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Impact of circular economy on the long-term allocation structure of primary and secondary lithium

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Lithium is key for a clean energy transition but faces sustainability challenges in the global supply. Here, we use a bottom-up approach to study the evolution of the global lithium-ion battery industry from 2023 to 2050. The supply and demand trends are predicted to determine the supply potential and allocation structure of primary and secondary lithium. The results indicate a projected global lithium demand of 1.93 million metric tons in 2050, a significant increase of 26.2 times compared to 2023. In the process of global lithium resources shifting from underground reserves to in-use stocks, population and Gross Domestic Product (GDP) influence regions' lithium endowment and per capita primary consumption, respectively. If the European Union's new battery regulation is implemented globally, then it is projected to reduce global primary lithium consumption by 1.03 million metric tons by 2050, with a 53.48% decrease in the proportion of primary lithium consumption.

Lithium, with its distinctive chemical and physical properties[1,2], has become a pivotal mineral for today's energy transition, with extensive applications in sectors such as batteries and renewable energy[3,4]. Over the last three decades, global lithium production has surged dramatically, increasing from 6100 metric tons in 1994 to 180,000 metric tons in 2023—an almost thirteenfold increase[5]. Since 2000, Australia has been at the forefront of primary lithium production, contributing 47.7% to the global output in 2023, with Chile trailing at 24.4%[6]. Both countries are expected to continue as principal lithium suppliers. Owing to its pivotal role in modern technology, profound economic significance, scarcity, and finite future availability, lithium has been designated a critical material by entities such as the US, the EU, Japan, and the United Nations Environment Programme[7,8]. Similarly, key producing nations such as Australia and Chile have recognized lithium as a critical mineral. Consequently, ensuring a sustainable supply of lithium represents a key challenge for global development[9–11].

Lithium is applied in the guise of lithium oxide and lithium hydroxide, and these two compounds collectively account for more than 90% of global lithium consumption[12]. In recent years, lithium has undergone a burgeoning adoption in battery production, underpinned by its attributes—notably, its high energy density, extended lifecycle, and comparatively low self-discharge rate[13]. Lithium-ion batteries (LiBs) have assumed a pivotal role, with their application in electric vehicles (EVs) and battery energy storage systems (BESSs) accounting for 88% of the LiB market[14]. Aligned with the global ability to arrest the temperature rise to being within 1.5 °C, the growth of renewable energy sources, spanning solar and wind power, is primed for exponential proliferation. Projections indicate that it the use of such renewable energy sources will soar from the current 28% to 91% by 2050[15]. Moreover, it is anticipated that the demand for BESSs will increase by 50% accordingly[16]. Moreover, continuous advancements in electrification will drive the rapid development of EVs, with the demand for LiBs for automotive use expected to increase 217-fold by 2050[17]. Propelled by the meteoric proliferation of renewable energy sources, lithium demand is poised to sustain an annual growth of 18% over the next three decades[18]. However, with lithium production growing annually by only 3-6%, the widening gap between supply and demand is expected to result in rising lithium prices and may lead to a lithium supply crisis in the medium to long term[19,20].

After consumption, primary lithium gradually accumulates in societal systems, exhibiting a trend of shifting from underground reserves to in-use stocks. The demand for LiBs has concurrently spurred an increase in the mass of scraped LiBs. Due to the relatively long lifecycle of LiBs, scraped LiBs have not reached a large-scale generation stage, with an average annual growth of only 1–3 GWh[21]. However, subsequent growth will increase notably, and it is estimated that by 2035, the scraped mass of LiBs for global EVs alone will reach 305.9 GWh, an increase of 240 times compared to the amount in 2023[22]. Thus, recovering lithium from scraped LiBs has become a key focus for addressing resource shortages and will gradually form an allocation pattern where both primary and secondary lithium are able to meet market demand[23,24]. However, unlike the natural endowment of lithium reserves in different countries, secondary lithium comes from the in-use stocks of each country, which in turn come from that country's previous consumption and trade of primary lithium[25,26]. Thus, as the proportion of secondary lithium increases notably, its great uncertainty in the regional

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supply structure and lithium quantity will arise, thus necessitating quantitative evaluation.

At the same time, due to the limited recycling scale, currently, only approximately 5% of scraped batteries worldwide are officially collected and recycled[27]. To address the lithium supply-demand gap and promote the circular utilization of lithium resources, the EU took the lead in issuing the Regulation concerning Batteries and Waste Batteries (EU 2023/1542) in 2023. This regulation requires the full lifecycle management of batteries, promotes the development of a circular economy in the LiB industry, and explicitly mandates a minimum proportion of recycled lithium in LiBs and a minimum recovery and recycling rate for LiBs starting in 2027, which is expected to notably enhance the circular utilization of lithium resources[28]. However, there is a lack of quantitative research supporting how the circular economy will affect the process of lithium resources shifting from underground reserves to societal in-use stocks and will affect the future allocation of primary and secondary lithium in different countries. Consequently, the widespread global adoption of circular economy policies has yet to be realized, owing to the lack of quantitative research substantiating the implications of such policies.

This study adopts a bottom-up research framework, considering the primary application domains of the following two LiB types: EVs and BESSs. EVs, which are closely related to public demand, are studied by forecasting the per capita stock of EVs based on historical data. Using a stock-driven approach, we calculate the annual installation and scraps of EV LiB cells up to 2050. BESSs, conversely, serve as a fundamental infrastructure for the peak shaving of renewable energy such as photovoltaic and wind power. Based on SSP1-RCP1.9 societal energy data and using a flow-driven approach, we estimate the annual installation and scrapping rates of LiB cells for global BESSs. By integrating these two LiB application domains, we predict the trends in in-use lithium stock, lithium consumption, and scraps from 2023 to 2050 across 133 countries and six typical types of LiB cells. This study traces the evolutionary pathway from lithium reserves to in-use lithium stocks and analyses the impact of the Regulation (EU 2023/1542) on the lithium supply and demand structure across different regions globally, thus providing quantitative support for the sustainable supply of global lithium.

Results

Global in-use lithium stock

The in-use lithium stock of EVs and BESSs is projected to increase from 0.2 million metric tons in 2023 to 14.02 million metric tons by 2050. The global share of regions such as Europe and East Asia is gradually decreasing, showing a trend of shifting towards regions such as South Asia. In 2023, East Asia emerged as the dominant region in terms of global in-use lithium stock, accounting for a 38.31% share, as detailed in Supplementary Fig. 2. Moreover, West Europe held a 20.18% stake in the global in-use lithium stock landscape, while North America claimed the third-largest share, contributing 10.40% to the worldwide in-use lithium stock in 2023. By 2050, the landscape is projected to shift notably. The region with the largest share of global in-use lithium stock is expected to be South Asia, accounting for 36.4%, a remarkable 1790-fold increase compared to the share in 2023. Following South Asia, Sub-Saharan Africa is anticipated to have the second-highest share, at 11.96%, a 1234-fold increase from the 2023 level. As all regions aim to achieve decarbonization targets globally, the relatively late-starting regions, South Asia and Africa, are expected to become key focus areas for the accumulation of in-use lithium stock.

From an application standpoint, the in-use lithium stock of EVs is projected to experience exponential growth, rising from 0.17 million metric tons in 2023 to 13.83 million metric tons by 2050 (Supplementary Fig. 3). In contrast, the in-use lithium stock of BESSs is expected to grow at a relatively slower, yet still notable, rate. BESS-related in-use lithium stock is expected to increase from 0.029 million metric tons in 2023 to 0.49 million metric tons by 2050—a nearly 16-fold increase. The proportion of in-use lithium stock from BESSs is expected to decrease from 14.80% to 3.48%, as the growth in demand for EVs is faster than that for BESSs, despite the continued high-level societal demand for BESSs. Compared to other regions, the shift of in-use lithium stock towards BESSs will be more pronounced in Europe and Melanesia by 2050, increasing by 15-fold and 16-fold, respectively. In terms of cathode materials, by 2050, nickel-cobalt-aluminum oxide (NCA) and lithium ferro phosphate (LFP) battery cells are expected to account for a notable market share of in-use lithium stocks, reaching 34.76% and 15.83%, respectively (as shown in Fig. 1); these battery cells are used primarily in EVs. For BESSs, except for East Asia, NCA battery cells are still the mainstream (46.4%), increasing from 8.75 thousand metric tons in 2023 to 151.26 thousand metric tons by 2050.

Global flow of lithium

With the widespread application of LiBs in EVs and BESSs, lithium consumption is projected to exhibit a notable growth trend during the forecast period (Supplementary Fig. 5). The lithium consumption trends for NCA and NMC523 battery cells are similar (Fig. 2a, b). Under a business-as-usual scenario, South Asia, North America, and Sub-Saharan Africa emerge as the primary regions driving global lithium consumption for the two battery cell types. In 2050, South Asia's lithium consumption for these two battery cell types will reach 0.32 and 0.14 million metric tons, respectively. Furthermore, before 2030, the lithium consumption of NMC523 battery cells in North America will follow a similar trend to that of NCA battery cells, but after 2030, the consumption of this cell type will decrease, and the consumption of NCA battery cells will increase (Supplementary Fig. 4).

The regions with notable lithium consumption of LFP battery cells will be East Asia and North America, accounting for 60.24% and 17.08%, respectively, of the global total in 2050 (Fig. 2c). Compared to that in 2030, the share of global lithium consumption for LFP battery cells in East Asia will decrease to 85.99% by 2050, even though the overall lithium consumption for LFP battery cells will increase by 10% in that same period. The reason for this is primarily due to the fact that East Asian countries such as Japan and South Korea are increasingly favoring the use of NCA battery cells. The lithium consumption trends for NMC111, NMC622, and NMC811 battery cells (Fig. 2d–f) are similar. Over the 2030-2050 timeframe, the regions with notable lithium consumption of the three battery cell types will be East Asia, South Asia, and Sub-Saharan Africa. This shift in regional lithium consumption patterns will represent a notable departure from the trends observed prior to 2030, particularly in the case of Sub-Saharan Africa.

However, lithium scrap from LiBs exhibits a notable time lag compared to lithium consumption. The lag period varies notably among the six LiB types (Supplementary Fig. 6). Our calculations suggest that the lag period for lithium scrap from EVs is approximately 6–8 years, while for BESSs, it is 2–3 years due to differences in LiB lifespans (several years or a decade).

Global shift in lithium endowment

As lithium reserves are continually depleted, the amount of in-use lithium stock is constantly increasing. In 2023, the regions with abundant lithium reserves had relatively small populations, resulting in large per capita lithium reserves, such as 185 kg per person in Australia and New Zealand. In the early stages of the development of the lithium industry, the rapid growth of the new energy industry led to a rapid depletion of lithium reserves, as the social stock was still limited and products had not yet reached the concentrated scrapping cycle (Fig. 3a). Assuming the current proportions of primary lithium supply (business-as-usual scenario), the lithium reserves of the traditional lithium-rich regions of Latin America and the Caribbean and Australia and New Zealand are projected to decrease by 90.35% and 54.97%, respectively, by 2050. As lithium resources gradually shift from lithium reserves to in-use stock and as LiBs reach their scrapping cycle, secondary lithium will continuously replenish social demand (lithium reserves data see Supplementary Figs. 10–12 and Tables 5–6). The speed of this transition from lithium reserves to the in-use stock of lithium supply sources first increases and then decreases, with the peak expected to reach 20.79 million metric tons in 2043. In 2042, the in-use stock is projected to surpass the lithium reserves and become the primary source of the global lithium

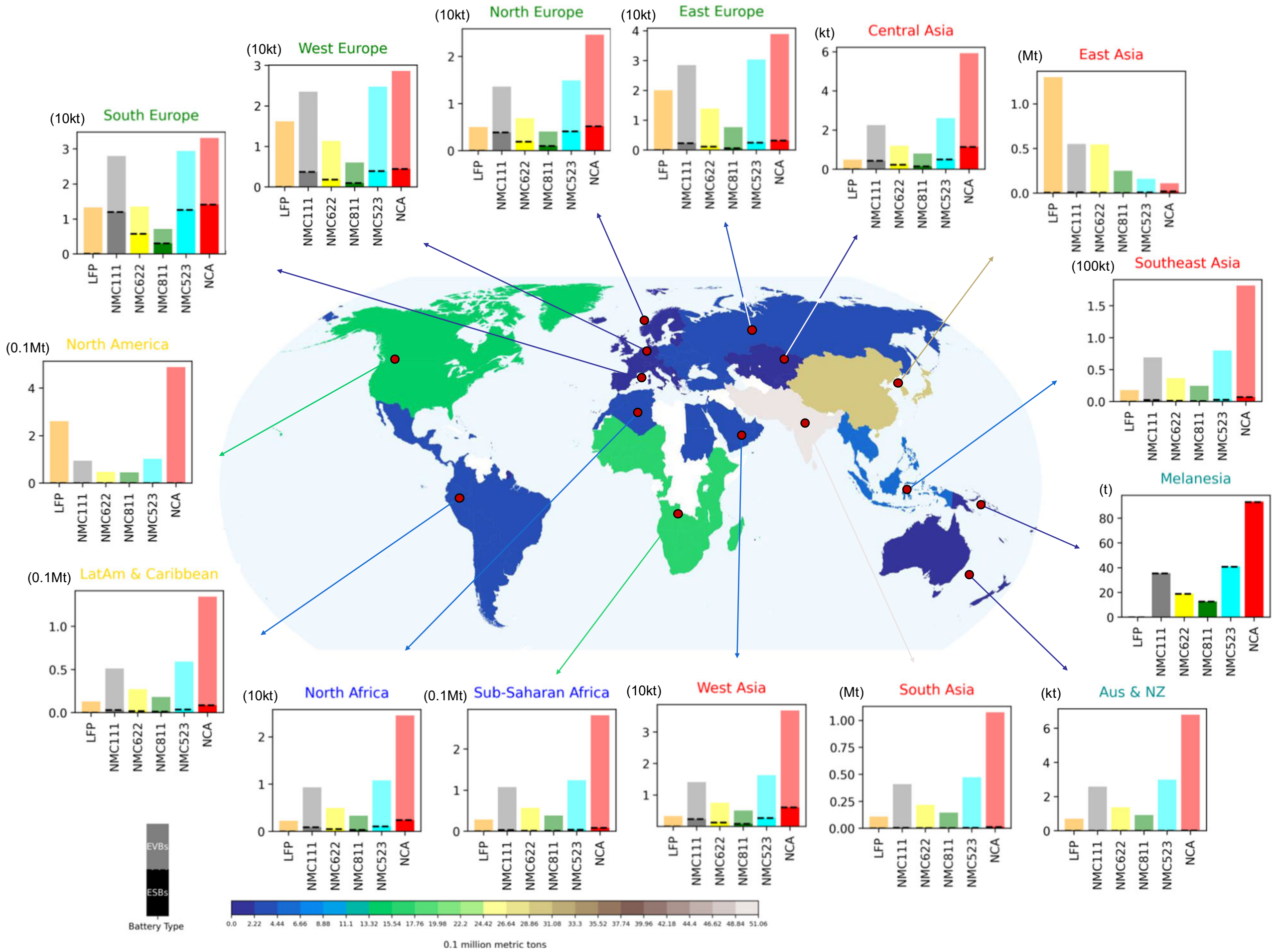

Fig. 1 | In-use lithium stock of EVs and BESSs by region and cathode materials in 2050. The map section represents the total in-use lithium stock by region. The bar charts represent the lithium in-use stock of different cathode materials in the two application domains; the upper part of the bars is for EVs, and the lower part is for BESSs. kt = 1000 metric tons, and Mt = 1 million metric tons. White areas in the map indicate missing data.

supply. By 2050, the in-use stock is expected to reach 14.02 million metric tons, which is 129.76% greater than the available lithium reserves.

We expand the concept of lithium endowment to include both lithium reserves and in-use stock. The evolutionary trends of regional lithium endowments indicate a global redistribution of lithium resources (Fig. 3b). The lithium-rich regions of Latin America and the Caribbean and Australia and New Zealand will experience a continuous decline in their lithium endowment, while traditional lithium-poor regions such as South Asia will experience a steady increase, with their share of global lithium endowment growing from 0% to 25.37% by 2050. The lithium endowments of Central Asia and West Asia are projected to increase 114-fold and 457-fold, respectively. By 2050, Asia is expected to account for more than 50% of the global lithium endowment, as depicted in Supplementary Fig. 13–14. Concurrently, a notable shift is projected to occur across North Europe, North America, and Sub-Saharan Africa. These lithium endowments are expected to transition from being dominated primarily by lithium reserves to becoming dominated by in-use lithium stock around 2025, 2044, and 2037, respectively. Other regions in the Americas, Europe, and Africa are also expected to exhibit similar trends, and thus, these three regions should actively optimize their lithium supply structures around 2040. Further analysis shows that the range (difference between the maximum and minimum) of the amount of global lithium endowment across different regions is expected to decrease by 54.98%, declining by 11.35 million metric tons from 2023 to 2050, indicating a gradual convergence towards a more balanced global lithium endowment.

Enhancing effect of the global circular economy model

Scenario setting. To analyse the impact of the global circular economy model on the evolutionary trends of lithium resources, we set up the following scenarios based on the EU Regulation (EU 2023/1542) regarding lithium recycling requirements (Supplementary Table 7) and based on relevant literature: the battery collection scenario, lithium recycling scenario, enhanced lithium recycling scenario, lithium reduction scenario, and combined scenario (see Table 1).

Effects of policy implementation. As shown in Fig. 4a, the business-as-usual scenario (scenario 1) trend indicates that in 2050, global primary lithium consumption will increase by 25.53 times compared to that in 2023. By implementing circular economy policies, global primary lithium consumption will show varying degrees of reduction. By 2050, when juxtaposed against the business-as-usual scenario (scenario 1), scenario 2 will culminate in a marginal 1.08% contraction of global primary lithium consumption. In contrast, scenarios 3 and 4 will achieve more substantial reductions, cutting primary lithium consumption by 8.07% and 22.15%, respectively. However, scenario 5 will exhibit the most profound impact, remarkably curtailing global primary lithium consumption by an astonishing 32.09%, equivalent to a staggering 8-fold reduction in the global primary lithium consumption level recorded in 2023. The impact of the combined scenario (scenario 6) will further decrease by 33.62% compared to that of scenario 5. This finding indicates that merely increasing the battery collection rate or lithium recovery rate will have a

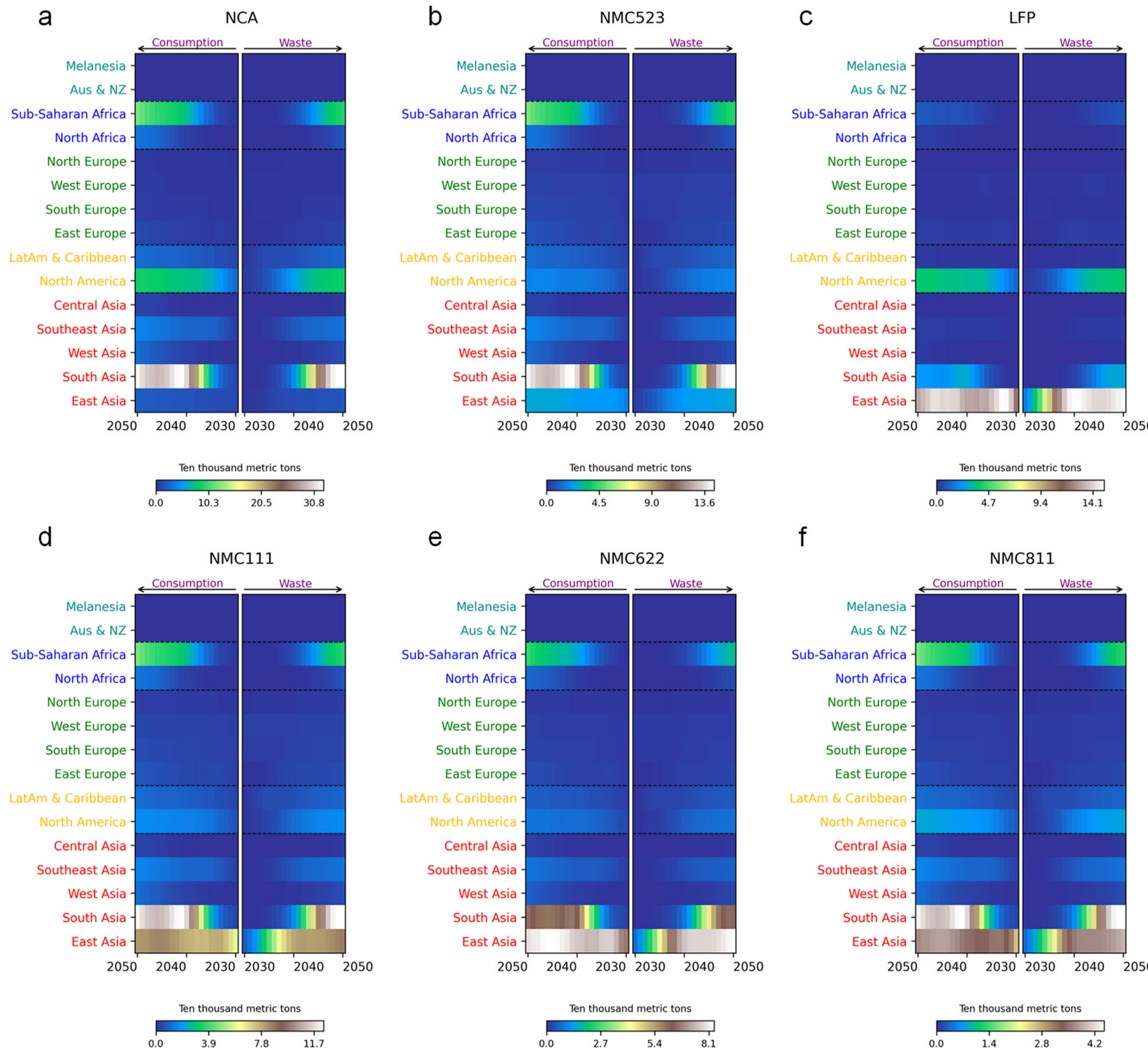

Fig. 2 | Trends in lithium consumption and scrap across six cathode materials from 2030 to 2050. The heatmap on the left shows the lithium consumption (Consumption) from LiB cells with different cathode materials, broken down by region. (**a**) NCA, (**b**) NMC523, (**c**) LFP, (**d**) NMC111, (**e**) NMC622, and (**f**) NMC811. The y-axis labels on the subplots are colour-coded according to the five major continents, and the heatmap boundaries are separated by dashed lines. The heatmap on the right shows the lithium scrap generation (Waste) measured in million metric tons.

very limited effect on reducing global primary lithium consumption. Lithium mass reduction is crucial for reducing global primary lithium consumption, and the combination of scenarios enhances the effect of the circular economy to the optimal level, reducing primary lithium consumption by more than half of the global primary lithium consumption compared to that in Scenario 1.

As shown in Figs. 4b–p, the circular economy has varying degrees of impact on the primary lithium consumption of the 15 regions in this paper. For Asia, the effects of the circular economy on reducing primary lithium consumption in East Asia and Southeast Asia have begun to manifest during the policy implementation period and will gradually amplify after 2038. By 2050, the lithium reduction measures implemented in scenario 5 will exert the most profound impact on curbing primary lithium consumption in East Asia, resulting in remarkable reductions of 37.73% and 27.09%, compared to those in scenario 1. However, scenario 6 will prove even more potent, further diminishing primary lithium consumption by an additional 31.44% and 33.26% relative to the already substantial cuts achieved under scenario 5. The circular economy will have a lagging effect on primary lithium consumption in South Asia. Specifically, the impact of the circular economy on primary lithium consumption has not been notable during the policy implementation period, but it will become more apparent after 2038 and peak around 2042. Compared with scenario 1, scenario 6 will reduce primary lithium consumption by 36.54%. From 2042 to 2050, the impact will exhibit a fluctuating growth trend (the trends during the policy implementation period can be seen in Supplementary Fig. 18).

For the Americas, Europe, and Oceania, the circular economy's influence was initially muted during the policy implementation period across the Americas. However, its influence has steadily amplified and manifested itself in an increasingly conspicuous manner as time has progressed. Among these, in 2050, compared with scenario 1, scenario 6 will reduce primary lithium consumption in North America by 58.19%. For Australia and New Zealand, Western Europe, and Eastern Europe, the impact of the circular economy on primary lithium consumption was more noticeable towards the end of the policy implementation period, with Australia decreasing by 34.91% and the other two regions decreasing by approximately 30% compared to scenario 1. As the energy transition in

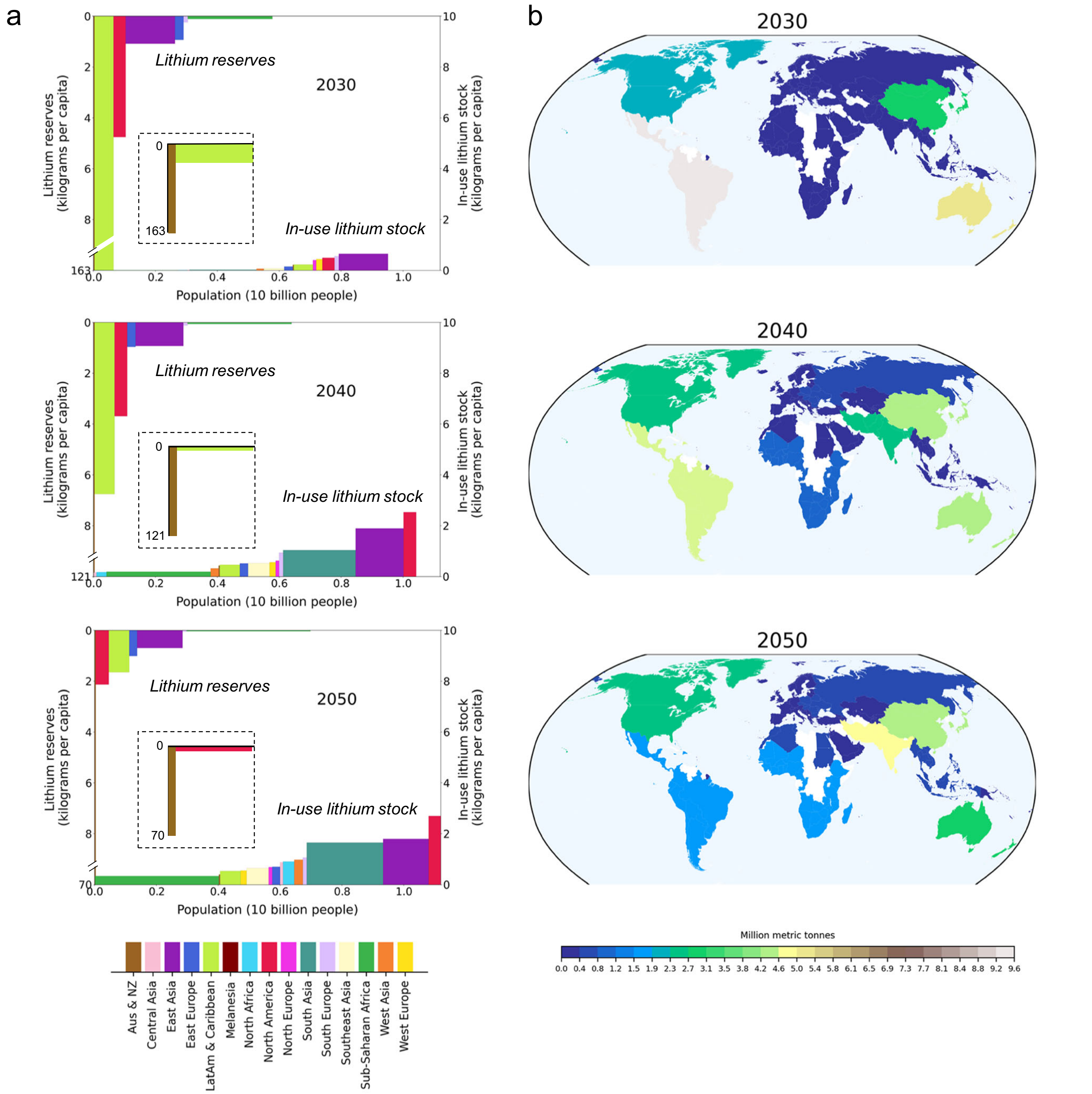

Fig. 3 | Trends in the changes in the lithium supply structure from 2030 to 2050. a Lithium reserves and in-use lithium stock across regions over time in business-as-usual scenario. **b** Lithium endowment across regions over time in business-as-usual scenario.

most European regions gradually matures, the impact of the circular economy on the European region will slow after 2038. During 2038-2050, scenario 6 will increase primary lithium consumption in Eastern Europe and Northern Europe by 49.81% and 20.65%, respectively. However, the impact of the circular economy on Australia and New Zealand and Latin America and the Caribbean will not weaken during this period. For instance, from 2038 to 2050, scenario 6 will reduce primary lithium consumption in Australia by 25.15%. In 2050, compared to scenario 1, scenario 6 will reduce primary lithium consumption in Latin America by 52.75%.

For the African region, the effect of the circular economy also shows a trend of being weak at first and then becoming stronger. The impact of scenario 6 on primary lithium consumption in North Africa and Sub-Saharan Africa will reach its peak in 2042 and 2048, respectively, and then stabilize. However, the impact of the circular economy on West Asia and Melanesia is not notable (comparisons of other scenarios can be found in Supplementary Figs. 19–25). Overall, the circular economy not only has a notable impact on regions prioritizing energy transition (Western Europe, Eastern Europe, East Asia, and North America) but also has a more notable improvement on primary lithium-producing regions (Australia and New Zealand and Latin America and the Caribbean).

The analysis depicted in Fig. 5 scrutinizes the influence of population and economic factors on primary lithium consumption across different nations and regions, contrasting the scenarios before and after the implementation of circular economy policies (scenarios 1 and 6). Figure 5a shows that in 2050, the primary lithium consumption of different countries will be positively correlated with population size (upper-right figure). However, for individual countries (blue dots, lower-left figure), there is no clear correlation between per capita GDP and per capita primary lithium consumption.

Table 1 | Single-strategy targets and combination scenario settings

Scenario	2025–2040				2040–2050
	LiB collection rate	Lithium recovery rate	Mandatory minimum levels of recycled lithium	Average gravimetric energy density of battery cells	
Scenario 1 (business-as-usual scenario)	50% by 2040[44]	6% by 2040[45]	1% by 2040[16]	250 Wh/kg cell by 2040[46]	50% battery collection rate, 6% lithium recovery rate, and 1% recycled lithium by 2050 for new battery manufacturing; the average energy density of battery cells will be 250 Wh/kg by 2050.
Scenario 2 (battery collection scenario)	50% to 65% by 2025, 65% to 70% by 2030, 70% by 2040*	6% by 2040[45]	1% by 2040[16]	250 Wh/kg cell by 2040[46]	70% battery collection rate, 6% lithium recovery rate, and 1% recycled lithium by 2050 for new battery manufacturing; the average energy density of battery cells will be 250 Wh/kg by 2050.
Scenario 3 (Lithium recycling scenario)	50% by 2040[44]	12% by 2027, 24% by 2031 and 36% by 2040*	1% by 2040[16]	250 Wh/kg cell by 2040[46]	50% battery collection rate, 36% lithium recovery rate, and 1% recycled lithium by 2050 for new battery manufacturing; the average energy density of battery cells will be 250 Wh/kg by 2050.
Scenario 4 (enhanced lithium recycling scenario)	50% by 2040[44]	6% by 2040[45]	6% by 2031, 12% by 2037, 17% by 2040*	250 Wh/kg cell by 2040[46]	50% battery collection rate, 6% lithium recovery rate, and the mandatory minimum levels of recycled lithium will increase from 17% by 2050 for new battery manufacturing; the average energy density of battery cells will be 250 Wh/kg by 2050.
Scenario 5 (lithium mass reduction scenario)	50% by 2040[44]	6% by 2040[45]	1% by 2040[16]	Annual growth 3.6%[47], the limit is 435 Wh/kg cell[48]	50% battery collection rate, 6% lithium recovery rate, and 1% recycled lithium by 2050 for new battery manufacturing; the average energy density of battery cells has been increasing by 3.6% per year.
Scenario 6 (combined scenario)	50% to 65% by 2025, 65% to 70% by 2030, 70% by 2040*	12% by 2027, 24% by 2031, 36% by 2040*	6% by 2031, 12% by 2037, 17% by 2040*	Annual growth 3.6%[47], the limit is 435 Wh/kg cell[48]	70% battery collection rate, 36% lithium recovery rate, and the mandatory minimum levels of recycled lithium will increase from 17% by 2050 for new battery manufacturing; the average energy density of battery cells has been increasing by 3.6% per year.

*Requirements regarding lithium recycling stipulated in the Regulation concerning Batteries and Waste Batteries (EU 2023/1542)[49]

From a regional perspective (red dots), regional GDP and per capita primary lithium consumption exhibit a significant positive correlation ($r = 0.84$).

Figure 5b shows that after the implementation of circular economy policies (scenario 6), the impact of population and economic factors on primary lithium consumption will be weaken. The upper-right figure shows that the total primary lithium consumption decreases for countries with the same population, while the lower-left figure shows that the per capita primary lithium consumption also decreases for regions with the same GDP. A comparative analysis of Figs. 5a, b reveals that after the implementation of circular economy policies, the dispersion of per capita primary lithium consumption will decrease by 58%, while the dispersion of total consumption will decrease by 57%, indicating a congruence in the magnitudes of change. After contrasting Figs. 5a, b, it becomes evident that following the enactment of circular economy policies, the dispersion of per capita primary lithium consumption will decrease by a substantial 58%, while the dispersion of total consumption will exhibit a commensurate reduction of 57%, signifying a striking congruence in the magnitudes of change. Remarkably, however, the decline in the mean value of per capita consumption will be approximately 48%, decreasing from 0.15 to 0.078, which will prove to be markedly lower than the 55% decrease in the mean value of total consumption, decreasing from $5.9 \times 10 \times 4$ to $2.5 \times 10 \times 4$. As shown in the changes in the lower-left figure, after implementing the circular economy, the number of countries within the optimal range of per capita consumption will increase from 65 to 84, implying that the relationship between economic development and consumption will tend to be more balanced, which will thus be conducive to narrowing the global gap (the relationships between other factors are detailed in the Supplementary Fig. 15–17).

Figure 5c analyses the changes in the proportion of primary lithium consumption on different continents under a single policy scenario at different time points. In 2030, except for Europe, the policy impact will not be notable on other continents. In 2040, the changes within continents will be relatively balanced, with scenarios 3 and 4 having a notable impact, particularly in reducing primary lithium consumption in the Americas and Oceania. In 2050, the impact of scenario 4 will be more pronounced than that of scenario 3, with a particularly significant effect on Europe. On the whole, the policy measures will prove efficacious in curbing the proportion of primary lithium consumption in the Americas and Oceania regions over the short term. However, in the long run, the primary impact will be concentrated on diminishing the proportional consumption in European and Oceanic countries.

Discussion

The global demand for lithium continues to surge, driven primarily by the pivotal role of lithium-ion battery manufacturing and renewable energy sectors. However, the substantial demand for lithium and its uneven distribution have sparked widespread concerns worldwide regarding its future supply security and sustainability. Lithium endowments exhibit notable disparities across different regions, not only due to variations in geological reserves but also attributable to different consumption patterns and resource management strategies. In recent years, the in-use lithium stock in North America, East Asia, and Europe has gradually emerged as the primary reserve for these regions. This transition has been facilitated by the emphasis in these regions on lithium recycling and the application of advanced technologies, effectively enhancing lithium reuse efficiency[29]. In contrast, Australia and Latin America have nearly depleted their lithium reserves, as these regions have relied heavily on intense lithium mining activities for an extended period, lacking effective resource recycling policies, leading to a rapid depletion of their reserves. The evolution of global lithium use indicates that the future storage and supply of lithium will increasingly depend on in-use stocks rather than on traditional mining. With advancements in resource recycling technologies and heightened global environmental awareness, it is anticipated that the total lithium reserves in most regions worldwide will gradually converge, forming a more balanced and sustainable global lithium management landscape.

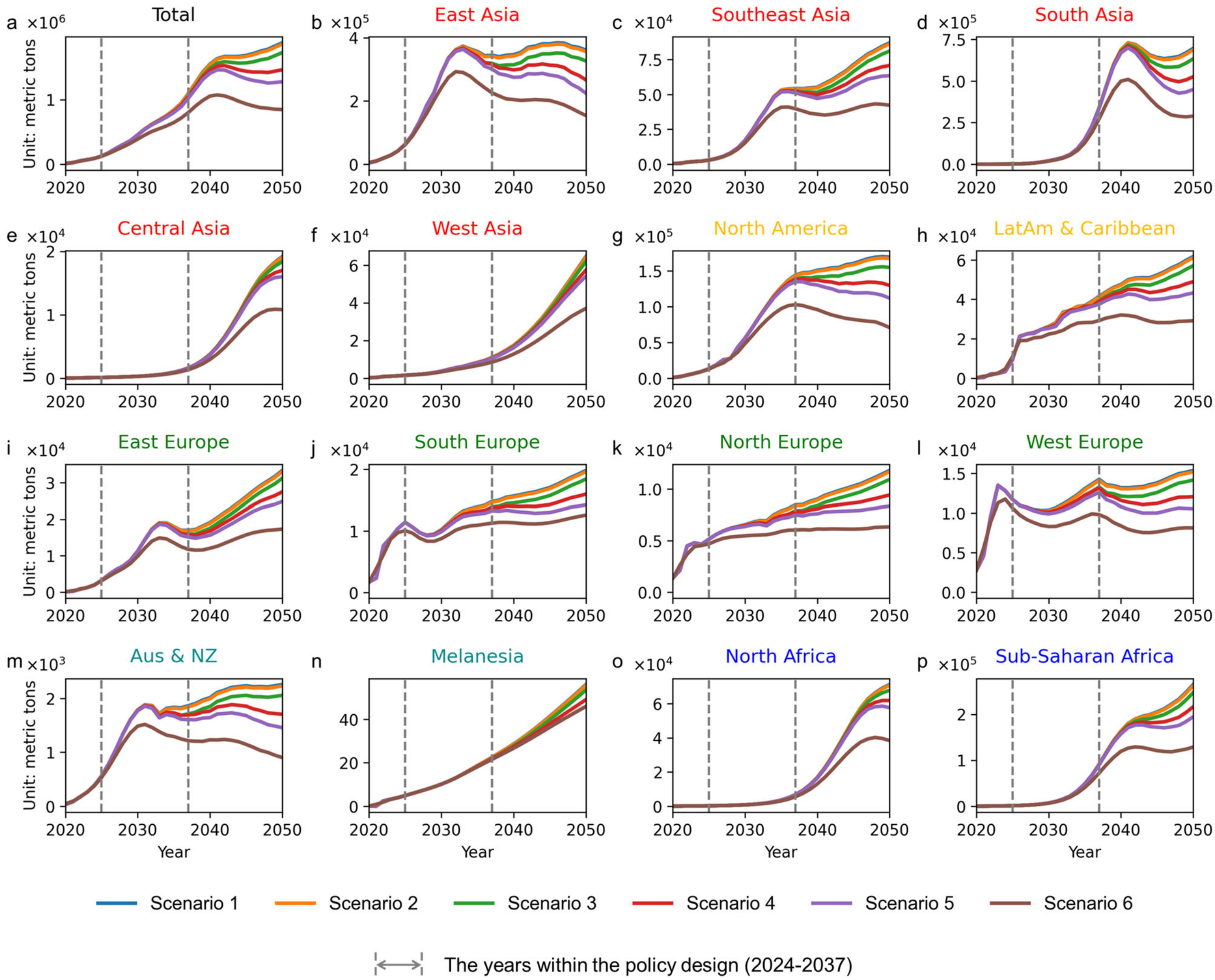

Fig. 4 | Changes in primary lithium consumption across 15 regions under the circular economy. **a** Different colored curves represent the changes in global primary lithium consumption over time under six categories of circular economy policies. **b**–**p** Different colored curves represent the changes in primary lithium consumption over time for 15 regions under six categories of circular economy policies. The x-axis represents years, and the y-axis represents primary lithium consumption in metric tons. The dashed lines represent the starting years of the Batteries and Waste Batteries Regulation (policy design).

During the ongoing process of global lithium endowment redistribution, population and economic factors largely determine trends in in-use lithium stock changes. The persistent growth in the population and the acceleration of urbanization processes have not only substantially increased the demand for energy transition minerals (ETMs) such as lithium but also driven the development of circular economy policies and resource recovery technologies. Actively promoting circular economy policies for lithium worldwide, particularly in regions with high levels of population growth potential, provides a safeguard for a sustainable lithium supply. For instance, the EU Regulation concerning Batteries and Waste Batteries (EU 2023/1542) strictly regulates battery recycling rates and the use of recycled materials, effectively mitigating global lithium scarcity and improving resource utilization efficiency (see Table 1). Furthermore, the implementation of this directive can effectively narrow the gaps in lithium supply in Asia, North America, and Australia, and we recommend that this policy model be extended to these regions in advance. We also find that a substantial portion of lithium resources are wasted within social systems; for example, in 2022, Cameroon's lithium dissipation was on par with its annual demand, and by 2050, some countries (such as Germany, Italy, and Portugal) will have lithium dissipation levels exceeding their demand[25]. Lithium mining and purification processes not only are costly but also have negative environmental effects, making the effective recovery of this wasted lithium an essential component of lithium management strategies[30]. Recognizing dissipated lithium resources as a vital component of urban mining can contribute to the establishment of a comprehensive lithium recovery system and the enhancement of lithium management strategies.

In summary, faced with the challenges of uneven global lithium distribution and rapid consumption growth, the adoption of a comprehensive and integrated management strategy is crucial. Such a strategy includes but is not limited to promoting circular economy policies, strengthening technological innovation, improving resource recovery and utilization efficiency, and fostering policy coordination and cooperation globally, particularly in regions with rapid population growth and high levels of lithium demand (Supplementary Fig. 1). Through these measures, sustainable lithium management can be achieved, meeting the future demands of energy transition while maintaining global resources and environmental security.

Methods

Research framework

Lithium consumption is driven by the following two types of LiBs: those used in EVs and those used in BESSs. The number of EVs is closely related to population size, and their in-use stock is often counted at the household level[31]. By combining data on the per capita

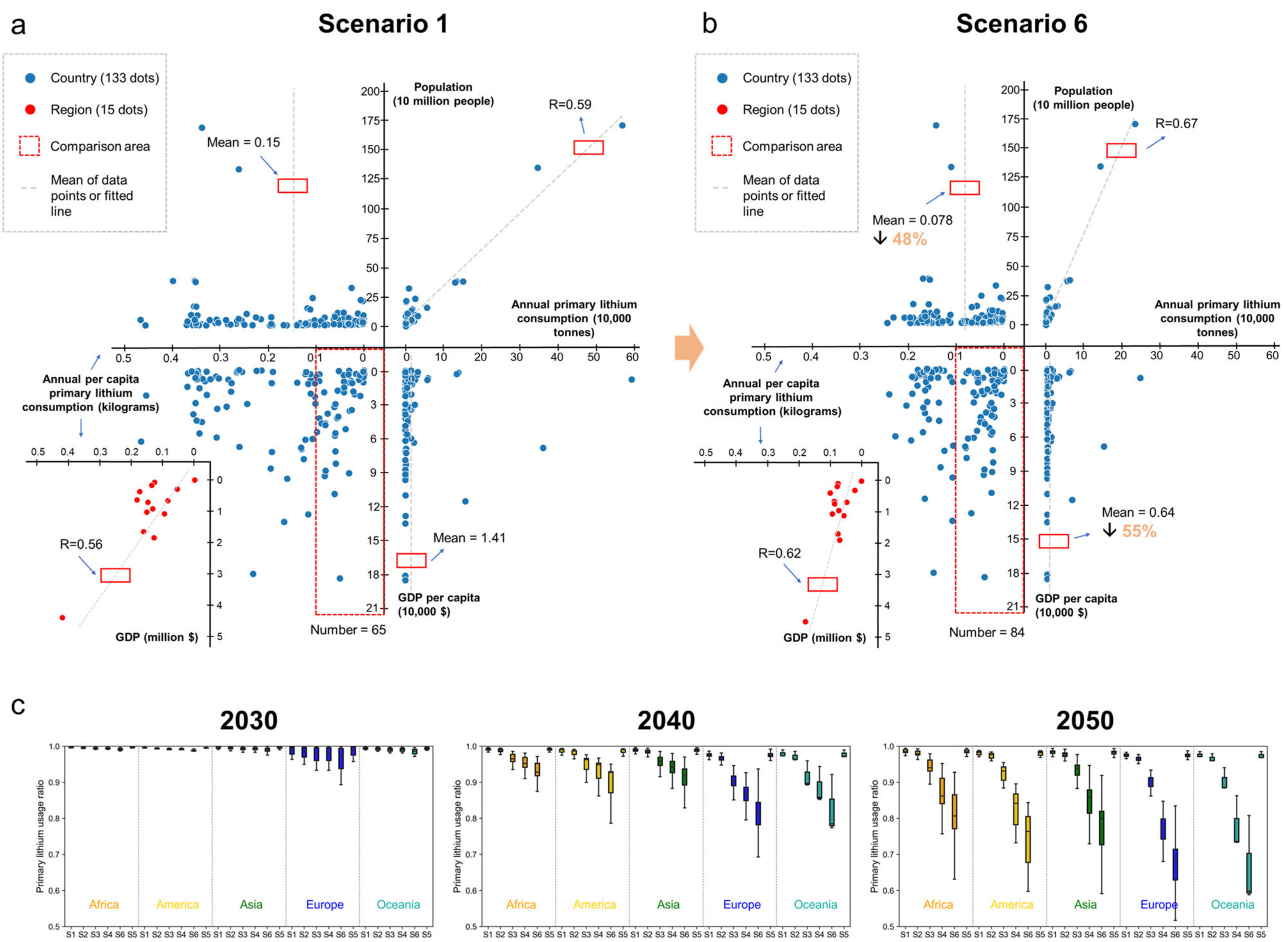

Fig. 5 | Factors affecting primary lithium consumption across countries and regions. **a** and **b** describe the relationships between population, GDP, per capita primary lithium consumption, and total primary lithium consumption in countries or regions in 2050, as influenced by the circular economy. Scenario 1 (**a**) and Scenario 6 (**b**) represent the baseline scenario and the optimal policy scenario, respectively. The vertical dashed lines perpendicular to the x-axis indicate the average annual primary lithium consumption (per capita or total) in the dataset of countries under both scenarios. The inclined dashed lines represent the fitting lines generated to describe the correlation between annual primary lithium consumption and population (for countries) or between annual per capita primary lithium consumption and GDP (for regions) under both scenarios, used to compare the changes in correlation between the two types of variables as influenced by the circular economy. The red solid boxes indicate the specific values corresponding to the dashed lines. The correlation is represented by the correlation coefficient "R", where an absolute value of R close to 1 indicates a strong correlation between the two types of variables. The red dashed boxes indicate the optimal range divided by annual per capita primary lithium resource consumption, with "Number" representing the count of countries entering the optimal range. The downward black arrows below indicate the decrease in corresponding values. **c** shows the impact of different circular economy policies on the primary lithium usage ratio (the ratio of primary lithium consumption to total lithium consumption) across five continents in 2030, 2040, and 2050. The box plots in different colors distinguish the median and quartiles of the primary lithium usage ratio for all countries in the five continents under different circular economy policies. Outliers in the data sets are not included. Other scenarios can be found in Supplementary Figs. 26–29.

in-use stock of EVs, we use a stock-driven approach to calculate the global number of LiB installations in EVs over their lifespan. In contrast, BESSs are deployed in the industrial sector, often in conjunction with facilities such as photovoltaic or wind power facilities, making it difficult to predict their LiB installation levels based on population data[32]. Therefore, we use a flow-driven approach, selecting social energy data from the SSP1-RCP1.9 scenario (Supplementary Tables 2–3) as the basis for estimating global LiB installation levels in BESSs[33]. Based on the law of conservation of mass, the changes in the in-use stock of the two types of batteries should be consistent with the changes in flow (Eq. (1)). The lithium demand is met by both the production from mineral resources and the recycled amount converted from scrapping batteries (Eq. (2)).

$$S_i(t) = \int_{t_0}^{T} (M_i(t) - O_i(t))dt \tag{1}$$

$$M_i^U(t) = D_i(t) - O_i(t) \times \varepsilon_i \tag{2}$$

where $M_i(t)$ is the lithium consumption of domain i in year t, $S_i(t)$ is the in-use lithium stock of domain i in year t, $O_i(t)$ is the lithium scrap of domain i in year t, $M_i^U(t)$ is the primary lithium consumption of domain i in year t, $D_i(t)$ is the lithium demand, and t_0 is the year when the in-use lithium stock first appears.

For the calculation of the two types of battery-related quantities, the only distinction made is in the installed amount. The lithium mass is calculated by converting the lithium content in different types of LiBs (Supplementary Table 8). To elucidate the coupling configuration structure and evolutionary trends of primary and secondary lithium in various countries, we choose per capita consumption and the usage ratio of primary lithium as indicators and analyse the impact of various scenarios on these two metrics (Fig. 6). For the scope of this study, we limit our analysis to the period until 2050 only by mentioning a clause that in the next two decades no notable replacement of lithium is going to happen.

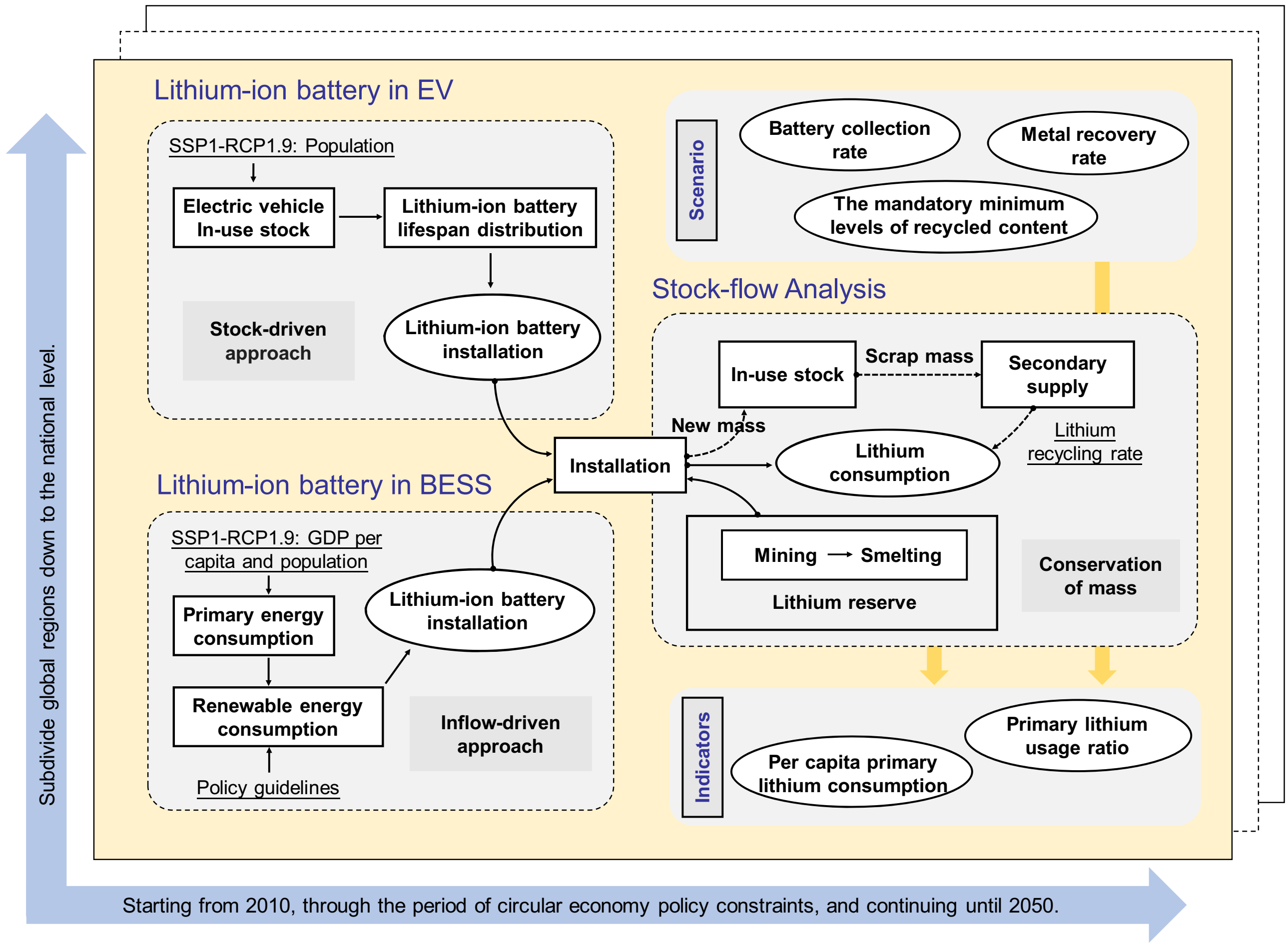

Fig. 6 | Bottom-up research framework. The top-down research framework is interpreted as the computational logic for each target country, composed of the content in the yellow area, showing the changes in various indicates of the framework over time (up to 2050). Within the framework, variables in oval boxes are obtained through calculations, while variables in rectangular boxes are derived from literature or reports. Dashed boxes represent the three modules included in the framework, namely: the LiB installation in EV calculation module, the LiB installation in BESS calculation module, and the stock-flow analysis module. Solid arrows with endpoints indicate the direction of primary lithium flow, while dashed arrows with endpoints represent the flow of secondary lithium. Underlined text denotes key input variables.

Global LiB installation in EVs

The forecast of EV LiB installation depends on the lifespan of the EVs and the final disposition of the LiBs. A Weibull density function with two parameters (Eq. 3) is used to calculate the lifespan distribution of LiBs for EVs as follows:

$$G_t(t|\eta,\beta) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}\exp\left(-\left(\frac{t}{\eta}\right)\right), t \geq 0 \tag{3}$$

where η is the scale parameter indicating when most EVs will fail, and β is the shape parameter of the function. However, in the actual use of EVs, due to their chemical stability in batteries, their degradation occurs over a shorter time than that of the EVs themselves (detailed in Supplementary Table 1), thus leading to situations where battery replacement occurs during the use of EVs. In this study, the actual retirement process of LiBs used in vehicles is divided into two parts (Eq. (4)).

$$O(t) = \int_{t_0}^{t}(M_{EVb}(t)\times G_{EVb}(t) + M_{EV}(t)\times G_{EV}(t)\times\varepsilon)dt \tag{4}$$

where M_{EVb} is the consumption (mass) of LiB cells in EVs, M_{EV} represents the consumption (number) of EVs, G_{EVb} is the lifespan curve of LiBs, G_{EV} is the lifespan curve of EVs, ε is the mass conversion coefficient, and t is the lifespan of LiBs.

Global LiB installation in BESSs

Renewable energy sources such as wind and solar power are affected by climate conditions such as sunlight intensity and wind speed, leading to notable fluctuations in the energy supply. Accompanying electrochemical storage systems can facilitate a stable energy supply. The consumption of primary energy determines the upper limit of renewable energy consumption[34,35], and LiB installation in BESSs is closely related to the consumption of renewable energy[36]. Therefore, we use renewable energy consumption data as an indirect means through which to achieve LiB installation in BESSs (Eq. (5)). More detailed information on the calculation process can be found in Supplementary Figs. 7–9.

$$M(t) = \sum_{t}^{T} E_g(t)\times(\mu_w\cdot R_o^w + \mu_s\cdot R_o^s) \tag{5}$$

where $E_g(t)$ is the consumption of renewable energy in year t and $M(t)$ is the LiB installation in BESSs in year t. The process of converting energy to electricity incurs energy loss, and the actual ratio of energy converted to electricity is referred to as the energy conversion rate. $R_o{}^w$ is the wind energy conversion coefficient, and $R_o{}^s$ is the solar energy conversion coefficient. μ_w is the energy storage device conversion coefficient in wind power generation, and μ_s is the energy storage device conversion coefficient in solar photovoltaic power generation. Notably, the conversion rate of energy storage devices differs for different power generation sources (solar photovoltaic or wind power). We assume that renewable energy sources other than solar and wind power will remain unchanged in the future (see Supplementary Table 4).

Data availability

In order to more comprehensively explore the reality of the two types of lithium-ion batteries, this study further subdivided the five continents into 15 regions based on the United Nations' M49 standard[37], Primary energy and renewable energy data come from the Statistical Review of World Energy Database[38], The battery power data of grid-connected energy storage equipment comes from DOE Global Energy Storage Database[39]. The proportion of renewable energy consumption in total energy consumption in 2050 is as follows: India, 77%[40]; European Union, 97%[41]; United States, 76%[42]; China, 68%[43] and another region, 74%[15]. The model output data used to produce Figures are available at: [https://zenodo.org/records/11160283].

Code availability

The code for the machine learning classifier, as well as for processing and visualizing the data, is made available at: [https://zenodo.org/records/11160283].

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Author contributions
G.Y., and W.Y. led the project and conceived the original idea. G.Y. and Y.Q. designed the research. Y.Q., Z.M. and Y.M. developed the model, ran the simulation, drew the figures and paper. W.Y. and H.G. enhanced the discussion. All authors analyzed the results and contributed to writing this paper.

Competing interests
The authors declare no competing interests.

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