From Demand to Circularity: Rethinking National Strategy on Automobile Battery Supply Chain for Sustainability

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Article

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Abstract

The rapid electrification of transport is driving soaring demand for lithium-ion batteries (LIBs), straining critical mineral supply chains. While policy efforts increasingly emphasize circularity, the diverse and uncertain impacts of supply chain interventions remain poorly understood. We develop a globally applicable scenario-based dynamic material flow simulator incorporating eight drivers with 20 policy options to assess their individual and combined effects on resource conservation and circularity in automotive LIBs. Using the world's largest car exporter, Japan, as a case, we show that even late EV adopters can rapidly close critical mineral loops through intensive policy measures, though results depend strongly on policy combinations. Supplier-side policies can at best reduce mineral demand, while user-side actions more strongly boost circularity. Accelerated recycling of end-of-life LIBs is most influential, followed by advanced battery design. Cross-border traceability, mandatory collection, recycling infrastructure, carbon-neutral fuels, and compact urban design moderately reduce demand but contribute less to circularity. Extending battery life presents trade-offs while restricting the export of used vehicles has a limited effect. We reveal strong synergies among coordinated policies and trade-offs between short-term resource efficiency and long-term circularity. Our results stress the need for integrated, stage-specific strategies that align resource security with circular economy goals. Openly accessible online, the simulator enables nations to craft tailored policies and support international negotiation.

1 Introduction

The rapid expansion of electric vehicles (EVs) and batteries is reshaping climate and industrial strategies. EV deployment and battery recycling are increasingly recognized as essential for transport decarbonization[1], while also raising concerns over economic security and supply chain resilience[2]. In 2022, the transport sector emitted 7.98 Gt-CO_2, accounting for 23% of global emissions[3]. Expanding EV adoption with a decarbonized power system is therefore critical, but it requires large amounts of critical minerals for lithium-ion batteries (LIBs)[4], including lithium[5], nickel, cobalt[6], and manganese[7]. The global EV stock reached 28 million in 2022 and is projected to grow to 790 million by 2035 to align with net-zero targets for 2050[8]. This growth would raise mineral demand 20–40 times by 2040 compared with 2020 levels[9], with prices expected to rise sharply under net-zero scenarios[10]. Given these pressures, together with risks of shortages and humanitarian crises linked to conflict minerals, improving resource efficiency and advancing circularity in the automotive LIB sector is imperative[11].

To address these challenges, numerous policy measures have been proposed and tested, yet no single effective solution has emerged due to limited quantitative assessment of their merits and drawbacks. While advances in battery technology and recycling are widely recognized strategies to improve resource efficiency in the automotive LIB supply chain[12], they cannot immediately close the gap between the increasing demand and the delayed secondary supply of critical minerals[13]. Reducing the cobalt content of batteries through chemical shifts[14], such as wider adoption of lithium iron phosphate (LFP)[15], or raising energy density with lithium-sulphur (Li-S) and lithium-air (Li-Air) batteries[16] can reduce dependence on primary minerals. However, recycling of LFP batteries lacks economic incentives[17] due to the absence of collection premiums and low lithium recovery rates[18], with even the questionable quality of recovered lithium requisitioned for reuse in LIB manufacturing[19]. Next-generation chemistries require decades to commercialize[20] and reducing cobalt increases nickel demand[21], while cobalt is still projected to remain in use for performance gains[22]. Recycling maximizes the recovery of critical minerals[23] but is hindered by the low collection rates and secondary use[24] and by challenges in environmental impacts[25] – recent mainstream pyro- or hydrometallurgy treatments cannot avoid huge energy and resource inputs[26]. Furthermore, expedited recycling could forfeit substantial economic benefits from secondary use in peak shaving and stationary storage[27]. Beyond these strategies, improving collection and recycling rates and extending battery lifespans[28] are also frequently emphasized. In summary, the extent to which such measures can drive meaningful improvements individually or together in the circularity of critical minerals remains insufficiently understood.

To reshape a sustainable automotive LIB supply chain, leading EV manufacturers and exporters are accelerating efforts to secure recycled materials, strengthen supply chain resilience, and increase material circularity. The EU has enacted stringent battery regulations together with the Carbon Border Adjustment Mechanism, enforcing circularity targets and deadlines for critical minerals in LIBs[29]. This creates strong pressure on manufacturers and exporters worldwide. In the USA, the revised Inflation Reduction Act excludes batteries containing critical minerals extracted, processed, or recycled by foreign entities of concern from the Clean Vehicle Tax Credit. China has rushed investments into recycling capacity that are quetioned to double the global supply of end-of-life batteries by 2030[8]. The large exports of used hybrid vehicles from Japan[30] have sparked debates on restricting used-EV exports for collecting spent LIBs[31]. With more countries designating battery minerals as strategic resources, national battery passports and traceability systems are being introduced. The EU has already launched its own battery passport, and Japan has initiated the Ouranos Ecosystem Project to track EV and LIB supply chains[32]. Looking ahead, the global LIB industry will be subject to growing policy interventions at nation level, even in times of world crisis, direct governmental control remains possible.

Two major challenges emerge during rapid global shifts. First, policies across countries are fragmented, covering the entire supply chain yet lacking prioritization. Regulations on battery recycling differ widely in enforcement, producer responsibility, waste classification, targets, design standards, public participation, and incentives[33]. Such disparities impede cross-border data sharing and unified regulation, and only a small share of retired LIBs currently reach high-quality reuse or recycling facilities[34]. Given the complexity of supply chains and the uneven resource distribution, even national measures can have global ripple effects, making international coordination on standards essential[35]. Second, market responses to battery electric vehicles (BEVs) diverge. For example, the United States trails the EU and China, Japan is still at an early stage of development, and Southeast Asia is now an emerging market after the EU and China[36]. Since extraction and smelting still dominate life cycle burdens[26], distribution of industrial development, EV markets, and socio-environmental impacts reveal high disparity. National-level assessment of individual and combined supply chain policies is crucial for advancing regional governance, international coordination, and life cycle management[37]. Japan, which is both the world's largest automobile exporter and a latecomer in EV adoption, is particularly exposed to domestic and foreign policy shifts, making it a representative case for circular strategy design.

This study develops a scenario-based integrated dynamic material flow simulator to model material circulation in automotive LIBs, grounded in ongoing global debates on resource security policies. The simulator is designed as a transparent and easy-to-use tool: by setting local parameters and choosing policies, users can automatically calculate the outcomes of any combination of policy options. It can thus be adapted by any nation to design optimized circularity strategies, strengthen its negotiating position, and support constructive international dialogue. Building on previous dynamic materials flow analyses, our model incorporates a broad set of supply- and demand-side factors, including battery upgrades, lifespan, traceability, recycling progress, EV penetration, secondary use, used-car exports, and traffic demand management (Fig. 1). We apply the simulator to Japan, a nation with limited mineral resources but a leading role in global automobile exports. The results show that even Japan, a latecomer in EV industrial development, could reduce total demand for critical minerals by up to 82% and raise circularity above 80% by 2050 through robust combined policy interventions. The complex interactions between supplier- and user-side measures produce diverse impacts on the LIB supply chain, and these uncertainties were explicitly quantified in our simulation. These findings underscore the role of comprehensive resource management in advancing sustainable battery supply chains and shaping fairer international negotiations.

2 Results

2.1 Framing of policy options and scenario design

To capture the variability in the demand for and circularity of critical minerals stemming from policy interventions across the automotive LIB supply chain, we identified eight key drivers and 20 policy options which span both supplier- and user-side interventions (Fig. 1b).

Supplier-side options include: ☒ Battery chemical shifts – accounting for transitions from Co-rich chemistries to Co-free alternatives, such as LFP, and future candidates, such as Li-S or Li-Air; ☒ Service life of LIBs – reflecting durability and performance enhancements through policy and technological innovation; ☒ Tracing and mandatory collection – encompassing domestic regulations and Japan's influence via overseas export channels; ☒ Advancements in recycling – addressing the current challenges in LFP recycling and improving recovery rates for critical minerals.

User-side options include: ☒ BEV penetration vs. carbon-neutral fuels (CNF) penetration – reflecting the balance between BEV deployment and the adoption of CNF in plug-in hybrid electric vehicles (PHEVs); ☒ Secondary use vs. expedited recycling – capturing trade-offs between economic value and critical mineral circulation speed; ☒ Regulation on used-car exports – targeting material losses through untracked cross-border flows; ☒ Traffic demand management – leveraging compact city planning and car-sharing schemes to reduce passenger car demand.

These socio-economic changes and policy interventions drive key variations. In Japan, passenger vehicle ownership is anticipated to decline from 60.7 million in 2024 to 53.2 million by 2050 due to depopulation, and further to 47.2 million under compact city and car-sharing policies (Figure S10). Annual registrations and deregistrations are also expected to both fall by about 20% during 2025–2050 (Figure S16). By 2050, internal-combustion engine vehicles (ICEVs) will have nearly disappeared, while hybrid electric vehicle (HEV) ownership peaks in 2040 before dropping to 20 million by 2050. EVs account for about two-thirds of passenger vehicles (Figure S21). Depending on policy combinations, spent LIB collection in 2050 ranges from 400 to 3,000 kt pack weight with diverse chemistries (Figure S25). Meanwhile, used-EV exports steadily rise, reaching about 400,000 units by 2050 (Figure S27).

To systematically explore the interactions among these policies, each option was assigned a level of influence (i.e. 1 = weak, 2 = moderate and 3 = strong), forming a 3·3 matrix of nine scenarios (i.e. S11–S33, Fig. 1c). These scenarios represent varying degrees of policy ambition and system transformation. S11 reflects the status quo in Japan with minimal supply chain intervention, while S33 represents an ambitious pathway where all policies are enacted at their strongest levels. Intermediate scenarios (e.g. S21, S22, S23, S32) reflect mixed levels of policy intensity. An additive scenario matrix is further constructed to assess both the individual and synergistic effects of each option relative to the baseline (S11), thereby identifying effective strategies for enhancing critical mineral circularity. The selection and structuring of these policy options are based on the premise of leveraging national influence to govern various segments of the battery supply chain and thereby control the material flow of critical metals. Disruptive innovations or major shifts in international dynamics that are unpredictable or beyond national control are not included in this study. Parameter settings are detailed in the Materials and Methods section and Supplementary Document.

2.2 Critical mineral demand and circularity across integrated scenarios

The above nine integrated scenarios reveal that Japan can substantially reduce the total input of critical minerals for automotive LIBs by 2050 – up to 82% compared with the baseline (S11) – but this heavily depends on combined policy interventions. Reductions are more responsive to supplier-side than user-side interventions. Figure 2 shows the projected critical mineral demand from 2025 to 2050. Without intervention (S11), cumulative input reaches 11.1 Mt-LiNiCoMn. In the most ambitious scenario (S33), this drops to 2.0 Mt. Supplier-side policies alone (S11–S13) reduce inputs by 53%, while user-side policies (S11–S31) achieve a 39% reduction. Even in LFP-oriented scenarios, NMC batteries remain a major contributor to critical mineral demand. Immediate recycling slightly increases LIB use in stationary storage but has a limited impact due to degraded battery health and LFP dominance in stationary applications. Mid-level supplier-side interventions (e.g. S22, S23) appear sufficient for balancing resource conservation with policy feasibility.

Figure 3 highlights a more complex relationship between the material flow and circularity. While virgin material inputs can be reduced significantly, improving circulation rates is more difficult. In S11, virgin inputs rise steadily, reaching 705.2 kt/year by 2050. Under stronger interventions (S12, S13, S21, S31), virgin inputs stabilize by 2035 at ~ 300 kt/year, or peak earlier (2030) in S33, dropping to ~ 35 kt/year by 2050. User-side interventions (S11–S31) place greater stress on recycling systems, whereas supplier-side interventions (S11–S13) more effectively minimize both demand and losses. Recycling capacity alone cannot offset inefficiencies without complementary tracing and chemical shifts. In S33, a near-closed-loop system emerges post-2040, enabled by policy synergies. Although user-side interventions contribute less to demand reduction, they are key for increasing circularity, particularly by boosting inflow and outflow circulation rates through expedited recycling. Supplier-side measures like longer battery life may delay recycling, reducing short-term circularity. However, they help reduce total demand and support recovery when paired with collection and recycling upgrades. Overall, average circulation rates align more closely with inflows than outflows, due to mismatches between the secondary supply and material demand. Strong user-side interventions help narrow this gap significantly.

Figure 4 compares scenario performance across multiple indicators. Across scenarios, stronger interventions yield generally better outcomes, but not uniformly. Some indicators exhibit trade-offs or reversals, particularly in scenarios combining long service life with delayed recycling. S11 performs worst on demand indicators, while S12 and S13 underperform on circularity. Supplier-side policies are more effective in reducing demand, while user-side policies better enhance circulation. However, scaling up supplier-side actions often introduces uncertainty or trade-offs, with divergent effects on short- and long-term outcomes (indicators in 2050 reveal relatively worse from 2035 in S12, S21, S22, S31, and S32, see Figure S33).

2.3 Impact assessment on individual policies and combinations

To complement the integrated scenario analysis, we conducted a scenario matrix evaluation to isolate the individual effects of each policy option and explore potential synergies between the paired interventions. Figure 5 illustrates the outcomes in terms of two key indicators (i.e. annual virgin input of critical minerals and inflow circulation rate) at two time points: 2035 and 2050. The diagonal points represent the impact of individual policy options, while the off-diagonal points capture the combined effects of two policies, all benchmarked against the baseline (S11).

In the short term (2035), only policy □ (expedited recycling) demonstrates a dual benefit – substantially reducing virgin material input while also increasing circularity. Policies □ (i.e. battery chemical shifts to LFP), □ (i.e. extended battery life), and □ (i.e. traffic demand reduction) show moderate reductions in virgin inputs but limited effect on circularity. Notably, while policy □ appears effective in reducing virgin inputs, it consistently suppresses circularity across all pairings, due to delays in material return to the recycling loop.

In the long term (i.e. until 2050), more policy options contribute to reduced virgin material input, with policy □ (i.e. shifting toward Li-S/Air chemistry) yielding the largest gains. The effectiveness of policy □ further amplifies in combination with policies □, □ (i.e. mandatory collection), or □ (i.e. recycling technology advancement), resulting in the lowest virgin inputs and highest inflow circularity. In contrast, policy □ (CNF-oriented PHEV expansion) performs better than policy □ in reducing long-term virgin input and boosting circularity. Policy □ (i.e. used-car export regulation) has only a marginal effect on both indicators, suggesting limited leverage unless other policies fail. A simple test on synergy effects also indicates significant synergies between policy □ (i.e. expedited recycling) and other options, while policy □ (i.e. extended battery life) appears to enter a trade-off against the other policies (Figures S37, S38). Taken together, these results reveal that expedited recycling consistently delivers strong returns, both independently and in combination, whereas extended service life may conflict with circularity goals if not paired with enhanced collection and recycling. Policy designs should consider synergies and conflicts.

3 Discussions

Our results indicate that even economies with slower EV adoption can still achieve high circularity, though only under intensive policy intervention. In the case of Japan, the primary demand for critical minerals has the possibility to fall by up to 80% while circulation exceeds 80% by 2040, without relying on imported secondary resources. This suggests that ‘latecomer’ economies are not excluded from circularity transitions. However, Japan really has difficulties in regulating or interfering with the market. Initial boom for buying EVs is crucial to form a faster recycled material market from spent LIBs, but consumers’ willingness to purchase EVs still remains very low[36], even in Japan, which has provided attractive subsidies for EV purchases in 2022[38]. Japan appears to face difficulties in cultivating a domestic EV market large enough to support the secondary mineral supply inputs for EV exports. A shortage of both primary and secondary resources may increase supply chain risks and weaken industrial competitiveness in pioneer economies. In response to this concern, Japan may rush to extend producer responsibilities, including importing companies, restrict the used-car exports, and even mandate collecting all spent LIBs for recycling locally, as in the case of solar panels[39]. However, these options involve great trade-offs with market heat and corporate profit, which leaves the pathway to circularity highly contested. Therefore, regulations on early circularity indeed appear more favourable to pioneer economies with existing advantages in recycling systems[40].

Evidence-based policy design must carefully balance demand reduction and circularity, as our simulation reveals mismatches between these goals, complex interactions among policies, and uneven indicator changes across time horizons. Setting early-stage circularity targets without well-organized strategies risks unintended trade-offs. Increasing circularity does not necessarily reduce primary demand (e.g. S12/S13 vs. S21/S31), and policies differ in their short- versus long-term effectiveness: for example, S12, S22, and S32 perform better on demand reduction by 2035, while S21 and S31 achieve higher circularity by 2035 but not by 2050. Overemphasis on a single indicator, such as immediate recycling of all spent LIBs or maximizing battery lifetime, can distort outcomes, either reducing user value or suppressing circularity. Similarly, batteries' short guarantee periods may accelerate circularity but increase resource input, while rapid LFP adoption reduces critical mineral use but may hinder the diffusion of advanced chemistries. Our results highlight that policy combinations generate greater and more stable improvements than individual measures, with synergies that can even offset trade-offs. For Japan, which is a market-driven economy, flexible policy-making is essential by adjusting intensity, timing, and combinations of measures to accommodate uncertainties. Expedited recycling consistently proves globally impactful, while excluding LFP from secondary use or requiring LIB pre-removal from exported vehicles appears less decisive unless other policies fail. Investments in recycling infrastructure should be scaled cautiously to avoid overcapacity risks, given uncertain LIB availability. Ultimately, advancing a closed-loop system for critical minerals requires refined management of multiple indicators, balancing feasibility with policy incentives, and dynamically adjusting strategies to guide the industry toward long-term sustainability.

Given the diversity of national conditions and the interaction effects among policies, international coordination should emphasize negotiation and rule-making rather than simply competing to raise circulation rate targets. Key priorities include harmonizing extended producer responsibility, clarifying ownership of spent LIBs, establishing traceability systems for second-hand EVs, and regulating cross-border flows of spent LIBs. Without such coordination, setting rigid global targets risks disadvantaging late-adopting economies, forcing them into costly competition for recycled materials already controlled by pioneers, thereby slowing EV penetration. Competition has already begun. For example, China is revising regulations to capture global flows of spent LIBs[41], while Japanese firms test overseas recycling to secure secondary supply[42]. To move forward, consensus on flexible targets and fair governance mechanisms is essential. International efforts, such as unique traceability codes for LIBs[43], battery passports with circularity information[44], and International Organization for Standardization policies (e.g. TC323, TC333) show progress, but stronger negotiation frameworks are needed. We suggest prioritizing international consensus and cooperative rule-making, which would allow diverse national strategies while avoiding excessive costs and ensuring a fair and effective transition toward circularity.

Under relatively lenient international rules, an economy can enjoy path dependence in technology development without precluding balanced circular strategies. Japan has established strength in NMC and solid-state batteries[45] and the relative weakness in LFP technologies[46] illustrates the risks of abrupt chemical shifts on national research and development[47]. A forced shift to LFP could undermine domestic capabilities. However, our analysis shows that even NMC-oriented strategies can halve total primary critical mineral demand and achieve 50–80% circulation by 2050 under interventions (see Figure S39). In contrast, in the case of maximizing user value, all secondary-use strategies can also potentially halve the demand while remaining an acceptable circularity (see Figure S40). Combining these measures offers a feasible pathway toward both reduced input and enhanced circularity, suggesting that transitions must be adaptive to industrial legacies rather than prescriptive toward one chemistry. Such path dependence will support a wider public acceptance towards EVs and stimulate the enterprises' investment enthusiasm. Our simulator enables a nation/region to evaluate and investigate customized policy combinations that align with the established technology roadmap.

Our simulation also supports, different minerals respond very differently to circular economy interventions, requiring tailored policy mixes. Under most intensive policy intervention, Co primary demand can be almost eliminated by 2040 (Figure S29), while Ni primary demand accordingly declines but slower due to the substitution of Co in battery chemical shifts (Figure S30), which is consistent with previous studies[21]. Li is far more resistant: that is, only expedited recycling or breakthroughs such as Li-S/Air achieve substantial reductions (Figure S28). Thus, the lithium supply chain will still be dominated by several exportors[48] in the near future. Additional analysis on Cu flow proves even less flexible with demand continuing to rise until 2050 under all scenarios (Figure S31), which verifies the concerns from the International Energy Agency (IEA) report[36]. These contrasting trajectories highlight that circularity is not a uniform challenge. Effective policy design will depend on mineral-specific strategies aligned with both technological potential and market dynamics.

4 Materials and methods

4.1 Modelling, definitions, and research boundary

As shown in Fig. 1(a), we developed a scenario-based dynamic material flow[49,50] simulator to simulate the demand and circularity of lithium, cobalt, nickel, and manganese in Japan's automotive LIB supply chain from 2025 to 2050. The model integrates projections of passenger car ownership, battery technology adoption, material composition, and end-of-life recycling. Vehicle fleet size and powertrain composition are projected under demographic, economic, and mobility scenarios using an econometric stock model calibrated to Japanese transport data. Battery technology configurations (e.g. NMC, NCA, LFP, Li–S/Air) are assigned according to scenario-specific technological trajectories drawn from literature and policy outlooks. End-of-life flows are modelled for both domestic and exported vehicles using a Weibull distribution calibrated to 2020 fleet data. Closed-loop recycling is tracked through a mass balance framework, while open-loop flows and cross-border returns are conservatively excluded in the baseline. Three indicators (i.e. inflow circulation rate, outflow circulation rate, and weighted average circulation rate) quantify circularity outcomes annually and cumulatively. Nine integrated scenarios explore interactions between battery strategies and circular economy policies, including extended producer responsibility, direct recycling, and domestic production support. Full methodological details are provided in the Supplementary Document.

The system boundary excludes buses, trucks, and special vehicles, which are in a small proportion or are expected to favour fuel cell technologies. The simulation focuses on LIBs originally installed in passenger EVs for the Japanese market or for export. Directly exported new LIBs (OEM) are excluded due to their unclear market share and limited data. The extraction phase of virgin raw materials is not modelled. Several key assumptions also apply. First, all spent automotive LIBs for potential secondary use are assumed to be collected and controlled by companies and are 100% collected after retirement, though losses occur during dismantling and used-car trading due to weak regulatory oversight. Second, the secondary-use market is assumed to have unlimited capacity to accept spent LIBs from Japan. Third, all passenger vehicles follow a common survival curve, and battery refurbishment is treated as a service-life extension. Fourth, all first-use stationary energy storage systems are assumed to employ LFP batteries.

4.2 Policy options and the parameter settings

The dynamic material flow simulator accounts for annual changes in stock, usage, recycling, and disposal flows of LIBs under varying policy conditions. Key parameters are calibrated based on literature and national statistics. For instance, the predicted market shares of battery chemistries under the 'Battery Chemistry Shift' option were derived from Xu, et al. [20]. The potential doubling of LIB service life is based on projected technology roadmaps[51]. The collection rates for spent LIBs in domestic regions are informed by METI surveys[52], while overseas collection rates consider local regulations[29] and the proportion of passenger cars sent to these regions[53]. Critical mineral recovery rates are set based on the latest assessments[17]. EV penetration trajectories and the share of PHEVs using CNF follow estimates from *JAMA*[54]. The trade-off between secondary use and expedited recycling is modelled by adjusting delay times before recycling[28]. Export restrictions are reflected through reduced outflows of used vehicles and improved traceability, while traffic demand shifts are modelled via reductions in car stock per capita, aligned with demographic trends. As summarized in Fig. 1(b) and Table 1, these options are ordered from 'a' to 'b' to 'c', based on the regulatory intensity of resource conservation and circulation.

Table 1
Policy options in the LIB supply chain and parameter settings.

Factors	**Policy options**	**Descriptions**
☒ Battery chemistry	a. NCX-oriented	NMC batteries dominate the automobile market. Figure S24(a).
	b. LFP-oriented	LFP batteries dominate the automobile market. Figure S24(b).
	c. Li-S/Air-oriented	Li-S/Air batteries dominate the automobile market. Figure S24(c).
☒ Battery service life	a. Current situation unchanged	The guarantee periods of LIBs for BEVs, PHEVs, and stationary energy storage are set at 7, 8, and 10 years, respectively[13].
	b. Extended scenario	The above guarantee periods are extended to 11, 12, and 15 years, respectively (average during 2025–2050)[51] (Table S8).
☒ Tracing & mandatory collection	a. Current situation unchanged	75% of spent LIBs domestically and 10% overseas are collected in closed-loop systems[52].
	b. Strengthened via sales network	95% of spent LIBs domestically and 40% overseas are collected in closed-loop systems.
	c. Strengthened via international rule-making	95% of spent LIBs domestically and 90% overseas are collected in closed-loop systems (Table S11).
☒ Recycling progress	a. Low level	LFP batteries are not recycled; the recycling rate for Li is 50%, and for Ni, Co, and Mn it reaches 90%[17].
	b. Moderate level	LFP batteries are recycled; the recycling rate for Li, Ni, Co, and Mn reaches 90%.
	c. Ambitious level	LFP batteries are recycled; the recycling rate for Li, Ni, Co, and Mn reaches 99% (Table S10).
☒ EV penetration	a. BEV-oriented	ICEVs exit the domestic new sales market by 2035, while BEVs dominate by 2050. Overseas market share changes follow IEA projections[8] (Figure S19(a)).
	b. CNF-oriented	ICEVs exit the domestic new sales market by 2035, while BEVs and PHEVs each account for about half of the market by 2050. Overseas market share changes follow IEA projections[8] (Figure S19(b)).
☒ Secondary use	a. All to secondary use	All spent LIBs are accepted for stationary energy storage and used worldwide.
	b. LFP–only secondary use	Only LFP batteries are accepted for stationary energy storage and used worldwide.

Factors	Policy options	Descriptions
	c. All to immediate recycling	All spent LIBs are immediately recycled. Instead, stationary energy storage demand is met by new LFP batteries. The substitution ratio of spent LIBs for new LIBs is set at 80% (State of health = 80%) (Table S29).
Used-car export	a. Export with LIB	LIBs are exported with used cars as usual.
	b. Export without LIB	LIBs are prohibited from being exported with used cars (Figure S27).
Traffic demand management	a. Current situation unchanged	No reduction in road infrastructure or promotion of car-sharing domestically.
	b. Car-sharing & compact city	Road infrastructure is reduced due to depopulation, and car-sharing is promoted domestically (Figure S10).

4.3 Vehicle fleet and market projections

We first estimate the size and composition of Japan’s passenger car fleet. Total domestic passenger car ownership (S) is projected using a modified econometric model adapted from Nakamura et al.[55], incorporating the number of households (N), annual household income ($\bar{I}$), average vehicle purchase price ($\bar{P}$), and car-sharing trends:

$$S = \frac{N \cdot \gamma \cdot (1 - \eta \cdot \delta)}{1 + \alpha \cdot \exp(-\beta \cdot \frac{\bar{I}}{\bar{P}})}$$

1

Here, η is the car-sharing membership rate, and δ is the reduction in car ownership per membership, based on findings from a report by the ECOMO[56]. The parameter γ, representing mobility demand, is estimated as a function of paved road length per capita (r) and population density in densely inhabited districts (D_{DID}):

$$\gamma = \epsilon_1 \cdot r^{\epsilon_2} \cdot {D_{DID}}^{-\epsilon_3}$$

2

Coefficients α, β, ϵ_1, ϵ_2, and ϵ_3 are calibrated using Japanese transport data (see Table S4). A compact city scenario assumes constant population density in DIDs and proportional decline in local road infrastructure (accounting for 80% of the total) after 2025. Vehicle usage intensity will be reduced by compact city policies, but it should be partially offset by car-sharing services.

Passenger vehicle survival rate at age t ($F(t)$) is modelled using a Weibull distribution calibrated to 2020 fleet data[57]:

$$F\left(t\right)=1-e^{-\left(\frac{t}{}\right)^{m}}$$

3

Parameters m and μ are calibrated to 1.93 and 16.02, respectively. Passenger car exports are assumed to remain constant at the 2017–2023 average: that is, 3.82 million new and 25% of deregistered vehicles annually exported. Market shares for new vehicle sales follow the IEA's Announced Pledges Scenarios[8]: 48% BEVs and PHEVs in 2030, 67% in 2035, and 98% in 2050.

4.4 Battery technology configurations

We model four major LIB types: LFP, NCA, NMC, and Li-S/Air, and tentatively exclude sodium-ion and magnesium batteries, etc[58]. The market share trajectory of each battery type is dependent on the scenario. The baseline assumes continued dominance of NMC and NCA in EVs, with LFP adoption limited by Japan's cost disadvantage and reliance on imports. Li-S and Li-Air represent high-performance post-Li-ion technologies with potential for domestic leadership. Battery parameters (e.g. energy density, material content per kWh, cycle life, and vehicle range) are derived from peer-reviewed literature and industry reports as mentioned before, with values summarized in Tables S6 and S7. Advanced configurations assume Li-S/Air batteries reach technical maturity after 2035 under certain scenarios. A unified battery design is assumed for each technology per scenario. Annual material demand for new Evs is calculated by multiplying projected EV sales by battery capacity per vehicle and per-kWh material intensities.

4.5 End-of-life flows and circularity indicators

Considering service life of battery mismatches with vehicles[59], we track LIBs from both domestic and exported vehicles according to their usage abroad and potential return or recycling in foreign markets. Exported used vehicles are assumed to serve their full lifespan overseas. As shown in Figure S4, material flows include closed-loop recycling (e) (i.e. recovered LIB materials reused within Japan's automotive battery production), and final disposal (c) (i.e. uncollected or unrecoverable LIB materials). Open-loop recycling ($b,\ d$), which represents flows to/from other industries or countries, is excluded due to insufficient data. Recycling yields and collection efficiencies are parameterized by battery chemistry and recovery technology, drawing from prior studies and updated projections mentioned before (Table S8–S11). Delamination and direct recycling processes are ranged for advanced scenarios.

The Indicators for evaluating the Impact on critical mineral circularity IIe the cumulative Input of critical minerals, the annual input of virgin raw critical minerals, and the circulation rate. We adopt three indicators to evaluate circularity outcomes for critical minerals. The inflow circulation rate is defined as the proportion of recycled materials in total resource input. The outflow circulation rate indicates the share of recovered materials in the post-consumer waste flow. The weighted average circulation rate combines these two, capturing both supply- and demand-side effects. These are calculated as follows:

Inflow circulation rate $R_{in}=\frac{e}{a+b+e}$ (4)

Outflow circulation rate $R_{out} = \frac{e}{c+d+e}$ (5)

Weighted average circulation rate $\bar{R} = \frac{R_{in} \cdot (a+b+e) + R_{out} \cdot (c+d+e)}{(a+b+e)+(c+d+e)}$ (6)

where a denotes the inflow of virgin material input. These indicators are computed annually and cumulatively from 2025 to 2050, aligned with definitions by WBCSD[60]. More details can be found in the Supplementary Document.

4.6 Limitations and uncertainties

Our scenario-based simulation inevitably involves uncertainties stemming from assumptions about EV adoption, battery technology evolution, and vehicle longevity. Future EV adoption in Japan and worldwide may diverge from current projections due to shifting consumer preferences[61] and evolving domestic and international tendencies[62]. Rapid battery innovation may also lead to more diverse application scenarios[63] and higher efficiency, energy densities and stability than anticipated[64]. The service life of EVs remains uncertain compared to conventional cars, with studies showing much shorter lifespans in China[65] compared to parity in Great Britain[66]. We also assume fixed battery capacities, although trends suggest increasing demand for high-capacity batteries, particularly for heavy-duty transport. To address these uncertainties, we conducted sensitivity analyses on key parameters; detailed results are available in the Supplementary Information (Figure S41). Given these constantly evolving conditions, further parameter adjustments and validation of results are necessary.

Declarations

Lead contact

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Declaration of interests

The authors declare no competing interests.

Author contributions

Conceptualization, Y.D.; methodology, Y.D.; investigation, Y.D.; writing—original draft, Y.D.; writing—review & editing, Y.D., A.H., and Y.K.; funding acquisition, Y.D., A.H., and Y.K.; resources, Y.D. and A.H.; supervision, Y.D., A.H., and Y.K. All authors contributed to writing this paper.

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References

1. Crabtree, G. The coming electric vehicle transformation. *Science*366, 422-424 (2019). https://doi.org/10.1126/science.aax0704
2. Olivetti, E. A., Ceder, G., Gaustad, G. G. & Fu, X. K. Lithium-Ion Battery Supply Chain Considerations: Analysis of Potential Bottlenecks in Critical Metals. *Joule*1, 229-243 (2017). https://doi.org/10.1016/j.joule.2017.08.019
3. IEA. CO2 Emissions in 2022. (International Energy Agency (IEA), Paris, 2023).
4. IEA. Energy Technology Perspectives 2023. (International Energy Agency (IEA), Paris, 2023).
5. Greim, P., Solomon, A. A. & Breyer, C. Assessment of lithium criticality in the global energy transition and addressing policy gaps in transportation. *Nature Communications*11, 4570 (2020). https://doi.org/10.1038/s41467-020-18402-y
6. Sun, X., Hao, H., Liu, Z., Zhao, F. & Song, J. Tracing global cobalt flow: 1995–2015. *Resources, Conservation and Recycling*149, 45-55 (2019). https://doi.org/https://doi.org/10.1016/j.resconrec.2019.05.009
7. Sun, X., Hao, H., Hartmann, P., Liu, Z. W. & Zhao, F. Q. Supply risks of lithium-ion battery materials: An entire supply chain estimation. *Mater Today Energy*14 (2019). https://doi.org/ARTN 100347 10.1016/j.mtener.2019.100347
8. IEA. Global EV Outlook 2024. (International Energy Agency (IEA), Paris, 2024).
9. IEA. The Role of Critical Minerals in Clean Energy Transitions. (International Energy Agency (IEA), Paris, 2021).
10. IMF. IMF Working Paper: Energy Transition Metals. (International Monetary Fund (IMF), 2021).
11. Ali, S. H. *et al.* Mineral supply for sustainable development requires resource governance. *Nature*543, 367-372 (2017). https://doi.org/10.1038/nature21359
12. Harper, G. *et al.* Recycling lithium-ion batteries from electric vehicles. *Nature*575, 75-86 (2019). https://doi.org/10.1038/s41586-019-1682-5
13. Zeng, A. *et al.* Battery technology and recycling alone will not save the electric mobility transition from future cobalt shortages. *Nature Communications*13, 1341 (2022). https://doi.org/10.1038/s41467-022-29022-z
14. Dunn, J., Slattery, M., Kendall, A., Ambrose, H. & Shen, S. H. Circularity of Lithium-Ion Battery Materials in Electric Vehicles. *Environ Sci Technol*55, 5189-5198 (2021). https://doi.org/10.1021/acs.est.0c07030

15. Rossi, F. *et al.* Environmental optimization model for the European batteries industry based on prospective life cycle assessment and material flow analysis. *Renewable and Sustainable Energy Reviews* **183**, 113485 (2023). https://doi.org/https://doi.org/10.1016/j.rser.2023.113485
16. Jiang, S. Y. *et al.* Assessment of end-of-life electric vehicle batteries in China: Future scenarios and economic benefits. *Waste Manage* **135**, 70-78 (2021). https://doi.org/10.1016/j.wasman.2021.08.031
17. Dai, Q. *et al.* EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model (Argonne National Laboratory). (2019).
18. Wang, X., Gaustad, G., Babbitt, C. W. & Richa, K. Economies of scale for future lithium-ion battery recycling infrastructure. *Resour Conserv Recy* **83**, 53-62 (2014). https://doi.org/10.1016/j.resconrec.2013.11.009
19. Ziemann, S., Müller, D. B., Schebek, L. & Weil, M. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: A dynamic MFA approach. *Resour Conserv Recy* **133**, 76-85 (2018). https://doi.org/10.1016/j.resconrec.2018.01.031
20. Xu, C. J. *et al.* Future material demand for automotive lithium-based batteries. *Commun Mater* **1** (2020). https://doi.org/10.1038/s43246-020-00095-x
21. Baars, J., Domenech, T., Bleischwitz, R., Melin, H. E. & Heidrich, O. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. *Nature Sustainability* **4**, 71-79 (2021). https://doi.org/10.1038/s41893-020-00607-0
22. Gent, W. E., Busse, G. M. & House, K. Z. The predicted persistence of cobalt in lithium-ion batteries. *Nature Energy* (2022). https://doi.org/10.1038/s41560-022-01129-z
23. Nurdiawati, A. & Agrawal, T. K. Creating a circular EV battery value chain: End-of-life strategies and future perspective. *Resour Conserv Recy* **185** (2022). https://doi.org/ARTN 106484 10.1016/j.resconrec.2022.106484
24. Kastanaki, E. & Giannis, A. Dynamic estimation of end-of-life electric vehicle batteries in the EU-27 considering reuse, remanufacturing and recycling options. *J Clean Prod* **393**, 136349 (2023). https://doi.org/https://doi.org/10.1016/j.jclepro.2023.136349
25. Ciez, R. E. & Whitacre, J. F. Examining different recycling processes for lithium-ion batteries. *Nature Sustainability* **2**, 148-156 (2019). https://doi.org/10.1038/s41893-019-0222-5
26. Sakunai, T., Ito, L. & Tokai, A. Environmental impact assessment on production and material supply stages of lithium-ion batteries with increasing demands for electric vehicles. *Journal of Material Cycles and Waste Management* **23**, 470-479 (2021). https://doi.org/10.1007/s10163-020-01166-4
27. Yang, D. *et al.* Evaluating the recycling potential and economic benefits of end-of-life power batteries in China based on different scenarios. *Sustainable Production and Consumption* **47**, 145-155 (2024). https://doi.org/10.1016/j.spc.2024.04.001
28. Shafique, M., Rafiq, M., Azam, A. & Luo, X. Material flow analysis for end-of-life lithium-ion batteries from battery electric vehicles in the USA and China. *Resources, Conservation and Recycling* **178**, 106061 (2022). https://doi.org/https://doi.org/10.1016/j.resconrec.2021.106061

29. IEA. EU Sustainable Batteries Regulation. (International Energy Agency (IEA), 2023).
30. Wang, S., Yu, J. & Okubo, K. Estimation of End-of-Life Hybrid Vehicle number in Japan considering secondhand vehicle exportation. *Waste Manage***104**, 198-206 (2020). https://doi.org/10.1016/j.wasman.2020.01.022
31. Sato, F. E. K. & Nakata, T. Recoverability Analysis of Critical Materials from Electric Vehicle Lithium-Ion Batteries through a Dynamic Fleet-Based Approach for Japan. *Sustainability-Basel***12** (2020). https://doi.org/ARTN 14710.3390/su12010147
32. METI. *Whitepaper: Ouranos Ecosystem Dataspaces Reference Architecture Model*. (Ministry of Economy, Trade and Industry (METI), Japan, 2025).
33. Giosuè, C. *et al.* An Exploratory Study of the Policies and Legislative Perspectives on the End-of-Life of Lithium-Ion Batteries from the Perspective of Producer Obligation. *Sustainability-Basel***13** (2021). https://doi.org/ARTN 1115410.3390/su132011154
34. Nguyen, R. T., Fishman, T., Zhao, F., Imholte, D. D. & Graedel, T. E. Analyzing critical material demand: A revised approach. *Sci Total Environ***630**, 1143-1148 (2018). https://doi.org/10.1016/j.scitotenv.2018.02.283
35. Su, D., Mei, Y., Liu, T. C. & Amine, K. Global Regulations for Sustainable Battery Recycling: Challenges and Opportunities. *Sustainability-Basel***17** (2025). https://doi.org/ARTN 3045 10.3390/su17073045
36. IEA. Global EV Outlook 2025. (International Energy Agency (IEA), Paris, 2025).
37. Gianvincenzi, M., Marconi, M., Mosconi, E. M., Favi, C. & Tola, F. Systematic Review of Battery Life Cycle Management: A Framework for European Regulation Compliance. *Sustainability-Basel***16** (2024). https://doi.org/ARTN 10026 10.3390/su162210026
38. IEA. Global EV Outlook 2023. (International Energy Agency (IEA), Paris, 2023).
39. Tanaka, M. in *NIKKEI Asia* (2024).
40. Melin, H. E. *et al.* Global implications of the EU battery regulation. *Science***373**, 384-+ (2021). https://doi.org/10.1126/science.abh1416
41. Reuters. (2025).
42. Sasaki, S., Ishimoto, Y. & Takagi, H. Toward the Creation of the Asian xEV Battery Recycling Zone. *Research & Development in Material Science***16** (2022).
43. Yang, J.-L. *et al.* Progress and prospect on the recycling of spent lithium-ion batteries: Ending is beginning. *Carbon Neutralization***1**, 247-266 (2022). https://doi.org/https://doi.org/10.1002/cnl2.31
44. Content Guidance for the EU Battery Passport. (Battery Pass Consortium, 2023).
45. Greitemeier, T. & Lux, S. The intellectual property enabling gigafactory battery cell production: An in-depth analysis of international patenting trends. *Journal of Energy Storage***108**, 115083 (2025). https://doi.org/https://doi.org/10.1016/j.est.2024.115083
46. Voltcoffer. *The Current Status of LiFePO4 Battery Patent Technology*, <https://www.voltcoffer.com/the-current-status-of-lifepo4-battery-patent-technology/> (2025).

47. Moreno-Brieva, F. & Merino-Moreno, C. Technology generation of lithium batteries in leading countries. *Environ Sci Pollut R* **28**, 28367-28380 (2021). https://doi.org/10.1007/s11356-021-12726-y
48. Sun, X., Hao, H., Zhao, F. Q. & Liu, Z. W. Global Lithium Flow 1994-2015: Implications for Improving Resource Efficiency and Security. *Environ Sci Technol* **52**, 2827-2834 (2018). https://doi.org/10.1021/acs.est.7b06092
49. Brunner, P. & Rechberger, H. *Handbook of material flow analysis for environmental, resource, and waste engineers (Second edition)*. (CRC Press, 2020).
50. Graedel, T. E. Material Flow Analysis from Origin to Evolution. *Environ Sci Technol* **53**, 12188-12196 (2019). https://doi.org/10.1021/acs.est.9b03413
51. Yu, Z. *et al.* Molecular design for electrolyte solvents enabling energy-dense and long-cycling lithium metal batteries. *Nature Energy* **5**, 526-533 (2020). https://doi.org/10.1038/s41560-020-0634-5
52. METI. Presentation by the Study Group on the Sustainability of Batteries: Interim Summary. (Ministry of Economy, Trade and Industry of Japan (METI), Tokyo, 2022).
53. JAMA. The Motor Industry of Japan. (Japan Automobile Manufacturers Association (JAMA), Tokyo, 2024).
54. JAMA. Transitioning to Carbon Neutrality by 2050: A Scenario-Based Analysis. (Japan Automobile Manufacturers Association (JAMA), Tokyo, 2022).
55. Nakamura, K., Kato, H. & Hayashi, Y. Forecast of Motorization Progress Considering Railway Improvement Timing In Asian Developing Mega-Cities. *Journal of Japan Society of Civil Engineers, Ser. D3 (Infrastructure Planning and Management)* **68**, I_823-I_830 (2012). https://doi.org/10.2208/jscejipm.68.I_823
56. ECOMO. Verification of the eco effects brought about from car-sharing. (Foundation for Promoting Personal Mobility and Ecological Transportation (ECOMO), Tokyo, 2013).
57. AIRIA. Survey on vehicles average age by the end of fiscal year 2018. (Automobile Inspection & Registration Information Association (AIRIA), Tokyo, 2019).
58. Zeng, X. Q. *et al.* Commercialization of Lithium Battery Technologies for Electric Vehicles. *Adv Energy Mater* **9** (2019). https://doi.org/ARTN 1900161 10.1002/aenm.201900161
59. Richa, K., Babbitt, C. W., Gaustad, G. & Wang, X. A future perspective on lithium-ion battery waste flows from electric vehicles. *Resour Conserv Recy* **83**, 63-76 (2014). https://doi.org/10.1016/j.resconrec.2013.11.008
60. WBCSD. Circular Transition Indicators V4.0: Metrics for business, by business. (World Business Council for Sustainable Development (WBCSD), 2023).
61. Egbue, O. & Long, S. Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. *Energy Policy* **48**, 717-729 (2012). https://doi.org/https://doi.org/10.1016/j.enpol.2012.06.009
62. Investment, T. B. o. in *BOI NEWS* (2023).

63. Cano, Z. P. *et al.* Batteries and fuel cells for emerging electric vehicle markets. *Nature Energy* **3**, 279-289 (2018). https://doi.org/10.1038/s41560-018-0108-1
64. Janek, J. & Zeier, W. G. A solid future for battery development. *Nature Energy* **1**, 16141 (2016). https://doi.org/10.1038/nenergy.2016.141
65. News, B. (2023).
66. Nguyen-Tien, V., Zhang, C., Strobl, E. & Elliott, R. J. R. The closing longevity gap between battery electric vehicles and internal combustion vehicles in Great Britain. *Nature Energy* **10**, 354-364 (2025). https://doi.org/10.1038/s41560-024-01698-1

Figures

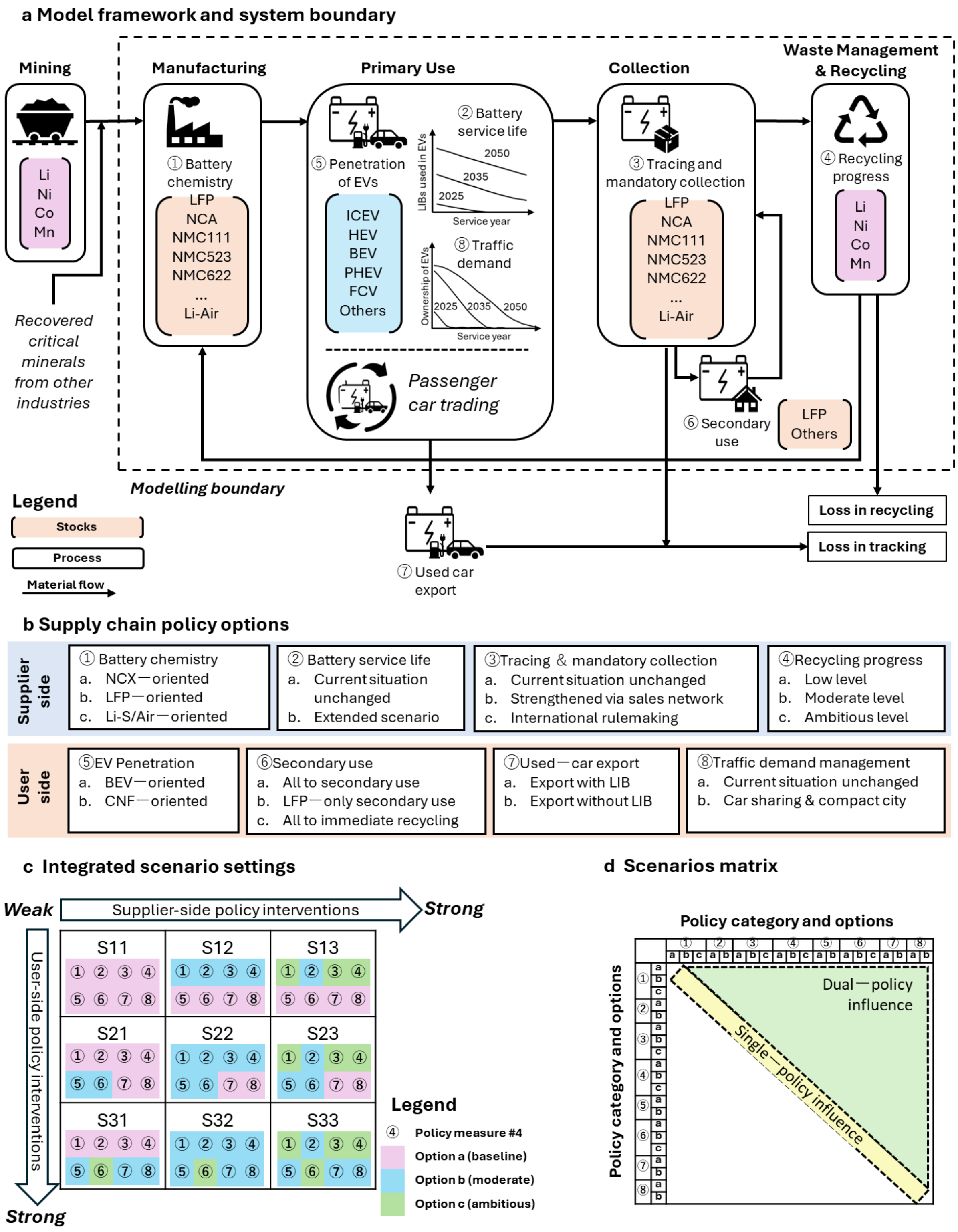


Figure 1

Schematic of the model framework and scenario design. The combination of these levels yields nine integrated scenarios, labelled S11 to S33, where 'S' denotes 'Scenario' and the numbers correspond to the strength of supplier- and user-side policy implementation. BEV, battery electric vehicle; CNF, carbon-neutral fuel; FCV, fuel cell vehicle; HEV, hybrid electric vehicle; ICEV, internal-combustion engine vehicle; Li-Air, lithium-air battery; Li-S, lithium-sulfur battery; LFP, lithium iron phosphate; NCA, lithium nickel cobalt aluminium oxide; NCX, NCA- and NMC-dominant; NMC, lithium nickel manganese cobalt oxide; PHEV, plug-in hybrid electric vehicle.

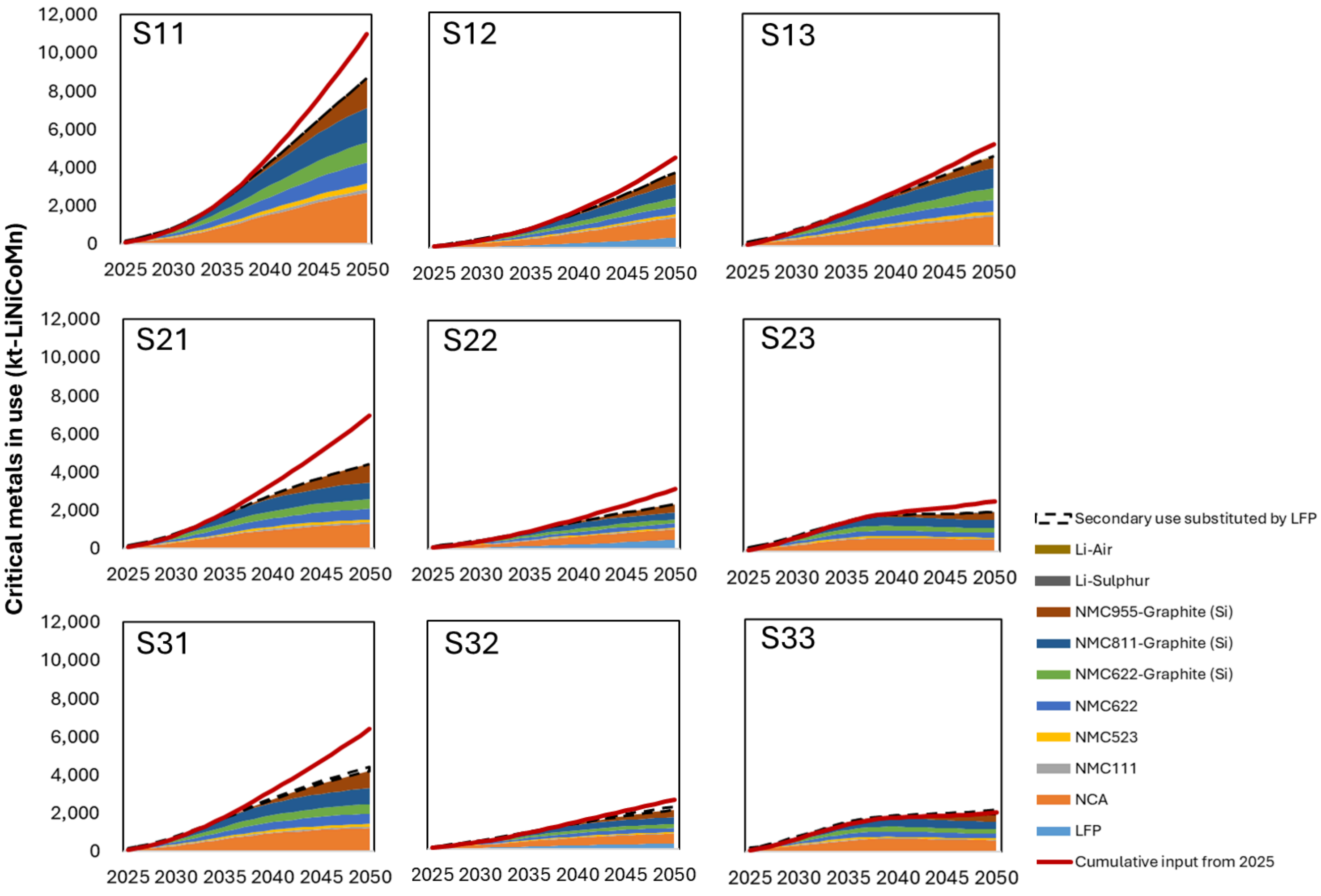


Figure 2

Demand for critical minerals across integrated scenarios. The red lines indicate total inputs, while the stacked areas denote materials controlled by battery chemistry type. The dotted areas reflect additional LIB demand for stationary energy storage under immediate recycling.

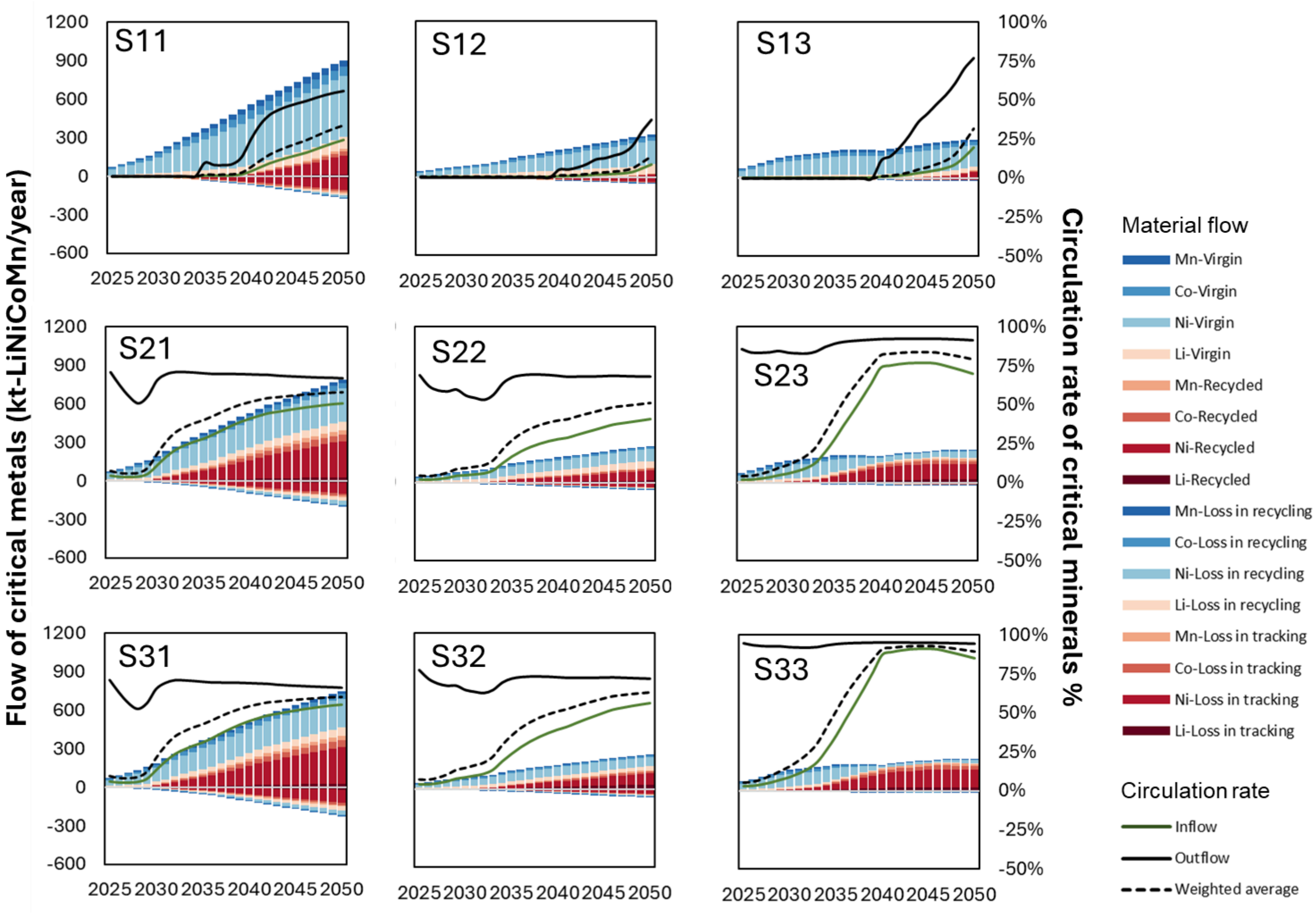


Figure 3

Material flows and circularity of critical minerals across integrated scenarios. The initial fluctuations in the outflow circulation rate were mainly due to the small amount of material being recycled, which made the indicator calculation highly sensitive to the statistical data.

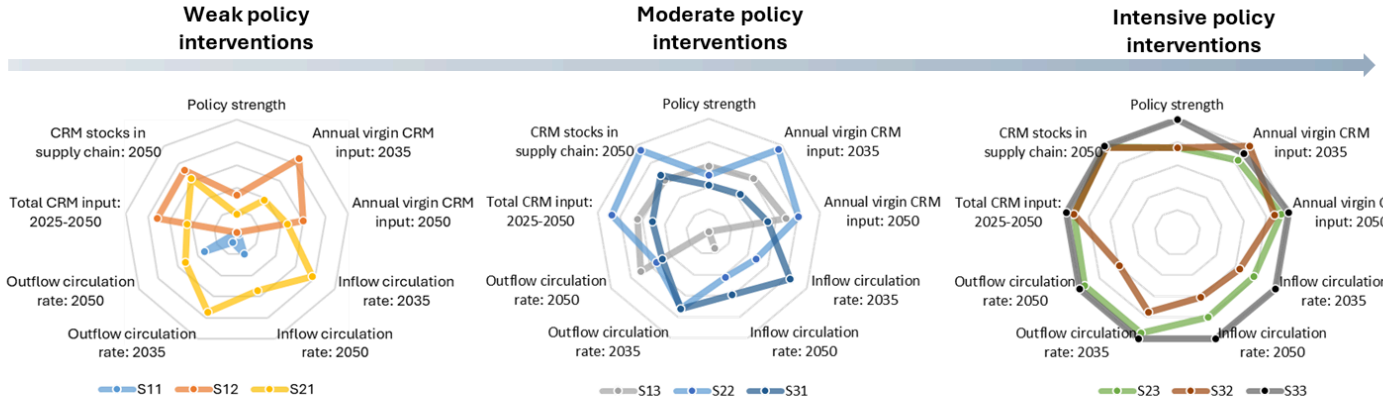
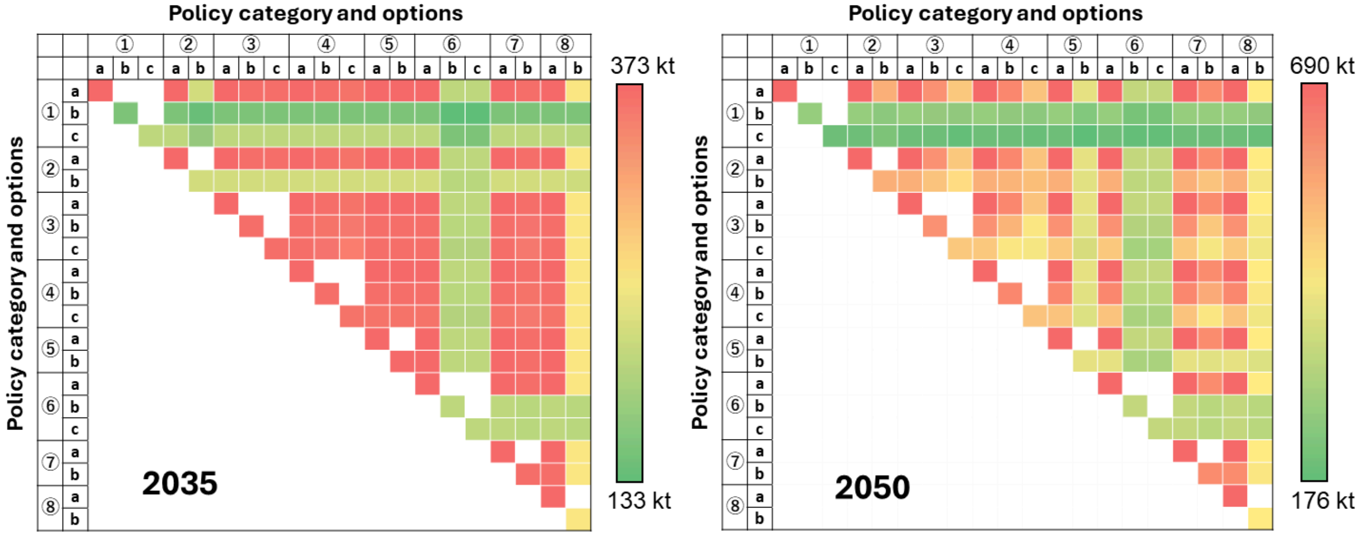


Figure 4

Comparison of indicators across integrated scenarios. A higher score means higher performance on the corresponding indicator. CRM, critical minerals.

a Annual input of virgin critical minerals under policy options in 2035 and 2050



b Circulation rates of critical minerals under policy options in 2035 and 2050

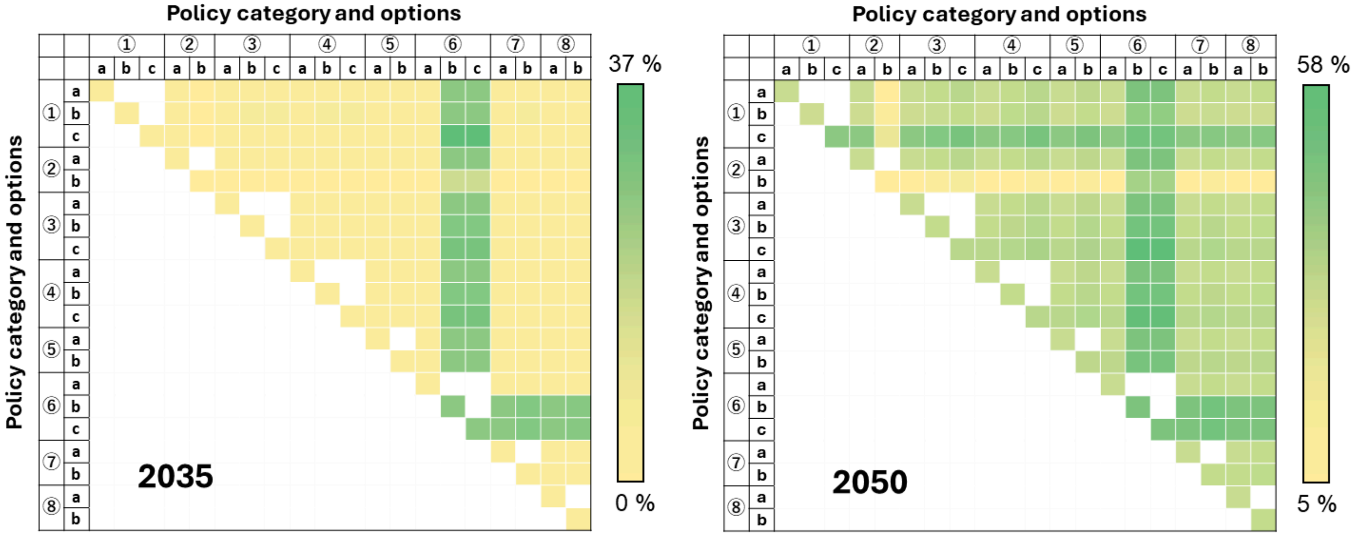


Figure 5

Virgin critical mineral input and circulation rates in 2035 and 2050 under the scenario matrix. Data can be found in Figures S34–36.

Supplementary Files

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