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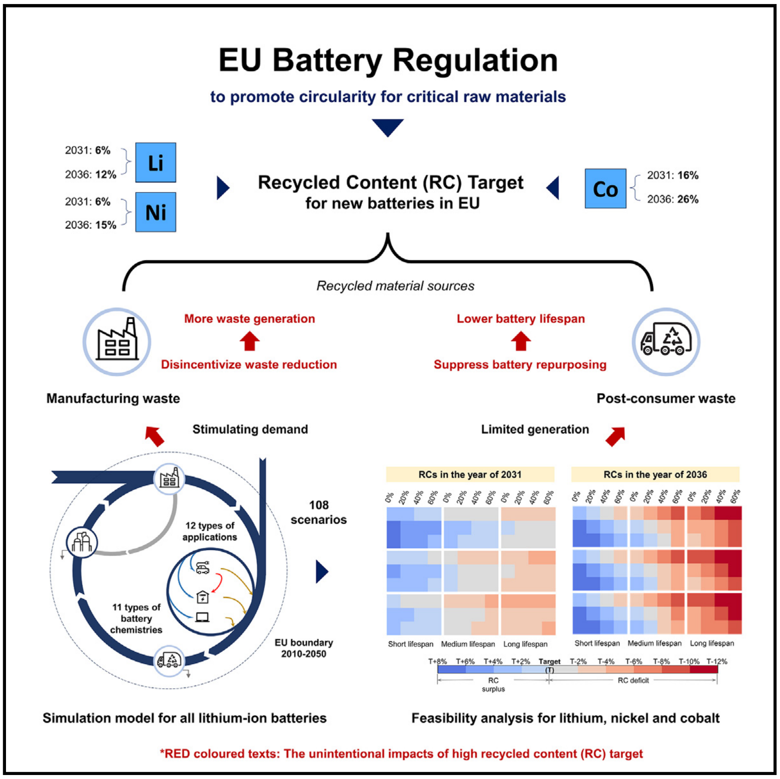
EU's recycled content targets of lithium-ion batteries are likely to compromise critical metal circularity

Graphical abstract



Highlights

- A comprehensive MFA model was developed for three major lithium-ion battery markets
- The EU's recycled content (RC) targets are analyzed under 108 scenarios
- It could be challenging to meet the EU's RC targets by 2036, especially for cobalt
- Meeting the RC targets could compromise other circular economy efforts

Authors

Haiwei Zhou, Yuyao Yang, Wen Li, Jon McKechnie, Sebastian Thiede, Peng Wang

Correspondence

wen.li3@unimelb.edu.au (W.L.), pwang@iue.ac.cn (P.W.)

In brief

The EU has proposed new rules for adopting recycled materials in new batteries, aiming to promote battery recycling and enhance battery sustainability. This will force battery manufacturers to procure sufficient recycled battery materials to enter the EU market. However, the feasibility and implications of the EU new rules remain unknown. Here, we fill the knowledge gap by exploring how the EU's new rules interact with the availability of recycled materials using a comprehensive material flow analysis under 108 scenarios. We reveal the unintended negative impacts of the new rules on battery material circularity, providing valuable insights for future policy-making efforts.

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EU's recycled content targets of lithium-ion batteries are likely to compromise critical metal circularity

Haiwei Zhou,[1] Yuyao Yang,[2,3] Wen Li,[1,6,*] Jon McKechnie,[4] Sebastian Thiede,[5] and Peng Wang[3,*]
[1]Faculty of Engineering and Information Technology, The University of Melbourne, Parkville, VIC 3010, Australia
[2]Guanghua School of Management, Peking University, Beijing 100871, China
[3]Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China
[4]Low Carbon Energy and Resources Technologies, Faculty of Engineering, University of Nottingham, University Park, NG7 2RD Nottingham, UK
[5]Chair of Manufacturing Systems, Department of Design, Production and Management, University of Twente, Enschede, the Netherlands
[6]Lead contact
*Correspondence: wen.li3@unimelb.edu.au (W.L.), pwang@iue.ac.cn (P.W.)
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SCIENCE FOR SOCIETY Batteries are playing an important role in the global transformation of the energy sector, helping to adopt electrification and reduce greenhouse gas emissions. Critical metals, such as cobalt, lithium, and nickel, are essential to battery chemistries and, thus, battery performance. However, mining these metals has led to soil and water contamination, biodiversity degradation, and human rights concerns, while geopolitical tensions are inflaming supply chain risks. To mitigate these challenges, the EU has introduced a new battery regulation: from 2031 onward, lithium-ion batteries that enter the EU marketplace must contain a minimum level of recycled content for the abovementioned three metals. To meet this legally binding target, battery manufacturers need to procure sufficient recycled battery materials. Based on our investigation of the supply-demand flows of these three critical metals under various scenarios, it is challenging to fulfill the EU's recycled content targets unless counterintuitive actions that compromise sustainability are taken by manufacturers. Our study encourages stakeholders to reexamine the feasibility of RC targets so that they align with circularity aspirations.

SUMMARY

Batteries, essential for a net-zero future, are highly dependent on critical metals, the extraction and supply of which inflict harm on society and the environment and are subject to geopolitical tensions. To reduce damages and secure supply, the EU has introduced ambitious targets for end-of-life battery recycling and critical metal recovery; however, the feasibility of such targets remains unclear. Here, to explore the impacts of the EU's proposed recycled content (RC) targets on battery material circularly, we develop a comprehensive material flow analysis model for the EU's lithium-ion batteries and consider different climate targets and battery chemistries, lifespans, and repurposing rates. Results show that achieving the EU's RC targets in 2036, especially for cobalt, is challenging. The RC targets become more achievable via, e.g., maintaining a high rate of manufacturing waste, disincentivizing battery repurposing, and forcing the early retirement of batteries, which could, however, undermine battery material circularity. Our analysis suggests that the EU should remain flexible in its RC targets.

INTRODUCTION

Batteries are indispensable for achieving a low-carbon future because of their vital role in decarbonizing the transport sector and offering grid flexibility to intermittent wind and solar power systems.[1–3] However, numerous challenges persist in the primary supply of battery materials, such as potential supply disruptions due to geopolitical tensions, considerable environmental impacts, and social and ethical concerns.[4–6] As an important source of critical materials, battery recycling could help secure regional material supply and typically results in reduced energy consumption and greenhouse gas emissions compared to primary production.[7–9] As a result, it is increasingly endorsed by both industry and policymakers. In August 2023, the European Union (EU) enacted the battery regulation (EU-BR), which introduces multiple measures to bolster battery recycling efforts.[10] In the EU-BR, various ambitious targets for end-of-life (EoL) battery collection rates, recycling efficiency, and material recovery levels are proposed. Given the EU's market influence, the EU-BR is deemed to have profound global implications.[11]

Notably, the EU-BR mandates the inclusion of ''minimum percentage shares of'' selected recycled materials (RMs; i.e., recycled content [RC]), either from battery manufacturing waste or post-consumer waste (not limited to batteries), for all batteries intended for the EU market. Specifically, the RC targets are 6% for lithium (Li) and nickel (Ni) and 16% for cobalt (Co) in 2031, which are subsequently raised to 12%, 15%, and 26% in 2036, respectively.[10] The RC targets for lead remain consistent at 85% for both 2031 and 2036. Manufacturers must meet these requirements otherwise they will be excluded from the EU market. These RC targets could have far-reaching impacts throughout the battery value chain, as they will compel battery manufacturers to procure sufficient RMs, further incentivizing collective efforts in EoL collection and battery recycling processes.

Nevertheless, there is a lack of thorough examination of how these RC targets can be met. This is largely due to the absence of a comprehensive model that is capable of evaluating the EU's RC targets thoroughly. While previous models have explored the battery material recycling potential on the global or national scale,[12–19] including the EU,[20,21] the majority have focused solely on light-duty electric vehicles (EVs). For instance, Abdelbaky et al.[22] estimated the potential RCs up to 2040 in Europe using a dynamic material flow analysis (MFA) model, only focusing on lithium-ion batteries (LIBs) for electric passenger cars.[22] Hoarau et al.[23] explicitly evaluated the EU's RC targets by decomposing RC into several factors using a simplified equation and found battery lifespan to be a critical influencing factor of RCs, but their simplified model cannot incorporate more complex dynamics in the LIB value chain. Both of these two studies neglected the LIB demand for the electrification of heavy-duty vehicles such as buses and trucks, which are reported to significantly contribute to the increased LIB demand in the future.[24] Other major LIB markets, such as battery energy storage systems (BESSs) and consumer electronics, are not considered in these two studies. In addition, neither of these two studies explored the recycling potential of battery manufacturing waste, which is expected to be the primary source of RMs in this decade.[10]

More critically, further investigation is required to understand the impacts of RC targets on the circularity of battery materials. The EU's RC targets are designed to promote battery recycling and ensure that the selected critical materials in EoL batteries will be recovered.[10] In addition to recycling, enhancing material circularity necessitates a multitude of other strategies, such as waste reduction, product reuse/repurposing, and lifespan extension, to retain materials within the technosphere for their maximum utility.[25–27] These strategies may interact with or constrain each other, such as the delayed realization of recycling potential due to promoting battery repurposing.[21] Potentially, there could be trade-offs between meeting the EU's RC targets and improving other circularity metrics, which remain a topic that requires further discussion.

Here, we present a comprehensive dynamic MFA model of LIBs intended for the EU market during 2010–2050. Our objective is to develop a reliable tool for evaluating the RC targets comprehensively and examine how these targets could impact battery material circularity. Our model stands apart from existing research by comprehensively modeling the LIB demand and the interactions of three major LIB market segments while also incorporating manufacturing waste into the RC calculations within a single comprehensive MFA model. Our results indicate that achieving the RC targets in 2036, especially for cobalt, is challenging. The target becomes more achievable under conditions that may compromise battery material circularity, such as maintaining a high manufacturing waste rate, shortening the battery lifespan to 10 years from 15 years, or decreasing the repurposing rate of spent batteries. These findings could inform decision-makers about the potential trade-offs in sustainability legislation and support future policy-making efforts.

RESULTS

Method summary

In this study, we focus on three of the four metals designated with RC targets—Li, Ni, and Co. These metals are categorized as ''critical raw materials'' by the EU due to their high levels of economic importance and supply risks.[28] Lead, not classified as a critical raw material by the EU, is not considered in our model. The selected three metals find applications in a variety of products, such as LIBs, stainless steel, alloy, etc. Nevertheless, the majority of RMs for battery manufacturing are anticipated to come from LIBs,[29] especially considering the expected growth of LIB demand[15] and the low recycling rate of other products[30] (further evidence can be found in Note S1). Accordingly, we develop a three-layer (i.e., product, battery, and material) dynamic MFA model for the LIBs intended for the EU market during 2010–2050 (Figure 1). These batteries may be manufactured within or outside of the EU. According to the International Energy Agency, more than 20% of the EU's battery demand for EVs relies on imports as of 2023.[31] However, the EU has made substantial investments to mitigate this reliance, and the planned battery production capacity is projected to exceed its total domestic demand as early as 2026–2028.[32,33] Accordingly, we assume that the EU's domestic production will align with its demand by 2030 and maintain this equilibrium thereafter. In addition, once the batteries reach their EoL, they must all be collected within the EU. Therefore, we establish the geographical boundaries of the four life cycle stages (i.e., manufacturing, in use, EoL collection, and recycling) within the EU market.

For each layer, a stock-driven or inflow-driven model[34] is used to estimate the inflows, stocks, and outflows, depending on data availability and model suitability. In the product layer, we follow the EU-BR to encompass a broad range of products, including all types of EVs (i.e., the EV sector), BESSs (i.e., the BESS sector), and five additional LIB-containing products (e.g., smartphones and electric scooters [e-scooters]) categorized as the ''others'' sector (Figure 1). These three market segments cover the majority of LIB demand.[35] In the battery layer, we include

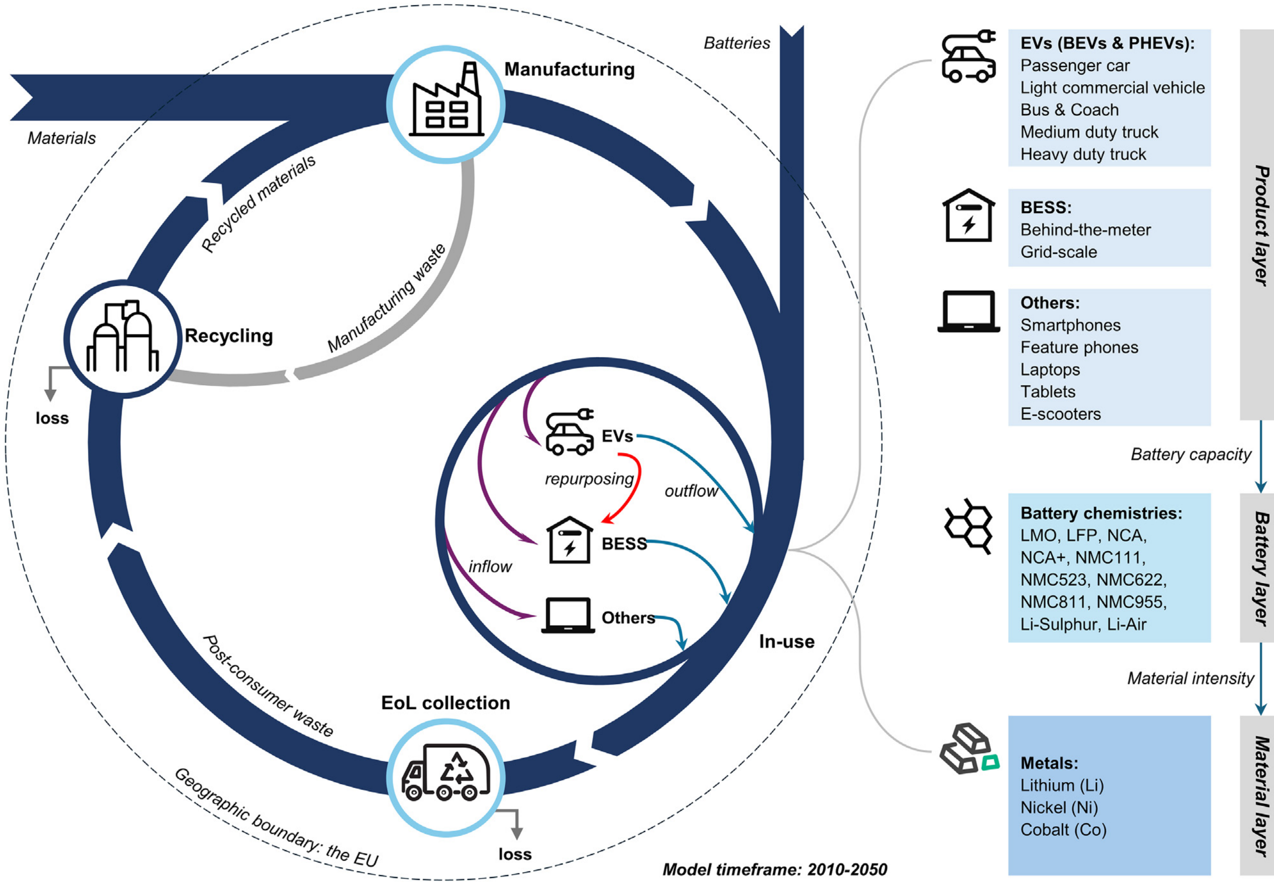

Figure 1. The framework of a dynamic MFA model for the EU's LIBs

The model consists of three layers (i.e., the product, battery, and material layers) and considers four life cycle stages of LIBs (i.e., manufacturing, in use, EoL collection, and recycling), with their geographical boundaries set as the EU market. The in-use stage considers three major market segments, the EV sector, the BESS sector, and the others sector, with a total of 11 different battery chemistries. The EU's batteries must all meet the RC targets, and once they reach their EoL, they must be collected within the EU (i.e., post-consumer waste). Given the restrictions on exporting battery waste, both the EU's post-consumer waste and manufacturing waste are assumed to be recycled within the EU.

eleven different battery chemistries (Figure 1), each with distinct material intensities (see the first table in Note S11). We consider two types of EV battery demand each year: (1) batteries installed in new vehicles to be sold and (2) the demand for battery replacement within the existing vehicle fleet, arising from the mismatch between vehicle lifespan and battery lifespan. Battery demand for BESSs is calculated by deducting the capacity of repurposed EoL EV batteries (assumed to retain 80% of their original capacity) from the required battery inflows to build up the BESS stock levels. Accordingly, we found that the EU's BESS sector can at least accommodate 60% of EoL EV batteries during the period 2030–2040 (see the figure in Note S12). Following the EU-BR, our calculation of RC includes materials recycled from both EoL batteries and battery manufacturing waste, a significant source of RMs in the short term.[10,36] Notably, the EU-BR makes a distinction between manufacturing waste and manufacturing scrap. The former is included in our calculation of RCs, while the latter should be excluded from the RCs, as it "can be reworked or reused in the same processes."[10] More detailed model descriptions can be found in the experimental procedures section.

Previous studies have shown that numerous factors could influence the RCs, and we have chosen to focus on four key factors based on their significance in terms of sustainability and material circularity (Table 1). Firstly, within the context of achieving net-zero emissions, climate targets determine the long-term demand for LIBs in EVs and BESSs, despite the complex supply and demand dynamics in the LIB market.[13,14,37,38] Secondly, driven by continuous technological advancement, the evolving battery chemistry mix (i.e., the market shares of different battery chemistries) could result in substantial shifts in the material intensities of LIBs, consequently influencing battery material demand (MD).[14,15,20] While experts agree on the dominance of nickel manganese cobalt (NMC) batteries in the near term, there are three different opinions on battery chemistry prospects beyond 2030.[39] Accordingly, we have developed three battery chemistry mix scenarios to represent the uncertain technological pathways. Thirdly, battery lifespan determines the timing of battery retirement and affects the materials available for recycling.[15] It also influences the battery demand. For instance, a shorter lifespan leads to increased demand for battery replacement and higher annual inflows of batteries to build up the required stock

Table 1. An overview of key influencing factors and scenario settings

Key factors	Scenario design	Detailed assumptions
Climate targets[40,41]	three International Energy Agency (IEA) climate scenarios are adopted to represent low, medium, and high levels of LIB demand for EVs and BESSs, namely, the stated policies scenario (STEPS), the sustainable development scenario (SDS), and the net-zero emissions by 2050 scenario (NZE); we have made our assumptions where the IEA's data are unavailable	Note S9
Battery chemistry[14,15]	(1) the nickel manganese cobalt (NMC)-dominated scenario (i.e., NMC scenario): the NMC batteries sustain their dominance, with NMC811 and NMC955 chemistries accounting for a 75% market share by 2050 (2) the lithium iron phosphate (LFP)-dominated scenario (i.e., LFP scenario): LFP batteries steadily increase their market share, surpassing NMC batteries and capturing 60% of the market by 2050 (3) the technology breakthrough scenario (i.e., TBS scenario) envisions the widespread commercialization of post-LIBs beginning by 2030, with their market share reaching 70% by 2050	Note S11
Battery lifespan (ref.[12–17,19–22])	(1) the short scenario: an average lifespan of 10 years for EV and BESS and 5 years for repurposed EV batteries (2) the medium scenario: an average lifespan of 12.5 years for EV and BESS and 7.5 years for repurposed EV batteries (3) the long scenario: an average lifespan of 15 years for EV and BESS and 10 years for repurposed EV batteries	Note S10
Repurposing rate of EoL EV LIBs[42–44]	we found that the EU's BESS sector can accommodate at least 60% of EoL EV batteries during the period 2030–2040; however, numerous economic and technological barriers could hinder the full realization of this potential; as a result, we have formulated four scenarios with different repurposing rates (r = 0%, r = 20%, r = 40%, r = 60%)	Note S12
Manufacturing waste rate	the manufacturing waste rate is not treated as a factor for scenario settings in this study; instead, we run our model with 100 different manufacturing waste rates and calculate the corresponding recycled content for three metals to explore the relationship between waste rate and recycled contents	Figure 5

levels.[14] Lastly, repurposing EoL EV batteries in the BESS could prolong battery retirement timelines by 5–10 years, thereby limiting short-term battery recycling potential.[21–23] On the other hand, it could help reduce the overall LIB demand by eliminating a portion of the new batteries needed for the BESS.

Our model fully represents the above-mentioned mechanism of how these four factors impact the RCs. To comprehensively explore their uncertainties, we have also developed multiple scenarios for each factor (Table 1), resulting in a full factorial of 108 = 3 × 3 × 3 × 4 scenarios. In addition, we consider manufacturing waste rate as a critical parameter and investigate its impacts on potential RCs (Table 1). Detailed assumptions and data sources for these key factors are provided in Notes S9–S12.

LIB demand

Our results show that the EU's total LIB demand will increase rapidly from 0.05 TW-hours (TWh) in 2020 to 2.4–4.8 TWh in 2050, largely depending on the climate targets (Figure 2A). The surge in LIB demand is primarily driven by the rapid growth of EV sales, which are expected to rise from 1.1 million in 2020 to 18.3 million in 2050 under the stated policies scenario (STEPS) (Figure 2A). The deeper electrification of road vehicles in the sustainable development scenario (SDS) and net-zero emissions by 2050 scenario (NZE) leads to annual EV sales by 2050 that are 0.2 and 0.6 times greater than those in the STEPS. Among all vehicle types, passenger vehicles are the most readily electrifiable, accounting for more than 80% of the total EV sales. The second largest share of EV sales is attributed to light-duty commercial vehicles, which could also be 100% electrified by 2050. However, the electrification of trucks, particularly heavy-duty trucks, will be more challenging.[45] Also, alternative technologies such as fuel cell EVs could be used to decarbonize trucks.[46,47] Accordingly, we assume that battery EVs will constitute up to 60% of truck sales by 2050 at most in the most optimistic NZE (see the second table in Note S9).

The EU's total LIB demand is projected to reach 0.7–1.2 TWh in 2031 and 1.3–2.1 TWh in 2036 (Figure 2B). Passenger cars emerge as the primary contributor to LIB demand in 2036, accounting for two-thirds of the EU's total LIB demand under the STEPS (Figure 2B). This share will be lower under the NZE because of an increase in LIB demand for other commercial vehicles and the BESS sector. It is worth noting that trucks and commercial vehicles contribute to a substantially higher share of the LIB demand than their relatively small share in total EV sales (Figure 2B). Despite much lower sales volume, trucks and commercial vehicles require an average battery capacity

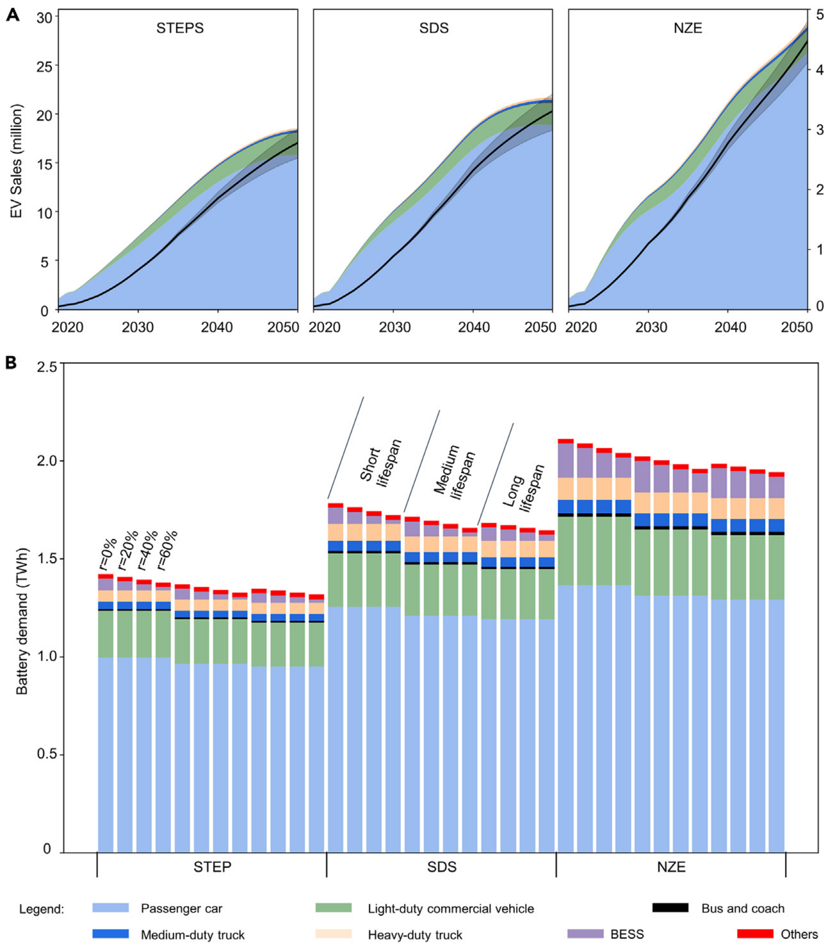

Figure 2. Projected EV sales and LIB demand in the EU

(A) The EU's EV sales by vehicle type (left axis) and total LIB demand (right axis) under three climate target scenarios during 2020–2050. The lines denote the median levels of LIB demand (right axis), and the filled area indicates the potential ranges (right axis).

(B) The EU's LIB demand by product in 2036. Each bar represents the result of one scenario. There are 36 scenarios, which are first categorized into three groups according to climate target scenarios (i.e., STEPS, SDS, and NZE). Each group is further divided into three subgroups, i.e., short, medium, and long battery lifespans. The lowercase r indicates different repurposing rates of EoL EV batteries.

that is 2–6 times larger than that of passenger cars (Table S1), translating to a battery demand that is one-third to one-half of that for passenger cars. Consequently, previous studies that solely focused on passenger cars might significantly underestimate the MD for EVs in the future. There is huge potential in repurposing EoL EV batteries to reduce the demand for LIBs in BESSs starting in 2030. For instance, under the STEPS, repurposing 60% of the EoL EV batteries could nearly eliminate the need for new battery demand for BESSs. It is worth noting that the repurposing rate could surpass 60%, particularly if the BESS sector experiences a significant expansion, such as under the NZE (Figure 2B). Consumer electronics and e-scooters (i.e., the others sector) will only account for a small fraction of the total LIB demand in 2036 (Figure 2B).

Material demand and recycled materials

The EU's battery MD (i.e., the amount of material required for battery production, hereinafter) will increase rapidly in the next decade (Figure 3A), reaching 116.1 kt (median across 108 scenarios) for Li, with a potential range of 85.2–148.5, 390.8 kt for Ni (277.7–610.8 kt), and 59.9 kt for Co (44.5–91.7 kt) in 2031. These figures are expected to further increase to 197.2, 640.2, and 90.5 kt in 2036, respectively. MD for LIBs is highly dependent on climate target scenarios. Anticipating higher penetration rates of EVs and greater BESS demand, the NZE necessitates, on average, 50% more materials cumulatively during 2020–2050 than the STEPS (Figure S5). Another significant factor impacting the MD is the future battery chemistry mix, particularly for Ni and Co. On average, the cumulative MD during 2020–2050 for Ni and Co in the lithium iron phosphate (LFP)-dominated scenario is 30% less than that in the NMC-dominated scenario (Figure S5). The technology breakthrough (TBS) scenario anticipates only half of the cumulative MD for Ni and Co compared to the NMC scenario (Figure S5). However, this scenario necessitates a higher demand for Li due to the increased requirement for Li metal used in post-LIBs.[14,48]

The available RMs are projected to experience rapid growth from 2030 to 2040 (Figure 3A). The amount of recycled materials will reach 9.6 kt (median across 108 scenarios) for Li, 38 kt for Ni, and 9.5 kt for Co in 2031, further rising to 26.2, 102.4, and 20.1 kt in 2036, respectively. This surge is primarily attributed to the rapid growth of EoL EV batteries. Battery manufacturing waste is projected to be a significant source of RMs in 2031, accounting for shares of 39.0%–74.1% for Li, 40.0%–78.8% for Ni, and 24.6%–52.5% for Co across scenarios. These shares will decrease as more EV batteries reach EoL in 2036 yet remain substantial (Figure S4).

Challenges in meeting the RC targets

The broad range of estimated MD and RMs leads to significant uncertainties in the estimation of potential RCs for the three metals. Our results indicate that RC targets for Li and Ni (6%) in 2031 can be met across all scenarios, with potential RCs of 6.4%–12.1% and 7.1%–14.0%, respectively (Figure 3B). However, meeting the RC targets for Co is difficult, as more than half of the scenarios fall short of the 16% target in 2031. The situation for all studied metals worsens when looking ahead to 2036, as the once-achievable targets in 2031 for Li and Ni will become uncertain, and meeting the target for Co will be more challenging. Excluding battery manufacturing waste will make achieving the RC targets highly unlikely.

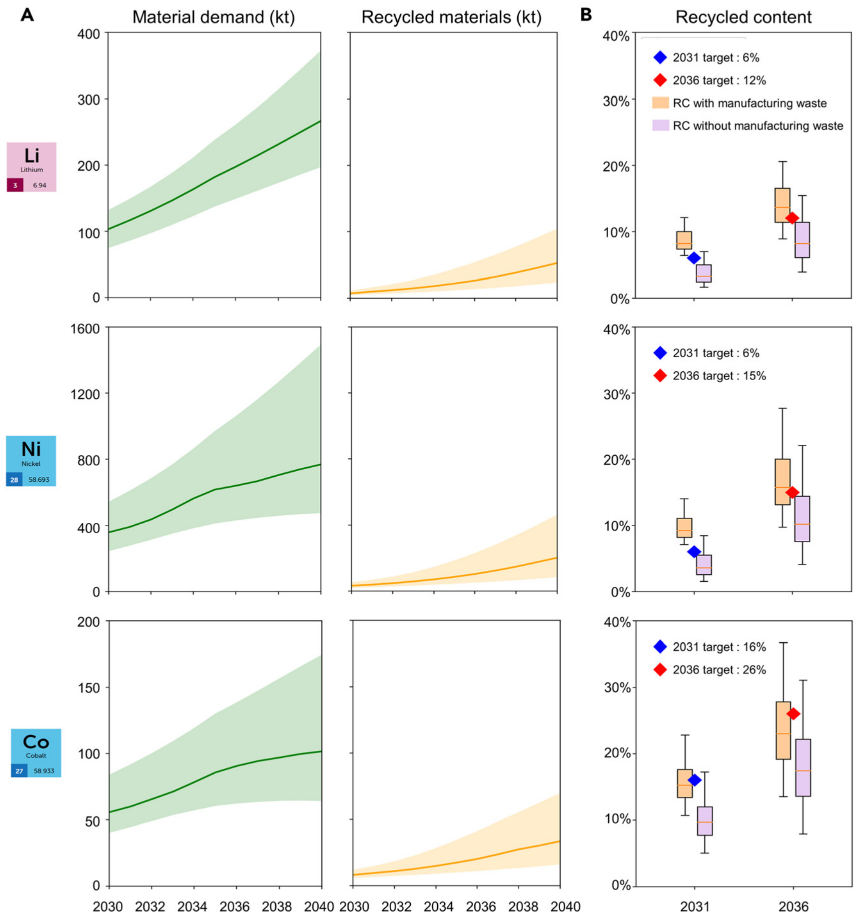

Figure 3. Material demand, avaiable recycled materials, and potential RCs for EU's LIBs during 2030–2040

(A) The EU's material demand and avaiable recycled materials for LIBs. The lines depict the estimated median values across 108 scenarios, and the filled areas indicate the potential ranges. (B) Potenial RCs for EU's LIBs. The box plot shows the significant uncertainties regarding RCs (with/without battery manufacturing waste) and compares them with the EU's RC targets. The top and bottom boundaries of the box represent the first quartile and the third quartile of potential RCs, respectively. The line inside the box indicates the median. The whiskers extend to the smallest and largest values excluding any outliers.

To meet both the EU's battery demand and RC targets in 2031, the annual demand for RMs will reach 5.1–8.9 kt for Li, 16.7–36.6 kt for Ni, and 7.1–14.6 kt for Co. These numbers will further increase to 17.9–31.3, 64.4–159.0, and 16.1–36.0 kt in 2036, respectively. In 2036, it is likely that the available RMs will not meet this demand. A shortage of recycled Co is observed in 69 out of 108 scenarios, and in 39 of these scenarios, the shortfall exceeds 20% of its demand. A comparable deficit of over 20% is also identified in 15 scenarios for Ni. Taking a representative scenario as an example, which assumes net-zero emissions by 2050 (NZE), an average EV battery lifespan of 15 years, the dominance of NMC batteries in the EV market, and a 40% repurposing rate of EoL EV batteries, gaps 5.0 kt of recycled Li, 43.1 kt of recycled Ni, and 14.3 kt of recycled Co are anticipated in 2036 (Figure 4).

Potential adverse effects

Figure 3 illustrates the potential challenges in meeting the RC targets for Co, despite the good likelihood of meeting the RC targets for Li and Ni. Furthermore, our analysis of the conditions under which the RC targets can be achieved unveils several adverse effects associated with meeting these targets.

Disincentivizing manufacturing waste reduction

The substantial shares of manufacturing waste in RMs imply that RCs are highly sensitive to manufacturing waste rates. Furthermore, our simulation shows that the RCs increase proportionally as the manufacturing waste rate increases (Figure 5). Although manufacturing waste rate is a critical parameter in estimating RCs, there are significant discrepancies in the reported waste rates found in the literature. Those who work in the LIB industry typically report higher waste rates, which could be up to 30%, while other sources indicate much lower values, potentially as low as 1% by 2030[49,50] (more discussions are presented in the experimental procedures). For our analysis, we adopt the default cathode material yield of 94.1% in cell manufacturing processes from the BatPaC model[51] and assume 95% of finished cells pass the final inspection.[52,53] The material losses during manufacturing and inspection processes together result in an overall waste rate of 10.6% (=1–94.1% × 95%) at the current level, which is assumed to decrease to 5.9% by 2030 and remain stable thereafter (Table S6). With these assumptions, the average RCs of Ni and Li will exceed their targets in 2036, but the average RC of Co will be 23.7%, notably lower than the target. If the waste rate is further reduced to ∼3% in 2036 as optimistic projections have suggested,[54,55] the average RCs for all three metals will fall below the EU's targets. The average RC of Co only hits the targeted 26% when the waste rate reaches ∼9% (Figure 5). The above analysis suggests that maintaining the waste rate at higher levels favors the attainment of the RC targets. Consequently, imposing the EU's RC targets carries the risk of undermining efforts to minimize manufacturing waste or, worse still, incentivizing excess manufacturing waste generation. This highlights the inherent conflict between the overarching goal of the EU-BR to reduce the overall life cycle impact of batteries and the fact that meeting its RC targets might impede potential reductions in battery manufacturing waste.

Discouraging battery lifespan extension

Among all factors other than manufacturing waste rate, potential RCs are particularly sensitive to the battery lifespan (Figure 6). Lifetime extension has long been recognized as an effective measure to increase material efficiency and promote the circular

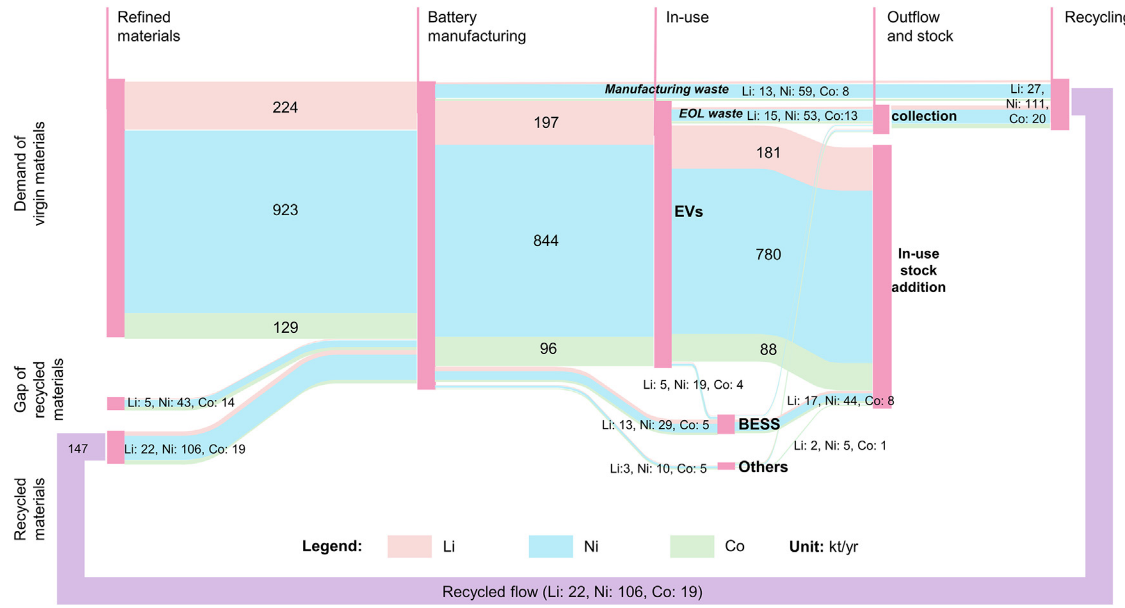

Figure 4. Material flows driven by the EU's LIB market in 2036 under a representative scenario

The scenario presented is characterized by a high level of LIB demand (i.e., net-zero emissions by 2050 pathway as defined by International Energy Agency), an average EV battery lifespan of 15 years, the dominance of NMC chemistry in the EV LIB market, and a repurposing rate of EoL EV batteries of 40%.

economy.[56,57] Extending battery lifespan has been the focus of cell manufacturers for decades, and it helps to reduce battery MD: the longer the batteries last, the fewer batteries (and consequently fewer MDs) will be required to build up and maintain a given EV stock level. With incremental technological improvements, it is conceivable that EV batteries could outlast the typical vehicle lifespan of ∼15 years in the future.[14,58] However, our results reveal a clear conflict between achieving the EU's RC targets and pursuing a longer battery lifespan. In nearly all scenarios with an average battery lifespan of 15 years, there is a clear shortfall in meeting the 2036 RC targets among all metals, and this deficiency is also evident when aiming to meet the 2031 RC target for cobalt (Figure 6). When the average lifespan is reduced to 12.5 years, it becomes likely that the 2036 targets for Li and Ni can be achieved, while the target for Co remains challenging. It only becomes more likely to reach the Co target in 2036 when the lifespan is reduced to 10 years (Figure 6). The above analysis suggests that the RC targets may discourage practices aimed at prolonging battery life. For example, EV batteries with minor issues that could be repaired and reintegrated into EVs may bypass repair efforts and be recycled directly. This scenario is possible when the value of EoL batteries for recycling is significantly inflated by the EU's RC targets, especially considering that battery repairs are costly in high-income economies.

Cannibalizing batteries for repurposing

Repurposing EoL EV batteries in the BESS generates environmental benefits compared to immediate recycling.[59] However, our results show a clear trade-off between meeting the RC targets and battery repurposing, as meeting the RC targets becomes increasingly challenging when the repurposing rate increases (Figure 6). In 2036, a repurposing rate 60% of EoL EV batteries will lead to average reductions in RCs of 3.2 percentage points (pct) for Li, 4.2 pct for Ni, and 6.1 pct for Co, compared to scenarios without repurposing. Notably, previous studies present significant uncertainties in estimating the potential of EV battery repurposing,[38,42,60] with its full realization hindered by various economic and technical challenges. For instance, repurposing EoL EV batteries produced a decade ago may be less cost effective compared with using newer, more advanced batteries due to ongoing technological advancements.[61] In addition, alternative technologies such as sodium-ion batteries are also competing with EoL EV batteries in the BESS market.[62] To facilitate repurposing efforts, designers can integrate circularity considerations into the design process to develop batteries well suited for repurposing. This can involve enhancing modularization and standardization to enable easier disassembly of EoL batteries, consequently reducing the cost of repurposing.[61] However, as our results indicate, these efforts may be discouraged because the pressure to meet the RC targets may divert EoL batteries away from repurposing initiatives toward direct recycling.

DISCUSSION

The battery chemistry evolution also has notable impacts on the RCs. For instance, in both 2031 and 2036, the LFP-dominated scenario will yield approximately a 2% higher RC for Co and Ni compared to the NMC-dominated scenario (Figure 6). Additionally, transiting to post-LIBs (such as lithium-air batteries and lithium-sulfur batteries)[14,48] from 2030 onwards (i.e., the TBS scenario) could further increase the potential RCs for Ni and Co. Our model shows modest impacts of climate targets scenarios on the RCs because an elevated LIB demand due to ambitious climate targets is accompanied by a larger quantity of EoL batteries. However, they do have a significant impact on the absolute demand for RMs. For instance, under the STEPS, the

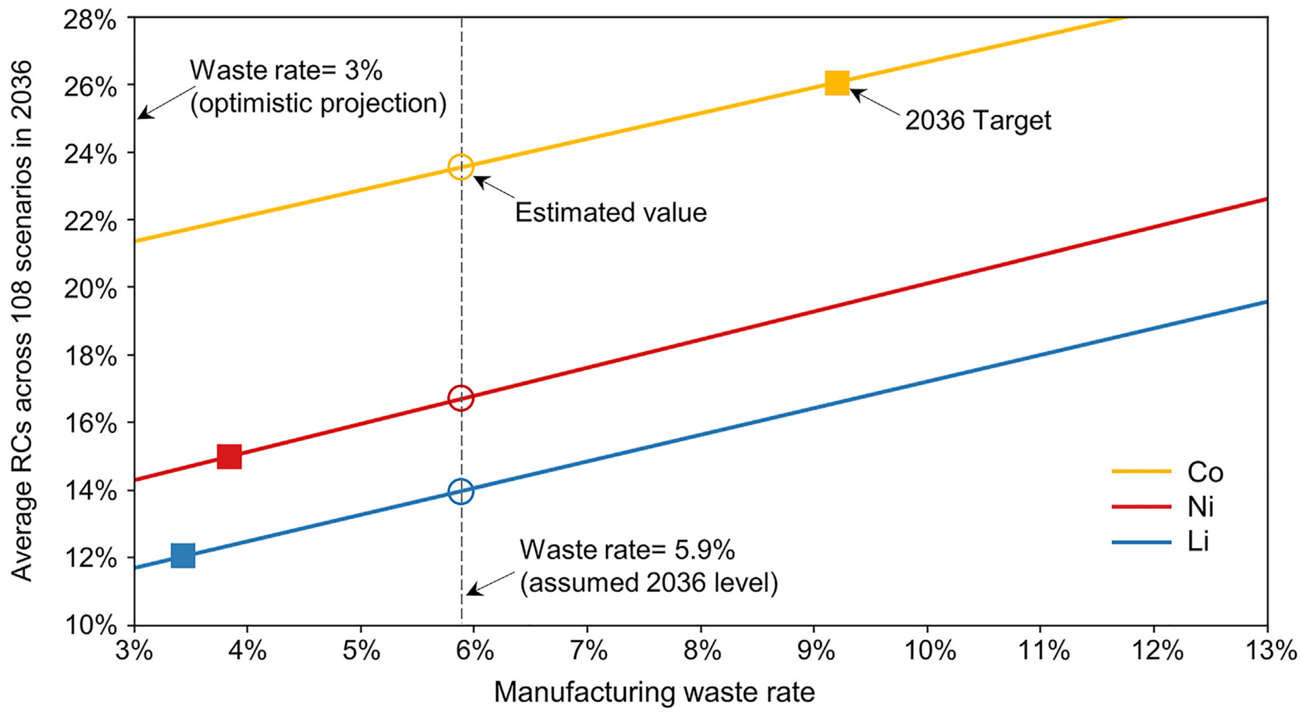

Figure 5. Average RCs across 108 scenarios in 2036 in relation to manufacturing waste rates
We conducted 100 runs of our model with 100 different waste rates. Each run produced RCs for three metals under 108 scenarios, which were subsequently averaged. The average RCs were then plotted against the corresponding waste rates to create this figure. From left to right, the lines depict a trend of increasing waste rate, accompanied by increasing average RCs. We assumed a waste rate of 5.9% in 2036, with its corresponding average RCs represented as circles. The squared dots denote the targeted RCs (y axis) and their corresponding waste rate levels (x axis).

EU will face a shortage of RM up to 10.4 kt for Co in 2036, which could increase to 16.0 kt under the NZE (Figure S3).

Apart from the four key factors discussed, many other factors could impact the RCs, such as the EoL collection rate and recycling efficiency. In our model, we assume batteries from EVs and BESSs to be collected at a 100% rate upon disposal, following the requirements of the EU-BR.[10] Battery recycling processes are assumed to recover 50% of Li, 90% of Ni, and 90% of Co from their feed by 2027, with subsequent improvements to 80%, 95%, and 95%, respectively, by 2031. However, these assumed recycling efficiencies could be difficult to achieve in practice. For instance, we have assumed a recovery rate of 80% for Li across all battery chemistries, while in reality, most LFP batteries are not effectively recycled due to the limited economic value of the metals they contain.[63] In other words, our estimation of RCs is based on optimistic assumptions for the collection-recycling ratio for EoL batteries. Relaxing these assumptions might further escalate the challenges associated with achieving the EU's RC targets.

Our results suggest that meeting the target of 26% RC in 2036 for cobalt could be challenging (Figure 3B). Optimistic projections show that recycled cobalt from LIBs can satisfy 60%–85% of the global cobalt demand by 2040, particularly due to the industry's shift toward low-cobalt or cobalt-free chemistries.[18] This discrepancy is mainly attributed to at least two reasons. Firstly, our model takes into account the latest trend: that cobalt-free LFP batteries have substantially gained market share in recent years due to their low material costs and improved energy density.[58,64,65] This means the average cobalt content in EV LIBs in our model has already been relatively low at the current level. Secondly, we adopt a more conservative stance regarding the future decrease in cobalt content in LIBs, recognizing the predicted persistence of cobalt in LIBs because it could enhance the performance and broaden the "design space" of LIBs.[66] Collectively, the projected cobalt content in our model does not experience as significant a reduction as prior optimistic estimations suggested. In fact, previous estimations have also reported lower RCs closer to our conservative projections, such as 14%–40%[20] for the EU and 24%–27%% for the US[52] by 2040.

The challenges of meeting the RC targets are interpreted with the assumption that the EU's domestic production will catch up with its demand and that EU manufacturers can only source RMs locally, as illustrated in the method summary. If the EU's battery production cannot reach the expectations, then the manufacturing waste obtained from the EU will be less than what we predict, which will result in a lower RC. It will also necessitate the need to import large numbers of batteries that meet the RC targets from other regions, which is incompatible with the EU's ambition to establish a self-sufficient battery supply chain. If the available RMs from around the world were used to produce batteries for the EU, then the RC targets would probably be effectively met. However, importing RMs from other regions may be impeded by heightened global competition. To retain

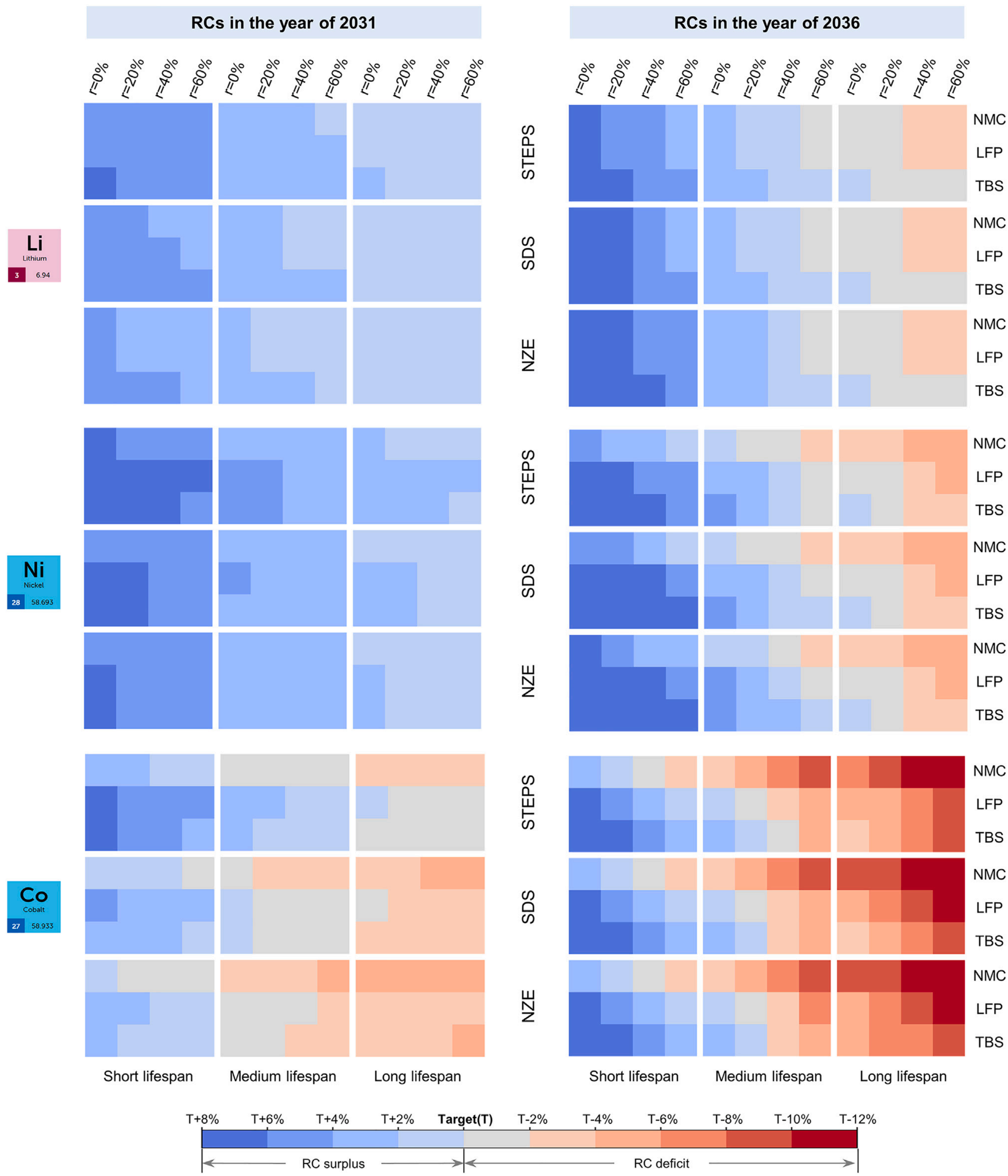

Figure 6. Potential recycled contents of Li, Ni, and Co across 108 scenarios in 2031 and 2036

Each cell in the heatmap represents the potential RC under one scenario. STEPS, SDS, and NZE are three climate target scenarios, requiring low, moderate, and high levels of LIB demand for EVs and BESS, respectively. Short, medium, and long indicate three battery lifespan scenarios. NMC represents the NMC-dominated scenario where the EV battery market is dominated by NMC batteries, LFP indicates the dominance of lithium iron phosphate batteries, and TBS stands for a technology breakthrough scenario where post-LIBs become widely adopted starting from 2030. The lowercase r stands for the repurposing rate of EoL EV batteries. Detailed assumptions of these scenarios are summarized in the supplemental information.

critical raw materials within its borders, the EU has proposed to restrict the export of waste LIBs and intermediate waste streams (known as black masses).[67–69] Meanwhile, the RC targets provide incentives for RMs around the world to be used for producing the EU's batteries. Collectively, these measures could essentially form a mechanism for the EU to stockpile RMs from the rest of the world. However, in the transition toward a net-zero future, nations are progressively engaging in competition to reposition themselves along the value chain of clean energy technologies through legislative efforts.[70,71] Other countries might likewise implement comparable measures to promote battery recycling and retain critical materials, hindering the exports of RMs.

The EU's RC targets are designed to stimulate demand for RMs and promote battery recycling. However, as our results suggest, this approach may inadvertently undermine material circularity. While effective policy targets require a certain degree of ambition to provide clear and strong signals to industries, we recommend that the EU's policymakers closely monitor the market and remain flexible in refining the RC targets if more evidence emerges to support modifications. From a scientific standpoint, substituting the RC with more comprehensive circularity indicators such as the circular input rate[72] (which captures recycling, reuse, and remanufacturing strategies) and average lifetimes[26] (which capture lifetime extension and material loss reduction strategies) may mitigate many of the adverse impacts, but the complexity involved in calculating and implementing these indicators could hinder their widespread application.

The EU-BR is a pioneering legislative effort to enhance the sustainability of batteries, with ambitious RC targets set for batteries intended for the EU market. Our study provided a comprehensive dynamic MFA model with 108 different scenarios to explore the conditions under which the EU's RC targets could be met. Results show that meeting the EU's RC targets heavily relies on the recycling of battery manufacturing waste and carries the risk of disincentivizing manufacturing waste reductions. The EU's RC targets could be ambitious (particularly for 2036 targets), and achieving them could come at the expense of discouraging battery lifespan extension and the repurposing of EoL EV batteries. These findings reveal the potential trade-offs in the EU-BR. More research is needed to carefully examine the potential of reducing manufacturing waste, extending battery lifespan, and repurposing EoL EV batteries. Given the wide implications of EU-BR, future research is suggested to explore more comprehensive circularity indicators and how they could be translated into practical policy targets to better serve the EU-BR sustainability purpose. In particular, policymakers need to stay flexible in refining RC targets, adjusting them as new evidence emerges to support modifications.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources should be directed to the lead contact, Wen Li (wen.li3@unimelb.edu.au).

Materials availability

This study did not generate new unique materials.

Data and code availability

The original data for this study have been deposited at https://doi.org/10.5281/zenodo.12179423. The calculating processes are documented in the supplemental information. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

Model overview

We develop a holistic, dynamic MFA model[34] for LIBs intended for the EU market to calculate the battery MD and RMs during 2010–2050 (see the figure in Note S2). The potential RCs are then determined as RM/MD. Our model follows the coverage of the EU-BR and includes three major LIB-containing product sectors: the EV sector (see the figure in Note S3), the BESS sector (see the figure in Note S7), and the others sector (see the first figure in Note S8). To increase granularity, the EV sector is further segmented into passenger cars (plug-in hybrid EVs and battery EVs), light-duty commercial vehicles, buses, coaches, and medium- and heavy-duty trucks. The BESS sector includes both grid-scale and behind-the-meter BESSs. The others sector includes five other LIB-containing products, namely, smartphones, feature phones, laptops, tablets, and e-scooters. The three sectors include a total of 13 different products, representing most of the LIB demand. Each sector consists of three layers, namely, the product layer, the battery layer, and the material layer. For each layer, inflows, stocks, and outflows are estimated using a stock-driven or inflow-driven model,[34] considering data availability and model suitability. For any products, components, or materials, using the stock-driven model, the inflows are calculated given a time series of stocks and an assumed lifetime distribution (Equation 1). In an inflow-driven model, the stocks are determined given a time series of inflows and an assumed lifetime distribution (Equation 2).

$$In(t) = S(t) - S(t-1) + \sum_{s<t} In(s) \times L(s,t) \quad \text{(Equation 1)}$$

$$S(t) = S(t-1) + In(t) - \sum_{s<t} In(s) \times L(s,t) \quad \text{(Equation 2)}$$

Here, t, s denote the year ($t, s = 2010, \ldots, 2050$). In and S represent the inflows and stock of products, respectively, and L is the lifetime distribution function of products. $L(s,t)$ denotes the probability that a product produced in year s fails and enters its EoL in year t. The lifetime distribution of batteries is assumed to follow a normal distribution,[15,22,73] with different average lifespans (see the table in Note S10). Note that in this study, the historical modeling spans from 2010 to 2022, while the projection period extends from 2022 to 2050. Detailed modeling equations for each sector are presented in the supplemental information.

Scenarios and data sources

Scenario analysis entails crafting multiple plausible future scenarios to evaluate potential outcomes and formulate strategies to tackle them. In scenario analysis, key variables and uncertainties are identified, and various combinations of these factors are used to construct different scenarios, which allows us to explore a wide range of possible futures, understand the uncertainties, and make more informed choices.

In this study, four variables are identified as key impacting factors of the potential RCs.

(1) Climate targets, which impact the prospective growth rates of LIB demand for EVs and BESSs.
(2) Battery lifespan, which determines the annual battery demand to build up stocks and the timing of waste battery generation.
(3) Battery chemistry mix, which impacts the material intensities of batteries, influencing both MD and recycling potential.
(4) Repurposing rate of EoL EV batteries, which impacts the LIB demand of BESSs and the timing of waste battery generation.

To examine their potential effects on potential RCs, we have created multiple distinct scenarios for each of these factors. More precisely, we have established three scenarios for varying climate targets, three scenarios for different battery lifespans, three scenarios for diverse battery chemistry mixes, and five scenarios for different repurposing rates of EoL EV batteries. This leads to a total of 108 scenarios (3 × 3 × 3 × 4). Detailed explanations of these scenarios are provided in Notes S9–S12.

Battery stock dynamics

In the EV sector, the widely used Gompertz model[74] is applied to forecast the EU's passenger car stock up to 2050 based on projected population[75] and per-capita gross domestic product data[76] (see the first figure in Note S4). The share of EVs in the total car stock is used to determine the EV stock under different scenarios (see the first table in Note S9). The EU's EV car sales are subsequently forecasted using a stock-driven model, assuming the vehicles have an average lifespan of 15 years that follows the Weibull distribution (Table S7).[14] For other commercial vehicles, historical sales data are collected from the European Automobile Manufacturers' Association (https://www.acea.auto/), which are extrapolated to estimate the prospective sales (see the figure in Note S4). EV sale shares within vehicles are then used to determine the EV sales (see Table S9), which are subsequently translated into EV stocks using the inflow-driven model. The stock of in-use battery packs equals EV stocks because each vehicle in use requires a battery pack, albeit with different energy capacities, depending on vehicle type (Table S1). The stock of battery packs is then translated into the annual inflows of battery packs using the stock-driven model, which is then translated into battery demand in capacity. For the EV batteries, we distinguish two types of battery demand: the new batteries deployed in newly sold vehicles and the batteries needed to be replaced within existing EV stock (we assume that batteries that failed within the warranty period, which is usually 8 years, will be replaced).[22] All EV batteries are assumed to be collected at their EoL. An indeterminate fraction of all EoL EV batteries, defined as the repurposing rate, may be repurposed within the BESS for a second life. Batteries not repurposed are presumed to undergo recycling.

The BESS sector has two types of inflows: new batteries deployed in the BESS and repurposed EoL EV batteries. Only the former contributes to the generation of new battery demand. Our model anticipates that the EU's BESS stock will range between 1.5 and 4.5 TWh by 2050 under different climate target scenarios (see the second table in Note S9), which aligns closely with the range of 1.9 to 5.3 TWh provided by the European Commission.[60] These projected BESS stocks are used to calculate the required annual BESS inflows. The battery demand for the BESS sector is determined by subtracting the amount of repurposed EoL EV batteries from the required BESS inflows.

The others sector has five LIB-containing products. Historical sales data are collected for these products from reliable sources, and projected sales from industry reports are adopted with the authors' prudence (Table S4). Saturate levels of product ownership are assumed for these products to estimate product sales up to 2050.

Battery demand is then determined by multiplying projected sales for different products and their corresponding battery capacities (Table S1). A more detailed description of the model framework, equations, and computation flows is available in the supplemental information (Notes S3–S8).

Battery manufacturing waste

The EU-BR defines battery manufacturing waste as "materials or objects rejected during the battery manufacturing process, which cannot be reused as an integral part in the same process."[10] The EU-BR expects it to be the major source of RMs in the short term before most existing EV batteries reach their EoL. Despite their significance, there is a lack of empirical evidence about the manufacturing waste rate, perhaps due to the highly confidential nature of this information among cell manufacturers. In our model, we adopt the default cathode material yield in cell manufacturing processes from the BatPaC model (94.1%)[51] and assume that 95% of finished cells pass the final inspection.[52,53] The material losses during manufacturing and inspection processes together result in an overall waste rate of 10.6% (=1–94.1% × 95%) at the current level. By way of comparison, Circular Energy Storage estimates a global average waste rate of 7.67% for 2023 and anticipates a decline to 4.34% by 2030.[54] Notably, industry practitioners typically report higher waste rates than our assumption, which sometimes go up to 30%.[49] The discrepancy may partly result from the fact there is no rigorous and universal definition of manufacturing waste. Although the EU-BR clearly distinguishes battery manufacturing waste and scrap and excludes the latter from the calculation of RCs,[10] it is hard to determine whether the reported values of waste rate include scrap or not. In addition, new factories in their early stage of scaling up production typically generate excess waste, while factories operating at high capacity utilization generate less waste. With incremental improvements, battery production processes have experienced a gradual decrease in waste rate.[49] Recent studies even predicted waste rates as low as 1%–3% in 2030.[49,55] Balancing different evidence, our model assumes that the manufacturing waste rate will decrease to 5.9% by 2030 and then stabilize thereafter (Table S6). If waste rates prove to be lower (higher) than 5.9% in the future, our assumptions will lead to an overestimation (underestimation) of materials available for recycling and, consequently, an overestimation (underestimation) of potential RCs.

Material demand and recycled content

Because it is the manufacturers who will need to meet the RC targets, we estimate the MD for the available RMs for battery manufacturers to determine the potential RCs. MD (i.e., the amount of material required for manufacturing processes, which could be either primary or recycled materials) is the product of battery demand and material intensity, adjusted by waste rates. There are significant variations in material intensity among different battery chemistries (see the first table in Note S11). Specific battery chemistry mixes are assigned to different LIB products (see the second and third tables in Note S11) since their performance requirements vary significantly. Following the EU-BR, RMs from both EoL batteries and battery manufacturing waste are included in the calculation of RCs. EoL batteries from the EV and BESS sectors are assumed to be 100% collected following the EU-BR. The collection rates of EoL batteries in consumer electronics are assumed to align with the targets outlined in the EU-BR, progressively increasing from 45% in 2023 to 63% in 2027 and further to 73% in 2030, then remaining stable thereafter from 2030 onwards (Figure S1). Battery recycling processes are assumed to recover 50% of Li, 90% of Ni, and 90% of Co from their feed by 2027, with subsequent improvements to 80%, 95%, and 95%, respectively, by 2031.

Limitations and uncertainties

Following the boundary of the EU-BR, our study focuses on LIBs intended for the EU market. We estimate RMs generated from the material cycles of these batteries but do not consider possible sources other than LIBs, which might result in an underestimation of potential RCs. Our model does not encompass all LIB-containing products (e.g., digital cameras), although we include three major LIB market segments, which cover most of the LIB demand. Creating an exhaustive list of LIB-containing products and modeling them together in a single model is particularly challenging due to the limited data availability and continuous emergence of new products. In addition to the 11 distinct battery chemistries featured in our model, there are other types of battery chemistries holding potential for widespread commercialization in the future, such as the cobalt-free Lithium Manganese Nickel Oxide (LNMO) cathode, notwithstanding several hurdles that must be overcome before their practical use.[77] However, we believe the impacts of widespread commercialization of such promising battery technologies on MD reduction could have been largely captured by the TBS scenario, which is characterized by the wide commercialization of post-LIBs that contain no cobalt or nickel at all. We have modeled the uncertainties and impacts of four selected key factors on RCs and discussed other factors such as the EoL collection rate and recycling efficiency. Apart from these factors, other parameters could potentially influence the RCs, such as the battery capacity of vehicles. Nevertheless, our sensitivity analysis indicates that a ±30% variation in battery capacity for passenger cars by 2050 only leads to a ±1.4% fluctuation in RCs for Co and negligible deviations in RCs for Li and Ni (Table S8).

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.06.017.

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AUTHOR CONTRIBUTIONS

W.L. and P.W. conceived the original idea and supervised the research. H.Z. and Y.Y. developed the model and collected the data. H.Z. developed the Python programming, ran the simulations, and drafted the paper. H.Z. and Y.Y.

drew the figures. All authors enhanced the discussion, analyzed the results, and contributed to writing this paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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