nature portfolio

Peer Review File

Lithium-ion battery recycling relieves the threat to material scarcity amid China's electric vehicle ambitions

Corresponding Author: Dr Qingyao Xin

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
The topic of this study is common, which is to predict the future battery-related metal demand using the MFA model, and further calculate the environmental benefits based on LCA results. As the authors said in literature review section, for the resource demand part, there are already many studies working on the topic at the global level or the national level. Thus, the innovative point should be the consideration of multiple technology routes and dynamics of various markets. Regarding this point, the novelty of this study is not satisficing. The system boundary does not have a big difference with that of previous literature. Even worse, some underlying assumptions are completely unrealistic which make the model results not policy-guiding. Based on the current quality of this paper, I think it is not suitable to be published in Nature Communications now. At least a major revision is needed. See below for my detail comments.

1. There is only one scenario for the ownership of EVs based on the Global Change Assessment Model (GCAM), in which the ownership of EVs will remain unchanged after 2040 (Fig. 2). There are many studies on predicting the demand for electric vehicles, so why not use some authoritative results? How to explain the EV's demand trajectory? In addition, I cannot see from the supplementary materials whether this study considered the electrification of future electric trucks. The electrification of trucks will greatly increase the prediction of future demand for batteries and materials.

2. The future metal demand for batteries not only depends on the ownership of EVs s, but also on the battery capacity per EV and the specific energy density of batteries, which are the key points for future battery technology breakthroughs. However, these important parameters were not considered in the scenario setting.

3. The benchmark recovery rate for spent LIBs is set at 60%. Whether based on the Regulation (EU) 2023/1542 of the European Parliament and of the Council concerning batteries and waste batteries or the actual situation in China, this recycling rate is set too low.

4. In the OPT scenario, this study shows that some resources may even oversupply. However, in some related studies, for example the study of Liu et al. (2023), the comprehensive scenario can alleviate resource pressure but cannot achieve resource self-sufficiency in LIBs. Therefore, I believe that the results of this study should be compared with some relevant research results and the reasons for the differences in results should be explained.
Liu, M et al. To what extent can recycling batteries help alleviate metal supply shortages and environmental pressures in China? Sustainable Production and Consumption, 2023, 36: 139-147.

5. There may be significant uncertainty in the environmental performance results of battery recycling. If you want to calculate the environmental benefits or impacts, you need to clarify the spatial boundary and temporal boundary for these data and also the assumptions for energy mix and emission factor of various energy sources like thermal power, solar power, wind power, etc. In addition, you only stated the environmental impacts of battery recycling. But the environmental impacts of battery or material production are also essential because you want to calculate the environmental improvement benefits. It means that you need to calculate the differences of emissions from battery production and recycling. Also, at this point in the LCA, there is a serious fundamental problem in the method to estimate the benefits of carbon reduction from future battery recycling. The resource demand model is dynamic, but the LCA model is static. You amplify the environmental benefits of

battery recycling now with future demand. In other words, you multiplied the battery demand in 2060 by the emission factor of the current battery recycling technologies to get the result. However, it should be noticed that the environmental impact is also evolving with the energy transition. When LIBs become popular on a large scale, the proportion of renewable energy generation in the energy supply will be completely different from today. Then the emission factor of battery recycling at that time is also completely different from that of today. If this point is ignored, the calculated results are completely meaningless.

6. All in all, the manuscript should provide a detailed and comprehensive analysis and discussion of the results. An in-depth analysis or explanation should be given. Because the novelty in this paper has to be demonstrated in these areas.

Reviewer #3

(Remarks to the Author)
This paper is titled “ Lithium-ion battery recycling relieves the threat to electric vehicle ambitions of critical material scarcity under China’s carbon neutrality” looks very interesting, but it needs a serious major revision, and my comments are as follows:
In the Abstract section
The authors mentioned that they have done a customized integrated modelling framework with the future prediction of EV demand and LIB scrappage, and material recycling simulation which results in a great benefit to LIBs recycling. Also, they have mentioned that their findings highlight the urgent need to electrify and decarbonize the automotive sector with more developed closed-loop lithium-ion battery cycle strategies.

• They didn’t mention any relation between these findings with the economic cost and its impact and contribution to the domestic and global economy and the other merits of the energy storage sector must be clearer.
In the Introduction section:
The authors have done a good survey about Evs, and the related investigations done in this issue, however, the beginning must start at least with information about the role of LIBs recycling and the decarbonization process that occurs in energy-related applications, it depends on closed-loop LIBs recycling methods.

• The author must be clear in this section and they have to introduce their topic as well.
Also, they have to show evidence that this modelling tool is very close to the results obtained from experiment investigations as well.

In the Result section:
!- All given images and figures are very bad in resolution and it need to be higher in resolution as well
2- However the authors mentioned they had given more scenarios of evaluation for EV material demand and recovery in the process of LIB recovery, but they didn’t mention how they selected these types or in what base they have selected it.
3- They have done some calculations about the cost but it is not complete. They have to show the evidence that the findings and obtained results compared to experimental investigation done in that relation are close and costly effective.
4- They have to clearly demonstrate the challenges and limitations facing this method of working
5- Proofread of some sentences and paragraphs need to be checked again,

Reviewer #4

(Remarks to the Author)
Sustainable sources of critical minerals are crucial for the mass production of lithium-ion batteries (LIBs) and electric vehicles (EVs), essential instruments for achieving net zero targets. This study employs an integrated framework to model resource conservation and environmental benefits associated with EV LIB recycling in China, a pivotal player in global EV expansion. To do so, the authors use an integrated framework that combines material flow analysis with life cycle assessment, examining nine scenarios that vary in battery mix, service life, recycling configuration, recycling rate, and critical mineral recovery rate.

While I find the research questions interesting and important, I have some comments and questions as follows:

- Shorten the manuscript to enhance conciseness; for instance, the first paragraph (from line 31) can be significantly condensed.

- In line 51, the assertion that "A typical EV requires six times the mineral inputs of fossil-fuel-based vehicles" originates from an IEA report. This should be amended, as the report only considers selected minerals like copper and critical minerals, excluding others such as steel and aluminium.

- Correct the term "HPEV" in Figure 1.

- In line 189, correct "NMC623."

- In Table 1, verify the critical materials recovery rate of RP-PYR. Which materials can be recovered through this process?

- Given the numerous scenarios, the author may consider including a chart illustrating ensemble scenarios and related analysis.

- In line 362, I disagree with the statement, "Although inexpensive-material cathode technology (LFP currently) could help free China from its dependence on critical and scarce materials, this cathode type is doubted regarding environmentally friendly selection in recycling treatment when concerned about reducing the carbon footprint." From a life cycle perspective, the focus for a net-zero future should be on minimizing the carbon footprint across the entire life cycle, rather than solely in a single stage (recycling treatment).

Questions:
- What is the role of second-life methods in the context of the study?

- How do the authors account for carbon emissions related to the transport and collection of spent batteries in the current modelling? Is there potential for Is there a potential role for optimising the geospatial configuration of a future lithium-ion battery recycling industry in the transition to electric vehicles given the size of China?

- How does the uncertainty in electric vehicle (EV) adoption affect the overall uncertainty in the analysis?

- Are all three recycling processes financially viable, and if so, to what extent?

- What is the relationship between the geographic location and ownership of critical mineral miners, and how does this affect the study's findings?

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
After a thorough review of the revision and the response, I remain concerned that the study's novelty is unsatisfactory. Several underlying assumptions and explanations appear unrealistic, rendering the model results less applicable for policy guidance. Therefore, I believe the manuscript is not suitable for publication in Nature Communications at this time. Below are my detailed comments:

1. Response to Comment 3: The authors stated, “We set the benchmark recovery rate at 65% per year (RS), which complies with Regulation (EU) 2023/1542 of the European Parliament and the Council concerning batteries and waste batteries.” This is the first unreasonable assumption. The Regulation pertains to collection targets for portable and LMT batteries but does not specify recycling targets for power batteries. Furthermore, the Regulation sets recycling efficiency targets of 65% by the average weight of lithium-based batteries. However, the recovery rate of 65% per year in the study should correspond to the recycling efficiency of 65% outlined in the Regulation. The term ‘recycling efficiency’ means the ratio, expressed as a percentage, obtained by dividing the mass of output fractions accounting for recycling by the mass of the waste batteries' input fraction, in relation to a recycling process (Definition given by Regulation). It seems the authors may have conflated the meanings of ‘recycling efficiency’ and ‘recycling rate’ from the Regulation.

2. Response to Comment 4: The authors confirmed the reliability of their results by comparing them with other literature. However, the comparison with “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)” is not appropriate. Zeng et al. examined global cobalt flows across various sectors, including electric vehicles, energy storage systems, and others, while the authors' study focuses specifically on cobalt flows in Chinese power batteries. Additionally, Zeng et al.'s study projects new LFP batteries to dominate (100% by 2050) in their most optimistic scenario, whereas the current study predicts NCA batteries will dominate (80% by 2060) in the optimal technology scenario. Thus, the comparison between these two studies is irrelevant.

3. Response to Comment 5: The authors used a carbon emission factor of 1.001 kg CO_2-eq/kWh. However, the carbon emission factor for electricity in China for 2021, as reported by the Ministry of Ecology and Environment, is 0.5568 kg CO_2-eq/kWh. International estimates also suggest a figure around 0.8 kg CO_2-eq/kWh. Therefore, a carbon emission factor of 1.001 kg CO_2-eq/kWh is significantly higher than actual values in China, which undermines the reliability of the results. This is the third unreasonable assumption.

4. For the comment 5, I mentioned that “environmental impacts of battery or material production are also essential because you want to calculate the environmental improvement benefits. It means that you need to calculate the differences in emissions from battery production and recycling. Also, at this point in the LCA, there is a serious fundamental problem in the method to estimate the benefits of carbon reduction from future battery recycling. The resource demand model is dynamic, but the LCA model is static. You amplify the environmental benefits of battery recycling now with future demand”. The authors did not address this fundamental issue, which is critical for the paper's publication in Nature Communications.

(Remarks on code availability)
I don't have Matlab installed on my computer and can't open these code files.

Reviewer #3

(Remarks to the Author)
The authors have replied to all my comments and they have accordingly edited the manuscript and related documents. So the paper now can be accepted in this form and published in the journal

(Remarks on code availability)

Reviewer #4

(Remarks to the Author)
I appreciate the authors' efforts in extensively incorporating a range of comments from the editor, other referees, and myself to improve the manuscript. After reading the revised manuscript and each response carefully. I find it has been significantly improved. However, there are still some points that need further refinement.

1. A central finding of this manuscript, reiterated throughout the abstract, main text, and conclusion, is that "EV deployment to achieve China’s carbon-neutrality target could significantly increase the cumulative demand for critical materials, surpassing global mineral reserves by up to 2.8 times." This is a surprisingly strong yet vague statement. In the literature, the primary concern for many critical minerals is often the limited production capacity rather than the total reserves, and whether production can be scaled up to meet rising demand. To substantiate this claim, it is essential to specify which critical minerals are being referenced among those assessed. The calculations presented between lines 140-142 need to be carefully reviewed with meticulous attention to unit conversions and clearly elaborated, ideally in the form of a table.

2. I’m glad to see that the revised manuscript has addressed the viability of recycling. The author illustrates the profitability of the circular economy solution in the main text. However, the authors have not made it clear that this assessment is for a snapshot of 2060. What about earlier years? Methodologically, the manuscript fails to clarify how economies of scale are incorporated into the financial assessment of recycling. This is a key point in optimizing the geospatial configuration of recycling, as excessive competition may severely impact plant-level viability. It appears that the authors have built a cost model directly from BATPAC, but it is unclear what benefits this approach offers over using EverBatt, which is a more specific tool for this purpose. Please elaborate.

3. There are still several opportunities for the authors to review the writing more carefully to correct typos and enhance clarity for the audience:
• Please rewrite lines 25-29 to make it clearer that repurposing and recycling are also part of circular economy strategies like reuse. Given the scope of the manuscript, it might be more effective to focus directly on recycling when setting the stage.
• The EU example in lines 30-31 should be moved to a footnote, which should also include examples of other “major jurisdictions.”
• The sentence in lines 113-117 is difficult to comprehend and assess. Please break it down and rewrite it with greater clarity.
• Similarly, the sentence in lines 208-210 is hard to understand. Please rewrite it for better clarity.
• In line 406: What is LFA?

4. Maps like Supplementary Figures 29 and 30 include features linked to controversial, unsubstantiated territorial claims, which do not contribute to the scientific content of this research.

(Remarks on code availability)

Version 2:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
The manuscript has shown considerable improvement in terms of quality and content, making it suitable for publication. I am pleased to grant my approval for its release. Congratulations to the authors on their outstanding efforts and achievements!

Reviewer #4

(Remarks to the Author)
Again, I highly appreciate the effort of the authors to incorporate different feedback to improve the manuscript, including the extension of models to take into account the role of geospatial optimization and the use of the EverBatt model, which is more appropriate for capturing the economics of recycling (and its environmental benefits). However, I'm not convinced the manuscript in its existing form is ready for publication. Here are some issues:

1) Conceptual issues: I don't think LIB recycling should be categorized as a "reuse channel" as stated in lines 36-37, especially in the context of the circular economy mentioned in the previous sentence. For example, they are referred to as two circularity strategies (R3/R8) in Morseletto (2020) [Targets for a circular economy]. If one wants to say recycling is a cascading step from the second use of EV batteries (for example, in less demanding applications such as static energy storage), one may elaborate more rather than using such a confusing concept. Note that many EV batteries can go straight to recycling without a reuse/refurbishment step.

2) Technical issues: I'm particularly concerned about the technical reliability of the recycling viability assessment (lines 316-392). The key finding (but not reported in the manuscript) in panel b if Fig5 is that recycling is not economically feasible in almost every scenario (except for some special extreme scenarios) as the recycling net profit is negative. Surprisingly, recycling in the high CC-NMC scenario is less viable than in the CC-LFP scenario, while it is expected that recycling NMC will help recover more precious materials like cobalt. The literature mainly concerns that the shift to LFP would reduce the economic incentive of recycling. Can you please elaborate on these strange results and consolidate them with previously published results?

Similarly, direct cathode recycling in Fig. 5, the new and more economical method, is shown to cause more loss than hydrometallurgical recycling (RS scenario) and pyrometallurgical recycling. Could you elaborate more on this?

These strange results may cast some questions on the assumptions, data sources, or the use of suitable methodology and the calculations involved. Importantly, if recycling is not economically viable, it raises the question of whether environmental benefits might justify the economic losses, and if so, who would bear the cost? Does the use of recycled material justify itself instead of the alternative (i.e., virgin materials)?

A specific technical issue I can see is "diseconomies of scale" mentioned in line 353. If the EverBatt model is set up correctly, the increase in throughput will reduce the recycling cost (such as lower average fixed cost) and hence improve viability. As time passes, the volume of spent batteries that need to be recycled will rise, increasing the viability of the industry - that's the economy of scale expected in this context.

The huge losses of recyling computed in this manuscript may come from the fact that the modeler set up so many recycling sites (hence just allocating spent batteries but not "optimizing" yet). In fact, recycling is a capital-intensive business requiring large-scale operations; hence, the intensive network of recyclers shown is not economically sustainable.

This may be the root cause of the huge loss of recycling in the base scenario, even with the large recycling demand in 2060. In short, the failure to properly model the economic structure of the recycling industry has caused the artifact of "diseconomies of scale" and the strange results presented.

3) Result discussion: I appreciate the authors' effort to highlight the specific materials that could be the bottleneck of EVs in China that recycling can help, such as cobalt and manganese, rather than lumping them together with other materials with fewer issues, such as nickel. How about lithium? It would deserve some discussion (even if it is less serious). Remember, the issue with cobalt and manganese could be partly solved by the shift to LFP (which again could discourage the recycling incentive). But lithium would stay there as long as lithium-ion batteries remain dominant, so it applies to all scenarios presented. For a more complete discussion, the authors may want to briefly mention the prospect of some new battery advancements (such as sodium batteries) as they could again change the bottleneck issues and challenge the solutions discussed.

There are still some vague aggregated statistics in lines 130-134: "The LIB recycling roadmap reveals that the total demand for cobalt, lithium, nickel, and manganese in EV production soared to 204, 222, 602, and 195 hundred tons in 2020 - a 900-fold increase from 2010 levels (Fig. 1). However, only 2.8, 3.1, 8.3, and 2.7 hundred tons of these critical materials were sourced from recycled batteries, meeting just 1.4% of the total demand." Please elaborate on what the 900-fold increase and 1.4% refer to when discussing the materials separately.

4) Map representation: In the rebuttal letter, in response to my previous request related to Supplementary Figs, the authors acknowledge that "To ensure that our work aligns with the scientific focus and publication standards, we remove controversial, unsubstantiated territorial claims in the manuscript." I insist that such a principle must be applied throughout the manuscript, including panel a of figure 5 that is newly inserted.

5) Writing: There remain many opportunities for the authors to improve word choices and grammar issues to make the manuscript more readable. Below are some examples (but not an exhaustive list) - please review again thoroughly.

- "donate" (Fig2, 5, Line 298) -> "denote"
- “a strategically full-spectrum framework” (Line 9): Consider rephrasing to “a comprehensive framework” for clarity and conciseness.
- “with a at least 84% battery collection target” (Line 10): remove "a"
- “disassembly and recycling process” (Fig 5):-> "processes”
- “maximums cost-efficiency” (Line 17): Correct to “maximizes cost-efficiency.”
- “projected to reach 54 and 116 times their 2022 production capacities” (Line 14,174): The phrasing is awkward. Consider: “expected to exceed their 2022 production capacities by 54 and 116 times.”
- “latent risk of soaring prices” (Line 67): “potential risk” for better flow.

- “scrapped LIBs trends” (Line 141): This could be rephrased to “trends in scrapped LIBs.”
- “coupled with the lifetime distribution forecasting model with the retrospective material flow analysis” (Line 116): Overly complex; simplify
- “the waste batteries are first used for the direct application” (Fig 1) -> “waste batteries are initially used for direct applications.”
- “flows onto the recycling market” (Line 123): Replace “flows onto” with “enters.”
- “Detailly put” (Line 121): Replace with “In detail” or “Specifically.”
- “latent scenarios” (Line 586): Consider “potential scenarios”.
- "life-cycle unit" (Line 346): replace unit by cost.
- Ensure consistent capitalization or lowercase for material names throughout the manuscript.(Nickel/nickel ...)

6) Method reference: Make sure to add relevant citations to the methods section to refer to methods and tools that you were building on. There are restrictions on the number of citations in the main text but not in the methods section.

Version 3:

Reviewer comments:

Reviewer #4

(Remarks to the Author)
Thank you to the authors for revising the manuscripts, particularly the section on the economics of recycling. The results now make more sense, and I agree that the paper is suitable for publication.

(Remarks on code availability)

Dear editor and reviewer,

Thank you for your timely response and valuable feedback on our paper. We appreciate the acknowledgment of the merit of our work and the constructive suggestions for the revisions. After thorough consideration of the comments and recommendations from the reviewers, we are fully committed to addressing their suggestions. Please see the point-by-point responses below for details. The modifications have been highlighted with RED color in the revised manuscript file.

Response to reviewers' comments

Reviewer #2 (Remarks to the Author)

The topic of this study is common, which is to predict the future battery-related metal demand using the MFA model, and further calculate the environmental benefits based on LCA results. As the authors said in literature review section, for the resource demand part, there are already many studies working on the topic at the global level or the national level. Thus, the innovative point should be the consideration of multiple technology routes and dynamics of various markets. Regarding this point, the novelty of this study is not satisficing. The system boundary does not have a big difference with that of previous literature. Even worse, some underlying assumptions are completely unrealistic which make the model results not policy-guiding. Based on the current quality of this paper, I think it is not suitable to be published in Nature Communications now. At least a major revision is needed. See below for my detail comments.

Response:

Thank you for your feedback on our manuscript. We appreciate the time and effort you have dedicated to evaluating our manuscript. Your constructive comments helped us enhance the overall quality of the manuscript. Following your feedback, we have conducted thorough revisions, such as the consideration of multiple technology routes to underline innovation, expanding the system boundary, revision of underlying assumptions, and modeling adjustments to make results policy-guiding. Four main points are revised and summarized as follows:

- We have developed two EV lifespan scenarios to reflect the uncertainty of EV adoption under climate goal. The electrification of trucks also has been considered to comprehensively prediction of future demand for batteries and materials.
- Based on the technological breakthrough related to the vehicle, battery, and recycling process, we have made more sensible assumptions related to the battery capacity and density, as well as the battery recycling rate.
- Predicting future battery-related material demand is well-explored in studies, for example, the study of Liu et al. (2023), we thus compare our results with the existing studies in the literature, illustrating the reasons for the consistencies and differences in our findings.
- We have also assumed the cleaner electricity mix scenario with gradually increasing penetration of renewable energy and decreased carbon emission factor, outlining environmental impact of battery recycling as it becomes more significant in future.

Thank you again for your valuable insights. Below we provide responses to each comment in detail (your comments are in black and our responses starting with Response are in blue).

Comment 1

There is only one scenario for the ownership of EVs based on the Global Change Assessment Model (GCAM), in which the ownership of EVs will remain unchanged after 2040 (Fig. 2). There are many studies on predicting the demand for electric vehicles, so why not use some authoritative results? How to explain the EV's demand trajectory? In addition, I cannot see from the supplementary materials whether this study considered the electrification of future electric trucks. The electrification of trucks will greatly increase the prediction of future demand for batteries and materials.

Response:

Thank you for your feedback on improving EV adoption forecasting model. We take several strategies to address your concerns. i) We improve our top-down and bottom-up integrated model to forecast the EV ownership under China's carbon neutrality by considering uncertainties in life span and technological advancements. ii) We compare our forecasting results with the existing studies. iii) electrification of trucks is also considered in our revised EV adoption forecasting model. Below are our detailed improvements to the points you raised:

(i) Consideration of uncertainty in forecasting EV adoption: We employ the top-down Global Change Assessment Model (GCAM) to simulate the intricacies of economic, societal, energy, and transportation service dynamics under China's climate goal scenarios. We begin with joint use of the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs) in the GCAM model to obtain the key parameters of population, economic development level, and carbon and energy prices. These parameters are linked to the Bass model, providing a context for predicting the future development trajectory of EVs under China's carbon neutrality goals. For the bottom-up part, the Bass model is employed to forecast EV adoption by considering innovation and imitation effects[1]. Factors such as EV price variations, market scale, usage behavior, infrastructure development, and EV lifetime distribution are considered, allowing for dynamic simulation of market changes.

To reflect the uncertainty of how EV ownership varies with its cost caused by technological advancement, we assume three learning rates, which are set between 3%, 6%, and 9%[2]. The assumption for future EV market size is based on the parameters such as population, and economic development level (to calculate vehicle ownership per 1,000 capita) derived from the output of the

GCAM model. Combined with the high-resolution EV driving data, we identify the annual real-world vehicle traveled kilometer to describe the vehicle usage. The impact of infrastructure construction on the development of EVs is also concluded in the integrated EV forecasting. Moreover, assuming the average lifespan of EVs is 15 years[3], the relationship between the annual scrappage and its new additions is characterized by the Weibull distribution.

To explore the effect of larger fleet turnover, i.e., higher prospective vehicle sales for fixed prospective stocks, we adopt a lower EV average lifespan (10 year) in our EV forecasting model[3,4]. Thus, we consider for uncertainties while constructing a comprehensive and technology-rich model to predict the EV evolution under China's carbon neutrality goal. Please see the **Method and Supplementary Note 2** for more details.

(ii) Comparison of our forecasts with existing studies: We review the literature on new EV sales and stock prediction, such as the results from Zhao et al.[5], and Wang et al., [6]. According to the estimation from Zhao et al., the EV stock in China would reach 857 million in 2050; With the prediction of Wang et al., the amount of stock varies range from 379-535 million under the various critical material price scenarios in 2060. Coupled with the constraint of climate goal, our results reflect a more moderate path of EV growth. EV stock increases to 540 million in 2050 and 638 million in 2060 with long EV lifespan. Please see the **Supplementary Table 19** for more details.

(iii) Forecasting electric truck ownership: Due to the later stage of electric truck electrification, there is not enough historical data to use the GCAM model coupled with a technologically detailed Bass model for prediction. For example, according to the data from the China Association of Automobile Manufacturers, the penetration rate of new energy light trucks and heavy trucks is only 6.2% and 5.3% among truck fleets in 2022. However, trucks contribute a noteworthy proportion of annual greenhouse gas emissions, and the electrification of trucks is pivotal in limiting global warming[7]. Thus, electrified trucks will experience rapid growth in the coming decades and will greatly increase the prediction of future demand for batteries and materials. Here, we adopt the stock-driven dynamic material-flow-analysis (dMFA) model to forecast the EV stock and sale[8,9]. We first calculate the vehicle-specific stock using the equations:

$$Truck_i(t) = D_i(t) \times L_i^{-1}(t) \times VKT_i^{-1}(t)$$

That is, the truck stock related to vehicle type i in year t is connected with the transportation demand, D_i, load factor, L_i, and the vehicle traveled kilometer, VKT_i. Although the GCAM does not count the stock of trucks explicitly, it provides the parameters of transportation demand and load factor with various truck fleets under China's carbon neutrality goal. Then, we use the stock-driven MFA model to estimate the sale (inflow) and scrappage (outflow) of trucks:

$$truck_{i,in}(t) = truck_i(t) - truck_i(t-1) + truck_{i,out}(t)$$

$$truck_{i,out}(t) = \sum_{s=t-w}^{s=t-1} truck_{i,in}(t) \times F_i(t,s)$$

Where the $truck_{i,in}$ is the number of sales of vehicle type i; $truck_{i,out}$ donates the scrappage. $F_i(t,s)$ is the vehicle survival distribution of vehicle type i at year s for vehicles sold in year t, and w represents the vehicle lifespan. Vehicle survival patterns are subjected to Weibull distribution. The average life is assumed to be 8 years, 10 years, and 12 years, for light trucks, medium trucks, and heavy trucks[10]. Please see the **Supplementary Note 2.4** for more details.

Reference cited above:

[1] Al-Alawi BM, Bradley TH. Review of hybrid, plug-in hybrid, and electric vehicle market modeling Studies. Renewable and Sustainable Energy Reviews 21, 190-203 (2013).

[2] Nykvist B, Nilsson M. Rapidly falling costs of battery packs for electric vehicles. Nature Climate Change 5, 329-332 (2015).

[3] Milovanoff A, Posen ID, MacLean HL. Electrification of light-duty vehicle fleet alone will not meet mitigation targets. Nature Climate Change 10, 1102-1107 (2020).

[4] Morfeldt J, Johansson DJA. Impacts of shared mobility on vehicle lifetimes and on the carbon footprint of electric vehicles. Nature Communications 13, 6400 (2022).

[5] Zhao X, Mignone BK, Wise MA, McJeon HC. Trade-offs in land-based carbon removal measures under 1.5 °C and 2 °C futures. Nature Communications 15, 2297 (2024).

[6] Wang H, et al. China's electric vehicle and climate ambitions jeopardized by surging critical material prices. Nature Communications 14, 1246 (2023).

[7] Link S, Stephan A, Speth D, Plötz P. Rapidly declining costs of truck batteries and fuel cells enable large-scale road freight electrification. Nature Energy, (2024).

[8] Hao, H. et al. Impact of transport electrification on critical metal sustainability with a focus on the heavy-duty segment. Nat. Communications 10, 1-7 (2019).

[9] Abdelbaky, M., Peeters, J. R. & Dewulf, W. On the influence of second use, future battery technologies, and battery lifetime on the maximum recycled content of future electric vehicle batteries in Europe. Waste Manage. 125, 1-9 (2021).

[10] Hao H, Wang H, Ouyang M, Cheng F. Vehicle survival patterns in China. Science China Technological Sciences 54, 625-629 (2011).

Comment 2

The future metal demand for batteries not only depends on the ownership of EVs, but also on the battery capacity per EV and the specific energy density of batteries, which are the key points for future battery technology breakthroughs. However, these important parameters were not considered in the scenario setting.

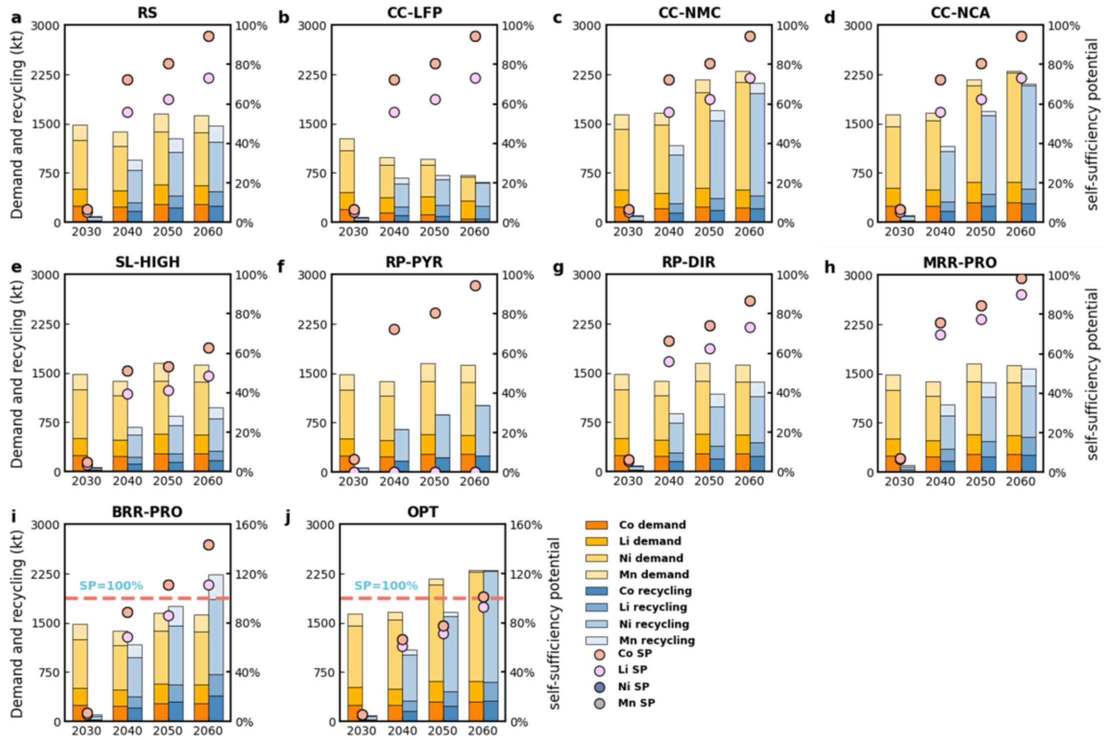
Response:

Thank you for this important suggestion. Due to the future battery technology breakthroughs, the battery capacity and density will increase, which are indeed likely to impact the critical material demand and supply. Therefore, we assume two battery characteristic scenarios to capture its technology evolution. In the first scenario, battery weight and other assumptions remain consistent with Baars et al.[1], and the PHEV's battery weight is half of BEV[2]. In the second scenario, the specific battery density will increase to 0.235 kWh/kg for all fleet segments, which is set according to the goal of the US Department of Energy to make EV commercial variable[3]. The underlying assumption is shown in the following **Supplementary Table 7**:

Supplementary Table 7 Assumption of battery capacity and density.

	battery capacity (kWh)		battery density (kWh/kg)	
	Low	High	Low	High
Compact car BEV	36	69	0.118	0.235
Compact car PHEV	18	34.5	0.118	0.235
Large car & SUV BEV	77	116	0.142	0.235
Large car & SUV PHEV	38.5	58	0.142	0.235
Mini car BEV	17	41	0.104	0.235
Mini car PHEV	8.5	20.5	0.104	0.235
Light truck	36	69	0.118	0.235
Medium truck	80	120	0.157	0.235
Heavy truck	270	423	0.15	0.235

Results show that an elevated battery capacity embraces a higher proportion of strategic resources at the package level. In this context, as the simultaneous growth in the supply from recycling and the demand driven by the boosted EV, the self-sufficiency potential (SP; the percentage of material supply via closed-loop recycling could make up for demand) from LIB recycling does not consistently increase, depending on the EV demand, scrappage pattern of LIB, and the battery and recycling technological assumption. For instance, in the OPT scenario, advanced battery capacity is associated with higher levels of SP of critical materials, the value of which ranges from 93% and 101% (**Supplementary Figure 17**).



Supplementary Figure 17 Demand, recycling, and self-sufficiency (SF) potential of critical materials considering higher battery capacity and density. *Abbreviations: RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology, battery recycling rate, and critical material rate develop according to current tendency. CC-LFP, CC-NMC, CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the battery is adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO and CRR-PRO refer to the progressive critical material recycling rate and battery recycling rate respectively. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The abbreviation of Co, Li, Ni, Mn refer to the cobalt, lithium, nickel, and manganese respectively. SP donates self-sufficiency potential.*

Reference cited above:

[1] Baars J, Domenech T, Bleischwitz R, Melin HE, Heidrich O. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nature Sustainability 4, 71-79 (2021).
[2] 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).
[3] US DRIVE-Electrochemical Energy Storage Technical Team Roadmap (DOE, 2017).

Comment 3

The benchmark recovery rate for spent LIBs is set at 60%. Whether based on the Regulation (EU) 2023/1542 of the European Parliament and of the Council concerning batteries and waste batteries or the actual situation in China, this recycling rate is set too low.

Response:

Thank you for pointing this out. We originally set the benchmark recovery of spent LIBs as 60% according to the literature of Dunn et al., (2022)[1], but it is possible that this value might not match the actual situation in China in the long run. To address to problem, we adapt several strategies to make it more cogent.

We set the benchmark recovery rate at 65% per year (RS), which complies with Regulation (EU) 2023/1542 of the European Parliament and the Council concerning batteries and waste batteries[2].

We also provide a progressive battery recycling rate scenario (PRO-BRR) in the manuscript to explore its role in resource relief and carbon mitigation. Under this scenario, the battery recycling rate is assumed to increase by 5% for every 5 years on the benchmark of 65%, and eventually achieve complete recovery till 2060.

Moreover, understanding how much the battery recycling rate could achieve a balance between demand and secondary supply in the automotive segment facilitates not only handling natural resource challenges but also saving energy in the recycling process under the constraint of climate goal. Therefore, we investigate the exact recycling rate where the demand-supply balance of these critical materials could be achievable in 2060. Results show that the battery recycling rate for cobalt, nickel, and manganese in 2060 should rise to 69% and 89% for lithium to exactly achieve demand-supply balance. Please see the section on **Requirement of critical materials and corresponding supplement from battery recycling (Page 9 Lines 193-207)** and **Fig. 3** in the revised manuscript for more details.

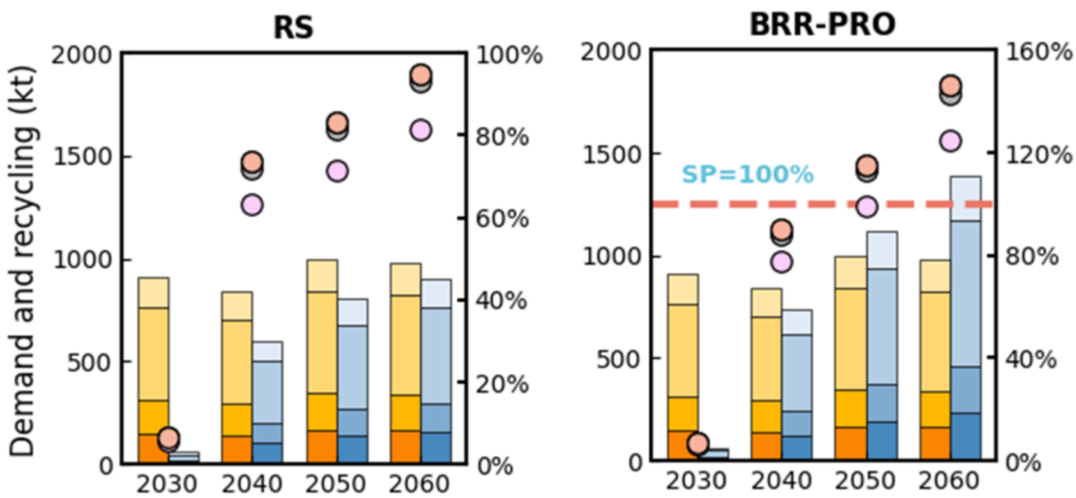


Fig. 3 Prospective demand, recycling, and self-sufficiency potential in revised battery recycling rate scenarios. *The Abbreviations is the same as Supplementary Figure 17.*

Reference cited above:

[1] Dunn J, Kendall A, Slattery M. Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. Resources, Conservation and Recycling 185, 106488 (2022).
[2] European Union. Regulation (EU) 2023/1542 on batteries and waste batteries. https://eur-lexeuropaeu/legal-content/ EN/TXT/?uri=CELEX%3A32023R1542, (2023).

Comment 4

In the OPT scenario, this study shows that some resources may even oversupply. However, in some related studies, for example the study of Liu et al. (2023), the comprehensive scenario can alleviate resource pressure but cannot achieve resource self-sufficiency in LIBs. Therefore, I believe that the results of this study should be compared with some relevant research results and the reasons for the differences in results should be explained.

Liu, M et al. To what extent can recycling batteries help alleviate metal supply shortages and environmental pressures in China? Sustainable Production and Consumption, 2023, 36: 139-147.

Response:

Thank you for the insightful comment. We appreciate your suggestion to compare our results to other relevant studies, such as Liu et al. (2023)[1]. To address this, we have added a comprehensive comparison with the literature related to resource self-sufficiency in LIBs in **Supplementary Table 20**.

We find battery recycling can reduce resource pressure but is basically difficult to achieve self-sufficiency in LIB materials in 2050 even though under an optimistic technology scenario, not only in the study of Liu et al. (2023) but also in our findings. However, the study of Liu et al. (2023) focuses on a comprehensive bottom-up estimation of LIBs and metals in 13 end-using sectors, while our research highlights the LIBs embodied in EVs and more extensive scenarios regarding battery and recycling technology evolution under China's carbon neutrality goals. Therefore, our research conclusions are consistent, though there are anticipated differences in the self-sufficiency potential rate. After extending the estimation period to 2060, in our optimal technological scenarios, LIBs recycling can achieve a supply-demand balance for critical materials except for lithium, supporting the EV deployment under China's carbon neutrality goal.

Supplementary Table 20 Comparison of results from literature for the material secondary supply

Year	Reference	Scenario	Material	Self-sufficiency potential
2040	Baars et al., (2021)[2]	Idealized scenario	Co	60%
			Li	53%
			Ni	57%
			Mn	53%
2050	Zeng et al., (2022)[3]	The most optimistic technology scenario	Co	>100%
2050	Qiao et al., (2021)[4]	Optimistic scenario	Li	49%
		Neutral scenario		53%
		Pessimistic scenario		60%
2050	Liu et al., (2023)[1]	Improved battery technology scenario	Co	77%
			Li	42%
			Ni	78%
			Mn	78%
			Cu	69%
			Al	68%
			Fe	40%
2040	This study	Optimal technology scenario	Co	66%
			Li	61%
			Ni	66%
			Mn	66%
2050	This study	Optimal technology scenario	Co	79%
			Li	72%
			Ni	79%
			Mn	79%
2060	This study	Optimal technology scenario	Co	101%
			Li	93%
			Ni	101%
			Mn	101%

Reference cited above:

[1] Liu M, Liu W, Liu W, Chen Z, Cui Z. To what extent can recycling batteries help alleviate metal supply shortages and environmental pressures in China? Sustainable Production and Consumption 36, 139-147 (2023).

[2] Baars J, Domenech T, Bleischwitz R, Melin HE, Heidrich O. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nature Sustainability 4, 71-79 (2021).
[3] 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).
[4] Qiao D, Wang G, Gao T, Wen B, Dai T. Potential impact of the end-of-life batteries recycling of electric vehicles on lithium demand in China: 2010–2050. Science of The Total Environment 764, 142835 (2021).

Comment 5

There may be significant uncertainty in the environmental performance results of battery recycling. If you want to calculate the environmental benefits or impacts, you need to clarify the spatial boundary and temporal boundary for these data and also the assumptions for the energy mix and emission factor of various energy sources like thermal power, solar power, wind power, etc. In addition, you only stated the environmental impacts of battery recycling. However, the environmental impacts of battery or material production are also essential because you want to calculate the environmental improvement benefits. It means that you need to calculate the differences in emissions from battery production and recycling. Also, at this point in the LCA, there is a serious fundamental problem in the method to estimate the benefits of carbon reduction from future battery recycling. The resource demand model is dynamic, but the LCA model is static. You amplify the environmental benefits of battery recycling now with future demand. In other words, you multiplied the battery demand in 2060 by the emission factor of the current battery recycling technologies to get the result. However, it should be noticed that the environmental impact is also evolving with the energy transition. When LIBs become popular on a large scale, the proportion of renewable energy generation in the energy supply will be completely different from today. Then the emission factor of battery recycling at that time is also completely different from that of today. If this point is ignored, the calculated results are completely meaningless.

Response:

Thank you for valuable suggestions to improve our various modeling assumptions. Firstly, to deal with the estimation of the environmental impacts, we further clarify the spatial boundary and temporal boundary. Specifically, the spatial boundary is focused on the life-cycle carbon emission estimation of LIBs for EVs, including the production, transportation, collection, and recycling of LIBs in China. The temporal boundary is based on the prospective analysis from 2020 to 2060 under China’s carbon neutrality path. To calculate the battery production emission, the life cycle assessment (LCA) method is used to evaluate the environmental impact. The production emission is determined by Simpro 9 software (with ecoinvent 3.8 database updated on September 2021 for up-to-date battery data module; https://simapro.com/), facilitating modular modelling on the cathode-specific or technology-specific base. We consider the six cathode chemistries, that is, LFP, NCA, NMC111, NMC523, NMC622, and NMC811. The bills of material and energy and correspondingly embodied emission are obtained from EverBatt (Argonne National Laboratory; https://www.anl.gov/amd/everbatt), a closed-loop battery life-cycle model to evaluate battery-related environmental impact and technology cost. Please see the **Calculating future life-cycle carbon emissions of battery section in Method (Pages 11-13)** and **Supplementary Note 5** for more details.

Secondly, we update the assumptions for the energy mix and emission factor of various energy sources, solving the problem of amplifying the environmental benefits. In detail, we develop two grid mix scenarios: The business-as-usual electricity scenario and the cleaner electricity scenario. Under the Business-as-usual electricity scenario, the electricity available on the medium voltage level in China from the Ecoinvent 3 database describes electricity inputs produced and from imports and transformed to medium voltage. This scenario assumes carbon emission factor of 1.001kg CO_2-eq/kWh. Under the cleaner electricity scenario, referring to the assumption of the future energy mix of Wu et al.[1] and Chen et al.[2], we set the dynamic carbon emission assumption every decade from 2020. The detailed electricity carbon emission and electricity mix is shown below:

Supplementary Table 18 Electricity carbon emission and electricity mix in a cleaner electricity scenario.

Item	Carbon emission (kgCO_2-eq/kWh)		2031-2040	2041-2050	2051-2060
Thermal power	0.930		45.0%	32.0%	14.0%
Hydropower	0.014		10.0%	9.0%	8.0%
Nuclear power	0.012		7.0%	8.0%	13.0%
Photovoltaic power	0		8.4%	10.5%	15.5%
Renewable power	Wind power	0.027	20.0%	23.8%	31.0%
	Biomass power	0.126	2.5%	3.0%	4.0%
	Solar energy generation	0.090	5.0%	7.0%	9.0%
	Geothermal power	0.080	1.5%	3.5%	4.5%
Garbage power		0.920	0.1%	0.2%	25.0%
Others		0.530	0.5%	3.0%	0.8%
Average carbon emission			0.433	0.330	0.155

The result shows the battery life-cycle emissions experience a substantial decrease with the higher penetration of renewable energy, especially in the RP-DIR scenario, which cumulatively achieved 2194 Mt carbon emission reduction in 2060 compared to 2020, indicating huge carbon emission mitigation potential of the battery recycling coupled with the cleaner electricity transition (**Fig. 4**). Please see the section of **Life-cycle CO_2 emission in lithium-ion battery (Page 12 Lines 251-256)**, **Fig. 4** in manuscript, and **Supplementary Table 18** for more details.

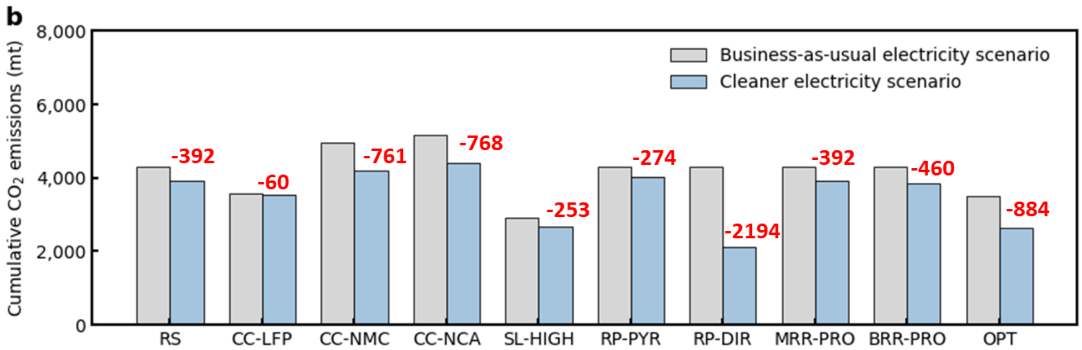


Fig. 4 Battery life-cycle emissions with cleaner grid mix under ten selected battery recycling scenarios. *The life-cycle emissions include the emissions from the battery manufacturing, transportation, collection, and recycling. The Abbreviations of scenarios is the same as Supplementary Fig. 17. The red annotated numbers signify the total carbon mitigation in cleaner electricity scenario compared with business-as-unusual scenario.*

Reference cited above:

[1] Wu W, Cong N, Zhang X, Yue Q, Zhang M. Life cycle assessment and carbon reduction potential prediction of electric vehicles batteries. Science of The Total Environment 903, 166620 (2023).
[2] Chen Q, et al. Investigating carbon footprint and carbon reduction potential using a cradle-to-cradle LCA approach on lithium-ion batteries for electric vehicles in China. Journal of Cleaner Production 369, 133342 (2022).

Comment 6

All in all, the manuscript should provide a detailed and comprehensive analysis and discussion of the results. An in-depth analysis or explanation should be given. Because the novelty in this paper has to be demonstrated in these areas.

Response:

Thank you sincerely for taking the time to review my manuscript and for providing valuable feedback. As you have seen above, we have made every effort to address your concerns and incorporate suggestions. If you have any specific recommendations regarding how we can further enhance the quality of the manuscript, we welcome your comments.

Reviewer #3 (Remarks to the Author)

This paper is titled "Lithium-ion battery recycling relieves the threat to electric vehicle ambitions of critical material scarcity under China's carbon neutrality" looks very interesting, but it needs a serious major revision, and my comments are as follows:

Response:

Thank you for your thorough review of our manuscript and the constructive feedback. We also appreciate your interest and recognition of the importance of our work. To tackle the issues you raised, we have revised three major points as follows:

- Following your feedback, we have revised the abstract, introduction and a significant portion of the results, enriched the discussion to explore how to select the battery recycling strategies based on our findings, and demonstrated the challenges and limitations of this work.
- We have evaluated the financial feasibility of battery recycling by conducting process-specific cost analysis of LIB and comparing with the existing studies.
- All given images and figures are now replaced with higher resolution versions to ensure clarity and enhance the overall quality of the manuscript, and the revised manuscript has been thoroughly checked for grammar.

Below we provide responses to each comment in detail (your comments are in black and our responses starting with Response are in blue).

Comment 1

In the Abstract section - The authors mentioned that they have done a customized integrated modelling framework with the future prediction of EV demand and LIB scrappage, and material recycling simulation which results in a great benefit to LIBs recycling. Also, they have mentioned that their findings highlight the urgent need to electrify and decarbonize the automotive sector with more developed closed-loop lithium-ion battery cycle strategies. They didn't mention any relation between these findings with the economic cost and its impact and contribution to the domestic and global economy and the other merits of the energy storage sector must be clearer.

Response:

This is a fair point raised by the reviewer. In response to your valuable suggestions, we have expanded the process-based model to complement detailed cost analysis and discuss the consequences associated with various cathode chemistries in three recycling methods, including hydrometallurgy, pyrometallurgy, and direct recycling. Moreover, since we focus on the closed-loop recycling of LIB, we concentrate on its impacts on the domestic economy, elaborating on how increased self-sufficiency in critical materials can enhance energy security and reduce dependency on imports.

In addition, to address the merits of the energy storage sector more clearly, we have developed a refined LIB reuse roadmap, which incorporates not only the recycling of LIB but also their cascading utilization into the model. When the battery state of health (SOH) is above 85%, it would be reused directly in low-speed EV applications (Direct reuse). If SOH is between 80% and 85%, the battery would be reused in the energy storage systems (Indirect reuse). Thus, the waste batteries are utilized as direct reuse first, followed by an indirect utilization and recycling. This repurposing way of LIB could contribute to extending their lifespan, reducing the need for new raw materials, decreasing carbon emissions, and promoting cost efficiency.

Specific to your question about cost analysis and comparison with the existing literature, we have provided details in response to your comment 5. By incorporating these revisions, we have provided a more comprehensive overview of the and technological implications (**supplementary Note 3**), environmental (**supplementary Note 5**) and economic (**supplementary Note 6**) of our findings. We believe these additions have enhanced the clarity and depth of our manuscript, addressing your concerns effectively.

Comment 2

In the Introduction section - The authors have done a good survey about EVs, and the related investigations done in this issue, however, the beginning must start at least with information about the role of LIBs recycling and the decarbonization process that occurs in energy-related applications, it depends on closed-loop LIBs recycling methods. The author must be clear in this section and they have to introduce their topic as well. Also, they have to show evidence that this modelling tool is very close to the results obtained from experiment investigations as well.

Response:

Thank you for your suggestion about improving the Introduction section. The structure of the revised Introduction follows the logic below:

According to your suggestion, the first paragraph discusses the role of LIB recycling in decarbonization process that occurs in energy-related applications, such as reducing the material supply gap and environmental impacts.

Subsequently, we discuss accelerated EV deployment under China's carbon neutrality goal, its impact of battery material demand, supply-demand gap, and the role of LIB recycling in this specific context.

We then discuss two practical challenges that must be addressed in LIB recycling. On the one hand, unclear recycling responsibilities and inadequate infrastructure lead to low recycling rates. On the other hand, the uncertainty of a secondary supply of critical material is likely to be caused by the unclear technical evolution of the battery. Therefore, the lack of long-term insights into battery technology direction and recycling process results in the increasing risk of supply shortages, thereby triggering supply chain vulnerability of the domestic battery industry.

We then highlight that the existing literature helps us to comprehend the characteristics of current EV battery recycling, including technological advancement of the recycling process, driver factors of recycling, the environmental impacts, and the supply potential of material for LIB recycling. However, the cost-effective battery recycling pathway to achieve the co-benefit of environment and resources has not yet been paid attention to.

Based on these practical challenges and theoretical gaps, we aim to assess the extent to which the strategies of closed-loop LIB recycling could meet the future LIB material supply needs and find the optimal pathway for the LIB closed-loop recycling system to facilitate EV diffusion to achieve China's carbon neutrality.

The first paragraph of **Introduction** about the role of LIB recycling and the decarbonization process that occurs in energy-related applications is reproduced below, please see the Introduction in the revised manuscript for more details.

The first paragraph of the revised Introduction section:

"Circular economy strategies (CES), such as lithium-ion batteries (LIBs) reuse, are promising to lead the world onto a resilient and renewable path, guided by Sustainable Development Goals (SDGs)[1, 2, 3, 4]. LIB repurposing and recycling has the potential to mitigate environmental impact by reducing or offsetting the emission from the battery raw material production and landfill disposal at the end of their service life[5, 6]. These strategies are widely initiated by major jurisdictions. The European Union aspires to achieve an 80% recycling rate of LIBs by 2030[7]. China issued extended producer responsibility mandates, urging power battery enterprises and automobile manufacturers to establish a waste LIBs recycling system[8]. Besides, recycling LIBs using closed-loop recycling methods, including hydrometallurgy, pyrometallurgy, and direct recycling, could alleviate the supply scarcity of critical materials (e.g., cobalt, lithium, nickel, manganese) to varying degree[9, 10]. Therefore, LIB recycling is deemed to have synergistic advantages in the decarbonization process that occurs in energy-related applications."

Moreover, we have also compared our modelling results related to the carbon emissions in battery manufacturing and recycling with the widely recognized literature, such as the study of Ciez and Whitacre (2019)[11]. The evidence shows that our findings are close to the ones obtained from the leading literature in the field of battery environmental impact assessment in the business-as-usual electricity scenario (**Supplementary Table 21**). Further, we have considered the cleaner electricity scenario, since the emission factor in the future is distinctly different from today due to higher proportions of renewable energy in the future grid mix. Therefore, the battery emission might be lower than the existing studies, which calculates the carbon emission based on the current emission assumption.

Supplementary Table 21 Comparison of results from literature for the carbon emissions in battery manufacturing and recycling.

Process	Reference	Cathode chemistry		Carbon emission
LIB manufacturing	Ciez and Whitacre (2019)[11]	LFP (Cylindrical)		4.500
		NMC (Cylindrical)		8.820
		NCA (Cylindrical)		9.310
		LFP (Pouch)		7.030
		NMC (Pouch)		9.720
		NCA (Pouch)		10.660
	This study (Business-as-usual scenario)	LFP		6.043
		NCA		13.040
		NMC111		13.882
		NMC523		12.669
		NMC622		12.793
		NMC811		12.157
	This study (Cleaner electricity scenario in 2060 grid mix)	LFP		6.043
		NCA		10.975
		NMC111		12.026
		NMC523		10.812
		NMC622		10.936
		NMC811		10.035
LIB recycling	Rosenberg et al., (2023)[12]	Hydro	NMC111	-3.000
			NMC811	-2.760
		Direct	NMC111	-4.550
			NMC811	-4.450
		Pyro	LFP	0.050

Mohr et al., (2020)[13]		NMC	-2.348
		NCA	-2.751
	Hyro	LFP	-0.387
		NMC	-2.796
		NCA	-3.159
	Advanced hyro	LFP	-1.180
		NMC	-3.577
		NCA	-4.233
This study (Business-as-usual scenario)	Pyro	LFP	0.829
		NCA	-0.607
		NMC111	-1.488
		NMC523	-0.707
		NMC622	-0.793
		NMC811	-0.253
	Hydro	LFP	0.821
		NCA	-1.367
		NMC111	-2.234
		NMC523	-1.537
		NMC622	-1.682
		NMC811	-1.194
	Direct	LFP	-1.389
		NCA	-9.097
		NMC111	-10.756
		NMC523	-8.932
		NMC622	-9.006
		NMC811	-8.064
This study (Cleaner electricity scenario in 2060 grid mix)	Pyro	LFP	0.582
		NCA	-0.826
		NMC111	-1.712
		NMC523	-0.929
		NMC622	-1.015
		NMC811	-0.473
	Hydro	LFP	0.655
		NCA	-1.540
		NMC111	-2.406
		NMC523	-1.709
		NMC622	-1.854
		NMC811	-1.365
	Direct	LFP	-2.794
		NCA	-10.460
		NMC111	-12.190
		NMC523	-10.325
		NMC622	-10.390
		NMC811	-9.394

Reference cited above:

[1] Govindan K. How digitalization transforms the traditional circular economy to a smart circular economy for achieving SDGs and net zero. Transportation Research Part E: Logistics and Transportation Review 177, 103147 (2023).
[2] Song L, et al. China's bulk material loops can be closed but deep decarbonization requires demand reduction. Nature Climate Change 13, 1136-1143 (2023).
[3] Aguilar Lopez F, Lauinger D, Vuille F, Müller DB. On the potential of vehicle-to-grid and second-life batteries to provide energy and material security. Nature Communications 15, 4179 (2024).
[4] Franks DM, Keenan J, Hailu D. Mineral security essential to achieving the Sustainable Development Goals. Nature Sustainability 6, 21-27 (2023).
[5] Vaccari M, et al. Assessing performance in lithium-ion batteries recycling processes: A quantitative modeling perspective. Resources, Conservation and Recycling 206, 107643 (2024).
[6] Harper G, et al. Recycling lithium-ion batteries from electric vehicles. Nature 575, 75-86 (2019).
[7] McKinsey & Company. Battery 2030: Resilient, sustainable, and circular. https://wwwmckinseycom/industries/automotive-and-assembly/our-insights/battery-2030-resilient-sustainable -and-circular#/ (2023).
[8] Li K, Qin Y, Zhu D, Zhang S. Upgrading waste electrical and electronic equipment recycling through extended producer responsibility: A case study. Circular Economy 2, 100025 (2023).
[9] Liu M, Liu W, Liu W, Chen Z, Cui Z. To what extent can recycling batteries help alleviate metal supply shortages and environmental pressures in China? Sustainable Production and Consumption 36, 139-147 (2023).
[10] Dunn J, Kendall A, Slattery M. Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. Resources, Conservation and Recycling 185, 106488 (2022).
[11] Ciez RE, Whitacre JF. Examining different recycling processes for lithium-ion batteries. Nature Sustainability 2, 148-156 (2019).
[12] Rosenberg S, et al. Combining dynamic material flow analysis and life cycle assessment to evaluate environmental benefits of recycling – A case study for direct and hydrometallurgical closed-loop recycling of electric vehicle battery systems. Resources, Conservation and Recycling 198, 107145 (2023).
[13] Mohr M, Peters JF, Baumann M, Weil M. Toward a cell-chemistry specific life cycle assessment of lithium-ion battery recycling processes. Journal of Industrial Ecology 24, 1310-1322 (2020).

Comment 3

In the Result section - All given images and figures are very bad in resolution and it need to be higher in resolution as well.

Response:

We appreciate your attention to detail. To address the issue with the resolution of the images and figures, we have re-created all of the images at a higher resolution in the **Results** Section. Moreover, we provide another supplementary file to display the high-resolution images, ensuring that the quality is preserved during the embedding process. Please see the **Fig. 1-4** in the revised manuscript for a quality check.

Comment 4

In the Result section - However the authors mentioned they had given more scenarios of evaluation for EV material demand and recovery in the process of LIB recovery, but they didn't mention how they selected these types or in what base they have selected it.

Response:

Thank you for this insightful suggestion. We agree with the reviewer that proposing appropriate selection strategies can better inform policy recommendations to devise the optimal pathways for the LIB closed-loop recycling system. Our selection criteria consider three elements: the potential for self-sufficiency in critical material, carbon mitigation benefits, and the economic returns related to recycling. In the discussion section, we provide a detailed analysis of the selection strategies, and supplemented our comparative evidence in the supplementary notes. Please see the **Discussion** section in the revised manuscript, **Supplementary Tables 23-24,** and **Supplementary Figures 32-34** for details.

After revision in Discussion section:

"In summary, it is imperative to account for multiple factors to select the most suitable and well-founded battery recycling strategy due to trade-offs between critical material supply and demand, environmental impacts, and technological costs. LIB recycling by enhancing the battery recycling rate (BRR-PRO; the progressive battery recycling rate scenario) would achieve 25%-46% material surplus after satisfying the material demand of EV deployment. However, this approach would cause relatively high cumulative carbon emissions over its entire lifecycle, reaching 4267 Mt CO_2-eq due to the insignificant reduction in emissions in the battery recycling process and dominance of emissions caused during the production process. In terms of strategy involving extending battery lifespan (SL-HIGH; the high battery service life scenario), although a reduced quantity of batteries would lead to lower emissions, it inevitably results in the lowest self-sufficiency potential of critical materials. Despite closed-loop recycling supplies lower critical materials when shifting towards the direct cathode recycling technology (RP-DIR; the direct cathode recycling technology scenario), it facilitates the preservation of structure and composition of LIBs, improvement in material reuse, and maximum environmental benefits and economic revenue. By integrating optimal battery and recycling technology, secondary supply through recycling could basically balance the supply and demand of critical materials and achieve decreased life-cycle CO_2 emission and maximum yields. Hence, understanding the potential trade-offs behind the battery recycling pathway is essential, as there might not be a supremely optimal technical strategy in all aspects. To better support EV deployment under China's emission mitigation pledge, the balanced and tailored selection between the resource, environment, and cost is urgently required."

Supplementary Table 23 Comparison of self-sufficiency potential in 2060 among battery recycling strategies.

Self-sufficiency potential (%)

Scenario	RS	CC-LFP	CC-NMC	CC_NCA	SL-HIGH	RP-PYR	RP-DIR	MRR-PRO	BRR-PRO	OPT
Co	95%	94%	95%	95%	64%	95%	87%	98%	146%	101%
Li	81%	81%	81%	81%	54%	\	81%	90%	125%	93%
Ni	95%	95%	95%	95%	64%	95%	87%	98%	146%	101%
Mn	93%	90%	93%	93%	62%	\	85%	98%	143%	101%

Note: The blue cells represent relatively lower self-sufficiency potential; the pink cells represent relatively higher self-sufficiency potential. Co, cobalt; Li, lithium; Ni, nickel; Mn, manganese.

Supplementary Table 24 Comparison of cumulative carbon emissions in 2060 among battery recycling strategies.

Cumulative carbon emission (Mt)

Scenario	RS	CC-LFP	CC-NMC	CC_NCA	SL-HIGH	RP-PYR	RP-DIR	MRR-PRO	BRR-PRO	OPT
Production	4296	3585	4959	5158	2930	4296	4296	4296	4296	3514
Transportation	45	45	45	45	45	45	45	45	45	45
Collection	5	5	5	5	4	5	5	5	7	5
Recycling	-130	46	-248	-273	-89	0	-1571	-130	-181	-261
Life-cycle	4216	3681	4762	4935	2889	4347	2775	4216	4167	3303

Note: The blue cells represent relatively higher cumulative carbon emission; the pink cells represent relatively lower cumulative carbon emission.

Comment 5

In the Result section - They have done some calculations about the cost but it is not complete. They have to show the evidence that the findings and obtained results compared to experimental investigation done in that relation are close and costly effective.

Response:

We understand your concern about the cost calculations. In the revised manuscript, we have provided a comprehensive breakdown of the cost analysis associated with LIB recycling. Specifically, we have conducted comprehensive cost-benefit analysis through the method of BatPaC[1] (Argonne national laboratory; https://www.anl.gov/partnerships/batpac-battery-manufacturing-cost-estimation) for each of the three recycling processes: pyrometallurgical, hydrometallurgical, and direct recycling by process-based cost model[2], taking the recycling step, material, and utilities costs of lithium iron phosphate (LFP) batteries, Nickel Manganese Cobalt (NMC, including NMC111, NMC523, NMC622, and NMC811) and Nickel Cobalt Aluminum (NCA) cathodes into consideration.

Process-based costs models disaggregate the inputs that constitute together in the battery recycling process into discreate unit. We calculate the value of per tonne of spent battery recycling. This type of bottom-up modelling makes it possible to make more granular comparisons between process technologies. In our breakdown model, the costs include step-by-step expenses, material costs, and utility expenses, along with the revenues generated from the materials recovered through battery recycling. We consider every step's cost for different recycling technologies. For example, in hydrometallurgical recycling, we access the equipment inputs according to every step's process, including the conveyor, shredder, low-temperature calciner, gas treatment, wet granulator, wastewater treatment, density separator, froth flotation, filter, precipitation tank, solvent extraction unit, and leaching tank. The overall cost of every equipment integrates the direct cost, indirect costs, fixed capital investment, working capital, and manufacturing cost. The costs of material and energy during the battery recycling process are also accounted for. For pyrometallurgical recycling and direct cathode recycling, we comply with consistent modelling techniques. Please see the **Supplementary Note 6** for more details.

We identify the number of manufacturing lines required for each step in the recycling and the equipment prices based on the equipment assumed for specific recycling technology in EverBatt[1]. The recycling plant is assumed to operate 300 days a year with 8-hour shifts per day to ensure continuous running. The equipment costs are adjusted with the location assumption in China. The equipment's useful life is 10 years. Assumptions about the cost of equipment, material and utilities, the calculation method, as well as the calculation process, are illustrated in a separate spreadsheet, listed in the **Supplementary dataset 1**.

We have also compared our estimation results with the existing experimental investigations in **Supplementary Table 22**. This comparison highlights the alignment between our results and experimental data, underscoring the cost-effectiveness of the proposed battery recycling strategies.

Further, based on the established research foundation, we have investigated the cost of broader battery cathode technology calculated from detailed battery recycling process. Please see the **Supplementary Table 22** and **Supplementary Figures 32-34** for details.

Supplementary Table 22 Comparison of results from literature for the cost analysis related to battery recycling ($/ton).

Reference	Recycling technology	Cathode	Cost	Profit
Zou et al., (2013)[3]	Hydro	NMC	6195	5023
Fan et al., (2020)[4]	Hydro	LFP	804	196
Laura et al., (2021)[5]	Pyro	LFP		-2285
		NCA		946
		NMC622		1126
		NMC811		425
	Hydro	LFP		-1181
		NCA		2078
		NMC622		2359
		NMC811		1598
	Direct	LFP		2585
		NCA		5256
		NMC622		3566
		NMC811		3065
Dunn et al., (2022)[6]	Pyro	LFP	4010	
		NCX	4040	
	Hydro	LFP	3910	
		NCX	3950	
	Direct	LFP	5460	
		NCX	5520	
This study	Pyro	LFP	943	281
		NCA	1017	1581
		NMC111	997	2181
		NMC532	998	1597
		NMC622	1061	1640
		NMC811	1010	1318
	Hydro	LFP	1137	616
		NCA	1138	2891
		NMC111	1074	3464
		NMC532	1069	2945
		NMC622	1162	2923
		NMC811	1046	2701
	Direct	LFP	876	2463
		NCA	1072	9244
		NMC111	1215	7903

	NMC532	1198	6977
	NMC622	1548	6207
	NMC811	1057	6149

Reference cited above:

[1] Dai Q, Spangenberger J, Ahmed S, Gaines L, Kelly JC, Wang M. EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model, Argonne National Laboratory (2019).
[2] Ciez RE, Whitacre JF. Examining different recycling processes for lithium-ion batteries. Nature Sustainability 2, 148-156 (2019).
[3] Zou H, Gratz E, Apeliana D, Wang Y. A novel method to recycle mixed cathode materials for lithium ion batteries. Green Chemistry 15, 1183-1191 (2013).
[4] Fan E, et al. Sustainable Recycling Technology for Li-Ion Batteries and Beyond: Challenges and Future Prospects. Chemical Reviews 120, 7020-7063 (2020).
[5] Lander L, et al. Financial viability of electric vehicle lithium-ion battery recycling. iScience 24, 102787 (2021).
[6] Dunn J, Kendall A, Slattery M. Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. Resources, Conservation and Recycling 185, 106488 (2022).

Comment 6

In the Result section - They have to clearly demonstrate the challenges and limitations facing this method of working.

Response:

Thank you for your suggestion to highlight limitations of our work. We have added a new subsection in **Discussion** section to underline the limitations of our approach.

An excerpt from the revised Discussion section:

Our work is not without limitations, laying out avenues for future research. First, our work investigates the critical material requirement and secondary supply, life-cycle carbon emission, and costs associated with closed-loop recycling LIBs with the deployment strategy under China's carbon neutrality. The impact and contribution of our findings are limited to the domestic market of China, while the international products trade (such as EVs, LIBs, and critical materials) could potentially impact the demand-supply structure. Future studies can investigate optimal pathways for LIB recycling considering geopolitical dynamics in a global economy. Second, while we consider three different cathode chemistries (LFA, NCA, and NMC), there is an uncertainty in the required resources and the environment of battery recycling process due to evolving battery technology. For example, if the adoption of lithium-air, lithium-sulfur, and solid-state batteries become more predictable, the future supply chain of LIBs and critical materials will be substantially altered. Future studies could consider broader cathode chemistries while modeling the battery market dynamic. Finally, given the potential role of the geospatial configuration of critical materials on the resource conservation, carbon mitigation, and cost reduction associated with logistics, transportation, and land use[1], the geographic optimization model of LIB recycling can be developed by future studies.

Reference cited above:

[1] Nguyen-Tien V, Dai Q, Harper GDJ, Anderson PA, Elliott RJR. Optimising the geospatial configuration of a future lithium-ion battery recycling industry in the transition to electric vehicles and a circular economy. Applied Energy 321, 119230 (2022).

Comment 7

In the Result section - Proofread of some sentences and paragraphs need to be checked again.

Response:

Thank you for highlighting the need for further proofreading the manuscript. In the revised manuscript, we have conducted thorough proofreading, correcting grammatical errors, awkward phrasing, and unclear statements. Additionally, one of our authors, who is a native speaker, has helped us refine the language and correct any inappropriate expressions for the advancement of clarity and accuracy. We believe these revisions have addressed your concerns and significantly enhanced the quality of our manuscript.

Reviewer #4 (Remarks to the Author)

Sustainable sources of critical minerals are crucial for the mass production of lithium-ion batteries (LIBs) and electric vehicles (EVs), essential instruments for achieving net zero targets. This study employs an integrated framework to model resource conservation and environmental benefits associated with EV LIB recycling in China, a pivotal player in global EV expansion. To do so, the authors use an integrated framework that combines material flow analysis with life cycle assessment, examining nine scenarios that vary in battery mix, service life, recycling configuration, recycling rate, and critical mineral recovery rate. While I find the research questions interesting and important, I have some comments and questions as follows:

Response:

Thank you for the insightful and positive feedback on this work. It is good to know that you find the research questions interesting and important. We have carefully addressed your comments about the structure of the manuscript, optimization of battery recycling configuration, uncertainty analysis, and financially viable assessment. We think that the revised manuscript has improved terms of clarity and robustness of findings. We have made four key changes, which are summarized below:

- We have modeled for the life-cycle carbon emissions, including LIBs manufacturing, transportation, collection, and recycling in our life cycle assessment model associated with the cathode chemistries of nickel cobalt manganese (NMC111, NMC 523, NCM622, and NCM811), nickel cobalt aluminum (NCA), and lithium iron phosphate (LFP).
- We have conducted a sensitive analysis considering the uncertainty in EV adoption.
- The economic feasibility of three recycling processes, consisting of pyrometallurgical recycling, hydrometallurgical recycling, and direct cathode recycling, has been evaluated based on the process-based cost model.
- We have meticulously revised the manuscript to address spelling and grammatical issues.

We believe that these revisions have addressed your concerns and improved the clarity and impact of our manuscript. Below we provide responses to each comment in detail (your comments are in black and our responses starting with Response are in blue).

Comment 1

a - Shorten the manuscript to enhance conciseness; for instance, the first paragraph (from line 31) can be significantly condensed.

b - In line 51, the assertion that "A typical EV requires six times the mineral inputs of fossil-fuel-based vehicles" originates from an IEA report. This should be amended, as the report only considers selected minerals like copper and critical minerals, excluding others such as steel and aluminium.

c - Correct the term "HPEV" in Figure 1.

d - In line 189, correct "NMC623."

e - In Table 1, verify the critical materials recovery rate of RP-PYR. Which materials can be recovered through this process?

f - Given the numerous scenarios, the author may consider including a chart illustrating ensemble scenarios and related analysis.

g - In line 362, I disagree with the statement, "Although inexpensive-material cathode technology (LFP currently) could help free China from its dependence on critical and scarce materials, this cathode type is doubted regarding environmentally friendly selection in recycling treatment when concerned about reducing the carbon footprint." From a life cycle perspective, the focus for a net-zero future should be on minimizing the carbon footprint across the entire life cycle, rather than solely in a single stage (recycling treatment).

Response:

Thank you for your thoughtful comments.

Your suggestions in Q1) a-d are related to the expression and writing errors in the manuscript. We have handled them while revising the manuscript. Thanks for thoroughly checking the manuscript.

For Q1e), we have clarified the critical materials recovery rate of RP-PYR. The recycling rate of cobalt and nickel are 98%; however, the pyrometallurgy cannot achieve the recovery of lithium and manganese.

Regarding Q1) f, we agree that a chart will help us illustrate ensemble of scenarios and related analysis in a more comprehensible and intuitive manner. Therefore, we have added a new chart that visually represents these scenarios, explaining our analysis more effectively. Please see **Table 1** in the revised manuscript and **Supplementary Table 8** for more details.

For your suggestion in Q1) g, we concur with your perspective that we should focus on the life-cycle analysis instead of focusing on the battery recycling stage solely. To better align with the life cycle perspective and emphasize the broader context of achieving a net-zero future, we have included the life-cycle carbon emission estimation of LIBs, consisting of battery production, transportation, collection, and recycling (**Fig. 4a**). Additionally, we pay attention to the battery recycling process under the ten selected recycling scenario to underline the carbon mitigation potential of the recycling treatment (**Fig. 4c**). Our findings suggest that battery production dominates carbon emissions from the life-cycle perspective, whereas battery recycling provides a latent carbon mitigation pathway aligning with the direct cathode recycling technology. Please see the **section of Life-cycle CO_2 emission in lithium-ion batteries (Pages 11-13)** and **Fig. 4** in the revised manuscript for more details.

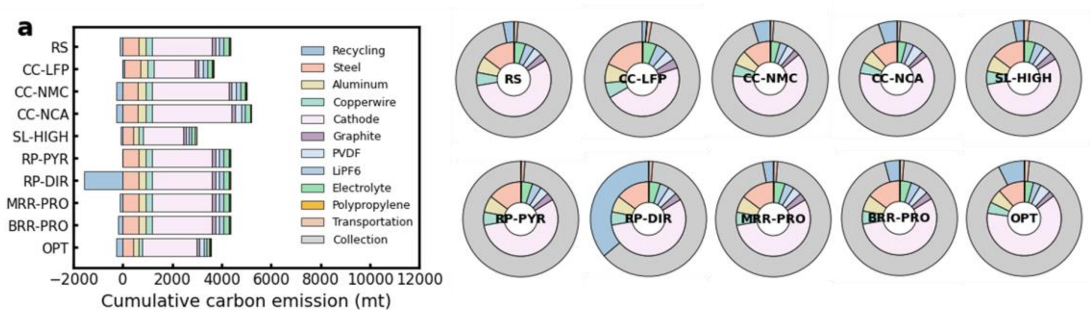


Fig. 4a Prospectively life-cycle CO_2 emission related to Lithium-ion battery under the ten selected scenarios considering LIB life-cycle CO_2 emissions. *In a circular chart, recycling emissions are depicted on the left side of the starting point to indicate that the recycling process increases emissions. This represents the proportion of recycling emissions within the full life cycle. Recycling emissions are illustrated on the left side of the starting point to indicate that the recycling process decreases emissions. This indicates that the emissions avoided from the recycling process offset the proportions of emissions from other processes (battery production, transportation, and collection).*

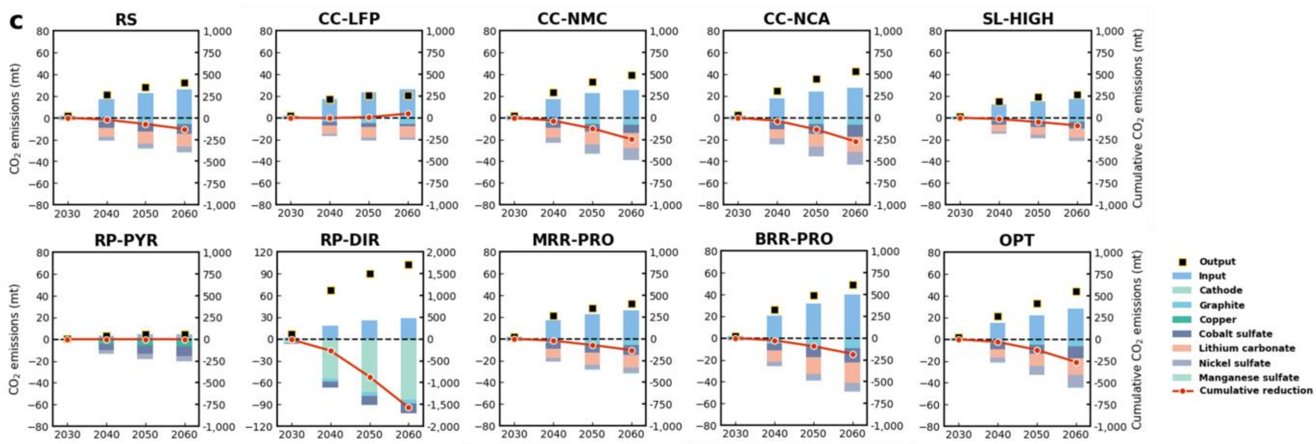


Fig. 4c Prospectively life-cycle CO_2 emission related to Lithium-ion battery under the ten selected scenarios considering battery recycling process CO_2 emissions.

Comment 2

How do the authors account for carbon emissions related to the transport and collection of spent batteries in the current modelling? Is there a potential role for optimising the geospatial configuration of a future lithium-ion battery recycling industry in the transition to electric vehicles given the size of China?

Response:

Thank you for pointing out importance of accounting emissions related to transport and collection. In the revised manuscript, we have considered these stages in the life-cycle carbon emission analysis of LIBs.

(i) Carbon emissions from lithium-ion battery transportation: The battery transportation stage includes the process of transporting power batteries from the battery manufacturers to the EV manufacturers, followed by transporting to the dealers for EV sales. Since data on spatial locations of all battery producers, manufactures, and dealers is infeasible to obtain, we compute these emissions using average distance and emission factor. To find average distances, we focus on Build Your Dreams (BYD) and Contemporary Amperex Technology Co., Limited (CATL). As the leading LIBs manufacturers in China, these two companies have different development patterns. BYD not only provides LIBs but also is the largest EV manufacturer in China. Therefore, when the batteries are manufactured, we assume they are directly supplied to downstream EV manufacturing companies. After the EVs are manufactured, they are transported to their dealers for sale. CATL is supplying their LIB to many EV manufacturers. Among all of the EV makes, Shanghai Automotive Industry Corporation (SAIC) is unique because the company cooperates with CATL in building a new EV plant to ensure the stable supplement of LIBs. Adopting the approach described in the Wang et al.[1], we assumed that the LIBs are transported from CATL to SAIC. When the SAIC receives batteries, they install LIBs into their EV model, namely ROEWE, followed by transporting EVs to respective dealers.

Considering these two types of networks from LIB manufacture to EV sales, we collected the point source data of LIB manufacturers, EV manufacturers, and EV dealers from Gaode Map (https://amap.com/). We then adopted the principle of the shortest transportation distance to calculate the average transportation distance by ArcGIS 10.8 software. The average distance from LIB manufacturers to EV manufacturers is 75 km and from EV manufacturers to EV dealers is 414 km. This transportation would be entirely by truck, with the carbon emission factor of 0.203 kg CO_2-eq/ton-mile[2]. The detailed point source location information of LIB manufacturers, EV makers, and EV dealers is shown in **Supplementary Note 5** and **Supplementary Figures 30-31**:

Supplementary Figure 30 Detailed point source location information of LIB manufacturers, EV manufacturers, and EV dealers.

(ii) Carbon emissions from lithium-ion battery collection: When the LIBs are retired, they will be collected and sent to authorized waste LIB recycling operators for material recycling. In China, the extended producer responsibility is complemented, meaning that automobile manufacturer enterprises bear the main responsibility of LIB recycling. Currently, EV manufacturers are working with their EV dealers to recycle wasted LIBs from EVs. Thus, we assume that the waste LIBs would be collected by the EV dealers first, followed by sending to authorized waste LIB recycling operators. According to policy regulations, there are a cumulative 156 waste LIB recycling operators authorized by the Chinese government until 2024. The average shortest distance to collect the LIBs from EV dealers to LIB recycling operators is 87 km. The LIBs are also collected by trucks and thus the same emission factor is used as the one for battery transportation. The detailed point source location information of LIB recycling operators is depicted below. More information can be found in **Supplementary Note 5**.

Supplementary Figure 31 Detailed point source location information of LIB recycling operators. *The green circle represents the recycling operators can implement recycling and cascade utilization, the blue circle donates the recycling operators can perform cascade utilization only, and the orange circle donates the recycling operators can perform recycling utilization only.*

While we acknowledge the importance of considering optimal geospatial configuration of the future LIBs recycling industry, we did not consider it in this study due to two reasons. Firstly, since emissions during transportation and collection of LIBs have a delicate share (less than 1%) from the life-cycle perspective, the results of the geospatial optimization might only marginally affect our main results. Secondly, geographical allocation of battery industry is not only market-driven phenomena, but it will be also affected by the recycling policies related to qualification and approvals by the government. Since the LIB recycling sector is at a nascent stage, these policies are likely to evolve significantly in the coming future. Therefore, our current model focuses on providing a foundational understanding of the whole of China, while keeping the province-specific analysis of the setting battery recycling industry as a future work.

Reference cited above:

[1] Wang S, Yu J. A comparative life cycle assessment on lithium-ion battery: Case study on electric vehicle battery in China considering battery evolution. Waste Management & Research 39, 156-164 (2020).

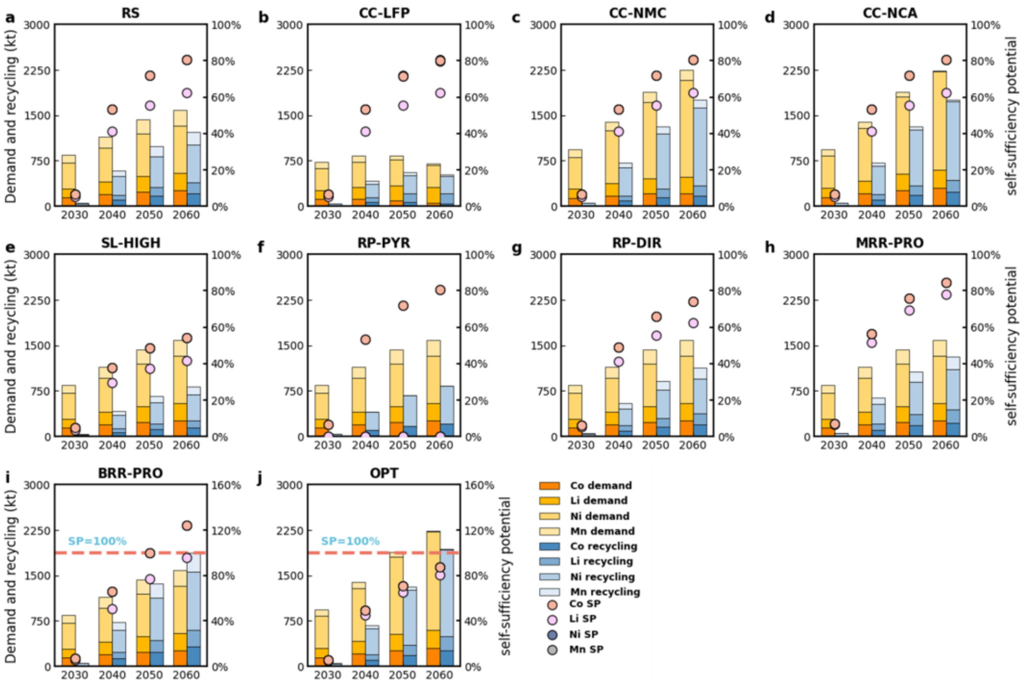
[2] The international council on clean transportation (ICCT). CO2 emissions from trucks in the EU: An analysis of the heavy-duty CO2 standards baseline data, (2021).

Comment 3

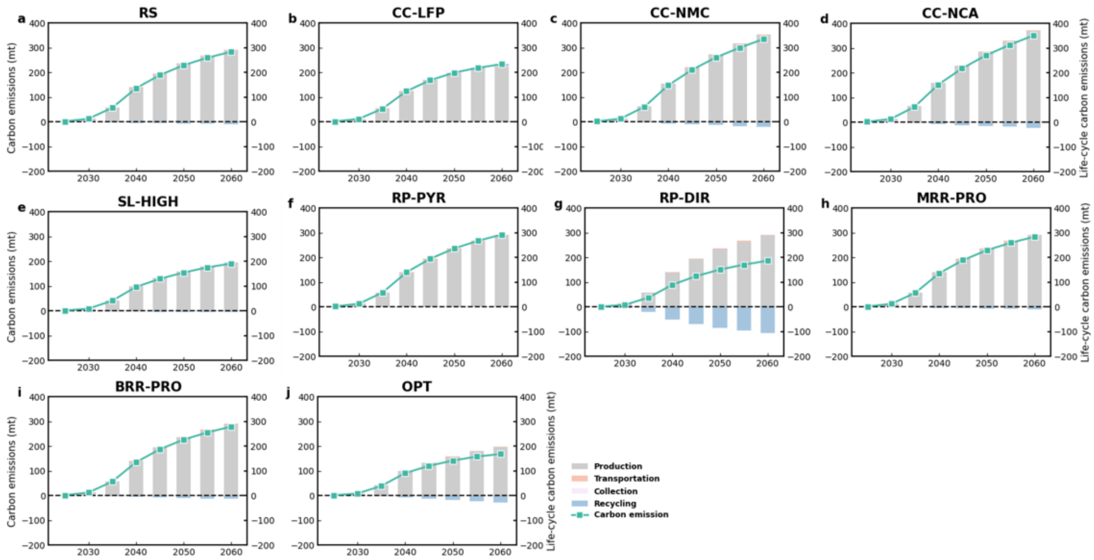
How does the uncertainty in electric vehicle (EV) adoption affect the overall uncertainty in the analysis?

Response:

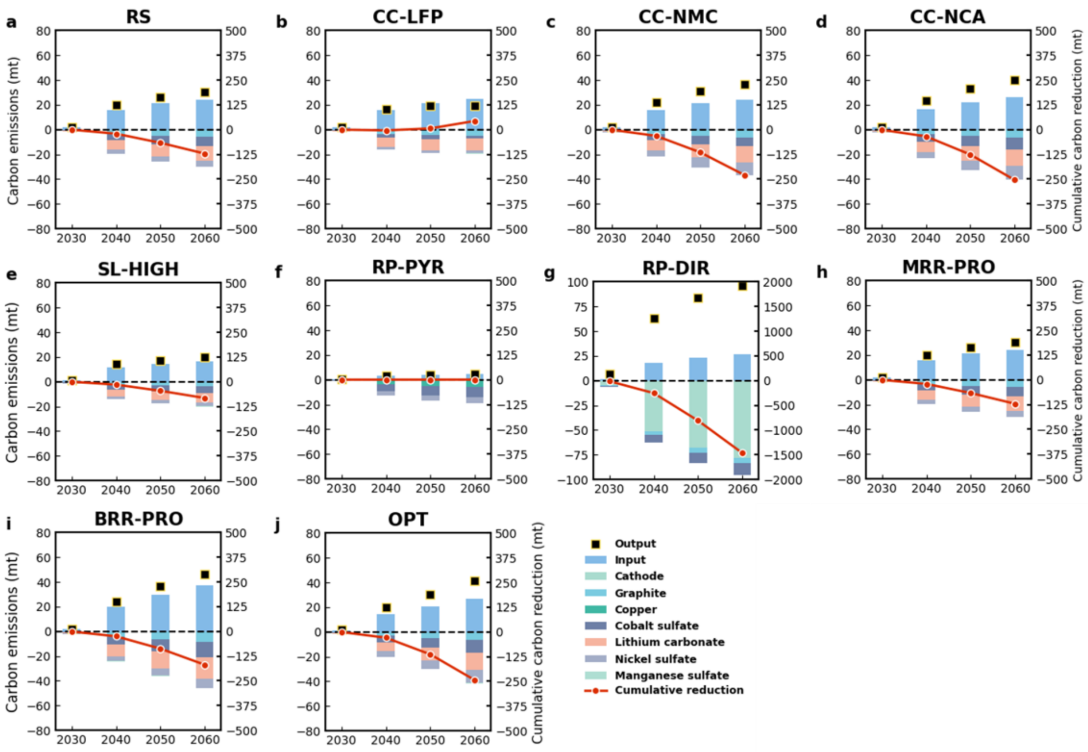
This is a fair point about considering uncertainty in EV adoption. Following your suggestion, we have considered two lifespan scenarios of EVs to analyze the downstream impact of EV ownership uncertainty. Specifically, aiming to explore the effect of larger fleet turnover, implying higher prospective vehicle sales for fixed prospective stocks, we adopt a lower EV average lifespan in our EV adoption forecasting model[1]. Referring to Morfeldt and Johansson (2022)[2], most EVs would be much less than 10 years old. If we set the EV average lifetime as 10 years, the resulting EV forecasting results are similar to the study by Wang et al. (2023)[3]. Results show that the higher EV deployment would result in lower critical material supply by closed-loop LIB recycling (**Supplementary Figure 16**) and higher life-cycle carbon emissions of LIB (**Supplementary Figure 28**) compared to the default lifespan assumption (i.e., 15 years), indicating that higher adoption of EV presents greater challenges for the development of the power battery recycling industry. Please see the **Supplementary Figures 16, 23, and 28** for more details.



Supplementary Figure 16 Secondary supply potential of critical materials considering the EV uncertainty. *Abbreviations: RS refers to the baseline scenario in which the cathode chemistry, battery lifespan, recycling technology, battery recycling rate, and critical material rate develop according to current tendency. CC-LFP, CC-NMC, CC-NCA represent the LFP-dominated, NMC-dominated, and NCA-dominated cathode evolution scenarios respectively. SL-HIGH is the high battery service life scenario. Under RP-PYR and RP-DIR scenario, the battery is adopted pyrometallurgical recycling and direct cathode recycling technology respectively. MRR-PRO and CRR-PRO refer to the progressive critical material recycling rate and battery recycling rate respectively. And the OPT scenario denotes the optimal battery technology and recycling technology transition. The abbreviation of Co, Li, Ni, Mn refer to the cobalt, lithium, nickel, and manganese respectively. SP donates self-sufficiency potential.*



Supplementary Figure 28 Life-cycle carbon emission considering the EV uncertainty.



Supplementary Fig. 23 Recycling emission considering the EV uncertainty. *Above the 0 axis indicates the material inputs in the battery recycling process, which add the carbon emission. Below the 0 axis indicates the avoided carbon emission because it reduces energy consumption and CO_2 emissions during raw materials extraction. The red line donates the cumulative carbon reduction in the recycling process.*

Reference cited above:

[1] Milovanoff A, Posen ID, MacLean HL. Electrification of light-duty vehicle fleet alone will not meet mitigation targets. Nature Climate Change 10, 1102-1107 (2020).

[2] Morfeldt J, Johansson DJA. Impacts of shared mobility on vehicle lifetimes and on the carbon footprint of electric vehicles. Nature Communications 13, 6400 (2022).

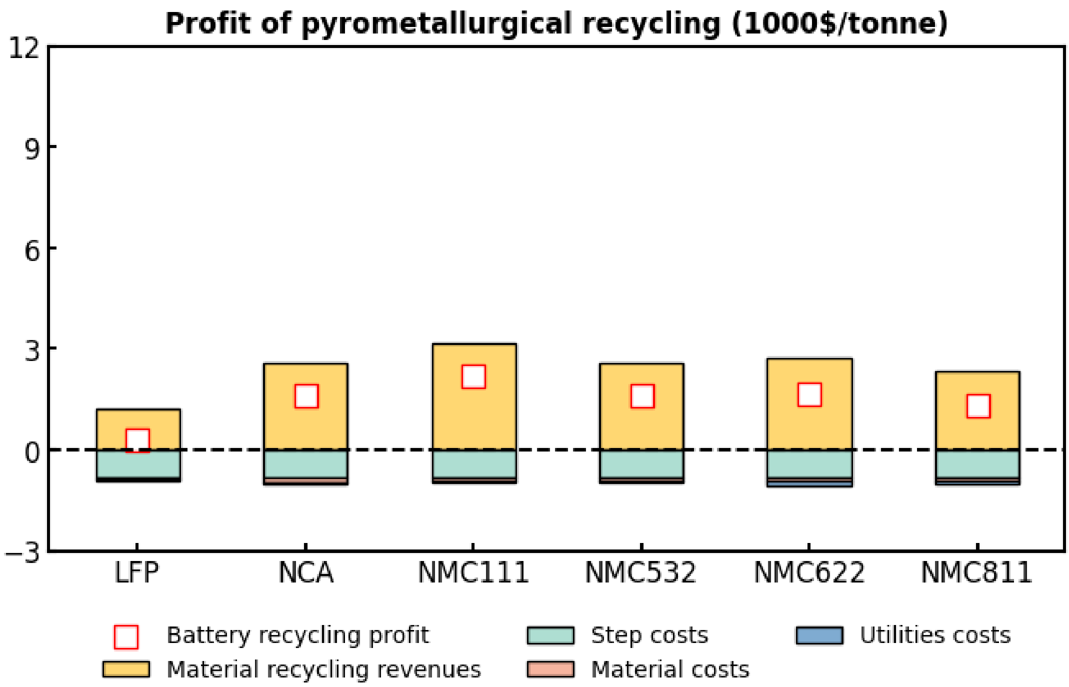
[3] Wang H, et al. China's electric vehicle and climate ambitions jeopardized by surging critical material prices. Nature Communications 14, 1246 (2023).

Comment 4

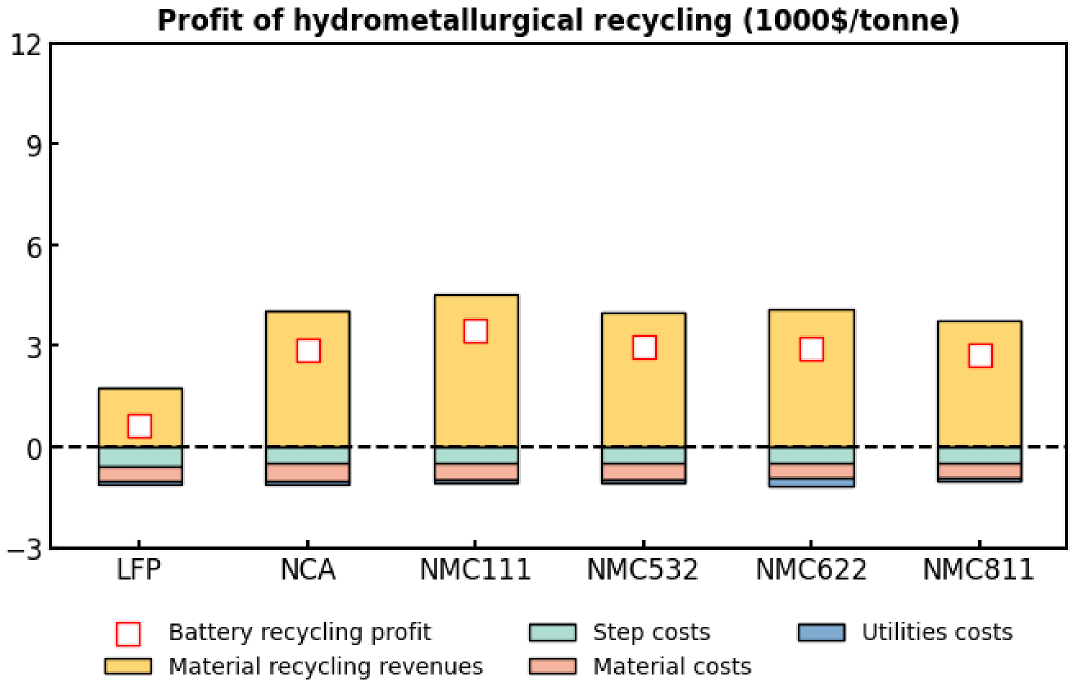
Are all three recycling processes financially viable, and if so, to what extent?

Response:

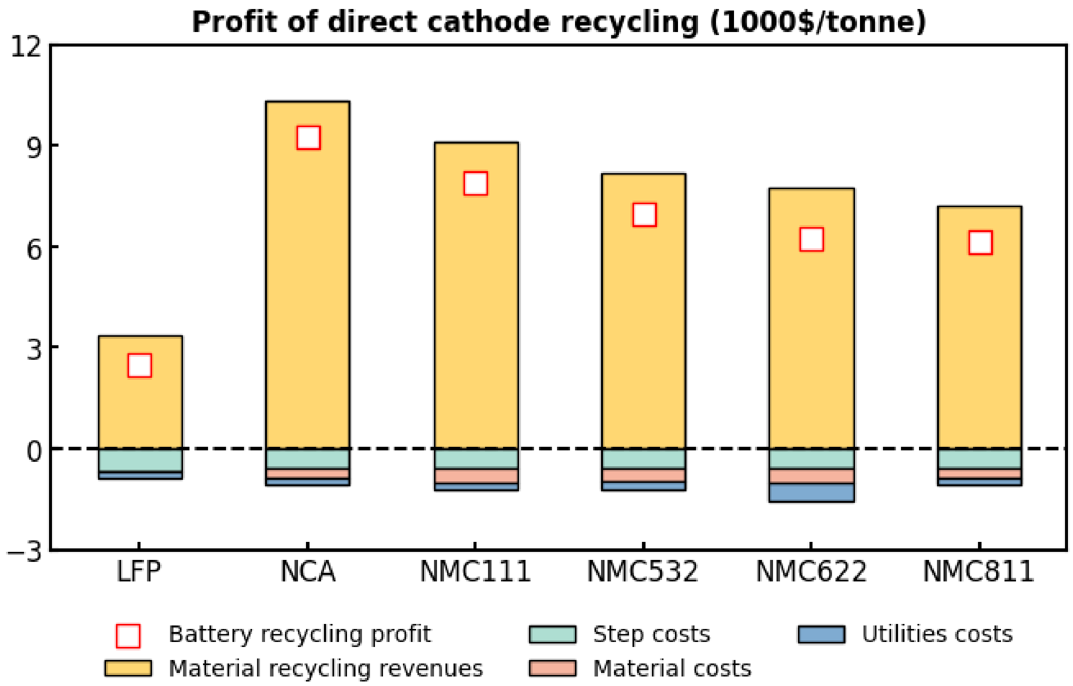
Thank you for your comment regarding the financial viability of the three recycling processes, which encouraged us to conduct detailed cost-effect analysis and consider it as another factor (in addition to self-sufficiency of critical materials and environmental benefits) in devising battery recycling pathways. We have conducted a comprehensive cost-benefit analysis using BatPaC[1] approach (Argonne National Laboratory; https://www.anl.gov/partnerships/batpac-battery-manufacturing-cost-estimation) for each of the three recycling processes: pyrometallurgical, hydrometallurgical, and direct recycling[2], taking the recycling step, material, and utility costs of lithium iron phosphate (LFP) batteries, Nickel Manganese Cobalt (NMC, including NMC111, NMC523, NMC622, and NMC811) and Nickel Cobalt Aluminum (NCA) cathodes into consideration. We find that EV battery recycling is profitable, but different recycling technologies and cathode chemistries significantly impact the profitability of the recycling process. The disparity of profits between the highest (NCA cathode with direct cathode recycling technology) and the lowest one (LFP cathode with pyrometallurgical recycling technology) can be as much as 33-fold (**Supplementary Figures 32-34**). Please see **Supplementary Note 6, Supplementary Figures 32-34, and Supplementary dataset1** for more details about cost inputs, such as equipment cost, working capital, and material cost, among others.



Supplementary Figure 32 Cost-benefit analysis of pyrometallurgical recycling. *Above the 0 axis indicates the revenues from power battery recycling, and below it indicates the recycling costs for each step, and the red square represents the battery recycling profit.*



Supplementary Figure 33 Cost-benefit analysis of hydrometallurgical recycling.



Supplementary Figure 34 Cost-benefit analysis of direct cathode recycling.

Reference cited above:

[1] Dai Q, Spangenberger J, Ahmed S, Gaines L, Kelly JC, Wang M. EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model. Argonne National Laboratory (2019).

[2] Ciez RE, Whitacre JF. Examining different recycling processes for lithium-ion batteries. Nature Sustainability 2, 148-156 (2019).

Comment 5

What is the relationship between the geographic location and ownership of critical mineral miners, and how does this affect the study's findings?

Response:

Thank you for raising this point. We acknowledge the importance of understanding the relationship between the geographic location and ownership of critical mineral miners and how it might influence our study's findings. However, our study primarily focuses on the critical material self-sufficiency, carbon mitigation, and economic feasibility associated with LIB recycling. While the geographic location and ownership of critical mineral miners are undoubtedly important factors, they fall outside the primary scope of our current analysis and are unlikely to largely affect main results of our study (as clarified in response to **your comment 2**). Our model and findings are designed to be broadly applicable at the national level, without delving into specific geopolitical and ownership details. Therefore, in light of your feedback, we have added the following text in the Discussion section to highlight the need for further research into optimizing the geospatial configuration of recycling facilities.

An Excerpt from the revised Discussion section

Finally, given the potential role of the geospatial configuration of critical materials on the resource conservation, carbon mitigation, and cost reduction associated with logistics, transportation, and land use[1], the geographic optimization model of LIB recycling can be developed by future studies.

Reference cited above:

[1] Nguyen-Tien V, Dai Q, Harper GDJ, Anderson PA, Elliott RJR. Optimising the geospatial configuration of a future lithium-ion battery recycling industry in the transition to electric vehicles and a circular economy. Applied Energy 321, 119230 (2022).

Response to reviewers' comments

Reviewer #2 (Remarks to the Author)

After a thorough review of the revision and the response, I remain concerned that the study's novelty is unsatisfactory. Several underlying assumptions and explanations appear unrealistic, rendering the model results less applicable for policy guidance. Therefore, I believe the manuscript is not suitable for publication in Nature Communications at this time. Below are my detailed comments:

Response:

Thank you for taking the time to review our work. We greatly appreciate the time and effort you invested in evaluating our manuscript.
Based on your thoughtful and detailed suggestion, we further refine the assumptions and improve the novelty of our work. We develop a dynamic and systemic assessment framework of lithium-ion battery (LIB) recycling embodied in electric vehicle (EV), elucidating the holistic view of resource compensation, environmental performance, geospatial configuration, and cost feasibility. In this unified model, we investigate what extent the strategically scenario-based battery recycling could assist China's EV deployment ambition driven by China's carbon neutrality target and select the financially effective LIB recycling pathway with the co-benefit of resource and environment. Moreover, to well address your concerns related to unrealistic and ungrounded assumption, we re-examine the literature and industry reports and revise them, ensuring the assumptions closely align with real-world data and potential future developments. Two main aspects are revised, which are summarized as follows:

- Regarding the dynamic simulation of resource demand-supply in battery recycling process, we adjust the key parameter of battery collection rate, ensuring the model's reliability and policy guidance. We obtain the critical material self-sufficiency potential under different battery recycling pathways by using this parameter as input to the material flow analysis (MFA), benchmarking the model results against existing literature.
- Regarding the assessment of life-cycle environmental performance, we develop two future electricity mix, China's carbon neutrality electricity mix and baseline electricity mix. Through updating the carbon emission factor every five years, we capture the decarbonization transition of electricity grid. Then, we integrate the continuously decreasing carbon emission factor into life-cycle assessment analysis (LCA), modeling emissions dynamically from the battery manufacturing to recycling across the long-term horizon.

Thank you again for your valuable insights. Below we provide responses to each comment in detail (your comments are in black font and our responses starting with Response are in blue font).

Comment 1

Response to Comment 3: The authors stated, "We set the benchmark recovery rate at 65% per year (RS), which complies with Regulation (EU) 2023/1542 of the European Parliament and the Council concerning batteries and waste batteries." This is the first unreasonable assumption. The Regulation pertains to collection targets for portable and LMT batteries but does not specify recycling targets for power batteries. Furthermore, the Regulation sets recycling efficiency targets of 65% by the average weight of lithium-based batteries. However, the recovery rate of 65% per year in the study should correspond to the recycling efficiency of 65% outlined in the Regulation. The term 'recycling efficiency' means the ratio, expressed as a percentage, obtained by dividing the mass of output fractions accounting for recycling by the mass of the waste batteries' input fraction, in relation to a recycling process (Definition given by Regulation). It seems the authors may have conflated the meanings of 'recycling efficiency' and 'recycling rate' from the Regulation.

Response:

Thank you for your insightful comment. We appreciate your attention and precision regarding the key parameter of battery recycling. We have taken several steps to address your valuable concerns: 1) We clarify the related terminology; 2) establish new reference standards and make reasonable assumption; 3) integrate the parameter of battery collection rate into the material flow analysis model to simulate the linkage between cortical material supply-demand; and 4) compare our result with existing studies to evaluate our model's applicability. Below are our detailed improvements to the points you raised:

- Clarification of terminology: The term "recycling rate" used in the previous manuscript refers to the collection target for EV batteries. To avoid conceptual confusion, we follow the terminology described in the with Regulation (EU) 2023/1542 for the collection target of LMT batteries, using the term "battery collection rate" instead of the "battery recycling rate".
- Establishing new reference standards for battery collection rate: In practice, it remains unclear what proportion of the waste batteries would end up in regulated and informal recycling channels. Thus, the real-world collection rate of batteries is uncertain[1,2]. To define appropriate collection rates for EV batteries, we conduct a comprehensive review of the literature and industry reports related to battery collection rate targets. Based on this, we develop low, medium, and high collection targets (65%, 85%, and 100%, respectively) for retired EV batteries to capture the uncertainty and variability in battery collection. This approach evaluates a wide range of scenarios, ranging from practical collection targets to the theoretically best-case (ideal) collection condition. The references for battery collection rates from the literature are summarized in Supplementary Table 23.

Supplementary Table 23. Reference of battery collection rate from literature.

Reference	Scenario
Liu et al., (2023)[3]	Low: 65%
	Medium: 85%
	High: 100%
Xu et al., (2020)[4]	100%
Dunn et al., (2021)[1]	100%
Kamran et al., (2021)[5]	from 80% in 2020 to 99% in 2050
Dunn et al., (2022)[2]	Step increase from 65% in 2025 to 90% in 2050 by 5% increments
	Flat collection rate from 2020 to 2050 analyzed for 7 different rates/scenarios: 65%, 70%, 75%, 80%, 85%, 90%, 95%.

- <u>Integration the parameter into the material flow analysis model:</u> We develop scenario-based recycling pathways for EV batteries, integrating above three collection rates into dynamic MFA model to quantify demand of critical materials and corresponding self-sufficiency potential from closed-loop battery recycling under China's carbon neutrality goal. This analysis provides a lower and upper bounds on self-sufficiency potential for each battery recycling strategies, facilitating robust insights for policy formulation. For example, the reference scenario (RS scenario) would achieve 87-134% material self-sufficiency potential of cobalt, nickel, and manganese, and 67-104% for lithium in 2060. Through increasing material recycling rate tied with upgrading battery recycling facilities and systems (MRR-PRO scenario), the material self-sufficiency potential of cobalt, nickel, and manganese would increase by 92-141%, and 84-130% for lithium in 2060. Under the optimal battery and recycling scenario (OPT scenario), the material self-sufficiency potential of these four critical materials would become 63-97% in 2060. Please see the details in the section of "Demand of critical materials and corresponding supply from battery recycling" in Result. The thorough results of demand and potential secondary supply from recycling under nine selected scenarios are displayed below:

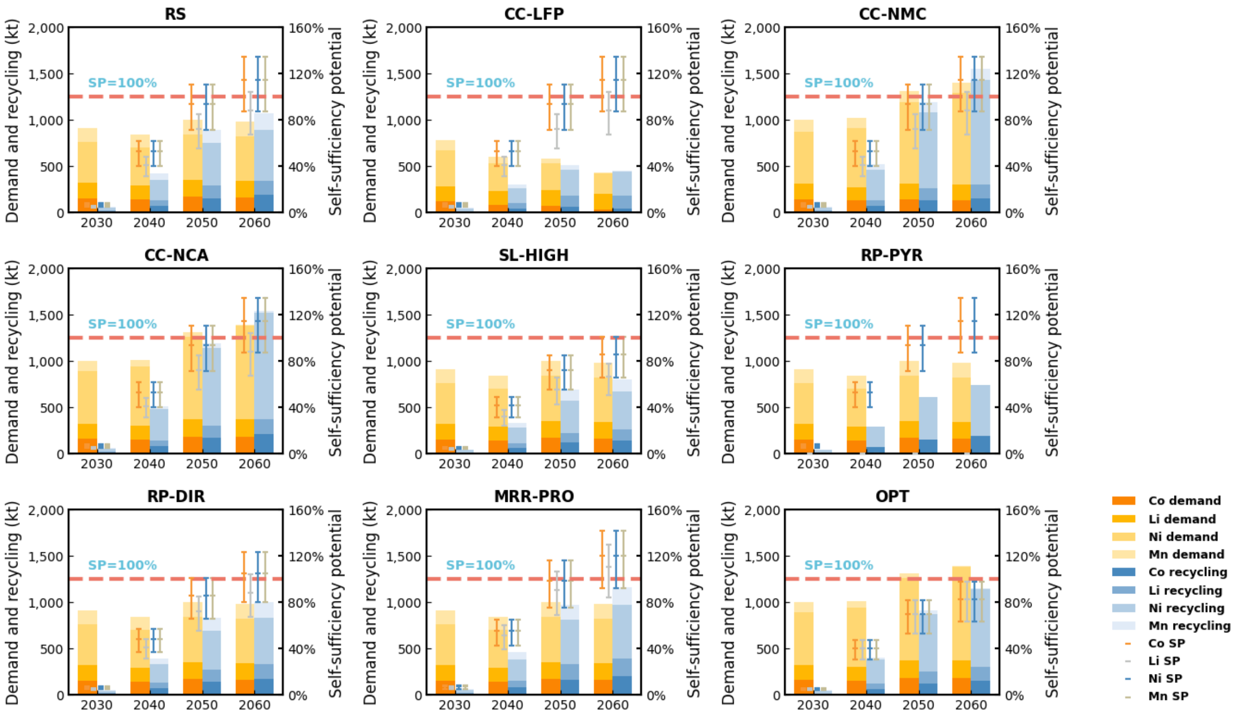


Fig. 3 Prospective demand, recycling, and self-sufficiency potential of critical materials embodied in LIBs for EVs. The SP across nine recycling strategies, based on three battery collection rates, is displayed from the lower to the upper bound. The light red dash line denotes the breakeven between the demand and secondary supply from battery recycling.

- <u>Comparison with existing studies:</u> To assess the robustness of the updated model, we compared the results obtained under the new parameters with those from previous studies. This comparison helps ensure that the model remains consistent and reliable despite parameter adjustment. The comparison is shown in Supplementary Table 24.

Supplementary Table 24. Comparison of results from literature for the critical material supply.

Year	Reference	Scenario	Material	Self-sufficiency potential
2040	Baars et al., (2021)[6]	Idealized scenario	Co	60%
			Li	53%
			Ni	57%
			Mn	53%
2050	Zeng et al., (2022)[7]	The most optimistic technology scenario	Co	>100%
2050	Qiao et al., (2021)[8]	Optimistic scenario	Li	49%
		Neutral scenario	Li	53%
		Pessimistic scenario	Li	60%
2050	Liu et al., (2023)[3]	Improved battery technology scenario	Co	77%
			Li	42%
			Ni	78%
			Mn	78%
			Cu	69%
			Al	68%
			Fe	40%
2050	This study	Reference scenario (RS scenario)	Co	71-110%
			Li	55-85%
			Ni	71-110%
			Mn	71-110%
2060	This study	Reference scenario (RS scenario)	Co	87-134%
			Li	67-104%
			Ni	87-134%
			Mn	87-134%
2050	This study	Optimal technology scenario (OPT scenario)	Co	53-82%
			Li	53-82%
			Ni	53-82%
			Mn	53-82%
2060	This study	Optimal technology scenario (OPT scenario)	Co	63-97%
			Li	63-97%
			Ni	63-97%
			Mn	63-97%

Reference cited above:

[1] Dunn J, Slattery M, Kendall A, Ambrose H, Shen S. Circularity of Lithium-Ion Battery Materials in Electric Vehicles. Environmental Science & Technology 55, 5189-5198 (2021).

[2] Dunn J, Kendall A, Slattery M. Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. Resources, Conservation and Recycling 185, 106488 (2022).

[3] Liu M, Liu W, Liu W, Chen Z, Cui Z. To what extent can recycling batteries help alleviate metal supply shortages and environmental pressures in China? Sustainable Production and Consumption 36, 139-147 (2023).

[4] Xu C, Dai Q, Gaines L, Hu M, Tukker A, Steubing B. Future material demand for automotive lithium-based batteries. Communications Materials 1, 99 (2020).

[5] Kamran M, Raugei M, Hutchinson A. A dynamic material flow analysis of lithium-ion battery metals for electric vehicles and grid storage in the UK: Assessing the impact of shared mobility and end-of-life strategies. Resources, Conservation and Recycling 167, 105412 (2021).
[6] Baars J, Domenech T, Bleischwitz R, Melin HE, Heidrich O. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nature Sustainability 4, 71-79 (2021).
[7] 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).
[8] Qiao D, Wang G, Gao T, Wen B, Dai T. Potential impact of the end-of-life batteries recycling of electric vehicles on lithium demand in China: 2010–2050. Science of The Total Environment 764, 142835 (2021).

Comment 2

Response to Comment 4: The authors confirmed the reliability of their results by comparing them with other literature. However, the comparison with "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)" is not appropriate. Zeng et al. examined global cobalt flows across various sectors, including electric vehicles, energy storage systems, and others, while the authors' study focuses specifically on cobalt flows in Chinese power batteries. Additionally, Zeng et al.'s study projects new LFP batteries to dominate (100% by 2050) in their most optimistic scenario, whereas the current study predicts NCA batteries will dominate (80% by 2060) in the optimal technology scenario. Thus, the comparison between these two studies is irrelevant.

Response:

This is a fair point. We are thankful for your important suggestions. To ensure our results remain comparable, we align our analysis with the study of Zeng et al.[1], which includes cobalt flows from EVs and features an optimistic scenario with LFP-dominated cathodes. We would like to bring the reviewer's attention to the fact that as our study also considers a technological pathway led by LFP recycling (CC-LFP), our CC-LFP scenario is comparable with Zeng et al. The comparison between our results and the study of Zeng et al., (2022) is as follows:

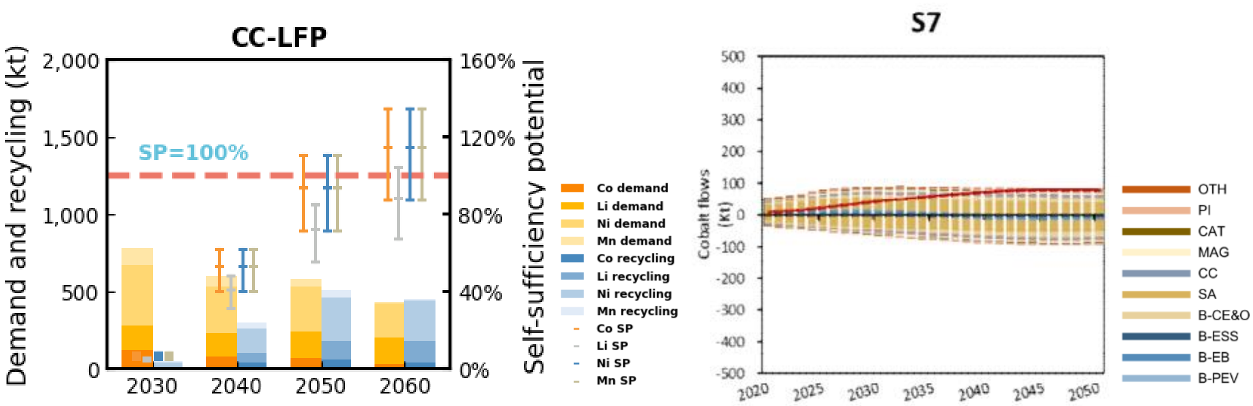


Fig. R1 The comparison between our results and the study of Zeng et al., (2022).

Table R1 The comparison between our results and the study of Zeng et al., (2022).

Year	Reference	Scenario	Material	Self-sufficiency potential
2050	Zeng et al., (2022)[1]	The most optimistic technology scenario	Co	>100%
2050	This study	LFP-dominated cathode scenario (CC-LFP scenario)	Co	71%-110%
2060	This study	LFP-dominated cathode scenario (CC-LFP scenario)	Co	87%-134%

The left image in Fig. R1 presents our research findings, while the right image shows the results of Zeng et al., (2022). 'B-PEV' in the right figure represents the EV sector, with positive values indicating cobalt demand and negative values representing cobalt's secondary supply. Zeng et al., (2022) suggests that, under the most optimistic scenario (new LFP batteries to dominate (100% by 2050)), cobalt self-sufficiency could be achieved by 2050 through secondary supply from EV battery recycling. By analyzing within the same research boundaries, we found that after 2050, under the CC-LFP scenario (The mature LFP cathode will constitute 80% of the cathode market by 2060) with ideal battery collection rates, cobalt (marked in orange) can also reach self-sufficiency through a closed-loop recycling process within the EV sector. However, with low to medium levels of battery collection rate, cobalt self-sufficiency is not attainable by 2050, though it can be achieved with medium rate by 2060.

Reference cited above:

[1] 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).

Comment 3

Response to Comment 5: The authors used a carbon emission factor of 1.001 kg CO2-eq/kWh. However, the carbon emission factor for electricity in China for 2021, as reported by the Ministry of Ecology and Environment, is 0.5568 kg CO2-eq/kWh. International estimates also suggest a figure around 0.8 kg CO2-eq/kWh. Therefore, a carbon emission factor of 1.001 kg CO2-eq/kWh is significantly higher than actual values in China, which undermines the reliability of the results. This is the third unreasonable assumption.

Response:

Thank you for your feedback regarding the carbon emission factor used in our study. We appreciate your observation and the opportunity to clarify our approach. The carbon emission factor plays a crucial role in assessing the environmental benefits throughout the life cycle of EV batteries, particularly during energy-intensive processes such as battery production and recycling. To ensure the reliability of our estimates, we adjust the carbon emission factor of future electricity grids.

Firstly, to align our assumptions with future energy structure of electricity, we consider two electricity mix: the China's carbon neutrality (CN60) electricity mix and the baseline (BAU) electricity mix[1]. The CN60 electricity mix represents a carbon neutrality pathway, optimized using the Global Change Analysis Model (GCAM) model, a dynamic-recursive and technology-rich model for simulating the interdependence of economic, energy, and climate systems. Through this framework, we project the energy composition of China's electricity from 2020 to 2060 at five-year intervals, ensuring that the energy mix aligns with different policy pathways.

Subsequently, by multiplying the proportion of each energy source by its respective carbon emission factor[2,3], we derive time-varying carbon intensity trends under both electricity mix. Incorporating scenario-specific carbon emission factors enables a more accurate estimation of the environmental benefits associated with battery recycling. The results highlight how the transition towards electricity decarbonization influences the life cycle emissions, providing insights into the policy relevance of recycling strategies under different energy transition pathways. The electricity mix and electricity carbon emission in CN60 and BAU electricity mix are listed below:

Table R2 Individual energy component's carbon emission factor (kgCO_2-eq/kWh).

Carbon emission factor	2020	2025	2030	2035	2040	2045	2050	2055	2060
Hydro	0	0	0	0	0	0	0	0	0
PV utility	0	0	0	0	0	0	0	0	0
PV distributed	0	0	0	0	0	0	0	0	0
Wind onshore	0	0	0	0	0	0	0	0	0
Wind offshore	0	0	0	0	0	0	0	0	0
Nuclear	0	0	0	0	0	0	0	0	0
Biomass	0	0	0	0	0	0	0	0	0
Coal	0.79	0.78	0.76	0.73	0.7	0.67	0.64	0.64	0.64
Gas	0.38	0.37	0.37	0.36	0.35	0.34	0.33	0.33	0.33
refined liquids	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72

Supplementary Table 19. The electricity mix and carbon emission in CN60 electricity mix.

	2020	2025	2030	2035	2040	2045	2050	2055	2060
Hydro	16.1%	13.7%	11.7%	10.4%	9.3%	8.5%	8.0%	7.8%	7.6%
PV utility	3.0%	9.5%	17.3%	22.4%	25.5%	28.3%	29.7%	30.0%	30.7%
Wind onshore	3.9%	8.6%	18.5%	25.6%	28.6%	29.6%	30.2%	29.9%	27.8%
Nuclear	4.2%	7.0%	13.3%	18.8%	21.3%	22.9%	23.6%	24.8%	26.4%
Biomass	1.1%	1.6%	2.8%	3.7%	3.6%	3.3%	3.1%	3.4%	4.1%
Coal	69.7%	57.5%	33.5%	16.2%	8.9%	5.1%	3.3%	2.4%	1.7%
Gas	2.3%	1.8%	1.8%	1.7%	1.5%	1.4%	1.3%	1.2%	1.2%
refined liquids	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.0%	0.0%	0.0%
Emission factor	0.560	0.456	0.262	0.125	0.069	0.039	0.026	0.019	0.015

Supplementary Table 20. The electricity mix and carbon emission in BAU electricity mix.

	2020	2025	2030	2035	2040	2045	2050	2055	2060
Hydro	16.1%	15.4%	13.5%	11.4%	9.9%	8.6%	7.6%	7.6%	7.6%
PV utility	2.0%	8.5%	16.2%	22.2%	26.5%	29.2%	29.6%	29.6%	29.6%
PV distributed	0.0%	3.0%	2.7%	3.7%	6.3%	8.3%	10.0%	10.0%	10.0%
Wind onshore	3.9%	12.4%	10.9%	9.7%	9.6%	11.3%	14.3%	14.3%	14.3%
Wind offshore	0.0%	0.4%	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%	0.2%
Nuclear	4.2%	4.1%	5.2%	5.7%	5.6%	4.9%	4.3%	4.3%	4.3%
Biomass	1.1%	1.3%	1.2%	1.0%	0.8%	0.7%	0.6%	0.6%	0.6%
Coal	69.7%	49.7%	45.6%	42.3%	37.9%	34.0%	30.7%	30.7%	30.7%
Gas	2.3%	5.1%	4.4%	3.7%	3.2%	2.9%	2.6%	2.6%	2.6%
Emission factor	0.560	0.406	0.363	0.322	0.276	0.237	0.205	0.205	0.205

Reference cited above:

[1] Zhuo Z, et al. Cost increase in the electricity supply to achieve carbon neutrality in China. Nature Communications 13, 3172 (2022).

[2] Fan J-L, et al. Co-firing plants with retrofitted carbon capture and storage for power-sector emissions mitigation. Nature Climate Change 13, 807-815 (2023).

[3] Wang Y, et al. Accelerating the energy transition towards photovoltaic and wind in China. Nature 619, 761-767 (2023).

Comment 4

For the comment 5, I mentioned that "environmental impacts of battery or material production are also essential because you want to calculate the environmental improvement benefits. It means that you need to calculate the differences in emissions from battery production and recycling. Also, at this point in the LCA, there is a serious fundamental problem in the method to estimate the benefits of carbon reduction from future battery recycling. The resource demand model is dynamic, but the LCA model is static. You amplify the environmental benefits of battery recycling now with future demand". The authors did not address this fundamental issue, which is critical for the paper's publication in Nature Communications.

Response:

Thank you for your insightful comments. We appreciate the opportunity to further improve our methodology and address the issue you raised regarding (i) separating manufacturing and recycling emissions, and (ii) the dynamic nature of the resource demand model versus the static approach of the LCA. We below address each of these concerns:

- Comparison of emissions from battery manufacturing and recycling: As highlighted in your previous feedback, assessing emissions from both the manufacturing and recycling phases is crucial, given that the manufacturing phase accounts for the majority of life cycle emissions. We would like to clarify that in response to your previous comments, we estimated the life-cycling carbon emissions of battery in EV and evaluated emissions in manufacturing and recycling processes in our previous revision. However, our presentation of results in the earlier revised manuscript did not clearly indicate the contribution of each component. For this round, we further refine the results, providing a more detailed and specific comparison of emissions across these two phases. The revised analysis highlights the emission consequence and differences between manufacturing and recycling process from life-cycle perspective, ensuring a clearer understanding of their specific and combined environmental performance.

- Addressing the static nature of the LCA model: We revise our approach to incorporate a time-dependent carbon emission factor into the LCA model, entailing that environmental benefits from recycling are evaluated dynamically over time. As indicated in our response to your Comment 3, we consider two electricity mix - CN60 and BAU electricity mix. In these two electricity structure, carbon emission factors are updated every five years to reflect the progressive decarbonization of the electricity grid. By integrating time-varying carbon emission factors into the LCA model, we ensure that both environmental benefit assessments and resource demand simulations evolve over time. This dynamic integration aligns the modeling framework with the logical and methodological requirements of long-term environmental and material flow assessment, enhancing the robustness and scientific rigor of our results.

The life-cycle CO2 emission related to LIB battery under carbon neutrality electricity mix is shown in Fig. 4, where we describe the specific material inputs in the battery manufacturing process, including steel, aluminum, copper wire, cathode, graphite, polyvinylidene fluoride (PVDF), LiPF6, electrolyte, and polypropylene. Results show that battery manufacturing is a substantial contributor to battery life-cycling emissions, especially in the process of cathode material: accounting for 42-56% of CO2 emissions under nine scenarios considering battery recycling strategies in CN60 electricity mix. The environmental friendliness of battery recycling partially depends on the cathode chemistry.

Battery recycling has potential to pave the way for the benefit of carbon mitigation, facilitating the transition towards electrified transportation. Recycling technology has an imperative role in the battery's life cycle emissions. Especially, the transition to direct cathode recycling could cumulatively mitigate 1671 Mt CO2-eq emission, equivalently offsetting 55% emissions from other processes (RP-DIR scenario). Given the optimal battery and its recycling technology (OPT scenario), cumulative CO2 emissions of approximately 1550 Mt CO2-eq will be avoided by LIB recycling in 2060, which is equivalent to twice the annual carbon emission of the China's passenger car sector[1]. Please see the details in the section of "Life-cycle CO2 emission in lithium-ion battery" in the Results section. The detailed results of battery life-cycle and recycling CO2 emission profile are provided below:

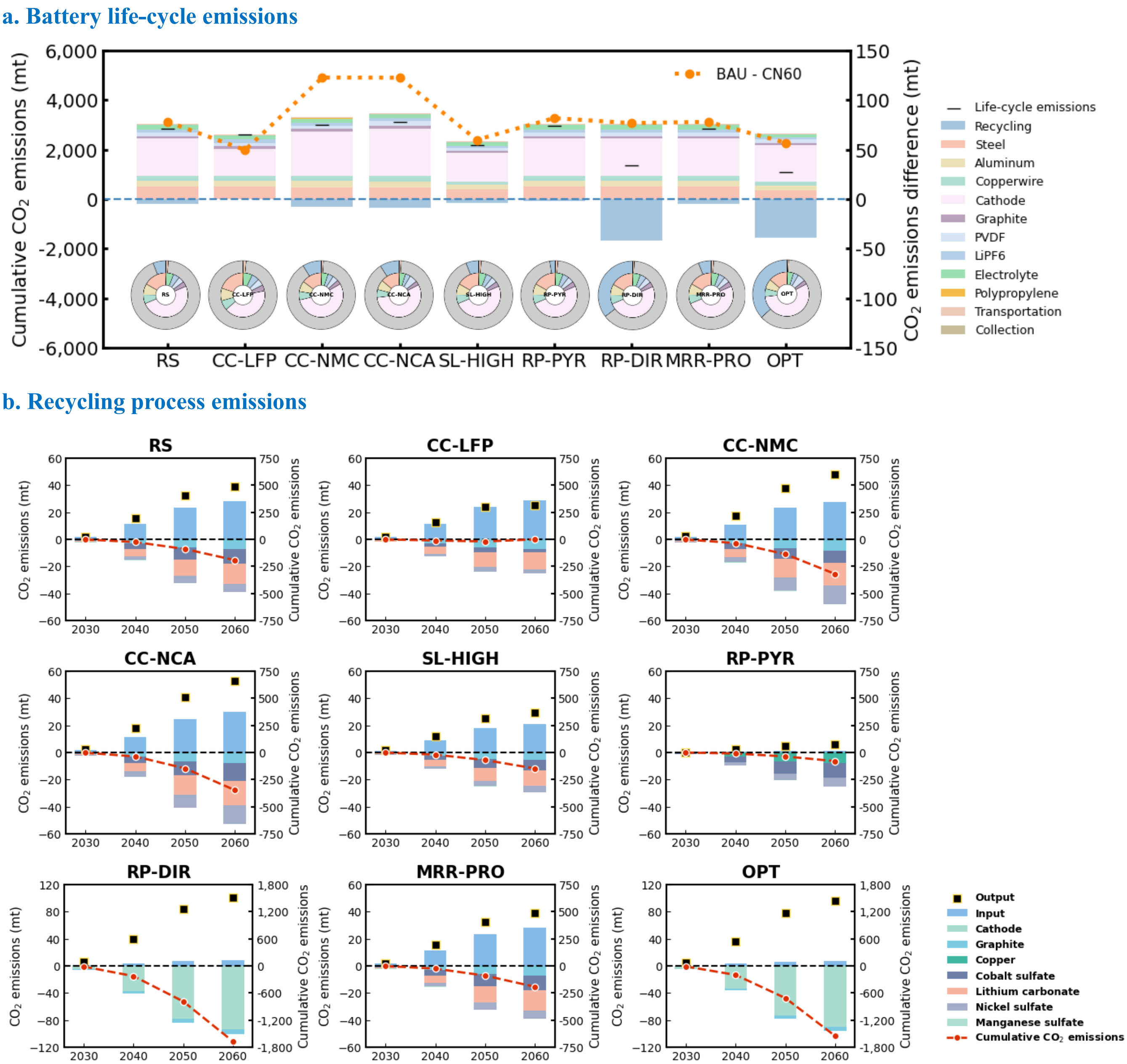


Fig. 4 Prospectively life-cycle CO2 emission related to Lithium-ion battery under the nine selected scenarios. In (a), BAU - CN60 value displayed in the secondary axis donates the difference of cumulative life-cycle carbon emissions between BAU electricity mix and CN60 electricity mix. In (b), the output is the annual avoided carbon emissions in the battery recycling.

Reference cited above:

[1] Chen W, et al. Carbon neutrality of China's passenger car sector requires coordinated short-term behavioral changes and long-term technological solutions. One Earth 5, 875-891 (2022).

We thank the reviewer again for several valuable comments which greatly help us to improve the robustness of results and scientific rigor of this study.

Reviewer #3 (Remarks to the Author):

The authors have replied to all my comments and they have accordingly edited the manuscript and related documents. So, the paper now can be accepted in this form and published in the journal.

Response:

Thank you for your kind feedback and for the time and effort you have dedicated to reviewing our manuscript. We are pleased to know that our revisions have addressed your concern.

Reviewer #4 (Remarks to the Author):

I appreciate the authors' efforts in extensively incorporating a range of comments from the editor, other referees, and myself to improve the manuscript. After reading the revised manuscript and each response carefully. I find it has been significantly improved. However, there are still some points that need further refinement.

Response:

Thank you for your insightful comments and encouraging feedback on this work. In the revised version, your comments have been carefully reviewed and addressed. We have made three key improvements:

- The core conclusions are revised to ensure scientifically rigorous expression, with findings related to cumulative imbalance of critical materials and the production capacity of the EV battery supply chain.
- The life-cycle cost assessment of EV batteries has been refined. In the revised manuscript, the EverBatt model replaces the BATPAC model to capture evolving manufacturing and recycling costs associated with temporal dynamics and production scale, reflecting the impact of economies of scale. Additionally, transportation cost calculations incorporate optimal spatial configurations, emphasizing the importance of logistical optimization in reducing life-cycle costs. By coupling the EverBatt model with a geospatial optimization model, we assess lifecycle costs with an optimized spatial layout for battery recycling facilities.
- The writing and grammar have been carefully reviewed to enhance clarity, consistency, and readability. All maps and figures have been evaluated, subjected to meet the standards for neutral and scientific presentation.

Thank you again for your precious suggestions. We believe these revisions address your concerns and improve the clarity and impact of our manuscript. Below we provide responses to each comment in detail (your comments are in black font and our responses starting with Response are in blue font).

Comment 1

A central finding of this manuscript, reiterated throughout the abstract, main text, and conclusion, is that "EV deployment to achieve China's carbon-neutrality target could significantly increase the cumulative demand for critical materials, surpassing global mineral reserves by up to 2.8 times." This is a surprisingly strong yet vague statement. In the literature, the primary concern for many critical minerals is often the limited production capacity rather than the total reserves, and whether production can be scaled up to meet rising demand. To substantiate this claim, it is essential to specify which critical minerals are being referenced among those assessed. The calculations presented between lines 140-142 need to be carefully reviewed with meticulous attention to unit conversions and clearly elaborated, ideally in the form of a table.

Response:

Thank you for your thoughtful and constructive feedback. We appreciate the opportunity to clarify and improve the presentation of our findings. Below, we address your comments in detail.

- Revision of the conclusion statement: In our original conclusion, we use the mineral reserves of critical materials as a reference to illustrate the potential supply-demand gap. However, as you precisely observed, in both the literature and real-world cases, the demand for key minerals in batteries is more constrained by production capacity bottlenecks, such as refining capacity and supply chain disruptions. In the revised manuscript, we emphasize the imbalance between supply and demand under the current recycling pathway and the urgent need for production capacity expansion. Additionally, we replace the generalized discussion of critical materials with specific analyses for each critical material, ensuring that our findings are presented with scientific rigor and precision.

  The revised section shown in line 174-183: The cumulative imbalance (the gap between materials demand and self-sufficiency by close-loop recycling) will increase substantially over the next four decades to 4638 kt for cobalt, 5226 kt for lithium, 4434 kt for manganese, and 13665 kt for nickel. Notably, the closed-loop supply and demand imbalance for these critical materials exceeds the production capacity. By 2060, the imbalance volumes of cobalt, and manganese are projected to reach 54 and 116 times their 2022 production capacities, respectively, exacerbating fragility and interruptions across supply chains[1,2,3].
- Review of calculations and tabular presentation: We carefully review the calculations presented between lines 140-142 (Results are shown in Fig. 2e). To further clarify the underlying calculations, we also provide a detailed numerical breakdown in tabular form (see Supplementary Table 21). This addition ensures transparency and improves the reproducibility of our results.

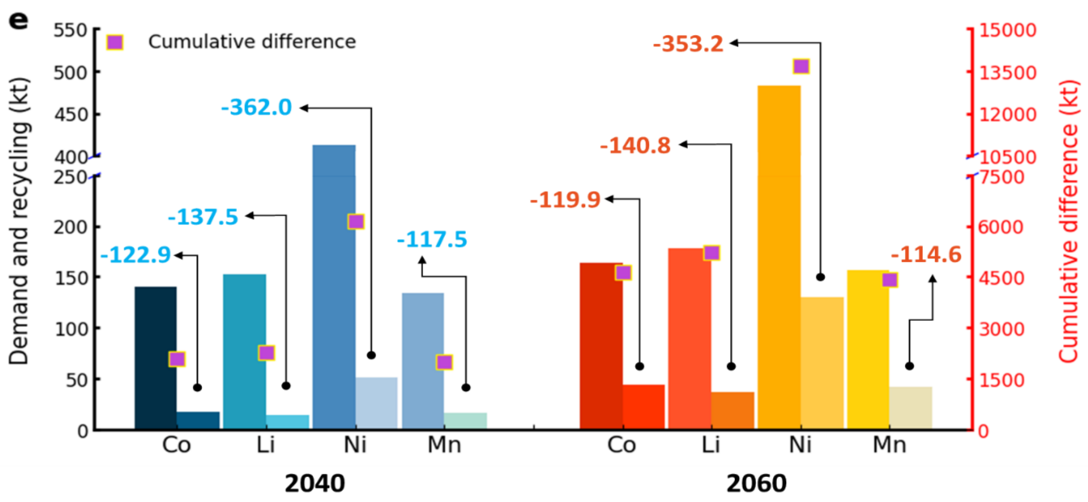


Fig. 2e The demand-supply gap of critical materials under China's carbon neutrality goal.

Supplementary Table 21 The demand-supply gap of critical materials in status quo (Unit: kt).

Year	Materials	Demand	Recycling	Demand-supply difference	Cumulative difference
2040	Co	140.23	17.37	-122.86	2081.24
	Li	152.10	14.57	-137.53	2283.93
	Ni	413.19	51.17	-362.02	6132.32
	Mn	134.06	16.60	-117.46	1989.68
2060	Co	163.83	43.96	-119.87	4637.88
	Li	177.69	36.87	-140.82	5225.81
	Ni	482.72	129.53	-353.19	13665.41
	Mn	156.62	42.03	-114.60	4433.85

■ Updates to the abstract, main text, and conclusion: We have revised the abstract, main text, and conclusion to ensure that the statements are more precise and closely aligned with the data presented in the manuscript. These changes place a stronger emphasis on the limitations posed by production capacity constraints for critical materials, consistent with prior research in the field. The revised conclusions are now more grounded in the data and provide a clearer understanding of the challenges facing the battery supply chain. Please see the abstract, main text (Section: Historical flows and the demand-supply imbalance of critical materials), and conclusion for more details.

Reference cited above:

[1] Cheng AL, Fuchs ERH, Karplus VJ, Michalek JJ. Electric vehicle battery chemistry affects supply chain disruption vulnerabilities. Nature Communications 15, 2143 (2024).

[2] United States Geological Survey. Mineral commodity summaries 2023. https://www.usgs.gov/publications/mineral-commodity-summaries-2023. (2023).

[3] International Energy Agency Global Supply Chains of EV Batteries (International Energy Agency, 2022).

Comment 2

I'm glad to see that the revised manuscript has addressed the viability of recycling. The author illustrates the profitability of the circular economy solution in the main text. However, the authors have not made it clear that this assessment is for a snapshot of 2060. What about earlier years? Methodologically, the manuscript fails to clarify how economies of scale are incorporated into the financial assessment of recycling. This is a key point in optimizing the geospatial configuration of recycling, as excessive competition may severely impact plant-level viability. It appears that the authors have built a cost model directly from BATPAC, but it is unclear what benefits this approach offers over EverBatt, which is a more specific tool for this purpose. Please elaborate.

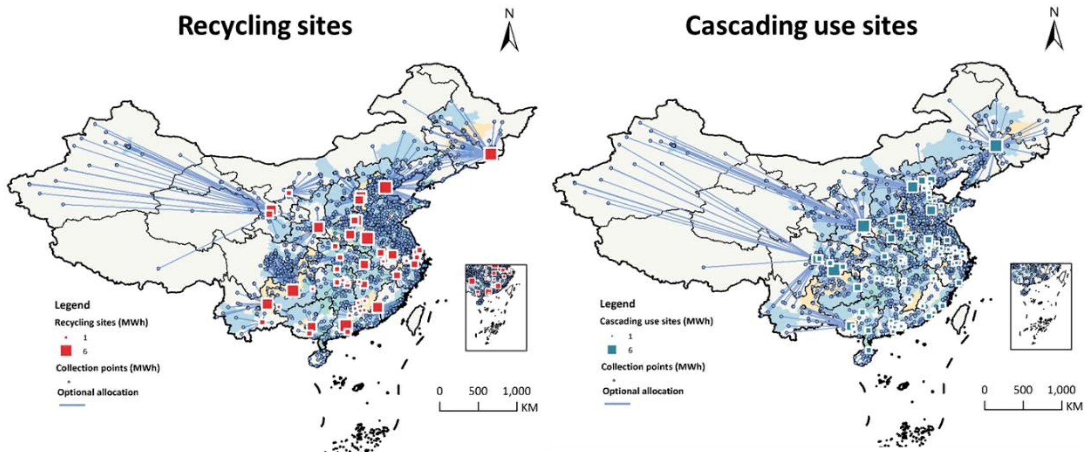
Response:

Thank you for your valuable questions regarding our cost modeling approach. We are grateful for your insightful comments. The core revisions consist of the following three items: 1) providing time-associated life cycle cost assessment to reflect the cost evolution; 2) EverBatt model substitutes BATPAC in revised manuscript for computing life-cycle cost to capture the effect of economies of scale; 3) life-cycle cost estimation considering optimizing battery recycling spatial configuration to minimize transportation costs. We provide detailed responses and clarifications below.

- Providing time-associated life-cycle cost trends: As you kindly pointed out, the life-cycle cost of EV batteries evolves over time, owing to the economics of scale, due to technological progress and improved resource allocation. To assess how economies of scale shape cost dynamics over time, in our revised manuscript, we model life-cycle costs at ten-year intervals, presenting unit and total battery industry costs for 2030, 2040, 2050, and 2060, yielding insights into the evolving economic sustainability of the battery recycling industry. These snapshots reflect the effects of key factors such as production scale, economies of scale, and geospatial deployment of recycling facilities on the economic feasibility of battery recycling. Through the temporal-based breakdown, our work highlights how the financial viability of recycling solutions changes over time, offering a more comprehensive view of cost evolution and decision-making in different timeframes.
- Using EverBatt for life-cycle cost assessment: We appreciate your observation regarding the use of appropriate models for cost calculations. In response, we utilize the EverBatt model for life-cycle cost assessment using parameter inputs from the BATPAC model to ensure consistency. EverBatt divides closed-loop battery recycling into submodules, including battery manufacturing, logistics and collection, disassembly and preprocessing, and recycling. The model incorporates economies of scale, simulating how costs evolve as production scales up or down. Inputs for the production process include material costs, direct labor, capital equipment, and building costs. EverBatt offers greater flexibility in customizing cost parameters, enabling tailored scenario analysis. We further integrate the model with a spatial location optimization model to link optimal recycling logistics routes to EverBatt's transportation and collection module. This combined approach allows us to evaluate life-cycle cost-effectiveness under various recycling strategies while optimizing transportation routes, ensuring efficient economic performance and environmental sustainability across the battery recycling network.
- Dynamic cost modeling with optimized geospatial configuration: Given China's vast geography and the dispersed distribution of waste batteries, a well-structured recycling network (including cascading use centers) is essential to avoid increased transportation costs and risks, such as fire or explosion during the transport of hazardous materials[1,2]. Spatial layout also interacts with economies of scale[3]: in areas with high battery supply, centralized recycling hubs promote industrial clustering through shared logistics, technology, and supply chains, driving down costs. In remote regions with lower battery availability, distributed facilities help reduce logistics costs. Therefore, we employ Location-Allocation analysis in ArcGIS to optimize the spatial distribution of battery recycling facilities by identifying optimal locations and minimizing transportation costs between collection points and recycling sites. The analysis integrates high-resolution road networks, candidate facilities, collection points, and transportation infrastructure to reflect real-world connectivity. Economic-technical and

geospatial factors such as demographics, automotive service facilities, and energy infrastructure are incorporated to enhance site suitability assessment. In alignment with national policies on battery recycling, EV manufacturers' sales networks are used as proxies for collection points, and authorized operators are identified as potential recycling or second-life facilities. Retired battery volumes are allocated across collection points based on population distribution. Optimizing the spatial configuration ensures that we determine the most efficient logistics patterns and facility capacities to minimize collection and transportation costs. Thus, by coupling EverBatt with geospatial optimization, we present a life-cycle cost model that offers robust insights into the optimal spatial configuration for future battery recycling facilities. Please see the details in the section of "Economically feasible lithium-ion battery recycling considering synergy of optimizing geospatial configuration" in Result. The optimizing battery recycling spatial configuration in 2060 is shown in Fig. 5a. The prospectively life-cycle cost estimation considering the economy of scale and geospatial configuration is illustrated in Fig. 5b.

a. Optimizing battery recycling spatial configuration



b. Life-cycle cost assessment of EV battery

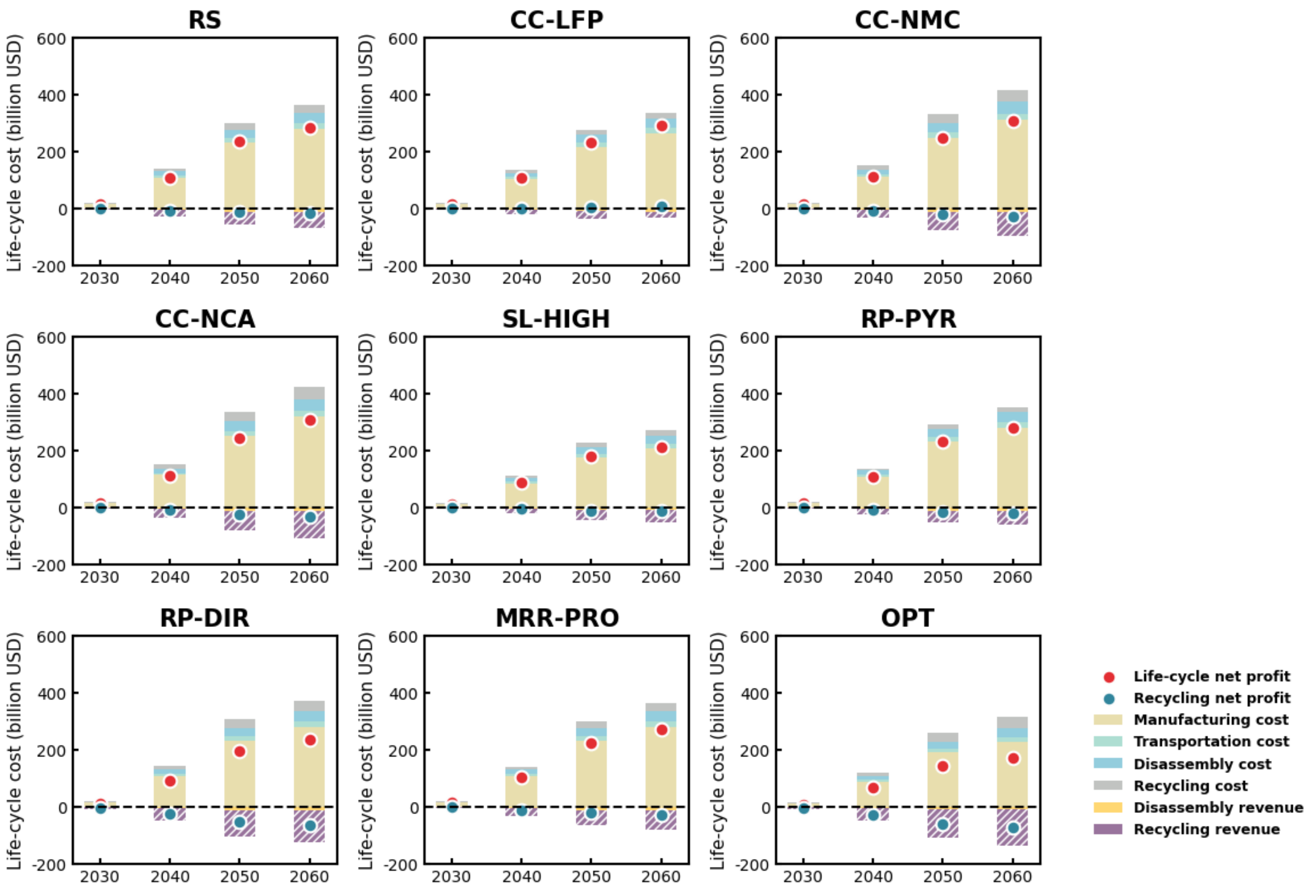


Fig. 5 Prospectively life-cycle cost estimation considering the economy of scale and geospatial configuration.

Reference cited above:

[1] Nguyen-Tien V, Dai Q, Harper GDJ, Anderson PA, Elliott RJR. Optimising the geospatial configuration of a future lithium ion battery recycling industry in the transition to electric vehicles and a circular economy. Applied Energy 321, 119230 (2022).

[2] Haynes MW, González RC, Hatzell MC. Optimizing geographic locations for electric vehicle battery recycling preprocessing facilities in California. RSC Sustainability 2, 377-389 (2024).

[3] Iloeje CO, et al. A systematic analysis of the costs and environmental impacts of critical materials recovery from hybrid electric vehicle batteries in the U.S. iScience 25, 104830 (2022).

Comment 3

There are still several opportunities for the authors to review the writing more carefully to correct typos and enhance clarity for the audience:

• Please rewrite lines 25-29 to make it clearer that repurposing and recycling are also part of circular economy strategies like reuse. Given the scope of the manuscript, it might be more effective to focus directly on recycling when setting the stage.

• The EU example in lines 30-31 should be moved to a footnote, which should also include examples of other “major jurisdictions.”

• The sentence in lines 113-117 is difficult to comprehend and assess. Please break it down and rewrite it with greater clarity.

• Similarly, the sentence in lines 208-210 is hard to understand. Please rewrite it for better clarity.

• In line 406: What is LFA?

Response:

We are very thankful for important suggestions. We have thoroughly revised the manuscript to address any remaining typos and improve clarity throughout, ensuring the text is as precise and accessible as possible for the audience. Specifically:

- Lines 25-29 have been revised to better emphasize the scope of the paper, focusing on battery recycling while streamlining other circular economy strategies. The revised expression is "Circular economy strategies (CES), such as lithium-ion batteries (LIBs) reuse, are promising to lead the world onto a resilient and renewable path guided by Sustainable Development Goals (SDGs)[1, 2, 3, 4]. LIB recycling, a key reuse channel in major jurisdictions, has the potential to mitigate environmental impact by reducing or offsetting the emission from the battery raw material production and landfill disposal at the end of their service life[5, 6]"
- Due to formatting guidelines of Nature Communications to not have footnotes (https://www.nature.com/ncomms/submit/article), we are unfortunately unable to move the EU example to a footnote. Nevertheless, we have revised the organization of this section considering your feedback.
- We rewrite and clarify lines 113-117. The revised expression is "The LIB recycling roadmap reveals that the total demand for cobalt, lithium, nickel, and manganese in EV production soared to 204, 222, 602, and 195 hundred tons in 2020 -- a 900-fold increase from 2010 levels. However, only 2.8, 3.1, 8.3, and 2.7 hundred tons of these critical materials were sourced from recycled batteries, meeting just 1.4% of the total demand. A huge demand-supply imbalance exists in the closed-loop LIB recycling due to a low battery collection rate. Consequently, the limited recovery of these key materials intensifies supply risk concerns for the EV industry."
- "LFA" is corrected to "LFP."
- Additionally, we conduct a thorough check for spelling and grammar throughout the manuscript to enhance its clarity.

Reference cited above:

[1] Govindan K. How digitalization transforms the traditional circular economy to a smart circular economy for achieving SDGs and net zero. Transportation Research Part E: Logistics and Transportation Review 177, 103147 (2023).

[2] Song L, et al. China's bulk material loops can be closed but deep decarbonization requires demand reduction. Nature Climate Change 13, 1136-1143 (2023).

[3] Aguilar Lopez F, Lauinger D, Vuille F, Müller DB. On the potential of vehicle-to-grid and second-life batteries to provide energy and material security. Nature Communications 15, 4179 (2024).

[4] Franks DM, Keenan J, Hailu D. Mineral security essential to achieving the Sustainable Development Goals. Nature Sustainability 6, 21-27 (2023).

[5] Vaccari M, et al. Assessing performance in lithium-ion batteries recycling processes: A quantitative modeling perspective. Resources, Conservation and Recycling 206, 107643 (2024).

[6] Harper G, et al. Recycling lithium-ion batteries from electric vehicles. Nature 575, 75-86 (2019).

Comment 4

Maps like Supplementary Figures 29 and 30 include features linked to controversial, unsubstantiated territorial claims, which do not contribute to the scientific content of this research.

Response:

Thank you for bringing this important issue to our attention. We appreciate your careful review and constructive feedback. To ensure that our work aligns with the scientific focus and publication standards, we remove controversial, unsubstantiated territorial claims in the manuscript. All maps and figures are complied with the publisher's guidelines and adhere to the standards for neutral and objective scientific presentation.

We thank the reviewer again for the valuable comments which greatly helped us to improve the quality of this study.

Dear editor and reviewer,

Thank you for your timely response and valuable feedback on our paper. We appreciate the acknowledgment of the merit of our work and the constructive suggestions for the revisions. After thorough consideration of the comments and recommendations from the reviewers, we have incorporated your suggestions. If there is any further feedback, we are fully committed to addressing them.

Please see the point-by-point responses below for details. The modifications have been highlighted with RED color in the revised manuscript file.

Response to reviewers' comments

Reviewer #2 (Remarks to the Author):

The manuscript has shown considerable improvement in terms of quality and content, making it suitable for publication. I am pleased to grant my approval for its release. Congratulations to the authors on their outstanding efforts and achievements!

Response:

Thank you for approving our manuscript and for your constructive feedback, which greatly strengthened the paper. We deeply appreciate your time and expertise in guiding this work to publication!

Reviewer #4 (Remarks to the Author):

Again, I highly appreciate the effort of the authors to incorporate different feedback to improve the manuscript, including the extension of models to take into account the role of geospatial optimization and the use of the EverBatt model, which is more appropriate for capturing the economics of recycling (and its environmental benefits). However, I'm not convinced the manuscript in its existing form is ready for publication. Here are some issues:

Response:

Thank you for your thoughtful and constructive feedback. We have carefully reviewed your comments and made the following key revisions to enhance the manuscript:

- Clarified conceptual issues related to lithium-ion battery (LIB) recycling and reuse, incorporating insights from Morseletto (2020) to provide a more precise discussion.
- Refined the explanation of recycling viability assessment results calculated using the EverBatt model, with a particular focus on the unexpected results regarding battery cathode materials, recycling technologies, and the impact of economies of scale.
- Expanded the discussion on lithium to explicitly address its long-term significance, considering the continued dominance of LIBs.
- Improved images, language, grammar, and formatting to ensure clarity, readability, and consistency throughout the manuscript.

Thank you again for your precious suggestions. We believe these revisions address your concerns and improve the clarity and impact of our manuscript. Below we provide responses to each comment in detail (your comments are in black and our responses starting with Response are in blue).

Comment 1

Conceptual issues: I don't think LIB recycling should be categorized as a "reuse channel" as stated in lines 36-37, especially in the context of the circular economy mentioned in the previous sentence. For example, they are referred to as two circularity strategies (R3/R8) in Morseletto

(2020) [Targets for a circular economy]. If one wants to say recycling is a cascading step from the second use of EV batteries (for example, in less demanding applications such as static energy storage), one may elaborate more rather than using such a confusing concept. Note that many EV batteries can go straight to recycling without a reuse/refurbishment step.

Response:

Thank you for your careful review and constructive remarks. We appreciate your attention regarding the conceptual issues of LIB recycling. As highlighted in the Morseletto (2020) [Targets for a circular economy], reuse (R3) is defined as the second or further use of a product that is still in good condition and continues to fulfill its original function. In contrast, recycling (R8) involves processing materials to obtain the same (high-grade) or lower (low-grade) quality of recycled materials. The core of reuse is to extend the lifespan of products and their components, whereas recycling focuses on the useful application of recovered materials. We fully agree with your comments that recycling and reuse represent distinct circularity strategies. Since the scope of our study is limited to battery recycling, our research aims to explore the demand and supply of critical material, carbon emissions mitigation, and cost feasibility related to battery recycling, without considering the reuse phase. To address this, we have revised the relevant section (lines 36-37) and removed the description of "reuse" to clearly introduce recycling within the circular economy framework. Additionally, as you pointed out, while some EV batteries may undergo second use in less demanding applications (e.g., stationary energy storage), others may proceed directly to recycling without reuse. We appreciate your constructive feedback. In our calculation of the scrapped battery volume for recycling, we have considered three sources of recycled batteries, including direct recycling of end-of-life batteries and those that have undergone a second use before recycling. We have further elaborated on the recycling and cascading process in the roadmap of LIB's second use and recycling.

- Revision of the relevant concept: "Circular economy strategies (CES), including recycling, are promising to lead the world onto a resilient and renewable path aligned with Sustainable Development Goals (SDGs)[1, 2, 3, 4, 5]. LIB recycling, a key component of recycling frameworks in major jurisdictions, mitigates environmental impacts by reducing or offsetting emissions associated with battery raw material production and landfill disposal at end-of-life[6, 7]." (Please see the revised section in lines 29-33)
- The framework of battery recycling and cascading process: Wasted batteries can be recycled from three main sources. (i) Battery replaced by early failure. Batteries that fail within the warranty period (8 years) can be partially repaired and reused in EVs, while non-repairable components are replaced and sent to the recycling market; (ii) Recycling from the cascading use. To extend lifespan and maximize application flexibility, the majority of batteries are prioritized for second-life use, either directly in low-speed EVs or indirectly in energy storage systems. Once their state of health (SOH) drops below 80%, they are ultimately recycled; (iii) Direct Recycling. Some end-of-life batteries, especially those unsuitable for cascading use, are sent directly for recycling without a second-use phase. (Please see further details in **Lithium-ion battery scrappage roadmap** in Method, Supplementary Figs. 2-3 and Supplementary Note 4)

Reference cited above:

[1] Govindan K. How digitalization transforms the traditional circular economy to a smart circular economy for achieving SDGs and net zero. Transportation Research Part E: Logistics and Transportation Review 177, 103147 (2023).

[2] Song L, et al. China’s bulk material loops can be closed but deep decarbonization requires demand reduction. Nature Climate Change 13, 1136-1143 (2023).

[3] Aguilar Lopez F, Lauinger D, Vuille F, Müller DB. On the potential of vehicle-to-grid and second-life batteries to provide energy and material security. Nature Communications 15, 4179 (2024).

[4] Franks DM, Keenan J, Hailu D. Mineral security essential to achieving the Sustainable Development Goals. Nature Sustainability 6, 21-27 (2023).

[5] Morseletto P. Targets for a circular economy. Resources, Conservation and Recycling 153, 104553 (2020).

[6] Vaccari M, et al. Assessing performance in lithium-ion batteries recycling processes: A quantitative modeling perspective. Resources, Conservation and Recycling 206, 107643 (2024).

[7] Harper G, et al. Recycling lithium-ion batteries from electric vehicles. Nature 575, 75-86 (2019).

Comment 2

Technical issues: I'm particularly concerned about the technical reliability of the recycling viability assessment (lines 316-392). The key finding (but not reported in the manuscript) in panel b if Fig5 is that recycling is not economically feasible in almost every scenario (except for some special extreme scenarios) as the recycling net profit is negative. Surprisingly, recycling in the high CC-NMC scenario is less viable than in the CC-LFP scenario, while it is expected that recycling NMC will help recover more precious materials like cobalt. The literature mainly concerns that the shift to LFP would reduce the economic incentive of recycling. Can you please elaborate on these strange results and consolidate them with previously published results?

Similarly, direct cathode recycling in Fig. 5, the new and more economical method, is shown to cause more loss than hydrometallurgical recycling (RS scenario) and pyrometallurgical recycling. Could you elaborate more on this?

These strange results may cast some questions on the assumptions, data sources, or the use of suitable methodology and the calculations involved. Importantly, if recycling is not economically viable, it raises the question of whether environmental benefits might justify the economic losses, and if so, who would bear the cost? Does the use of recycled material justify itself instead of the alternative (i.e., virgin materials)?

A specific technical issue I can see is "diseconomies of scale" mentioned in line 353. If the EverBatt model is set up correctly, the increase in throughput will reduce the recycling cost (such as lower average fixed cost) and hence improve viability. As time passes, the volume of spent batteries that need to be recycled will rise, increasing the viability of the industry - that's the economy of scale expected in this context.

The huge losses of recycling computed in this manuscript may come from the fact that the modeler set up so many recycling sites (hence just allocating spent batteries but not "optimizing" yet). In fact, recycling is a capital-intensive business requiring large-scale operations; hence, the intensive network of recyclers shown is not economically sustainable.

This may be the root cause of the huge loss of recycling in the base scenario, even with the large recycling demand in 2060. In short, the failure to properly model the economic structure of the recycling industry has caused the artifact of "diseconomies of scale" and the strange results presented.

Response:

Thank you for your insightful comments. We understand your concerns regarding the technical reliability of the recycling viability assessment, particularly the unexpected results in the high CC-NMC scenario compared to the CC-LFP scenario, as well as the cost comparison across different recycling methods.

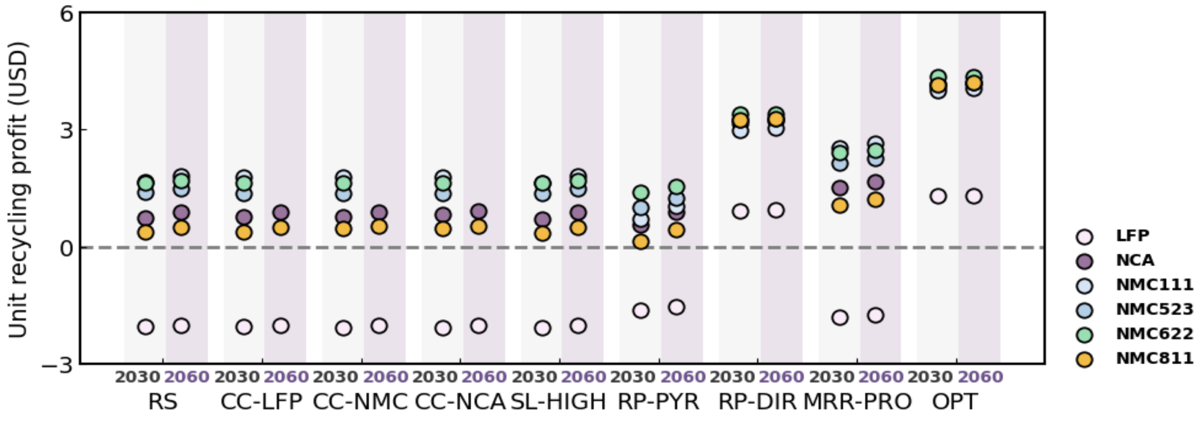
We would like to emphasize that in most scenarios, battery recycling is indeed economically viable. However, the previous manuscript may not have clearly conveyed the information in Figure 5, potentially leading to difficulties in interpreting the results. To address this, we have elaborated on the cost assessment process and revised Figure 5 to enhance clarity.

- Outline the cost assessment process. In the previous version of the manuscript, our cost assessment framework encompassed the life-cycle costs associated with virgin battery production, transportation and collection, disassembly, and recycling process. The reported aggregate cost was calculated as the sum of these components, minus the revenues generated from the disassembly and recycling processes. Specifically, recycling revenues were considered based on the value of recovered materials substituting virgin materials. However, in the cost calculation process, while the battery production cost was included, the battery sales revenue was not accounted for. Given the capital-intensive nature of battery production, this omission led to an aggregate negative net profit. Therefore, the negative profitability observed across most scenarios does not indicate that battery recycling is economically unviable. Rather, it quantifies the extent to which recycling can offset the costs throughout the entire life cycle. Focusing on whether recycling is profitable, it should not include the production cost of virgin battery without using recovered materials.

  Thus, we have classified the cost assessment process in the revised manuscript. The cost assessment now focuses on costs and revenues directly related to battery recycling, including transportation and collection, disassembly, and recycling process of spent batteries. Since battery production does not belong to the recycling phase, it has been excluded from the cost assessment. This revision provides a clearer depiction of the economic feasibility of battery recycling. Our analysis shows that recycling is economically viable in most scenarios, especially when high-value cathode materials are used (such as in CC-NMC and CC-NCA scenarios) or when advanced recycling technologies are applied (in RP-DIR and OPT scenarios). However, the recycling of LFP-dominant batteries using hydrometallurgical or pyrometallurgical technologies remains economically unviable in certain scenarios, such as in the RS and CC-LFP scenarios. (Please see the revised section in lines 375-384 and Figure 5b for more details)

- Modifying the presentation of figures. We acknowledge that the original representation of Figure 5b may have led to misinterpretations, particularly due to the y-axis being labeled as "cost", which resulted in profits appearing as negative values. This might have inadvertently conveyed the impression that battery recycling is economically unviable in most scenarios. To eliminate potential misunderstandings, we have revised the figure as follows: i) Reformatting Figure 5b to display cost/profit separately, where values above the zero axis now indicate profit (positive values), and values below the zero axis represent costs (negative values). This ensures that profitability is correctly interpreted and aligns with economic expectations. ii) Incorporating a new panel (Figure 5a) that presents unit recycling profit for each scenario, covering both 2030 and 2060 projections. This addition clearly illustrates the impact of economies of scale and highlights long-term profitability trends of battery recycling. iii) Comparing our battery recycling cost assessment with existing literature to reinforce the results. (Please see Fig. 5 and Supplementary Table 26)
- Clarification on economies of scale. Thank you for your insightful comments regarding the diseconomies of scale mentioned in line 353. We acknowledge that the initial setup of multiple recycling sites in our model may have led to suboptimal cost allocation, as the system was in an early-stage allocation phase rather than an optimized state. However, we would like to clarify that our cost assessment of the battery recycling process does not exhibit diseconomies of scale. As the volume of spent batteries increases over time, the cost per unit decreases, demonstrating that recycling benefits from scale efficiency. Our results indicate that battery recycling follows economies of scale across various scenarios, as shown in Figure 5a. For instance, among the various recycling processes, direct cathode recycling stands out as the most cost-effective, yielding positive revenues even for LFP batteries. Under the OPT scenario, the unit profit of LFP battery recycling grows from \$1.30/kg in 2030 to \$1.32/kg in 2060. Other cathode chemistries achieve even higher unit profits over this period: NCA from \$4.10/kg to \$4.18/kg, NMC111 from \$4.01/kg to \$4.06/kg, NMC532 from \$4.17/kg to \$4.21/kg, NMC622 from \$4.35/kg to \$4.37/kg, and NMC811 from \$4.16/kg to \$4.22/kg. (Please see the revised section in lines 368-374 and Figure 5a for more details)

a. Unit battery recycling costs and profits in 2030 and 2060



b. Recycling cost assessment of LIBs at the industry level

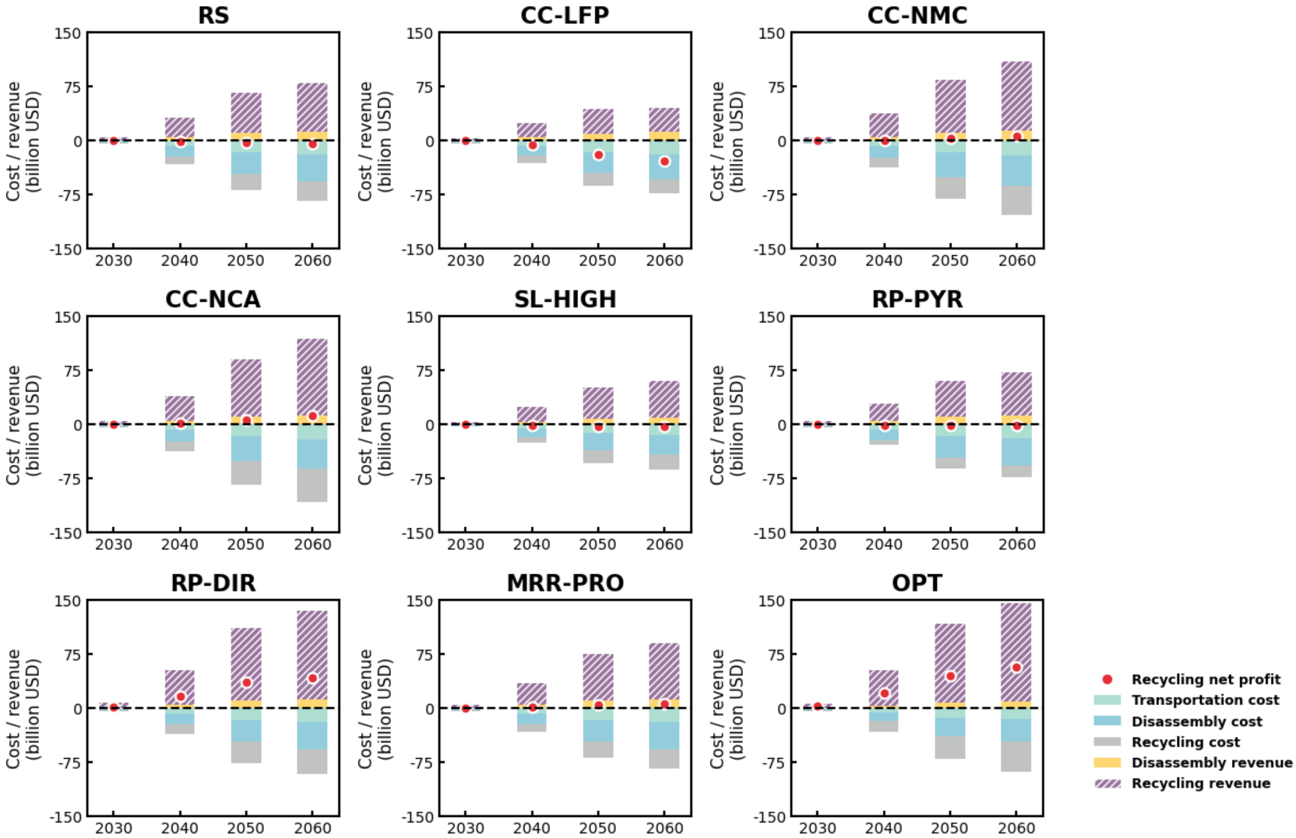


Fig. 5 Economic assessment of LIB recycling at unit and industry levels considering the economy of scale and geospatial configuration. a, unit battery recycling costs and profits in 2030 and 2060; b, Recycling cost assessment of LIBs at the industry level across nine recycling scenarios. *In each scenario of (a), the left dot denotes the unit battery recycling costs/profits in 2030, while the right dot indicates the unit battery recycling costs/profits in 2060, reflecting the impact of economies of scale. The battery recycling net profits aggregates the cost and revenue of disassembly and recycling processes, and the cost of transportation and collection.*

Supplementary Table 26. Comparison of results from literature for the cost analysis ($/ton).

Reference	Recycling technology	Cathode	Cost	Revenue	Profit
Zou et al., (2013)[1]	Hydro	NMC	6195	5023	
Fan et al., (2020)[2]	Hydro	LFP	804	196	
Laura et al., (2021)[3]	Pyro	LFP			-2285
		NCA			946
		NMC622			1126
		NMC811			425
	Hydro	LFP			-1181
		NCA			2078
		NMC622			2359
		NMC811			1598
	Direct	LFP			2585

		NCA			5256
		NMC622			3566
		NMC811			3065
Dunn et al., (2022)[4]	Pyro	LFP	4010		
		NCX	4040		
	Hydro	LFP	3910		
		NCX	3950		
	Direct	LFP	5460		
		NCX	5520		
This study (RS scenario)	Pyro	LFP	2800	1180	-1620
		NCA	5560	6130	570
		NMC111	5530	6250	720
		NMC532	4640	5640	1000
		NMC622	4640	6030	1390
		NMC811	5310	5450	140
	Hydro	LFP	3300	1250	-2050
		NCA	5910	6650	740
		NMC111	5820	7490	1670
		NMC532	4960	6350	1390
		NMC622	4990	6630	1640
		NMC811	5560	5940	380
	Direct	LFP	3200	4110	910
		NCA	6350	9500	3150
		NMC111	6800	9790	2990
		NMC532	5760	9020	3260
		NMC622	5900	9300	3400
		NMC811	6080	9320	3240

We greatly appreciate your feedback, which has helped enhance the clarity of our analysis. Thank you again for your thoughtful review. (Please see the section on **economically feasible lithium-ion battery recycling considering synergy of optimizing geospatial configuration** for more details)

Reference cited above:

[1] Zou H, Gratz E, Apeliana D, Wang Y. A novel method to recycle mixed cathode materials for lithium ion batteries. Green Chemistry 15, 1183-1191 (2013).

[2] Fan E, *et al*. Sustainable Recycling Technology for Li-Ion Batteries and Beyond: Challenges and Future Prospects. *Chemical Reviews* 120, 7020-7063 (2020).

[3] Lander L, *et al*. Financial viability of electric vehicle lithium-ion battery recycling. *iScience* 24, 102787 (2021).

[4] Dunn J, Kendall A, Slattery M. Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. *Resources, Conservation and Recycling* 185, 106488 (2022).

Comment 3

Result discussion: I appreciate the authors' effort to highlight the specific materials that could be the bottleneck of EVs in China that recycling can help, such as cobalt and manganese, rather than lumping them together with other materials with fewer issues, such as nickel. How about lithium? It would deserve some discussion (even if it is less serious). Remember, the issue with cobalt and manganese could be partly solved by the shift to LFP (which again could discourage the recycling incentive). But lithium would stay there as long as lithium-ion batteries remain dominant, so it applies to all scenarios presented. For a more complete discussion, the authors may want to briefly mention the prospect of some new battery advancements (such as sodium batteries) as they could again change the bottleneck issues and challenge the solutions discussed.
There are still some vague aggregated statistics in lines 130-134: "The LIB recycling roadmap reveals that the total demand for cobalt, lithium, nickel, and manganese in EV production soared to 204, 222, 602, and 195 hundred tons in 2020 - a 900-fold increase from 2010 levels (Fig. 1). However, only 2.8, 3.1, 8.3, and 2.7 hundred tons of these critical materials were sourced from recycled batteries, meeting just 1.4% of the total demand." Please elaborate on what the 900-fold increase and 1.4% refer to when discussing the materials separately.

Response:

We are very thankful for your insightful suggestions. We appreciate your attention to the discussion of results, particularly regarding the analysis of lithium and the issue of vague aggregated statistics. To address your concern, we first provide a more detailed discussion on lithium and advancements in battery cathode technology. We then clarify the aggregated statistics to ensure transparency and accuracy. Below are our detailed improvements to the points you raised:

- Discussion on lithium and new battery advancements: Although lithium poses a lower resource risk, it deserves greater attention due to two major challenges in supply and recycling. 1) Lithium has a lower recycling rate than other valuable materials such as cobalt and nickel[1]. A few companies are willing to extract lithium due to its low profitability. Additionally, lithium is recovered through hydrometallurgical process but not pyrometallurgical ones. By direct cathode recycling technology (in the RP-DIR scenario), our results indicate that self-sufficiency rates for cobalt, nickel, and manganese range from 80% to 123%, whereas for lithium, the range is only 67% to 104%. 2) Lithium is difficult to substitute in batteries[2]. While the cobalt and manganese supply issues can be partially mitigated by transitioning to LFP batteries, this does not resolve the lithium supply challenge as long as LIBs remain dominant. In this context, new battery advancements such as sodium batteries present a potentially viable substitute for LIBs.

  Based on the resource challenge of lithium, we further discuss the issue of lithium and battery advancements in the Discussion section, as outlined below:

  "Although inexpensive-material cathode technology (LFP currently) could help reduce China's dependence on critical materials like cobalt, manganese, and nickel, it fails to address the lithium shortage as long as lithium-ion batteries remain the mainstream technology. Moreover, this cathode type is the least effective in mitigating emissions. As EV adoption accelerates under China's carbon neutrality target, lithium will play an increasingly vital role in the national economic system[2,3]. Therefore, greater research efforts should be directed toward advancing battery cathode technology, such as sodium batteries, which serve as a low-cost alternative to lithium-ion batteries and are crucial for alleviating the burden on the critical materials supply chain caused by lithium-ion batteries[4,5]". (Please see the **Discussion** in lines 430-439)

- Clarify the aggregated statistics: We discuss the materials separately, and we also provide the source data of these statistics (Please see the Supplementary data related to Fig. 1 for more details).

  The revised sentences are as follows:

  "The LIB recycling roadmap reveals that the total demand for cobalt, lithium, nickel, and manganese in EV production surged to 204, 222, 602, and 195 hundred tons in 2020, a 900-fold increase from 2010 levels (Fig. 1). However, the supply of these materials from recycled sources remains marginal, covering only 1.3% of the demand for cobalt, nickel, and manganese, and an even lower 1.1% for lithium". (Please see the revised section in lines 124-128)

Reference cited above:

[1] Costa CM, Barbosa JC, Gonçalves R, Castro H, Campo FJD, Lanceros-Méndez S. Recycling and environmental issues of lithium-ion batteries: Advances, challenges and opportunities. Energy Storage Materials **37**, 433-465 (2021).

[2] Sun X, Hao H, Geng Y, Liu Z, Zhao F. Exploring the potential for improving material utilization efficiency to secure lithium supply for China's battery supply chain. Fundamental Research 4, 167-177 (2024).

[3] Sun X, Hao H, Zhao F, Liu Z. The Dynamic Equilibrium Mechanism of Regional Lithium Flow for Transportation Electrification. Environmental Science & Technology **53**, 743-751 (2019).

[4] Yao A, Benson SM, Chueh WC. Critically assessing sodium-ion technology roadmaps and scenarios for techno-economic competitiveness against lithium-ion batteries. Nature Energy, (2025).

[5] Vaalma C, Buchholz D, Weil M, Passerini S. A cost and resource analysis of sodium-ion batteries. Nature Reviews Materials 3, 18013 (2018).

Comment 4

<u>Map representation:</u> In the rebuttal letter, in response to my previous request related to Supplementary Figs, the authors acknowledge that "To ensure that our work aligns with the scientific focus and publication standards, we remove controversial, unsubstantiated territorial claims in the manuscript." I insist that such a principle must be applied throughout the manuscript, including panel a of figure 5 that is newly inserted.

<u>Response:</u>

Thank you for your careful review and for pointing out the concern of map representation. To ensure scientific rigor and clarity, we have removed the map inserted in Figure 5a and replaced it with a refined illustration that more explicitly conveys the economic viability of unit battery recycling. The revised figure offers a clearer and more quantitative representation of the economic performance of battery recycling across different scenarios, incorporating the effects of economies of scale. This modification aligns with the principle outlined in our previous response, ensuring that all visual representations in the manuscript adhere to scientific standards.

Comment 5

Writing: There remain many opportunities for the authors to improve word choices and grammar issues to make the manuscript more readable. Below are some examples (but not an exhaustive list)
- please review again thoroughly.
- "donate" (Fig2, 5, Line 298) -> "denote"
- "a strategically full-spectrum framework" (Line 9): Consider rephrasing to "a comprehensive framework" for clarity and conciseness.
- "with a at least 84% battery collection target" (Line 10): remove "a"
- "disassembly and recycling process" (Fig 5):-> "processes"
- "maximums cost-efficiency" (Line 17): Correct to "maximizes cost-efficiency."
- "projected to reach 54 and 116 times their 2022 production capacities" (Line 14,174): The phrasing is awkward. Consider: "expected to exceed their 2022 production capacities by 54 and 116 times."
- "latent risk of soaring prices" (Line 67): "potential risk" for better flow.
- "scrapped LIBs trends" (Line 141): This could be rephrased to "trends in scrapped LIBs."
- "coupled with the lifetime distribution forecasting model with the retrospective material flow analysis" (Line 116): Overly complex; simplify
- "the waste batteries are first used for the direct application" (Fig 1) -> "waste batteries are initially used for direct applications."
- "flows onto the recycling market" (Line 123): Replace "flows onto" with "enters."
- "Detailly put" (Line 121): Replace with "In detail" or "Specifically."
- "latent scenarios" (Line 586): Consider "potential scenarios".
- "life-cycle unit" (Line 346): replace unit by cost.
- Ensure consistent capitalization or lowercase for material names throughout the manuscript. (Nickel/nickel ...)

Response:

We sincerely appreciate your detailed feedback on word choices and grammatical improvements. Specifically, we have corrected the instances highlighted in your comments. Furthermore, we have conducted a thorough review of the manuscript to ensure overall grammatical accuracy, precise wording, and consistency in terminology beyond the examples listed. We greatly appreciate your meticulous attention to these writing details, which has been instrumental in further refining the manuscript.

Comment 6

Method reference: Make sure to add relevant citations to the methods section to refer to methods and tools that you were building on. There are restrictions on the number of citations in the main text but not in the methods section.

Response:

We appreciate the reviewer's suggestion regarding method citations. In response, we have carefully reviewed the methods section and incorporated relevant citations to appropriately reference the methodologies and tools we have built upon. Specifically, we have added the relevant method citations under the corresponding subtitles in the Methods section. (Kindly see the Methods section for more details)

Reference cited above:

■ Modeling overview

[1] Wang H, et al. China's electric vehicle and climate ambitions jeopardized by surging critical material prices. Nature Communications 14, 1246 (2023).

[2] Milovanoff A, Posen ID, MacLean HL. Electrification of light-duty vehicle fleet alone will not meet mitigation targets. Nature Climate Change 10, 1102-1107 (2020).

[3] Martínez-Hernando M-P, Bolonio D, Ortega MF, Llamas JF, García-Martínez M-J. Material flow analysis and regional greenhouse gas emissions associated to permanent magnets and batteries used in electric vehicles. Science of The Total Environment 904, 166368 (2023).

■ The forecasting of EV adoption under China's carbon neutrality target

[4] Wang Z, et al. Unequal residential heating burden caused by combined heat and power phase-out under climate goals. Nature Energy 8, 881-890 (2023).

[5] Kumar RR, Guha P, Chakraborty A. Comparative assessment and selection of electric vehicle diffusion models: A global outlook. Energy 238, 121932 (2022).

■ Lithium-ion battery scrappage roadmap

[6] Zubi G, Dufo-López R, Carvalho M, Pasaoglu G. The lithium-ion battery: State of the art and future perspectives. Renewable and Sustainable Energy Reviews 89, 292-308 (2018).

[7] Tao Y, Rahn CD, Archer LA, You F. Second life and recycling: Energy and environmental sustainability perspectives for high-performance lithium-ion batteries. Science Advances 7, eabi7633 (2021).

■ Simulation of critical material flows

[8] Rasmussen KD, Wenzel H, Bangs C, Petavratzi E, Liu G. Platinum Demand and Potential Bottlenecks in the Global Green Transition: A Dynamic Material Flow Analysis. Environmental Science & Technology 53, 11541-11551 (2019).

[9] Dong Z, et al. Projecting future critical material demand and recycling from China's electric passenger vehicles considering vehicle segment heterogeneity. Resources, Conservation and Recycling 207, 107691 (2024).

■ Calculating future life-cycle carbon emissions of battery

[10] Rosenberg S, et al. Combining dynamic material flow analysis and life cycle assessment to evaluate environmental benefits of recycling - A case study for direct and hydrometallurgical closed-loop recycling of electric vehicle battery systems. Resources, Conservation and Recycling 198, 107145 (2023).

[11] Feng T, et al. Energy transition in the new era: The impact of renewable electric power on the life cycle assessment of automotive power batteries. Renewable Energy 236, 121365 (2024).

[12] Yang H, et al. Life cycle assessment of secondary use and physical recycling of lithium-ion

batteries retired from electric vehicles in China. Waste Management 178, 168-175 (2024).
[13] Machala ML, et al. Life cycle comparison of industrial-scale lithium-ion battery recycling and mining supply chains. Nature Communications 16, 988 (2025).
[14] Cheng AL, Fuchs ERH, Michalek JJ. US industrial policy may reduce electric vehicle battery supply chain vulnerabilities and influence technology choice. Nature Energy 9, 1561-1570 (2024).
[15] Qi X, Liu Z, Li T. Design incentives of extended producer responsibility for electric vehicle producers with competition and cooperation. Omega 133, 103266 (2025).
■ Optimizing geospatial configuration of battery recycling
[16] Nguyen-Tien V, Dai Q, Harper GDJ, Anderson PA, Elliott RJR. Optimising the geospatial configuration of a future lithium ion battery recycling industry in the transition to electric vehicles and a circular economy. Applied Energy 321, 119230 (2022).
[17] Gonzales-Calienes G, Yu B, Bensebaa F. Development of a Reverse Logistics Modeling for End-of-Life Lithium-Ion Batteries and Its Impact on Recycling Viability—A Case Study to Support End-of-Life Electric Vehicle Battery Strategy in Canada. Sustainability 14, 15321 (2022).
■ Life-cycle cost-benefit analysis
[18] Lander L, et al. Financial viability of electric vehicle lithium-ion battery recycling. iScience 24, 102787 (2021).
[19] Xiong S, Ji J, Ma X. Environmental and economic evaluation of remanufacturing lithium-ion batteries from electric vehicles. Waste Management 102, 579-586 (2020).
[20] Dai Q SJ, Ahmed S, Gaines L, Kelly JC, Wang M. EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model, Argonne National Laboratory (2019).
[21] Dai Q, Spangenberger J, Ahmed S, Gaines L, Kelly JC, Wang M EverBatt: A Closed-loop Battery Recycling Cost and Environmental Impacts Model, Argonne National Laboratory (2019).

We sincerely appreciate the reviewer's valuable comments, which have significantly contributed to improving the quality of this study.

This paper is titled " **Lithium-ion battery recycling relieves the threat to electric vehicle ambitions of critical material scarcity under China's carbon neutrality**" looks very interesting, but it needs a serious major revision, and my comments are as follows:

In the Abstract section

The authors mentioned that they have done a customized integrated modelling framework with the future prediction of EV demand and LIB scrappage, and material recycling simulation which results in a great benefit to LIBs recycling. Also, they have mentioned that their findings highlight the urgent need to electrify and decarbonize the automotive sector with more developed closed-loop lithium-ion battery cycle strategies.

- They didn't mention any relation between these findings with the economic cost and its impact and contribution to the domestic and global economy and the other merits of the energy storage sector must be clearer.

In the Introduction section:

The authors have done a good survey about Evs, and the related investigations done in this issue, however, the beginning must start at least with information about the role of LIBs recycling and the decarbonization process that occurs in energy-related applications, it depends on closed-loop LIBs recycling methods.

- The author must be clear in this section and they have to introduce their topic as well.

Also, they have to show evidence that this modelling tool is very close to the results obtained from experiment investigations as well.

In the Result section:

!- All given images and figures are very bad in resolution and it need to be higher in resolution as well

2- However the authors mentioned they had given more scenarios of evaluation for EV material demand and recovery in the process of LIB recovery, but they didn't mention how they selected these types or in what base they have selected it.

3- They have done some calculations about the cost but it is not complete. They have to show the evidence that the findings and obtained results compared to experimental investigation done in that relation are close and costly effective.

4- They have to clearly demonstrate the challenges and limitations facing this method of working

5- Proofread of some sentences and paragraphs need to be checked again,