Sustainable Production and Consumption 54 (2025) 476–486

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Sustainability assessment of multi-life cycle recycling of copper based on the economic, resource and carbon criteria

Haixia Li [1], Yufeng Wu [*,1], Yifan Gu [*], Hongyang Yang, Zixin Bian, Huining Song, Guangli Zhou, Qingbin Yuan

Institute of Circular Economy, Beijing University of Technology, Beijing, China

ARTICLE INFO

Editor: Prof. Chao Zhang

Keywords:
Copper
Multi-life cycle recycling
Cumulative effect
Economic-resource-environmental
Sustainability

ABSTRACT

Copper's multi-life cycle recycling ensures sustainable copper supply but has brought about complex interrelated effects on the economy, resources, and environment. Examining the interconnections between the three to promote balance is crucial for the long-term sustainability of the copper industry. This study jointly utilized system dynamics, agent-based model, and life cycle assessment to construct interrelated pathways for the economy, resources, and carbon in multi-life cycle recycling of copper, then developed an economic-resource-carbon (ERC) sustainability assessment model to evaluate sustainability. The results indicate that carbon neutrality will lead to sustained growth in China's copper demand, which will reach a peak of 24.65 Mt in 2039 before slightly declining. Multi-life cycle recycling will rapidly increase the share of recycled copper, and the copper industry will have the copper that has been recycled 12 times by 2050. The cumulative contributions of profit increase, resource depletion reduction, and carbon reduction brought by multi-life cycle recycling will accumulate with the increase of recycling times, thereby improving the ERC sustainability. To promote the long-term sustainability of the copper industry, we recommend fully leveraging the advantages of new material substitution before 2030, implementing a carbon tax as soon as possible after 2030, and recognizing the potential of expanding copper concentrate imports after 2040 while enforcing the carbon tax policy.

Nomenclature

A	Total area of the radar chart formed by the various indicators
AS_{ERC}	Average Sustainability
E_{ERC}	Evenness of economic index, resource index, and carbon index
L	Most uniform distribution of all indicators with the same radar chart perimeter
r_i	The original value of indicator i
$r_{i,max}$	Maximum value of the original values of indicator i
$r_{i,min}$	Minimum value of the original values of indicator i
S_C	Index of carbon indicator
S_E	Index of economic indicator
S_{ERC}	ERC Sustainability
S_{max}	Maximum value of all indicator indices
S_{min}	Minimum value of all indicator indices
S_R	Index of resource indicator
w_i	Weight of indicator i

1. Introduction

In recent years, with the improvement of recycling scale and technology, the recycling model has gradually evolved towards multi-life cycle recycling (Gu et al., 2020). As a circular economy model, multi-life cycle recycling can reduce dependence on primary resources by extending the usage cycle of resources. Metal resources can theoretically be recycled infinitely (McMillan et al., 2012). Taking copper as an example, its resource recycling rate is approximately 95 % (Ciacci et al., 2015). Multi-life cycle recycling can enable 1 unit of primary copper resource extraction to cumulatively provide 20 units of copper services. This will contribute to achieving the sustainable supply of copper resources. In addition, by reducing the extraction of primary resources, multi-life cycle recycling slows down the depletion of non-renewable resources such as minerals and fossil fuels (Gu et al., 2020), thereby reducing environmental damage. It also helps mitigate the impact of raw material price fluctuations (Gorman and Dzombak, 2018). It is evident

* Corresponding authors.
E-mail addresses: wuyufeng3r@126.com (Y. Wu), guyifan@bjut.edu.cn (Y. Gu).
[1] These authors are co-first authors.

https://doi.org/10.1016/j.spc.2025.01.016
Received 4 November 2024; Received in revised form 17 January 2025; Accepted 24 January 2025
Available online 29 January 2025

that multi-life cycle recycling offers a new approach to achieving a balance between resources, environment, and economy.

Copper, as a key resource in the modern economy, is widely used in various fields such as power, electronics, building, and transportation (Lu et al., 2024). With the rising global demand for clean energy and infrastructure development, copper consumption is expected to continue growing in the future (Born and Ciftci, 2024; Guo et al., 2024; Vidal et al., 2019). It is estimated that global demand for refined copper will increase to around 62 million tonnes (Mt) by 2060, a 1.6-fold increase compared to 2020 (Gu et al., 2024). However, the growth in demand will lead to an annual increase in copper ore extraction, and the gradual depletion of high-grade ores will result in rising extraction costs (Sverdrup et al., 2014), ultimately causing price fluctuations that affect profits (Ryter et al., 2022). At the same time, primary copper refining is highly dependent on non-renewable resources such as minerals and fossil fuels. According to estimates, producing 1 t of primary copper consumes 34,154.6 MJ of non-renewable resource equivalents and generates 3417.5 kg of CO_2 equivalent, posing a threat to the ecological environment (Chen et al., 2019). It is evident that the copper industry faces multiple challenges, including economic fluctuations, resource depletion, and environmental disruption, which severely hinder the sustainable development of the copper industry. The United Nations' Sustainable Development Goals (SDG) (SDG, 2015) aim for balanced sustainability across multiple sectors, rather than focusing on just a single area (Watari and Yokoi, 2021; Xu et al., 2020). Due to the close interconnections between these sectors in the copper production link, improving the sustainability of the copper industry contributes to resources (SDG 12), the economy (SDG 8), and climate change (SDG 13). Therefore, it is urgent to explore new pathways for the sustainable development of the copper industry that balance the economy, resources, and the environment. Fortunately, copper can be recycled infinitely (Gu et al., 2020), making multi-life cycle recycling an effective approach to balancing the economic, resource, and environmental challenges of the copper industry. Each recycling process will generate the effects of profit growth, resource conservation, and environmental protection. After multiple cycles of recycling, it will produce significant cumulative effects on the economy, resources, and the environment (Li et al., 2023a). These cumulative effects are crucial in the circular economy and sustainable development. Therefore, evaluating the sustainability of multi-life cycle recycling of copper based on the economic-resources-environment multidimensional correlation system is crucial for the long-term sustainable development of the copper industry.

In recent years, the analysis of resources, environment, and economic effects from the perspective of the entire lifecycle of copper has been widely discussed. (Zhang et al., 2021) and (Zhang et al., 2023) indicate that the recycling of copper can reduce the depletion of non-renewable resources by more than 50 %, significantly alleviating the risk of resource depletion. (ICA, 2021) indicated that the production cost of recycled copper is much lower than that of primary copper, indicating that recycling helps to reduce costs and thus increase profits. The life cycle assessment (LCA) results of primary copper and recycled copper by (Chen et al., 2019) and (Zhang et al., 2023) show that recycling can reduce the environmental impact of copper production processes by more than 60 %. However, their current research has focused on the sustainability contributions of individual dimensions within a single recycling cycle, lacking studies on the sustainability of the economic-resource-environment multidimensional correlation system in the context of multi-life cycle recycling.

China is the largest consumer and producer of refined copper (Dong et al., 2020), accounting for 51 % and 37 % of global consumption and production, respectively (Nakajima et al., 2018; Yin et al., 2024). From 2013 to 2023, China's production of scrap copper reached 1.2 times the total amount generated before 2013, and it continues to grow exponentially (Li et al., 2024). It is evident that the multidimensional correlation between the economy, resources, and environment in the multi-life cycle recycling of copper in China will become more complex in the future. Studying the sustainability of China's copper industry based on the economic, resource and carbon criteria will provide valuable insights for the sustainable development of the global copper industry. Carbon neutrality has placed carbon emissions at the core of environmental issues (Liang et al., 2023), and carbon reduction in the metal industry is crucial for achieving carbon neutrality (Wu et al., 2024a). Therefore, this study aims to evaluate the sustainability of multi-life cycle recycling of copper in China based on the economic, resource and carbon criteria. The research questions to be addressed are as follows: (1) How do cumulative profit, cumulative resource depletion reduction, and cumulative carbon reduction change during the multi-life cycle recycling of copper? (2) How sustainable is copper multi-life cycle recycling based on the economic, resource and carbon criteria? (3) How do different policy scenarios affect the sustainability of copper multi-life cycle recycling? The rest of the paper addresses the following topics: In the literature review section, we summarized the existing literature on copper research to find research space. In the methodology section, we combined system dynamics (SD), agent-based model (ABM), LCA, and the ERC sustainability assessment model to develop an ERC sustainability evaluation framework for the multi-life cycle recycling of copper. In the results section, we calculated the ERC sustainability of copper multi-life cycle recycling. In the discussion section, we used policy simulations to explore ways to improve the ERC sustainability of the copper industry. In the conclusions section, we summarized the main findings of this study. Our goal is to provide valuable references for promoting the sustainable development of the multi-life cycle recycling of copper based on the economic, resource and carbon criteria.

The contributions and significance of this study are as follows. From a theoretical perspective, Firstly, this study constructs a quantitative model of the multi-life cycle recycling structure to account for the recycling structure of copper. This method demonstrates strong universality and can be broadly applied to the quantitative analysis of multi-life cycle recycling structure for other non-ferrous metals. Secondly, this study integrates SD, ABM, and LCA to construct a complex system that establishes an interrelated pathway for clarifying the relationships among economic, resource, and carbon indicators in the multi-life cycle recycling of copper. In particular, the coupling of SD and ABM enables a simultaneous understanding of macro-level dynamic feedback within the complex system and the micro-level decision-making processes among individual agents. Thirdly, this study develops an ERC sustainability assessment model, providing an innovative framework for transitioning the sustainability evaluation of the copper industry from a single-dimensional to a multi-dimensional approach. From a managerial perspective, this study provides valuable theoretical references for policymakers in formulating policies to enhance the sustainability of the copper industry. The policy simulation fully considers China's future development direction and provides valuable guidance for the sustainable development of the copper industry.

2. Literature review

The limited mining resources make recycling a new direction to promote sustainable development (Li et al., 2023a). With the improvement of recycling technology and the expansion of recycling scale, the recycling model have shifted towards a multi-life cycle recycling model (Gu et al., 2020). Especially for metal resources, they can theoretically be recycled infinitely (McMillan et al., 2012), thereby creating a multiplier effect on resource supply and offering potential for sustainable resource development. In recent years, theoretical and practical research on multi-life cycle recycling has made significant progress in various fields. In terms of theoretical advancements, (McMillan et al., 2012) stated that low recycling rates might limit recycling potential, thereby hindering the realization of multi-life cycle recycling. (Go et al., 2015) summarized that multi-life cycle recycling of products promotes economic sustainability and reduces environmental burdens. (Suhariyanto et al., 2017) reviewed the advantages and necessity of multi-life cycle assessment from nine aspects, including objectives, functional units, and system boundaries. (Gu et al., 2020) discussed the internal mechanism by which the infinite recyclability of metal resources leads to a multiplier effect on resource supply. In terms of practical applications, (Li et al., 2023a) developed an eco-efficiency evaluation model for multi-life cycle recycling of lead resources, and the results showed that the eco-efficiency increased with the increase of recycling times. (Gu et al., 2020) and (Mata and Costa, 2001) respectively constructed environmental performance accounting methods for multi-life cycle recycling of plastic bottles and beer bottles, and found that the environmental impact of plastic bottles and beer bottles gradually decreased with the increase of recycling times. (Aydin and Badurdeen, 2019) developed an environmental and economic assessment model for the multi-life cycle recycling of toner cartridges. They found that multi-life cycle recycling could save 25.4 % of the total cost and 21.6 % of non-renewable resource consumption compared to single-lifecycle recycling. (Yang et al., 2015) and (Krystofik et al., 2018) respectively evaluated the performance of multi-life cycle recycling of gasoline engines and office furniture, and found that both environmental benefits and long-term economic feasibility were improved. It is evident that scholars have conducted rich theoretical and practical research on multi-life cycle recycling of lead resources, plastic products, and other materials, providing important support for achieving sustainable development. In contrast, research on the multi-life cycle recycling of copper remains unexplored. However, as a critical resource, copper is widely used in various fields such as power, electronics, and transportation (Guo et al., 2024; Lu et al., 2024), and it is expected to play a vital role in the global energy transition driven by carbon neutrality goals (Gu et al., 2024; Yin et al., 2024). Therefore, conducting research on the multi-life cycle recycling of copper holds significant practical importance.

With the increasing importance of sustainable development, the sustainability of the copper industry has also attracted widespread attention. Scholars have conducted extensive research on the sustainability of the copper industry in various dimensions such as economy, resources, and carbon emissions. (Zhang et al., 2023) used LCA to evaluate the environmental impact of three types of copper waste: smelting slag, copper ash, and anode slide. The results showed that the recycling of copper can reduce the depletion of non-renewable resources by more than 50 %. (Zhang et al., 2021) and (Kulczycka et al., 2016) also reached similar conclusions in his research. The International Copper Association (ICA, 2021) indicated that the recycling of copper can significantly reduce production costs, thereby increasing profits. (Chen et al., 2019) used LCA to evaluate the environmental benefits of recycled copper and primary copper, and found that the total environmental impact of recycled copper was only 1/8 of that of primary copper. (Gu et al., 2024) used LCA to evaluate the carbon emissions of recycled copper from waste cables, and found that the recycling process reduced carbon emissions by 94.82 % compared to the primary process. Existing literature of the copper industry sustainability indicates that the recycling of copper not only alleviates the pressure from the depletion of non-renewable resources but also significantly reduces environmental impacts, while offering strong economic feasibility. It demonstrates notable sustainability advantages across the economic, resource, and environmental dimensions. However, existing research mainly focuses on the sustainability assessment of single-dimension aspects within a single recycling cycle, while comprehensive sustainability analysis of the economic, resource and carbon criteria across multi-life cycle recycling remains relatively insufficient. However, multidimensional comprehensive sustainability assessment has been widely applied in sustainability evaluations in fields such as agriculture (Keson et al., 2024; Shubbar et al., 2024), water management (Li et al., 2023b; Wu et al., 2024b), and renewable energy (Raihan and Mainul Bari, 2024; Wang et al., 2024a). Therefore, there is an urgent need to assess the multidimensional balanced sustainability of the copper industry, integrating economic, resource, and carbon emission aspects, to promote the long-term sustainable development of the copper industry.

By constructing a complex network system, it is possible to integrate resource, economic, and carbon multidimensional indicators. Current methods primarily include **multi-attribute decision making** (Du et al., 2025; Hussain et al., 2024), multilayer network model (Dai et al., 2024; Khomami et al., 2024), and social network analysis (Ghorbani et al., 2024; Wang et al., 2024b). However, these methods fail to capture the dynamic relationships or feedback effects between variables, or the evolution of the network over time. The copper industry involves multiple links, including mining, primary copper refining, and recycling. These links and the producers within each link are interconnected, forming a complex network of interactions and feedbacks. SD, as a powerful method for exploring the interconnections and feedbacks between elements in complex systems (Chintalapati et al., 2022), can effectively analyze the dynamic behavior of complex systems at a macro level, capturing the feedback relationships and long-term trends between variables. For example, the feedback relationships between supply and demand, prices, profit rates, capacity, and production in the copper industry. However, SD cannot visually capture the decision-making processes and interaction transmission mechanisms between micro-level agents (Tian et al., 2021). ABM can address this limitation. As an effective tool for simulating the behavior of agents in complex systems (Meng et al., 2018), ABM can clearly demonstrate the real decision-making processes and interaction behaviors between micro-level agents by designing rules and decision logic (Baqueri et al., 2019). For example, how each agent makes decision judgments based on market dynamics and changes. In summary, SD and ABM each have their own unique features. To understand the overall pattern of the complex system behavior at the macro level, while also capturing how decision-making among micro-level agents drives system changes, this study combines SD and ABM to fully leverage the strengths of both approaches. Furthermore, by combining LCA, a jointly driven complex system is constructed to achieve an integrated analysis of the economy, resources, and carbon in the copper industry.

3. Methodology

The research framework of this study is shown in Fig. 1. First, we constructed an SD + ABM coupling model to evaluate the supply-demand structure and prices of various links in the future copper industry. Among them, the copper demand and the scrapped copper for multi-life cycle recycling are calculated by a stock-based model (specific modeling processes of the stock-based model are detailed in Supplementary Information S1). Second, we used LCA to calculate the reduction in resource depletion (in this study, resource depletion refers to the consumption of non-renewable resources such as ores and fossil fuels) and carbon emissions in recycled copper production compared to primary copper production. Finally, we calculated the cumulative profit, cumulative resource depletion reduction, and cumulative carbon reduction, and used them as economic indicator, resource indicator, and carbon indicator to construct an ERC sustainability assessment model to evaluate the sustainability of copper multi-life cycle recycling.

The model proposed in this study features the following innovations: Firstly, the integration of SD, ABM, and LCA establishes an interrelated pathway for economic, resource, and carbon indicators in the multi-life cycle recycling of copper, facilitating the clarification of their complex interrelationships. Among them, the coupling of SD and ABM can more comprehensively describe the macroscopic dynamic behavior and microscopic decision-making process in complex systems. Secondly, the ERC sustainability assessment model is developed, which integrates the dimensions of profit growth, resource depletion reduction, and carbon reduction, achieving a multi-dimensional sustainability evaluation for the copper industry.

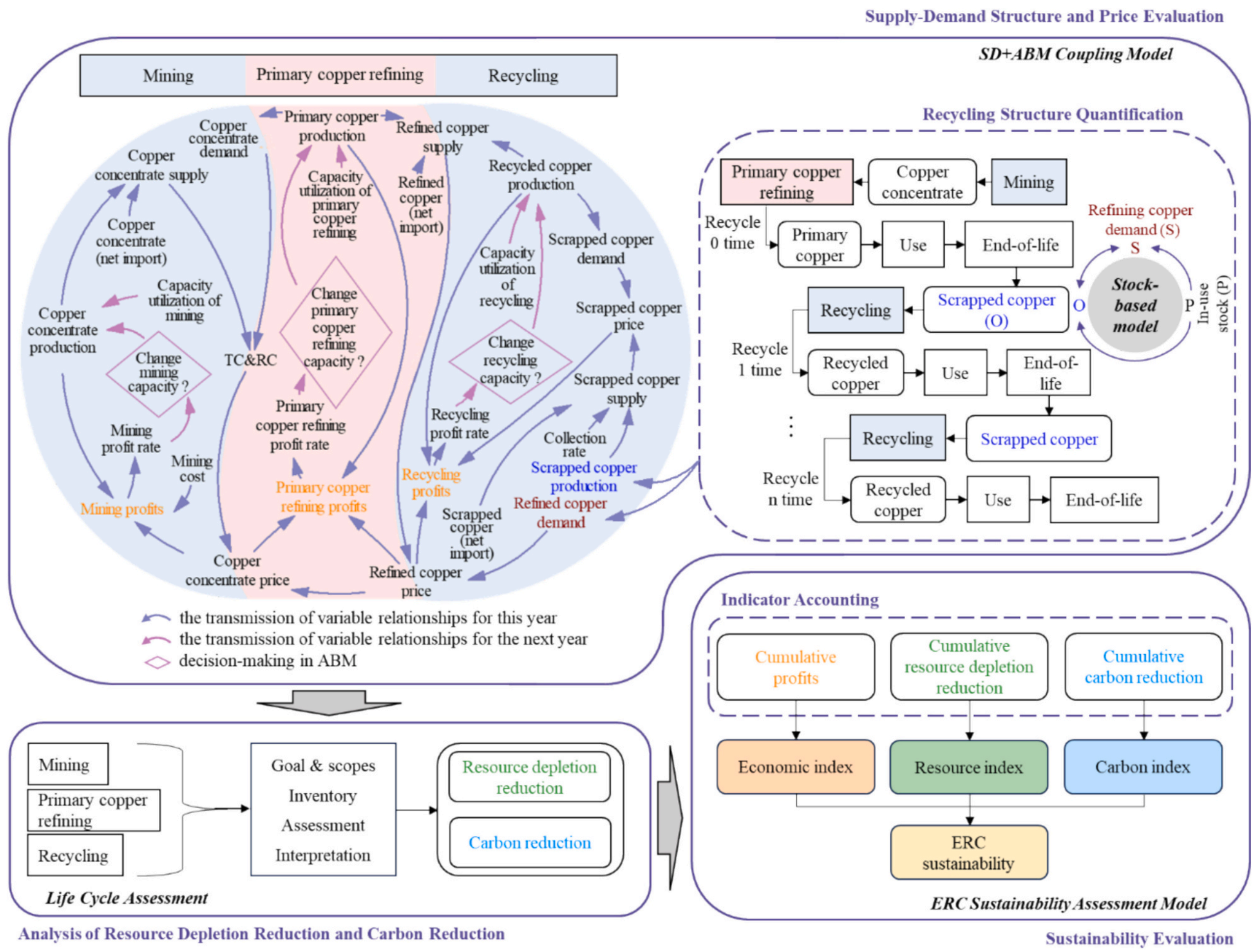

Fig. 1. Sustainability evaluation framework for multi-life cycle recycling of copper based on the economic, resource and carbon criteria.

3.1. Supply-demand structure and price evaluation

The profits, resource depletion, and carbon emissions of the copper industry mainly come from mining, primary copper refining (including smelting), and recycling links. Therefore, this study focuses on these three links.

Due to the laws of supply and demand in a market economy, there is a mutually driving and influencing relationship between supply, demand, and prices (Samuelson and Nordhaus, 2010). We used historical data from 2000 to 2020 to simulate the relationship between the supply-demand gap and prices of copper concentrate, refined copper, and scrapped copper. Based on these relationships, we constructed an SD + ABM coupling model to evaluate the supply-demand structure and prices of various links in the copper industry. Among them, the refined copper demand and the scrapped copper from multi-life cycle recycling, predicted by the stock-based model, serve as social constraints for the model. SD is used to understand the overall patterns of complex systems at the macro level and to capture feedback relationships between variables: The copper concentrate production and copper concentrate net imports (evolution trend of copper concentrate net imports is detailed in Notes 2 of Supporting Information S2) affect the copper concentrate supply; The primary copper production, recycled copper production, and refined copper net imports (evolution trend of refined copper net imports is detailed in Notes 3 of Supporting Information S2) affect the refined copper supply; The scrapped copper production, collection rate (detailed in Notes 1 of Supporting Information S2), and scrapped copper net imports (evolution trend of scrapped copper net imports is detailed in Notes 4 of Supporting Information S2) affect the scrapped copper supply; The supply-demand gaps for copper concentrate, refined copper, and scrapped copper are used to calculate the treatment charge and refining charge (TC&RC), refined copper price, and scrapped copper price, respectively; After price formation, mining agent use copper concentrate production, copper concentrate price, and mining cost (evolution trend of mining cost is detailed in Notes 5 of Supporting Information S2) to calculate profits; Primary copper refining agent use primary copper production, refined copper price, and copper concentrate price to calculate profits; Recycling agent use recycled copper production, refined copper price, and scrapped copper price to calculate profits; The profits of each link affect the profit rate; The profit rate impacts each agent's decision-making on whether to adjust capacity for the next year; Ultimately, the capacity and capacity utilization rates of each link (evolution trend of capacity utilization for each link is detailed in Notes 6 of Supporting Information S2) determine the production of copper concentrate, refined copper, and scrapped copper in the next year. The variables evolve year after year like this. In the process of evolution, how profit rate affects the decision-making of various agents to adjust capacity needs to be achieved through ABM designing rules and decision-making logic based on profit rate, otherwise the subsequent feedback of SD will be interrupted. On the contrary, without the profit rate feedback from SD, ABM will not be able to output decision results based on decision logic. The cooperation between SD and ABM ensures the smooth progress of the entire evolution process. The formulas between the above variables are detailed in Table S1 of Supporting Information S2.

3.2. Recycling structure quantification

We used a stock-based model to predict the scrapped copper generated from the multi-life cycle recycling of copper. After mining, copper concentrate is obtained, which then undergoes primary copper refining to produce primary copper. After use and end-of-life, primary copper generates scrapped copper, which then enters the recycling link and is recycled for the first time to produce recycled copper. The recycled copper production of each recycling is influenced by variables such as supply and demand, price, and profit rate during the recycling link. Then, the recycled copper will repeat the above process until it is recycled for the nth time (Gu et al., 2020). We refer to primary copper as copper that has been recycled 0 times; The recycled copper produced after the first recycling of scrapped copper is called recycled 1 time, and so on. From this, we can obtain the recycling structure of copper, which refers to the proportion of copper with different recycling times in the total amount of copper resources produced in society.

3.3. Analysis of resource depletion reduction and carbon reduction

We used LCA to separately calculate the resource depletion and carbon emissions of primary copper production (mining link + primary copper refining link) and recycled copper production (recycling link), and then analyzed the reduction in resource depletion and carbon emissions of recycled copper production compared to primary copper production. The fossil fuel and raw material consumption at the input end of each link, as well as the copper resource output and emission data at the output end, were obtained from the environmental impact assessment reports of leading and representative enterprises in China. The specific details of the implementation of LCA for each link are provided in Supporting Information S3. The input and output inventories for the mining link and the primary copper refining link are detailed in Table S2 and Table S3 of Supporting Information S3, respectively. For the recycling link, considering the diverse sources of scrapped copper, we classified scrapped copper into four categories based on the Chinese National Standard “Copper and Copper Alloy Scrap” (GB/T 13587–2020): high-quality scrap copper, low-quality scrap copper, waste cables, and waste circuit boards. The input and output inventories for the recycling of these four categories of scrapped copper are detailed in Table S4-S7 of Supporting Information S3, respectively.

3.4. Sustainability evaluation

In the multi-life cycle recycling of copper, each cycle of recycling will contribute to profit increase, resource depletion reduction, and carbon emission reduction. These contributions accumulate progressively with the increase in recycling cycles, ultimately generating a significant cumulative effect, which is crucial for sustainable development. Therefore, to evaluate the sustainability of the copper industry, we calculated the cumulative profit, cumulative resource depletion reduction, and cumulative carbon reduction (The method of indicator accounting is detailed in Supporting Information S4), which serve as economic, resource, and carbon indicators, respectively, and used these indicators to construct an ERC sustainability assessment model with reference to the sustainability assessment methods developed in recent studies (He et al., 2024; Hua et al., 2020; Jiang et al., 2022; Nhamo et al., 2020). The specific steps are as follows.

3.4.1. Normalization

Considering the uneven distribution of copper production over time, we take the average of each indicator (such as the average cumulative carbon reduction = cumulative carbon reduction/cumulative copper service). We normalize each indicator into a unified scale from 0 to 100. Since the indicators we selected are all positive indicators, the larger the original value, the more favorable it is. Therefore, the following methods are adopted for normalization (Lv et al., 2024; Wang et al., 2023).

$$S_{E,R,C} = \frac{r_i - r_{i,min}}{r_{i,max} - r_{i,min}} \times 100 \tag{1}$$

Where $S_{E,R,C}$is the index of economic, resource, and carbon indicators. The larger S, the stronger the sustainability (He et al., 2024). The indicator index here is relative, and a value of 100 does not necessarily mean complete sustainability (Xu et al., 2020). $r_{i,max}$ and $r_{i,min}$ are the maximum and minimum values of the original values for each indicator.

3.4.2. ERC sustainability

The arithmetic mean of the three indicator indices can represent the average sustainability (Schmidt-Traub et al., 2017; Xu et al., 2020). The equal weight of each indicator indicates that each indicator is equally important for achieving sustainability (Hua et al., 2020).

$$AS_{ERC} = (S_E + S_R + S_C)/3 \tag{2}$$

Where AS_{ERC} is the average sustainability.

When the three indices are uneven, the arithmetic mean may calculate the same average sustainability, which we solve by evaluating the evenness (He et al., 2024; Jiang et al., 2022).

$$E_{ERC} = \frac{A}{\pi \times (L/2\pi)^2} \tag{3}$$

$$A = \sum_{i=1}^{3} \pi w_i {S_i}^2 \tag{4}$$

$$L = 2(S_{max} - S_{min}) + \sum_{i=1}^{3} 2\pi w_i S_i \tag{5}$$

Where E_{ERC} is the evenness of the three indicator indices. The larger E_{ERC}, the more even the three indicators are. w_i is the weight, and the weight of each indicator is 1/3 to indicate the equal importance of each indicator (Hua et al., 2020; Schmidt-Traub et al., 2017). S_{max} and S_{min} are the maximum and minimum values of all indicator indices.

The ERC sustainability is expressed as:

$$S_{ERC} = \sqrt{AS_{ERC} \times E_{ERC}} \tag{6}$$

Where S_{ERC} represents ERC sustainability, indicating that the three indices are balanced and have a high average value.

3.5. Data sources and key assumptions

Data on production, consumption, imports and exports, prices, profits, and income for each link are sourced from the China Economic and Social Development Yearbook (CESDY, 2020). The goal of producers is to pursue maximum profit, and the level of profit determines their production decisions (Varian, 2014). We refer to (Meng et al., 2018) to set up the decision-making process for producers to adjust their production capacity. For the profit rate at which each entity decides to reduce capacity, we refer to (Zhang, 2021). For the profit rate at which capacity expansion is decided, the mining entities refer to (Fan, 2022), while the primary copper refining and recycling entities refer to (Zhang, 2021). When the profit rate falls between the two, no capacity changes are made. The setting standards for capacity increase and decrease values for each link are detailed in in Supporting Information S5.

4. Results

4.1. The evolution trend of China's copper industry

As shown in Fig. 2 (a), due to the rapid growth of recycled copper production in the future, the demand for primary copper will be

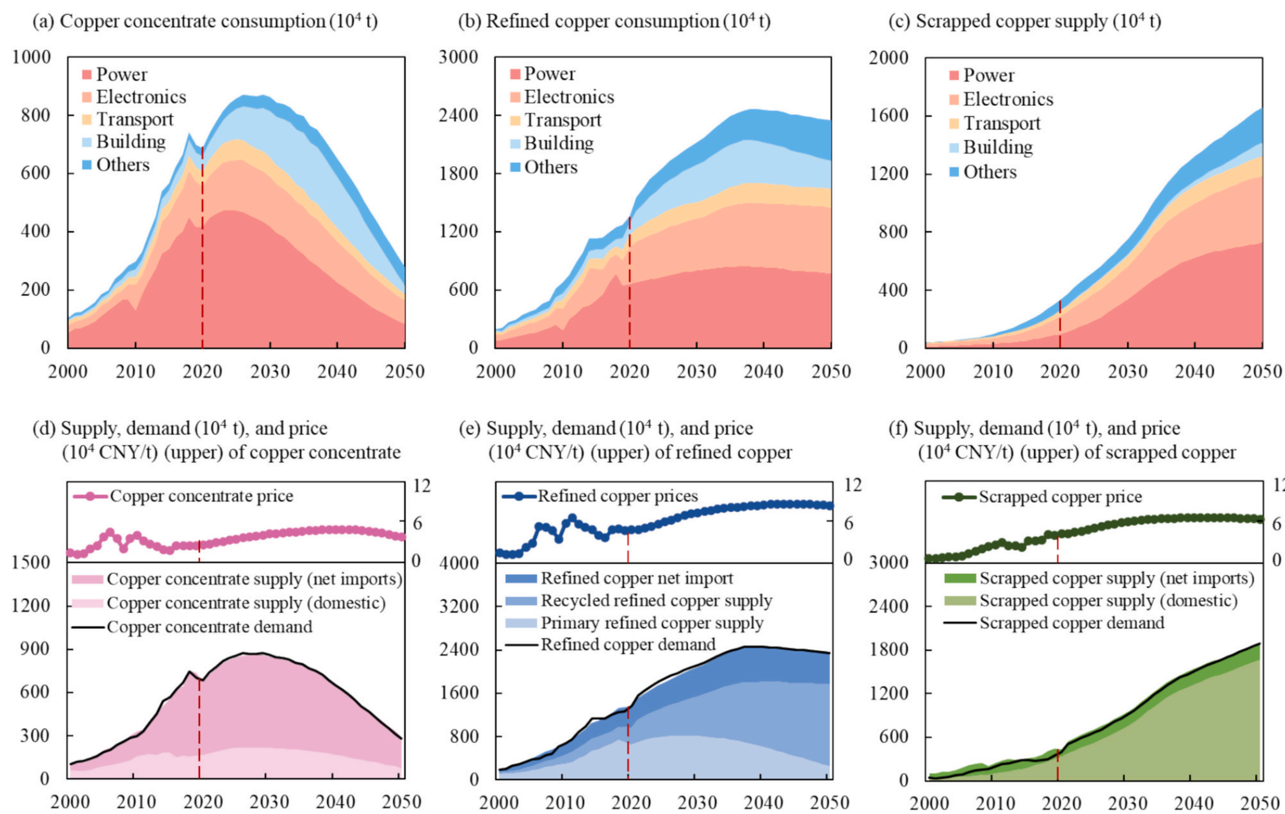

Fig. 2. Evolution trend of China's copper industry. (a) Copper concentrate consumption in each department. (b) Refined copper consumption in each department. (c) Scrapped copper supply from each department. (d) Supply, demand, and price of copper concentrate. (e) Supply, demand, and price of refined copper. (f) Supply, demand, and price of scrapped copper.

hindered. The consumption of copper concentrate, which is a raw material for primary copper production, will peak at 8.71 Mt in 2029 and then rapidly decline, reaching 2.79 Mt by 2050. Affected by carbon neutrality, the power sector will become the largest consumer of copper concentrate.

As shown in Fig. 2 (b), due to the gradual saturation of new energy infrastructure and the decline in the population in China, the demand for copper resources will peak at 24.65 Mt in 2039 after continuous growth, and then begin to decline slightly thereafter. The global trend towards electrification will drive rapid growth in copper demand in the power sector. However, due to the cyclical nature of the infrastructure in the power industry, once gradually improved, the growth rate of copper demand in this sector may slow down or even enter a stable period. The development of emerging technologies such as 5G, the internet of things, and artificial intelligence will drive sustained growth in copper demand in the electronics sector. However, the frequency of updates and replacements for electronic and electrical products is relatively high, and the copper demand in the electronics sector may continue to rise over a longer period. So, the power sector, influenced by carbon neutrality, will have the highest copper consumption, expected to peak at 8.46 Mt in 2037, followed by the electronics sector, which is projected to peak at 6.82 Mt in 2047.

As shown in Fig. 2 (c), the copper resources consumed in large quantities in the early stage will generate a large amount of scrapped copper after their lifespan expires. The scrapped copper supply is projected to increase from 3.36 Mt in 2020 to 16.62 Mt in 2050, representing a 3.94-fold increase. The power sector, which has the highest copper consumption, will also generate the most scrapped copper. It is projected that by 2050, scrapped copper from the power sector will account for 43.84 % of the total.

As shown in Fig. 2 (d), China's copper concentrate required for primary copper refining mainly relies on imports. It is expected that, due to the reduced demand for primary copper in the future, both domestic and imported copper concentrates will experience a rapid decline after reaching their peak. At the same time, the declining demand for copper concentrate will also cause its price to rapidly decrease after 2043.

As shown in Fig. 2 (e), The rapid growth of scrapped copper and advancements in recycling technology have significantly increased the proportion of recycled copper. By 2032, recycled copper will surpass primary copper and become the main support for refined copper consumption. The proportion of primary copper in consumption will be only 14.59 % by 2050. Before 2043, the demand for refined copper will continue to exceed supply, leading to a sustained rise in refined copper prices. After that, factors such as population decline are expected to reduce refined copper demand, resulting in a slight decrease in its price.

As shown in Fig. 2 (f), China's scrapped copper supply will mainly rely on domestic generation. Affected by the decreasing copper demand in China, the growth in scrapped copper demand is expected to slow down around 2040. As the supply of scrapped copper gradually meets the demand, it will lead to more stable scrapped copper prices.

4.2. The recycling structure of multi-life cycle recycling of copper

As shown in Fig. 3, the multi-life cycle recycling of copper leads to the emergence of recycled copper with different recycling times, and the quantity continues to grow. By 2050, the copper industry will have recycled copper that has been recycled 12 times, significantly enhancing the resource efficiency of copper use. Each recycling cycle is a process in which copper performs its function and provides copper services. According to estimates, multi-life cycle recycling will increase the resource efficiency of copper use to 2.74 by 2050 (Supporting Information S6). This means that, due to multi-life cycle recycling, 1 unit of primary copper resources developed in 1990 will have provided 2.74 units of copper resource services by 2050. This will gradually reduce the

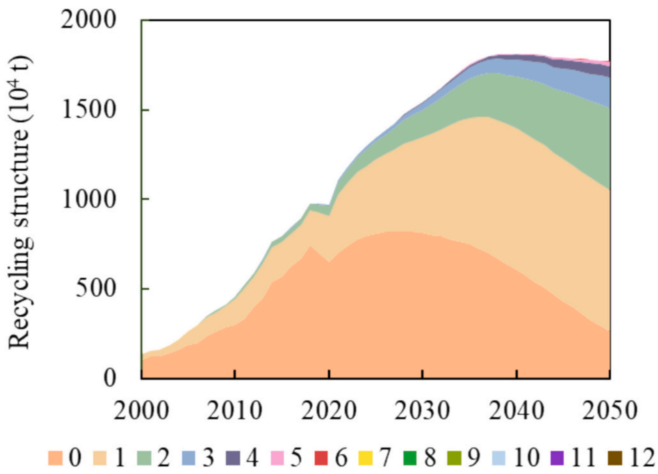

Fig. 3. Recycling structure of copper.

dependence on primary copper, with primary copper consumption decreasing to 2.59 Mt by 2050. Additionally, due to the relatively long lifespan of copper products in sectors such as building, by 2050, the proportion of recycled copper that has been recycled more than 6 times will remain extremely low.

Notes: The legend number represent the number of times refined copper has been recycled.

4.3. Analysis of cumulative profit, cumulative resource depletion reduction, and cumulative carbon reduction

As shown in Fig. 4 (a), the increase in the recycling times, the growth in the recycled copper, and the cost saving advantages of the recycling link have jointly promoted the increase in cumulative profits. The cumulative profit is expected to reach 871.15 billion CNY by 2050, a 10.26-fold increase compared to 2020. The increasing of recycling times leads to a gradual increase in the cumulative profit growth rate of multi-life cycle recycling. But after 2040, the growth rate will begin to decline slightly due to the decrease in copper demand. At the same time, the cumulative resource depletion reduction and the cumulative carbon reduction also show a similar trend. As shown in Fig. 4 (b, c), influenced by the increase in recycling times, resource conservation advantages and carbon reduction advantages of recycling link (Fig.S1), the cumulative resource depletion reduction and cumulative carbon reduction of copper multi-life cycle recycling will reach 705.48×10^6 GJ eq. and 81.58 Mt CO_2 eq. respectively by 2050, which are 4.84 times and 4.83 times higher than those in 2020. In addition, the growth rates of cumulative resource depletion reduction and cumulative carbon reduction exhibited trends akin to the changes in cumulative profit growth rate, initially increasing before slightly declining.

4.4. Copper industry ERC sustainability evaluation

As shown in Fig. 5 (a), from 2020 to 2050, the economic index, resource index, and carbon index all show a consistent upward trend, reaching 100 by 2050 due to the continuous growth of cumulative profits, cumulative resource depletion reduction, and cumulative carbon reduction. As shown in Fig. 5 (b), ERC sustainability will continue to grow, increasing from 7.91 in 2020 to 100 in 2050, a growth of 11.64 times. However, the growth rate is faster before 2040, slowing down thereafter. From 2020 to 2040, the increase is 10.27 times, while from 2040 to 2050, the growth is only 12.15 %. The changes in the economic index, resource index, and carbon index follow the same pattern. This is because the continuous increase in recycled copper leads to a gradual reduction in primary copper. At that time, the economic growth, resource conservation, and carbon reduction advantages of recycling compared to primary processes will gradually become ineffective, and the ability of multi-life cycle recycling to enhance the ERC sustainability will also gradually weaken. However, it should be noted that this conclusion is based on the predicted results of China's copper demand, recycled copper production, and recycling structure of copper in this study, which may be affected by model assumptions.

Notes: The inner to outer rings represent sustainability scores of 0, 25, 50, 75, and 100, respectively.

5. Discussion

5.1. Scenario setting

Considering that future trends such as the research and application of new materials, the imposition of carbon taxes, and the development of intelligent buildings, may affect the inventory and demand for copper in major downstream copper-using industries, thereby influencing copper recycling and ultimately impacting sustainability. In addition, changes in import volume of copper concentrate can also affect sustainability. We designed different scenarios for evaluation based on these considerations. The scenario setting and parameter setting are displayed in Table 1.

5.2. The impact of different scenarios on the ERC sustainability of the copper industry

As shown in Fig. 6 (a), stricter environmental and resource recycling policies have accelerated the development of new materials. In the power sector, advanced composites and high-conductivity plastics have emerged in recent years, capable of replacing copper in certain applications. In the electronics sector, flexible electronic technologies are driving the adoption of carbon-based materials, such as graphene, to

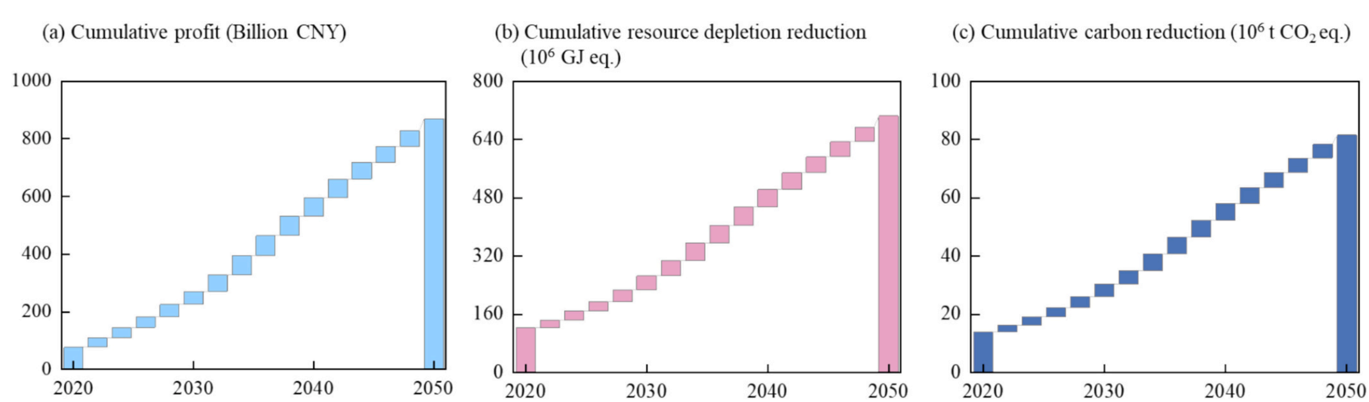

Fig. 4. The evolution of cumulative profit (a), cumulative resource depletion reduction (b), and cumulative carbon reduction (c) over time.

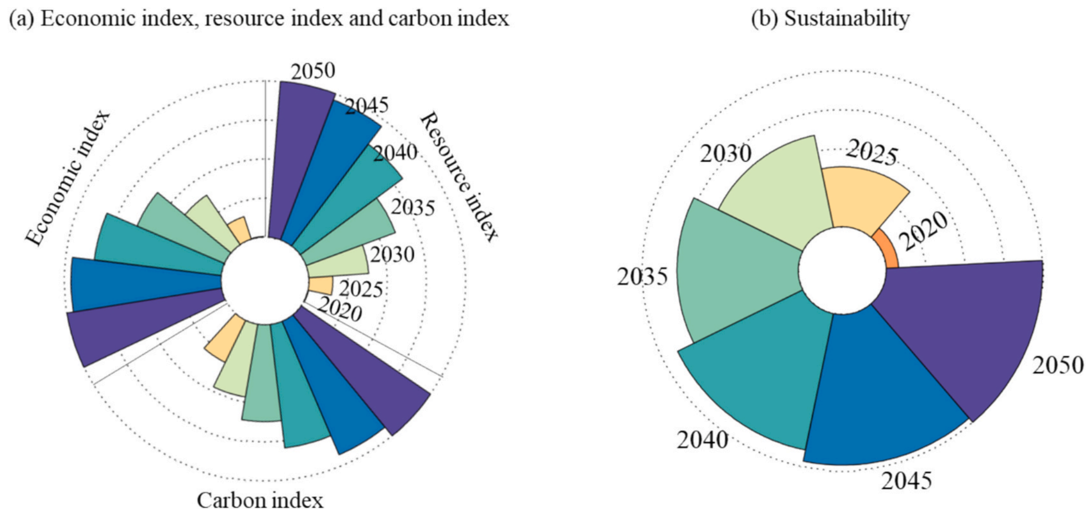

Fig. 5. (a) The evolution of the economic index, resource index, and carbon index over time. (b) The evolution of sustainability over time.

Table 1
Scenario setting and parameter setting.

Scenario	Scenario description and parameter setting	Reference
New material substitution (NMS)	New materials substitute copper resources in downstream copper-using sectors, reducing the per capita copper stock K by 10 %.	(Gu et al., 2024)
Levying carbon tax (LCT)	To reduce carbon emissions, the copper industry will impose a carbon tax, starting at 60 CNY/t CO_2 eq., with an annual increase of 40 CNY.	(Wu et al., 2024a, 2024b)
Expanding copper concentrate imports (ECCI)	To avoid carbon emissions and resource depletion caused by mining, copper ore imports will increase by an additional 1.5 % annually.	(Gu et al., 2024)
Promoting intelligent buildings (PIB)	The development of intelligent building technologies will increase the demand for copper, leading to a 10 % increase in the per capita copper inventory K.	Author assumption

replace traditional copper circuit boards. In the transportation sector, the development of electric vehicles is expected to lead to more lightweight materials that can substitute copper. Therefore, in NMS scenario, the substitution of copper by new materials results in a continuous decline in copper production, keeping its economic index at 0. However, while production decreases, the resource and carbon indices increase significantly, with both indices remaining at 100 until 2040 under NMS scenario.

After 2040, high carbon taxes of LCT scenario will significantly raise the costs of copper smelting and processing, potentially driving downstream copper-using industries to adopt more environmentally friendly alternative materials. These taxes will also drive businesses to improve resource efficiency, such as adopting efficient power system designs to reduce copper use in cables and transformers. Additionally, higher carbon taxes will boost scrap copper recycling rates, encouraging downstream sectors to rely more on recycled copper, reducing dependence on primary production. As shown in Fig. 6 (a), the reduction in copper production caused by LCT scenario will decrease resource depletion and carbon emissions, significantly boosting the resource and carbon indices. These indices will surpass those in NMS scenario, achieving a score of 100. At the same time, since producers compensate for increased costs by raising prices, the profit decline in various links under LCT scenario will be minimal. Even with a significant reduction in production after 2040, the economic index in LCT scenario will still perform well, with a 40.85 % increase by 2050 compared to 2021.

The continuous growth in net imports of copper concentrates under ECCI scenario will gradually result in supply exceeding demand, leading to a downward trend in copper concentrate prices. As shown in Fig. 6 (a), the raw material cost for primary copper refining will decrease, increasing the unit profit of primary copper and boosting the economic index from 19.73 in 2021 to 85.17 in 2050. However, as this does not reach the critical threshold for capacity adjustment, the impact on production remains minimal, resulting in only slight changes in the resource and carbon indices.

In intelligent buildings, electrical systems are evolving towards smart power, intelligent lighting, automatic temperature control, and smart grids, driving increased demand for copper as an efficient conductive material. Intelligent construction technologies also promote the use of automated equipment in security, air conditioning, heating, and ventilation, significantly increasing the demand for copper-based materials like cables, wires, and terminals. Additionally, intelligent buildings drive the demand for new copper-based composites widely used in electrical equipment, building facades, and wall decorations, such as copper-nickel and copper-aluminum alloys in wall systems and high-efficiency heat-conducting components. As shown in Fig. 6 (a), PIB scenario will increase copper demand, leading to higher production and resulting in greater resource depletion and carbon emissions, keeping its resource and carbon indices at 0. However, the increased production generates higher profits, keeping its economic index consistently at 100.

In Fig. 6 (b), we use the average ERC sustainability values for each decade to assess the sustainability trends across different scenarios. From 2021 to 2030, NMS scenario will have the highest ERC sustainability, reaching 79.92, which is 50.09 % higher than baseline scenario (BS). LCT scenario follows, with a score of 72.91. From 2031 to 2040, the scenario with the highest ERC sustainability score will shift from NMS scenario to LCT scenario, with a score of 88.99, an increase of 38.17 % compared to BS. LCT scenario also shows the fastest growth during this decade, increasing by 22.06 % compared to the previous decade. From 2041 to 2050, LCT scenario will continue to have the highest ERC sustainability score, reaching 83.56, an increase of 20.28 % compared to BS. The fastest-growing scenario during this decade will be ECCI scenario, with a growth rate of 11.27 % compared to the previous decade.

5.3. Policy implications

NMS scenario resulting in decreased production leads to continued growth in cumulative resource depletion reduction and cumulative

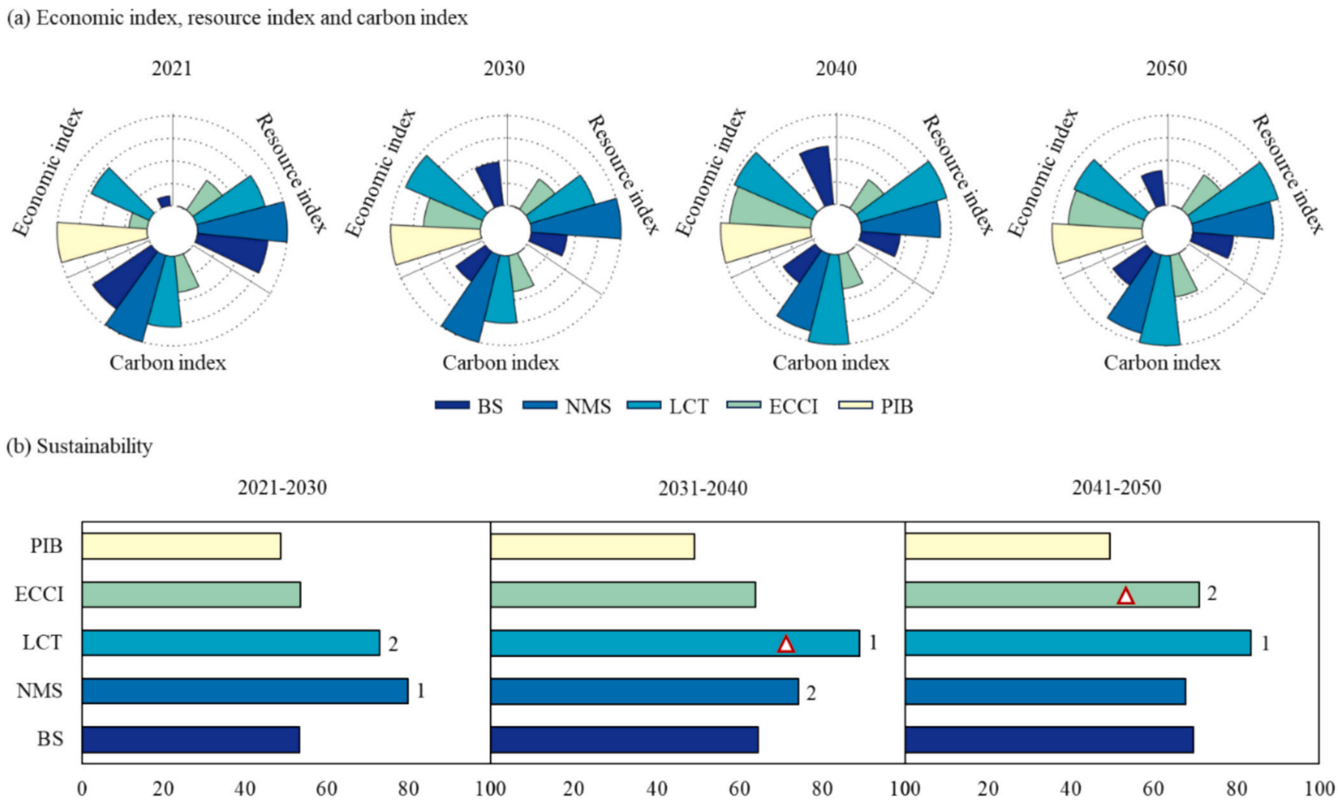

Fig. 6. (a) The evolution of the economic index, resource index, and carbon index for each scenario over time (the inner to outer rings represent scores of 0, 25, 50, 75, and 100, respectively). (b) ERC sustainability in various scenarios represented by the average ERC sustainability every decade (1, 2 indicate the top two ERC sustainability for this decade. The triangle symbol represents the scenario with the highest growth rate compared to the previous decade).

carbon reduction (Fig. S2), thereby improving the resource index and carbon index. By 2030, NMS scenario will enhance the ERC sustainability due to increases in resource and carbon indices. After 2030, the ability of NMS scenario to enhance the ERC sustainability will begin to decrease due to the impact of lower economic indices. This time is earlier compared to the period of notable sustainability improvement for lead in NMS scenario described by (Wu et al., 2024a, 2024b). This is because compared to the decline in future lead demand, the future copper demand remains strong. NMS scenario has played a significant role in suppressing primary copper mining in the short term, but its marginal effect gradually weakens as copper demand continues to increase. Therefore, policymakers should pay attention to the key role of NMS scenario in enhancing the ERC sustainability in the short term (Gu et al., 2024). However, to achieve long-term sustainability, policymakers need to more deeply consider the dynamic effects of different policy tools and their impacts on the economy, resources, and environment at different times.

LCT scenario will to some extent constrain copper demand (Liu et al., 2023), resulting in reduced production that will increase resource and carbon indices. Additionally, producers will raise prices to compensate for costs, leading to a slight decline in economic indices and significantly enhancing the ERC sustainability of the copper industry. However, with the introduction of high carbon taxes, production will be severely constrained. The resulting decline in cumulative profits due to reduced production (Fang et al., 2024) cannot be offset by price increases, leading to a sharp drop in the economic index and ultimately resulting in a modest increase in ERC sustainability. Based on this, policymakers should thoroughly assess the long-term impact of carbon taxes, considering the differences in effects across different time periods, optimize the implementation path of carbon tax policies. For example, in the early stages of policy implementation, the focus should be on leveraging the carbon tax to promote resource conservation and carbon reduction. In the later stages, supplementary measures such as technological innovation (Chen and Wang, 2023) and industry optimization should be adopted to mitigate the negative impact on the economic index caused by the severe production decline due to excessively high carbon tax rates.

The initial impact of ECCI scenario will be insignificant due to the limited baseline in the early years. However, as net imports of copper concentrate continue to increase, the growing supply-demand gap will gradually drive down copper concentrate prices. This will lead to an increase in unit profits from primary copper refining, thereby boosting the economic index. However, since this profit rate does not meet the standards for increasing capacity in the primary copper refining link, resource depletion and carbon emissions have no change. This differs from the conclusion in (Gu et al., 2024), which suggests a reduction in carbon emissions under the same scenario. The discrepancy arises because Gu's study only considers the impact of material flows and does not account for the relationship between economic benefits and material flows, nor the interactions between different production links in the copper industry. The implementation effect of ECCI scenario exhibits a certain time lag. Policymakers should pay close attention to the issues of resource depletion and carbon emissions management following the expansion of import volumes. It is suggested that while the import volume continues to increase, more environmentally friendly technology and equipment (Ehigiamusoe et al., 2024) should be introduced to reduce carbon emissions and resource depletion, to achieve the goal of jointly improving the resource index and carbon index while the economic index grows.

PIB scenario will have no impact on improving ERC sustainability. The sudden surge in copper demand cannot be met by recycled copper in the short term, leading to an increase in mining and primary copper refining, which will significantly reduce the resource index and carbon index. Although PIB scenario has a certain positive effect in the economic index, its pressure on resource index and carbon index cannot be ignored. Policymakers should promote technological innovation, improve recycled copper recovery rates (Anastassakis et al., 2015; Qiu et al., 2020), and optimize material usage in smart building designs to reduce reliance on primary copper, thereby balancing the conflict between the economic index, resource index, and carbon index.

6. Conclusions

This study establishes a sustainability assessment framework based on the economic, resource and carbon criteria to evaluate the sustainability of multi-life cycle recycling of copper. The results show that carbon neutrality will lead to a continuous increase in China's copper demand, which will peak in 2039 and then begin to decline slightly. Due to multi-life cycle recycling, China's copper industry will see the copper that has been recycled 12 times by 2050. The contributions of profit growth, resource depletion reduction, and carbon reduction gradually accumulate with the increase of recycling times, ultimately producing a huge cumulative effect, thereby enhancing the ERC sustainability of copper industry. Policy simulations indicate that NMS scenario and LCT scenario are more effective in improving the ERC sustainability of copper industry. However, it is important to note the differences in the effects of various policies over different time periods. Before 2030, the advantages of NMS scenario should be fully leveraged. After 2030, LCT scenario should be prioritized. After 2040, the potential to expand copper concentrate imports should be recognized.

This study primarily focuses on cumulative profit, cumulative resource depletion reduction, and cumulative carbon reduction to assess the sustainability of multi-life cycle recycling of copper. In future research, indicators such as resource efficiency, carbon emission intensity, pollutants, and social dimensions such as employment opportunities may be taken into consideration, which will help to more comprehensively reveal the overall sustainability of copper multi-life cycle recycling.

CRediT authorship contribution statement

Haixia Li: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Yufeng Wu:** Validation, Supervision, Resources, Funding acquisition, Conceptualization. **Yifan Gu:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Hongyang Yang:** Methodology, Data curation. **Zixin Bian:** Data curation. **Huining Song:** Formal analysis. **Guangli Zhou:** Data curation. **Qingbin Yuan:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the National Natural Science Foundation of China [grant number 52070007].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2025.01.016.

References

Anastassakis, G.N., Bevilacqua, P., De Lorenzi, L., 2015. Recovery of residual copper from low-content tailings derived from waste electrical cable treatment. Int. J. Miner. Process. 143, 105–111. https://doi.org/10.1016/j.minpro.2015.09.011.

Aydin, R., Badurdeen, F., 2019. Sustainable product line design considering a multi-lifecycle approach. Resour. Conserv. Recycl. 149, 727–737. https://doi.org/10.1016/j.resconrec.2019.06.014.

Baqueri, S.F.A., Adnan, M., Kochan, B., Bellemans, T., 2019. Activity-based model for medium-sized cities considering external activity–travel: enhancing FEATHERS framework. Futur. Gener. Comput. Syst. 96, 51–63. https://doi.org/10.1016/j.future.2019.01.055.

Born, K., Ciftci, M.M., 2024. The limitations of end-of-life copper recycling and its implications for the circular economy of metals. Resour. Conserv. Recycl. 200, 107318. https://doi.org/10.1016/j.resconrec.2023.107318.

Chen, J., Wang, Z., Wu, Y., Li, L., Li, B., Pan, D.A., Zuo, T., 2019. Environmental benefits of secondary copper from primary copper based on life cycle assessment in China. Resour. Conserv. Recycl. 146, 35–44. https://doi.org/10.1016/j.resconrec.2019.03.020.

Chen, M., Wang, K., 2023. The combining and cooperative effects of carbon price and technological innovation on carbon emission reduction: evidence from China's industrial enterprises. J. Environ. Manag. 343, 118188. https://doi.org/10.1016/j.jenvman.2023.118188.

China Economic and Social Development Yearbook (CESDY), 2020. https://data.cnki.net/yearBook/single?id=N2023040060.

Chintalapati, P., Nyaga, C., Walters, J.P., Koehler, J., Javernick-Will, A., Hope, R., Linden, K.G., 2022. Improving the reliability of water service delivery in rural Kenya through professionalized maintenance: a system dynamics perspective. Environ. Sci. Technol. 56, 17364–17374. https://doi.org/10.1021/acs.est.2c00939.

Ciacci, L., Reck, B.K., Nassar, N.T., Graedel, T.E., 2015. Lost by design. Environ. Sci. Technol. 49, 9443–9451. https://doi.org/10.1021/es505515z.

Dai, Y., Deng, L., Zhu, F., 2024. A model for predicting post-translational modification cross-talk based on the multilayer network. Expert Syst. Appl. 255, 124770. https://doi.org/10.1016/j.eswa.2024.124770.

Dong, D., Espinoza, L.A.T., Loibl, A., Pfaff, M., Tukker, A., Van der Voet, E., 2020. Scenarios for anthropogenic copper demand and supply in China: implications of a scrap import ban and a circular economy transition. Resour. Conserv. Recycl. 161, 104943. https://doi.org/10.1016/j.resconrec.2020.104943.

Du, X., Ren, W., Zhao, D., Jiang, M., Lü, M., 2025. Research on the discrimination and classification of multi-modal fault bearing based on multi-attribute decision-making mechanism. Measurement 242, 115910. https://doi.org/10.1016/j.measurement.2024.115910.

Ehigiamusoe, K.U., Dogan, E., Ramakrishnan, S., Binsaeed, R.H., 2024. How does technological innovation moderate the environmental impacts of economic growth, natural resource rents and trade openness? J. Environ. Manag. 371, 123229. https://doi.org/10.1016/j.jenvman.2024.123229.

Fan, Z.M.Z., 2022. Discussion on high-quality development of China's mining industry. Resource Industrial Economy. 35, 17–26. https://doi.org/10.19676/j.cnki.1672-6995.000751.(in Chinese).

Fang, X., He, W., Wen, F., An, M., Song, M., Wang, B., Ramsey, T.S., 2024. Simulation study on the effect of differentiated carbon tax adjustment on CO_2 emissions reduction in China from the perspective of carbon footprint. J. Clean. Prod. 434, 140071. https://doi.org/10.1016/j.jclepro.2023.140071.

Ghorbani, M., Esmaeili, B., Akbari, E., Yazdanparast, M., Avazpour, L., 2024. Measuring the adaptive capacity of rangeland users under drought stress in North-Eastern Iran: application of social network analysis. J. Arid Environ. 225, 105254. https://doi.org/10.1016/j.jaridenv.2024.105254.

Go, T.F., Wahab, D.A., Hishamuddin, H., 2015. Multiple generation life-cycles for product sustainability: the way forward. J. Clean. Prod. 95, 16–29. https://doi.org/10.1016/j.jclepro.2015.02.065.

Gorman, M.R., Dzombak, D.A., 2018. A review of sustainable mining and resource management: transitioning from the life cycle of the mine to the life cycle of the mineral. Resour. Conserv. Recycl. 137, 281–291. https://doi.org/10.1016/j.resconrec.2018.06.001.

Gu, Y., Yang, H., Wu, Y., Tuo, M., Xu, M., Hu, G., Zuo, T., 2024. Regulation mechanism for designing decarbonization pathways in the copper industry toward carbon neutrality. Environ. Sci. Technol. 58, 1518–1530. https://doi.org/10.1021/acs.est.3c09314.

Gu, Y., Zhou, G., Wu, Y., Xu, M., Chang, T., Gong, Y., Zuo, T., 2020. Environmental performance analysis on resource multiple-life-cycle recycling system: evidence from waste pet bottles in China. Resour. Conserv. Recycl. 158, 104821. https://doi.org/10.1016/j.resconrec.2020.104821.

Guo, J., Zhu, K., Cheng, Y., 2024. Deployment of clean energy technologies towards carbon neutrality under resource constraints. Energy 295, 131012. https://doi.org/10.1016/j.energy.2024.131012.

He, Q., Liu, D.L., Wang, B., Wang, Z., Cowie, A., Simmons, A., Xu, Z., Li, L., Shi, Y., Liu, K., Harrison, M.T., Waters, C., Huete, A., Yu, Q., 2024. A food-energy-water-carbon nexus framework informs region-specific optimal strategies for agricultural sustainability. Resour. Conserv. Recycl. 203, 107428. https://doi.org/10.1016/j.resconrec.2024.107428.

Hua, T., Zhao, W., Wang, S., Fu, B., Pereira, P., 2020. Identifying priority biophysical indicators for promoting food-energy-water nexus within planetary boundaries. Resour. Conserv. Recycl. 163, 105102. https://doi.org/10.1016/j.resconrec.2020.105102.

Hussain, A., Yin, S., Ullah, K., Waqas, M., Senapati, T., Esztergár-Kiss, D., Moslem, S., 2024. Enhancing renewable energy evaluation: utilizing complex picture fuzzy frank aggregation operators in multi-attribute group decision-making. Sustain. Cities Soc. 116, 105842. https://doi.org/10.1016/j.scs.2024.105842.

International Copper Association (ICA), 2021. Copper Recycling: Advancing the Circular Economy. Retrieved from International Copper Association: https://www.copperalliance.org/benefits-of-recycling-copper.

Jiang, Q., Bhattarai, N., Pahlow, M., Xu, Z., 2022. Environmental sustainability and footprints of global aquaculture. Resour. Conserv. Recycl. 180, 106183. https://doi.org/10.1016/j.resconrec.2022.106183.

Keson, J., Silalertruksa, T., Gheewala, S.H., 2024. Integrating the land–water–climate nexus approach with spatial-based sustainable agriculture production. Agric. Syst. 219, 104059. https://doi.org/10.1016/j.agsy.2024.104059.

Khomami, M.M.D., Meybodi, M.R., Rezvanian, A., 2024. Exploring social networks through stochastic multilayer graph modeling. Chaos, Solitons Fractals 182, 114764. https://doi.org/10.1016/j.chaos.2024.114764.

Krystofik, M., Luccitti, A., Parnell, K., Thurston, M., 2018. Adaptive remanufacturing for multiple lifecycles: a case study in office furniture. Resour. Conserv. Recycl. 135, 14–23. https://doi.org/10.1016/j.resconrec.2017.07.028.

Kulczycka, J., Lelek, A., Lewandowska, A., Wirth, H., Bergesen, J.D., 2016. Environmental impacts of energy-efficient Pyrometallurgical copper smelting technologies: the consequences of technological changes from 2010 to 2050. J. Ind. Ecol. 20, 304–316. https://doi.org/10.1111/jiec.12369.

Li, H., Gu, Y., Hu, G., Wu, Y., 2023a. Eco-efficiency evaluation and simulation optimization of multi-life cycle recycling of lead: evidence from China. J. Clean. Prod. 420, 138384. https://doi.org/10.1016/j.jclepro.2023.138384.

Li, X., Pu, X., Wang, W., Dong, X., Zhang, Y., Wang, J., Wang, Y., Meng, M., 2023b. Surface water environmental carrying capacity and surface water quality based on economy-society-environment nexus – evidence from China. Water-Energy Nexus. 6, 231–243. https://doi.org/10.1016/j.wen.2023.11.003.

Li, X., Ma, B., Wang, C., Chen, Y., 2024. Sustainable recovery and recycling of scrap copper and alloy resources: a review. Sustain. Mater. Technol. 41, e1026. https://doi.org/10.1016/j.susmat.2024.e01026.

Liang, Y., Zhong, Q., Deng, Z., Li, H., Jetashree, Yang, Z., Liang, S., 2023. Multiperspective decoupling analyses between global embodied carbon chains and global value chains. Environ. Sci. Technol. 57, 19690–19701. https://doi.org/10.1021/acs.est.3c06715.

Liu, N., Yao, X., Wan, F., Han, Y., 2023. Are tax revenue recycling schemes based on industry-differentiated carbon tax conducive to realizing the "double dividend"? Energy Econ. 124, 106814. https://doi.org/10.1016/j.eneco.2023.106814.

Lu, Y., Liu, G., Yue, Q., Fu, Y., Wang, H., Dou, Z., Wang, Y., Du, T., 2024. Research on copper flow and environmental load in China's new infrastructure industry for carbon neutrality. J. Clean. Prod. 466, 142857. https://doi.org/10.1016/j.jclepro.2024.142857.

Lv, Y., Li, Y., Zhang, Z., Luo, S., Feng, X., Chen, X., 2024. Spatio-temporal evolution pattern and obstacle factors of water-energy-food nexus coupling coordination in the Yangtze river economic belt. J. Clean. Prod. 444, 141229. https://doi.org/10.1016/j.jclepro.2024.141229.

Mata, T.M., Costa, C.A.V., 2001. Life cycle assessment of different reuse percentages for glass beer bottles. Int. J. Life Cycle Assess. 6, 307–319. https://doi.org/10.1007/BF02978793.

McMillan, C.A., Skerlos, S.J., Keoleian, G.A., 2012. Evaluation of the metals Industry's position on recycling and its implications for environmental emissions. J. Ind. Ecol. 16, 324–333. https://doi.org/10.1111/j.1530-9290.2012.00483.x.

Meng, X., Wen, Z., Qian, Y., 2018. Multi-agent based simulation for household solid waste recycling behavior. Resour. Conserv. Recycl. 128, 535–545. https://doi.org/10.1016/j.resconrec.2016.09.033.

Nakajima, K., Daigo, I., Nansai, K., Matsubae, K., Takayanagi, W., Tomita, M., Matsuno, Y., 2018. Global distribution of material consumption: nickel, copper, and iron. Resour. Conserv. Recycl. 133, 369–374. https://doi.org/10.1016/j.resconrec.2017.08.029.

Nhamo, L., Mabhaudhi, T., Mpandeli, S., Dickens, C., Nhemachena, C., Senzanje, A., Naidoo, D., Liphadzi, S., Modi, A.T., 2020. An integrative analytical model for the water-energy-food nexus: South Africa case study. Environ. Sci. Pol. 109, 15–24. https://doi.org/10.1016/j.envsci.2020.04.010.

Qiu, R., Lin, M., Ruan, J., Fu, Y., Hu, J., Deng, M., Tang, Y., Qiu, R., 2020. Recovering full metallic resources from waste printed circuit boards: a refined review. J. Clean. Prod. 244, 118690. https://doi.org/10.1016/j.jclepro.2019.118690.

Raihan, A., Mainul Bari, A.B.M., 2024. Energy-economy-environment nexus in China: the role of renewable energies toward carbon neutrality. Innovation and Green Development. 3, 100139. https://doi.org/10.1016/j.igd.2024.100139.

Ryter, J., Fu, X., Bhuwalka, K., Roth, R., Olivetti, E., 2022. Assessing recycling, displacement, and environmental impacts using an economics-informed material system model. J. Ind. Ecol. 26, 1010–1024. https://doi.org/10.1111/jiec.13239.

Samuelson, P.A., Nordhaus, W.D., 2010. Economics, 19th ed. McGraw-Hill Education.

Schmidt-Traub, G., Kroll, C., Teksoz, K., Durand-Delacre, D., Sachs, J.D., 2017. National baselines for the sustainable development goals assessed in the SDG index and dashboards. Nat. Geosci. 10, 547–555. https://doi.org/10.1038/ngeo2985.

Shubbar, H.T., Tahir, F., Al-Ansari, T., 2024. Bridging Qatar's food demand and self-sufficiency: a system dynamics simulation of the energy–water–food nexus. Sustainable Production and Consumption. 46, 382–399. https://doi.org/10.1016/j.spc.2024.02.017.

Suhariyanto, T.T., Wahab, D.A., Rahman, M.N.A., 2017. Multi-life cycle assessment for sustainable products: a systematic review. J. Clean. Prod. 165, 677–696. https://doi.org/10.1016/j.jclepro.2017.07.123.

Sustainable Development Goals (SDG), 2015. United Nations. Sustainable Development Goals: 17 Goals to Transform Our World. https://sdgs.un.org/goals.

Sverdrup, H.U., Ragnarsdottir, K.V., Koca, D., 2014. On modelling the global copper mining rates, market supply, copper price and the end of copper reserves. Resour. Conserv. Recycl. 87, 158–174. https://doi.org/10.1016/j.resconrec.2014.03.007.

Tian, X., Xiao, H., Liu, Y., Ding, W., 2021. Design and simulation of a secondary resource recycling system: a case study of lead-acid batteries. Waste Manag. 126, 78–88. https://doi.org/10.1016/j.wasman.2020.12.038.

Varian, H.R., 2014. Intermediate Microeconomics: A Modern Approach, 9th ed. Norton & Company, W.W.

Vidal, O., Rostom, F.Z., François, C., Giraud, G., 2019. Prey–predator long-term modeling of copper reserves, production, recycling, price, and cost of production. Environ. Sci. Technol. 53, 11323–11336. https://doi.org/10.1021/acs.est.9b03883.

Wang, Y., Shi, L., Song, M., Jia, M., Li, B., 2024a. Evaluating the energy-exergy-economy-environment performance of the biomass-photovoltaic-hydrogen integrated energy system based on hybrid multi-criterion decision-making model. Renew. Energy 224, 120220. https://doi.org/10.1016/j.renene.2024.120220.

Wang, Y., Song, C., Cheng, C., Wang, H., Wang, X., Gao, P., 2023. Modelling and evaluating the economy-resource-ecological environment system of a third-polar city using system dynamics and ranked weights-based coupling coordination degree model. Cities 133, 104151. https://doi.org/10.1016/j.cities.2022.104151.

Wang, Z., Wang, X., Wang, W., Deveci, M., Wu, Z., Pedrycz, W., 2024b. Consensus reaching-based decision model for assessing resilient urban public health safety ecosystem with social network analysis. J. Ind. Inf. Integr. 100716. https://doi.org/10.1016/j.jii.2024.100716.

Watari, T., Yokoi, R., 2021. International inequality in in-use metal stocks: what it portends for the future. Res. Policy 70, 101968. https://doi.org/10.1016/j.resourpol.2020.101968.

Wu, K., Wen, H., Wang, T., Chen, M., You, L., Liu, Y., Zhang, J., Li, Y., Huang, G., 2024b. Water rights trading planning and its application in water resources management: a water-ecology-food nexus perspective. Environ. Res. 249, 118377. https://doi.org/10.1016/j.envres.2024.118377.

Wu, Y., Li, H., Gu, Y., Hu, H., Zhou, G., Yuan, Q., 2024a. How can the lead industry improve sustainability based on the resource-economy-carbon nexus system? Sustainable Production and Consumption. 49, 82–91. https://doi.org/10.1016/j.spc.2024.06.012.

Xu, Z., Chau, S.N., Chen, X., Zhang, J., Li, Y., Dietz, T., Wang, J., Winkler, J.A., Fan, F., Huang, B., Li, S., Wu, S., Herzberger, A., Tang, Y., Hong, D., Li, Y., Liu, J., 2020. Assessing progress towards sustainable development over space and time. Nature 577, 74–78. https://doi.org/10.1038/s41586-019-1846-3.

Yang, S.S., Ngiam, H.Y., Ong, S.K., Nee, A.Y.C., 2015. The impact of automotive product remanufacturing on environmental performance. Procedia Cirp. 29, 774–779. https://doi.org/10.1016/j.procir.2015.01.017.

Yin, J., Liu, L., Ji, H., Zhang, L., Li, C., Yuan, Z., 2024. Sustain China's copper resources with domestic mining, trading, and recycling. Resour. Conserv. Recycl. 202, 107396. https://doi.org/10.1016/j.resconrec.2023.107396.

Zhang, N., 2021. Current situation and development trend of copper lead zinc industry in China. Sulphuric Acid Industry 1–5 (in Chinese).

Zhang, W., Li, Z., Dong, S., Qian, P., Ye, S., Hu, S., Xia, B., Wang, C., 2021. Analyzing the environmental impact of copper-based mixed waste recycling-a LCA case study in China. J. Clean. Prod. 284. https://doi.org/10.1016/j.jclepro.2020.125256.

Zhang, Y., Ji, Y., Xu, H., Yang, Y., Tian, L., 2023. Life cycle assessment of valuable metal extraction from copper pyrometallurgical solid waste. Resour. Conserv. Recycl. 191, 106875. https://doi.org/10.1016/j.resconrec.2023.106875.