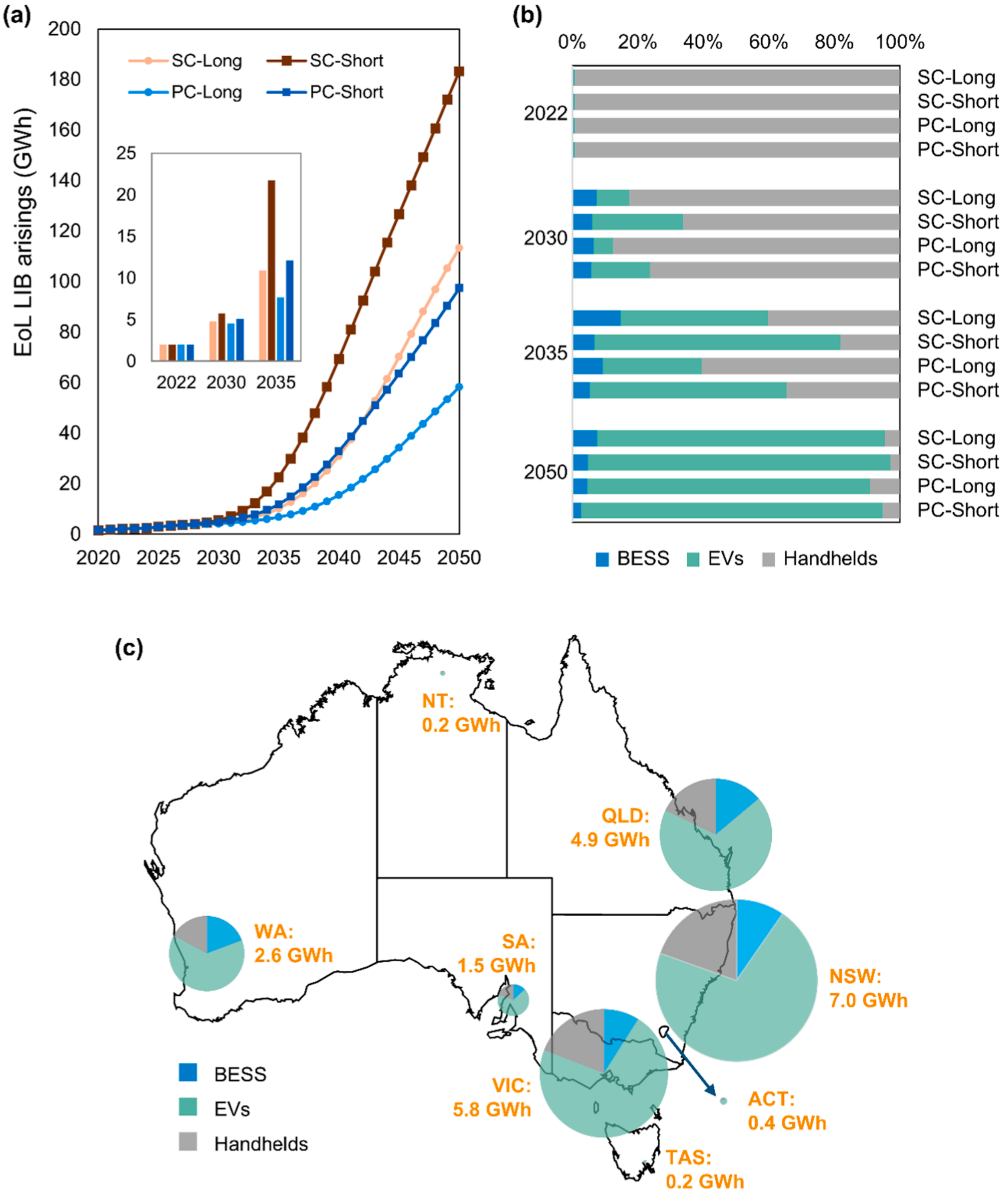

Fig. 3. Projected EoL LIB arisings in Australia. (a). The volume of EoL LIBs during 2020–2050 under different scenarios. (b). Contribution of three LIB markets to total EoL LIB arisings under different scenarios. (c). EoL LIBs arisings across eight states in 2035 under the SC-Short scenario. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

retirement of coal-fired power stations by 2030 (Climate Council, 2024), which drives greater BESS demand and subsequent BESS retirement volumes.

These spatial differences in both the volume and composition of EoL LIBs underscore the need for differentiated policy responses. It also reveals the limitations of national-level models, which often overlook region-specific waste dynamics. The vast geographic distances between states, along with the large area of each jurisdiction, could further increase the logistical costs of managing EoL LIBs and make localised processing solutions more economically attractive. States such as NSW, VIC, and QLD could prioritise scaling up recycling capacity and enhancing logistics infrastructure, while WA's distinctive BESS-heavy profile highlights the opportunity for early investment in second-life testing and the repurposing of EV batteries for BESS. Nonetheless, coordinated national strategies—such as harmonised classification and testing standards—could enhance overall system efficiency while still allowing for regionally tailored interventions.

3.4. From short-term gaps to long-term surplus: repurposing EV batteries for BESS

Leveraging a cross-sectoral MFA model, we assess whether and when repurposed EV batteries could meet Australia's future BESS demand. Fig. 4 illustrates the temporal relationship between BESS demand and

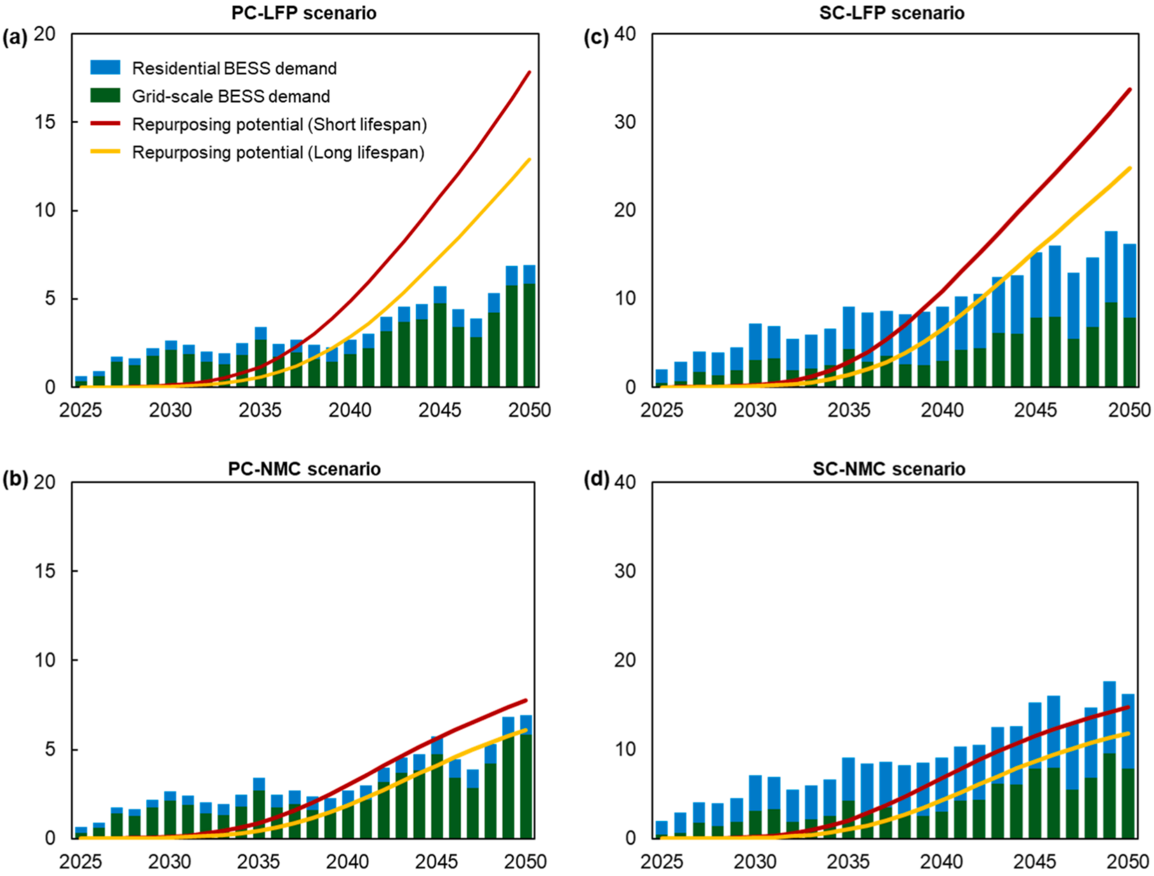

Fig. 4. Projected BESS demand and battery repurposing potential between 2025 and 2050. **(a–d)** show results under four scenarios combining two climate scenarios (SC and PC) and two chemistry mix scenarios (LFP and NMC). The bars represent the demand for residential and grid-scale BESS, while the curves represent the estimated repurposing potential with different EV battery lifespan assumptions. Note that while the trends are similar across SC and PC scenarios, the absolute values differ from each other.

repurposing potential across scenarios, highlighting a transition from short-term gaps to long-term surplus. Under the SC scenario (Fig. 4c and d), both repurposing potential and BESS demand are substantially higher than in the PC scenario (Fig. 4a and b); however, the relative magnitude between the two remains similar, indicating that both are similarly sensitive to climate scenario assumptions. Under all scenarios, the repurposing potential remains significantly lower than BESS demand in this decade, implying that Australia will continue to rely heavily on battery imports to meet its BESS demand. This is largely due to historically low EV adoption rates, which limit the availability of retired LIBs for second-life applications. Over the medium to long term, however, repurposing potential grows rapidly and is projected to exceed domestic BESS demand as early as 2038 under the PC-Short scenario, suggesting that Australia could use repurposed EV batteries to meet its BESS demand without relying on new battery imports. The surplus EoL EV batteries could also be repurposed for other applications such as low-speed vehicles or communication base stations (Ma et al., 2024).

Battery repurposing potential is influenced by battery lifespan assumptions—consistent with previous studies (Bobba et al., 2019)—and future battery chemistry mix. Our results show that repurposing potential is substantially lower in the NMC scenarios (Fig. 4b and d) than in the LFP scenarios (Fig. 4a and c), and only the LFP scenarios demonstrate sufficient capacity to meet domestic BESS demand. This outcome reflects our modelling assumption that only LFP batteries are repurposed, while NMC batteries are directed toward recycling (see Methods section and **SM-Note S6**). While these assumptions reflect the current constraints, ongoing technological advances may improve the repurposing feasibility of both LFP and NMC chemistries in the future. As such, our current estimates represent a conservative baseline, particularly for the long-term repurposing potential of NMC batteries.

3.5. Unlocking material recycling potential through onshore battery recycling

Australia also anticipates significant opportunities for material recovery from LIB recycling. The annual MRP for EoL LIBs by 2050 is projected to reach 11–18 kt for Li, 36–85 kt for Ni, 7–14 kt for Co, 7–13 kt for Mn, 94–135 kt for Cu, 86–129 kt for Al, and 86–136 kt for graphite under the most likely SC scenario (Fig. 5a). Notably, by 2050, the MRP for Co and Ni would amount to 128–245 % and 22–53 % of Australia’s current mine production (Fig. 5a), respectively. This highlights that even for a resource-rich country like Australia, battery recycling could be an important supplement to mine production for certain metals. Such opportunities may also exist in other major battery mineral suppliers. For instance, while Indonesia has abundant nickel resources, it lacks lithium resources and production, which could be supplemented by domestic LIB recycling.

Between 2025 and 2050, the cumulative MRP for seven minerals would reach 2481–4471 kt under the SC scenario. Notably, the cumulative MRP for Co and graphite during 2025–2050 would be equivalent to 4−7 % and 7−14 % of Australia’s current economic demonstrated resources (EDR), respectively (**SM-Table S11** and **Note S7**). MRP is significantly impacted by the lifespan of EV batteries: cumulative MRP under the Short scenario is 72–75 % higher than that of the Long scenario. The future battery chemistry mix also plays an important role, particularly for Ni and Co. For instance, the cumulative MRP for Co under the NMC scenario will be 24–30 % higher than that of the LFP scenario (Fig. 5b and c).

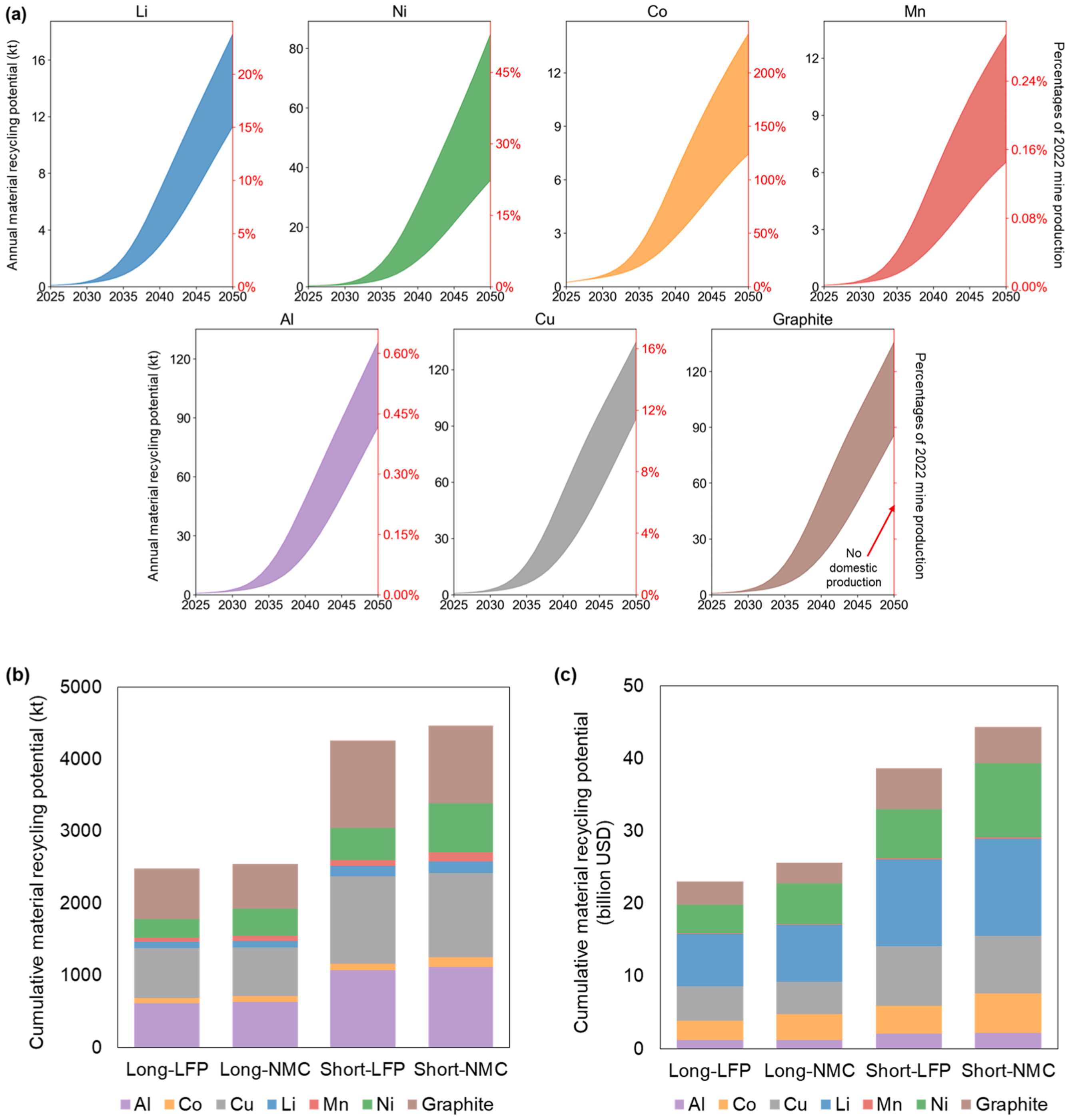

Fig. 5. Material recycling potential from EoL LIBs in Australia under the SC scenario. (a) Annual material recycling potential (MRP) for seven critical minerals from EoL LIBs. Note: the shaded area illustrates the potential range of MRP; the left y-axis represents the MRP by weight, while the right y-axis indicates the MRP as a percentage of Australia's current mine production as of 2022. (b-c): Cumulative MRP by weight (b) and economic value (c) from EoL LIBs between 2025 and 2050.

Based on the 10-year average metal prices (**SM-Table S9**), the total economic value of MRP for these seven minerals is estimated to be 23–44 billion US dollars (Fig. 5c). Li contributes the largest share (30–31 %), followed by Cu (18–21 %), Ni (17–23 %), graphite (11–15 %) and Co (10–14 %). Despite their relatively small share in recovered mass, lithium and cobalt contribute disproportionately to the total economic value of recovered materials due to their high market prices. This highlights the importance of considering not only material volumes but also economic drivers when evaluating the MRP of EoL LIBs. Nonetheless, the economic implications of establishing a domestic LIB recycling in Australia depend not only on the potential revenue from recovered materials but also on the costs and investments required to develop adequate recycling capacity, which remains to be studied. Fully realising the MRP requires continued strategic planning and forward-looking efforts by both policymakers and industry.

3.6. Integrating repurposing and recycling: trade-offs and policy implications

Although this study presents the repurposing potential and MRP of LIBs as separate scenarios, repurposing and recycling could co-exist in a fully integrated circular economy, where the dynamic trade-offs between them are important to consider. For instance, prioritising recycling may cannibalise batteries available for second-life use (Zhou et al., 2024), while promoting repurposing will delay the timing and scale of recycling flows (Bobba et al., 2019). Battery chemistry plays a critical role in shaping the trade-offs between repurposing and recycling. LFP batteries, characterised by high thermal stability, long cycle life, and low critical metal content, are well suited for repurposing as BESS. However, the absence of valuable nickel and cobalt in LFP diminishes their recycling value. In contrast, NMC batteries offer high economic value for direct recycling due to their rich metal content but pose greater challenges for safe and cost-effective repurposing. These chemistry-specific attributes suggest that the optimal EoL strategy for LIBs depends not only on both application and battery chemistry (Ma et al., 2024).

In the Australian context, deciding whether to prioritise repurposing followed by recycling, or to focus solely on recycling, requires careful consideration of infrastructure readiness, market dynamics, and policy objectives. Repurposing can delay waste generation, reduce immediate pressure on recycling systems, and support domestic energy storage goals—especially given Australia's rapidly expanding BESS market and the current immaturity of the domestic recycling industry. A differentiated strategy may therefore be most appropriate: promote the repurposing of LFP batteries where feasible, while directing NMC and other high-value chemistries toward immediate recycling.

3.7. Uncertainties and limitations

Despite accounting for three key scenario factors, our modelling results remain subject to considerable uncertainty due to numerous data inputs and parameter assumptions, with the EV battery size being a notable example. EV battery size has increased notably in recent years and is a key factor influencing future LIB flows. Our model assumes continued growth of EV battery size which then stabilises after 2030 (**SM-Table S2**). However, circular economy strategies such as vehicle downsizing may lead to a lower stabilisation level. Accordingly, we conducted a sensitivity analysis assuming battery sizes stabilise at 20 % below our baseline levels (**SM-Note S9**). Results show that near- to mid-term impacts are minimal. For example, projected EoL LIB volumes reduce by only 0.9–2.3 % in 2035 (**SM-Table S13**), with little change in repurposing potential (**SM-Fig. S2**). In the long term, however, EoL LIB volumes decrease by 9.3–12.6 % in 2050, and cumulative MRP between 2025 and 2050 reduces by 7.4–9.6 % (**SM-Table S13**). In addition, the model assumes all EoL batteries from EVs and BESS will be effectively collected for repurposing or recycling in the future, whereas currently an effective collection is still being developed. If future collection rates remain low, our model could overestimate MRP.

The model does not consider emerging LIB chemistries such as lithium manganese iron phosphate (LMFP) (Zhang et al., 2024) and all-solid-state batteries (Duffner et al., 2021), nor for alternative technologies including sodium-ion batteries and hydrogen fuel cell fuel vehicles, due to their early stage of market introduction and limited data availability. However, if these emerging technologies are widely commercialised, they could significantly reduce long-term dependence on LIBs and associated EoL battery flows. While this study explores the repurposing potential and MRP for LIBs, the analysis primarily adopts a material flow perspective without justifying their economic feasibility. Future research could build upon this MFA model to explore the economic and environmental implications of different EoL options.

4. Conclusion

The clean energy transition requires not only large-scale deployment of renewable technologies but also proactive EoL planning. By developing a comprehensive dynamic MFA model for three major LIB markets, this study provides a detailed analysis of the future LIB demand, EoL arisings, repurposing and material recycling potential in eight Australian jurisdictions. The results underscore the urgent need to improve collection rates for handheld batteries in the short term and to develop a cohesive national regulatory framework for EV and BESS batteries in the long term. We highlight regional heterogeneity in EoL LIB volumes and compositions and recommend differentiated policy responses. There is significant potential for repurposing EV LIBs in Australia, which could reduce reliance on battery imports to meet domestic BESS demand. We also highlight the opportunity of onshore material recycling to fully unlock the MRP and retain the economic value of EoL LIBs. Even if onshore material recycling does not materialise, it's still imperative to establish sufficient pre-processing capacities domestically as the direct export of battery waste is restricted. These identified challenges and opportunities may apply to other countries, particularly those similarly facing limited battery collection and recycling infrastructure. The study offers valuable insights into advancing a circular economy for LIBs in Australia, with broader implications for building a sustainable global battery value chain.

CRediT authorship contribution statement

Haiwei Zhou: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Wen Li:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Rusty Langdon:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Prakash J. Singh:** Writing – review & editing, Supervision, Investigation. **Peng Wang:** Writing – review & editing, Supervision, 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.

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Supplementary materials

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Data availability

Data sources and details are provided in the manuscript or supplementary materials

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