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Critical energy minerals: A material enabler for carbon neutrality

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Critical energy minerals: A material enabler for carbon neutrality

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Cobalt Demand for Automotive Electrification in China: Scenario Analysis Based on the Bass Model

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With accelerating automotive electrification process, quantitative analysis of cobalt demand becomes a critical issue in China. How much cobalt is expected to be needed from 2021 to 2030 to support a smooth automotive electrification in China? This study aims to answer this question comprehensively by examining the responses of annual cobalt demand to variations in electric vehicle sales, battery capacity factors, and cobalt substitution effects, which has not been fully explored in previous literature. Scenario analysis based on the Bass model is adopted and historical data from 2012 to 2020 are used for this study. The results show that 1) the peak annual cobalt demand will reach 35.58–126.97 kt/year during 2021–2030; 2) cobalt demand is expected to decline by 14.29% if the market share of ternary lithium-ion battery decreases by 10%; 3) while cobalt substitution can reduce the demand substantially, it cannot offset the growth of cobalt demand driven by the increasing EV sales and battery capacity. These results provide a knowledge base for policy suggestions to manage the cobalt demand—supply balance in China better.

Keywords: bass model, China, cobalt, electric vehicles, scenario analysis

1 INTRODUCTION

The transport sector is the second-largest source of carbon emissions in China, accounting for 9% of its total emissions (Xue et al., 2019). Decarbonizing transport *via* automotive electrification can help China mitigate emissions and achieve its carbon peak goal by 2030 (Huang and Ge, 2019). Driven by technological progress, infrastructure construction, and governmental subsidies, the annual sales of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) increased rapidly in China from 8159 units in 2011 to 1.2 million units in 2019 (CAAM, 2021), creating the largest global electric vehicle (EV) market to date (IEA, 2020). The pace and magnitude of automotive electrification has led to a massive increase in the demand for cobalt, a critical and expensive raw material essential for the functioning and integrity of current ternary lithium-ion batteries (TLIBs) ecosystems (Xu et al., 2020; Zhao et al., 2020). The Democratic Republic of the Congo (DRC) monopolizes the global supply of cobalt ores and concentrates (Shi et al., 2022); this geographical mismatch between the areas that represent the major supply and demand of cobalt presents new challenges to mineral security (IEA, 2021b). As China has accelerated its efforts toward automotive electrification, policymakers and domestic companies must ensure that China's demand can be met in a sustainable and secure manner. To assess the sustainable availability and security of cobalt for relevant decision makers at the macro and micro levels, it is essential to quantify the variations in future cobalt demand under different outlooks of EV sales and battery-related technologies.

Cobalt demand in China, the largest EV market worldwide, has received increasing scholarly attention. Such research can provide useful information for policymakers to respond to the challenges of mineral security better and offer long-term visibility for companies to invest in and supply cobalt-related products. By using material flow analysis (MFA), several studies estimated the cobalt consumption by various end-use products in China (Zeng and Li, 2015; Chen et al., 2019; Liu et al., 2021). Focusing on the cobalt consumption driven by the automotive electrification, the existing studies get started by forecasting electric vehicle sales and emphasize the impacts of EV market-related factors on cobalt demand. Among these explorations, Hsieh et al. (2020) featured an EV projection model based on price-related factors. Ou et al. (2021) made a more comprehensive consideration of the price-related factors and dual-credit policy in their New Energy and Oil Consumption Credits (NEOCC) model. In addition to the micro factors, Jones et al. (2020) studied the impact of macroeconomic variables on EV sales in their cost, macro, infrastructure, technology (CoMIT) model and highlighted China's cobalt demand in their analysis.

Previous studies have provided rich knowledge for understanding the cobalt demand driven by the automotive electrification transition in China. However, their models for projecting EV sales require highly on data and their benefits come at the cost of the sensitivities and uncertainties derived from the numerous or simplified assumptions of variables (Ou et al., 2021). The development of a concise model that shows a good fit with historical data and thus can provide the diffusion features of EVs deserves academic exploration. In addition, the effects of cobalt substitution have not been fully explored in previous studies. For example, while Ou et al. (2021) failed to explore nickel manganese cobalt (NMC) compositions beyond NMC622 and NMC9.5.5, Jones et al. (2020) failed to study the rich variations in cobalt demand under different scenarios of TLIBs market share and NMC chemistry developments. Finally, few studies have fully explored the responses of annual cobalt demand to variations in EV sales, battery capacity factors, and cobalt substitution effects in China.

Considering existing related studies, the marginal contributions of this study are summarized as follows. First, this study builds and estimates a Bass model for projecting EV sales in China. Using the latest historical EV sales data from 2012 to 2020 and the updated outlooks of EV market potential, this study calibrates the Bass model, which shows excellent fitness. Second, various market shares of TLIBs and battery mix scenarios are considered in projecting the cobalt demand by 2030. Through these new explorations, we complement the findings of existing studies regarding the outlook of cobalt demand for the EV sector in China and provide more scenario perspectives that could help decision makers rethink their policies on cobalt demand–supply balance. Finally, this study examines the responses of annual cobalt demand to variations in EV sales, battery capacity factors, and cobalt substitution effects, which enriches understanding of the sensitivity of cobalt demand.

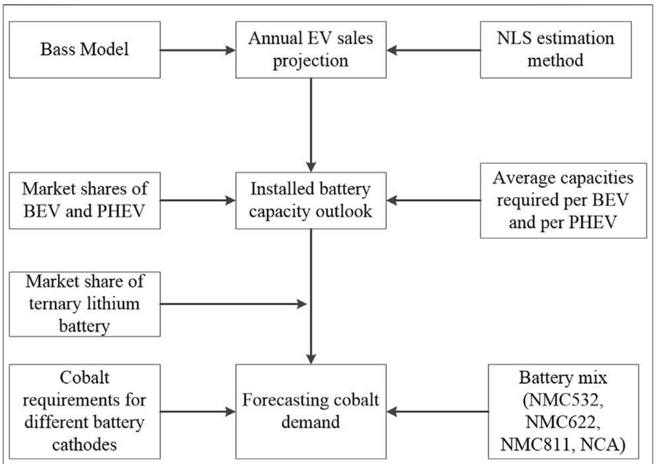

FIGURE 1 | Framework for forecasting the cobalt demand in China (2021–2030).

The remainder of this paper is organized as follows: **Section 2** introduces the framework to forecast cobalt demand and the data used for this study; **Section 3** presents the main results and related discussions; and the last section summarizes the main conclusions and offers several policy implications.

2 METHODS AND DATA

This study forecasted the annual cobalt demand driven by automotive electrification in China from 2021 to 2030 using a three-step process. The scale of EVs in China for the next decade was firstly projected, followed by the projection of the capacity of TLIBs. Based on the forecast of the annual installed battery capacity, the types and quantities of cobalt used in different battery chemistries were defined and the annual cobalt demand was projected. The forecasting framework for this study is illustrated in **Figure 1**.

2.1 Estimating the Scale of Annual EV Sales

2.1.1 Bass Model

The Bass model was developed by Frank M. Bass in 1969 to describe the timing of the initial purchase of new products (Bass, 1969). It has been widely adopted for predicting innovation diffusion (Meade and Islam, 2006). The diffusion of new products, like new electric vehicle, has often been found to follow a S-shaped curve. Bass model achieves a long success in describing this type of diffusion through a simple mathematical form (Massiani and Gohs, 2015). Specifically, its success builds on three factors: first, Bass model can predict a smooth diffusion curve, which is consistent with the common perception of the diffusion of new products; second, it is data parsimonious; third, the Bass approach fits sales almost as well as much more complex models. Due to these advantages, the simple Bass model still dominates other models in the field of diffusion studies (Massiani and Gohs, 2015).

In his basic model, Frank M. Bass categorized new product buyers or technology adopters into two groups–innovators and imitators–and proposed that the probability that an initial purchase made at time t is a linear function of innovators and imitators' influence, respectively (Bass, 1969; Bass et al., 1994), can be expressed by **Eq. 1**,

$$f(t)/(1-F(t)) = p + qF(t) \tag{1}$$

where $f(t)$ is the density function describing the proportion of purchasers to potential total buyers at time t, $F(t) = \int_0^t f(t)dt$ denotes the cumulative function, p is the coefficient of innovation that describes innovators making purchase decisions independently of previous buyers, and q is the coefficient of imitation that is positively influenced by previous buyers. The parameters p and q together form an S-shaped curve of buyers over time in the Bass model (Massiani and Gohs, 2015).

Assuming $F(0) = 0$, we can obtain the solution for the differential equation in **Eq. 1**, that is,

$$F(t) = \left(1 - e^{-(p+q)t}\right)/\left(1 + (q/p)e^{-(p+q)t}\right) \tag{2}$$

The density function then becomes:

$$f(t) = \left((p+q)^2/p\right)e^{-(p+q)t}/\left(1 + (q/p)e^{-(p+q)t}\right)^2 \tag{3}$$

With the density functions, if m (market potential) denotes the total number of ultimate buyers, we can obtain the number of buyers at time t (annual EV sales in this study), $n(t)$.

$$n(t) = m \times f(t) \tag{4}$$

In the Bass model, first-time buyers of a new product are considered, and repeated adopters are excluded for a certain period. Furthermore, buyers are assumed to purchase only one unit of the new product. In the case of purchasing EVs for a certain period, such as 10 years, these assumptions are reasonable. Therefore, the number of innovative buyers equals the number of times an innovation is adopted (Li et al., 2019).

2.1.2 Scenario Settings of EV Market Potential

Parameter m is treated as an exogenous parameter (Massiani and Gohs, 2015). Market potential is set with three scenarios, that is, pessimistic (abbreviation: PESS), baseline (abbreviation: BASE), and optimistic (abbreviation: OPTI) to reduce the impacts of the uncertainties of technological and market conditions (Li et al., 2019). In the technology roadmap for energy-saving and new-energy vehicles, the China Society of Automotive Engineers projected that there will be 80 million electric vehicles in China by 2030 (SAE-China, 2016). Therefore, we set our baseline scenario at a market potential of 80 million.

With the increasing number of charging stations, convenient infrastructure, cheaper expenditures on life-cycle usage, and the Chinese government's ambitious promotion policies to achieve carbon neutrality, EV sales are expected to increase significantly. Like Li et al. (2019), we set two times the baseline scenario as the optimistic scenario; that is, the market potential will be 160 million by 2030. The pessimistic scenario was set as half of the market potential of the baseline scenario; that is, the market potential will be 40 million by 2030.

TABLE 1 | Parameters of the Bass model under different market potential scenarios.

Scenario	Market potential	p	q	R^2
Pessimistic	40 million	0.0019*** (0.0004)	0.39*** (0.035)	0.98
Baseline	80 million	0.001*** (0.0002)	0.37*** (0.035)	0.98
Optimistic	160 million	0.0005*** (0.0001)	0.36*** (0.035)	0.98

*Note: * represents* p < 0.1, **p < 0.05, *and* ***p < 0.01. *Standard errors are reported in parentheses.*

2.1.3 Estimating Innovator Parameter *p* and Imitator Parameter *q*

In addition to the market potential, two parameters, p and q, are estimated in the Bass model; we selected nonlinear least squares (NLS) approach to estimate p and q because of its advantage in obtaining valid standard error estimates and one-step-ahead forecasts (Srinivasan and Mason, 1986). For the NLS approach, initial values of p and q are required to estimate the Bass model and the estimated parameters are sensitive to the initial values (Massiani and Gohs, 2015). Thus, ordinary least squares estimates obtained from **Eq. 5**, which is a transformed form of the alternative expression of the Bass model (**Eq. 6**), were used as initial values for estimating Bass model (Srinivasan and Mason, 1986). $N(t)$ denotes the cumulative buyers at time t.

$$n(t) = p \times m + (q-p) \times N(t) - q/m \times N(t)^2 \tag{5}$$

$$n(t) = p[m - N(t)] + q/m \times N(t) \times [m - N(t)] \tag{6}$$

The estimated p and q under different m values are listed in **Table 1**. R^2 value, **Supplementary Figures S1, S2** show that the predicted values fit the historical data well. Therefore, the estimated Bass model was found suitable to forecast future annual EV sales in China.

The historical data of China's EV sales from 2012 to 2020 (see **Supplementary Table S1**) indicate that the market share of BEVs and PHEVs on average is 80% and 20%, respectively. Therefore, the market structure parameter was assumed to be constant. With this constant, the annual BEV sales ($n(t)_{BEV} = 0.8 \times n(t)$) and PHEV sales ($n(t)_{PHEV} = 0.2 \times n(t)$) were projected[1].

[1]This study adopts a different estimation procedure of EV sales from Li et al. (2019) who firstly assigned market potentials to four EV types and then estimated the model parameters and projected the annual sales for each segment of EV market. On the contrary, this study firstly estimated the parameters for the whole EV market and projected the annual sales accordingly, and then assigned the annual sales to PHEVs and BEVs based on the ratio of PHEVs to BEVs.

TABLE 2 | Assumptions on major variables.

Market Potentials[a]	Pessimistic Scenario	40 million
	Baseline Scenario	80 million
	Optimistic Scenario	160 million
Average Battery Capacity[b]	BEV	66 kWh
	PHEV	12 kWh
EV Market Share[c]	BEV	80%
	PHEV	20%
Ternary Lithium Battery Market Share[d]	High	70%
	Medium	60%
	Low	50%
Cobalt Requirement by Cathode Chemistry Type[e]	NMC532	0.23
	NMC622	0.19
	NMC811	0.09
	NCA	0.13
Cobalt Substitution Scenario[f]	High cobalt	70% NMC532, 15% NMC622, 10% NMC811, 5% NCA
	Medium cobalt	20% NMC532, 30% NMC622, 50% NMC811, 10% NCA
	Low cobalt	90% NMC811, 10% NCA

[a]*See SAE-China (2016) and Li et al. (2019);*
[b]*See **Supplementary Tables S1, S2** of Xu et al. (2020);*
[c]*Assumption based on the historical data, see **Supplementary Table S1** of this study;*
[d]*Authors' setting based on GGII (2020);*
[e]*See Olivetti et al. (2017), Alves Dias et al. (2018) and Seck et al. (2022);*
[f]*Scenario setting based on Seck et al. (2022) and China's market features.*

2.2 Forecasting Annual Installed Ternary Lithium-ion Battery Capacity

The battery capacities required for BEVs and PHEVs are different. It has been reported that the average battery capacity required[2] for BEVs is approximately 66 kWh. and that for PHEVs is approximately 12 kWh (Xu et al., 2020). With this battery capacity assumption, we forecasted the newly installed battery capacity in year t, as given by **Eq. 7**,

$$y(t) = \alpha \times n(t)_{BEV} + \beta \times n(t)_{PHEV} \tag{7}$$

where *y(t)* denotes the newly installed battery capacity in year t, α is the average battery capacity required for BEVs, and β is the average battery capacity required for PHEVs.

There are currently several battery chemistries for EVs, which can be categorized as TLIBs and lithium iron phosphate (LFP) batteries.[3] In 2019, TLIBs accounted for 70% of the total market (GGII, 2020). With the development of cell–to–pack (CTP) technology by CATL company and the introduction of blade battery by BYD company, the market share of LFP batteries is likely to increase because of their increased driving mileage, lower price, and higher safety. Furthermore, other novel battery technologies, such as lithium–air batteries, may capture some market share. Owing to these technological developments, we set the battery capacity market share scenario for TLIBs as follows: the *high scenario* corresponds to 70% of *y(t)*, *medium scenario* to 60% of *y(t)*, and *low scenario* to 50% of *y(t)*.

2.3 Projecting Cobalt Demand for Ternary Lithium-ion Battery Capacity

In addition to EV sales, market structures of EVs, and battery type, the battery mix and its evolving trend were considered when projecting cobalt demand for EVs. Based on the cobalt content in the cathode chemistry of TLIBs, the NMC series is classified as NMC111, NMC532, NMC622, and NMC811. NMC111, the simplest form, was excluded here because of its higher usage and lower energy density than other NMC forms such as NMC532 (Azevedo et al., 2018). Consequently, the battery mix contains NMC532, NMC622, NMC811, and the NCA. The cobalt contents of these four chemicals are listed in **Table 2**. The annual cobalt demand estimation is expressed as **Eq. 8**.

$$D(t)_{ij} = \gamma_i \times y(t) \times \sigma_j \tag{8}$$

In **Eq. 8**, $D(t)_{ij}$ denotes the annual cobalt demand in year t under scenario i and j, γ_i denotes the market share of TLIB in scenario i, and σ_j denotes the cobalt content in the cathode chemistry j.

Owing to the increasing scarcity of cobalt resources and the consequent higher battery costs, automobile manufacturers and battery producers have invested more in less cobalt-intensive chemistries such as NMC811 and NCA.[4] The battery mix for EVs

[2]The average battery capacity required is measured as the mean value of small-, mid-, and large-sized EVs; the required capacity is the product of EV range, fuel economy, and the ratio of available battery capacity for driving EVs. See *S1* in the *SI* of Xu et al. (2020) for further details.

[3]There are five main battery chemistries for producing lithium-ion batteries (LIBs), including lithium cobalt oxide (LCO), lithium nickel manganese cobalt (NMC), lithium nickel cobalt aluminum (NCA), LFP, and lithium manganese oxide (LMO). Among them, LFP battery and LMO battery do not contain cobalt elements, and thus were excluded from the study. LCO is used extensively in portable electronics but not in EV applications due to its high usage of expensive cobalt (Azevedo et al., 2018). NMC series and NCA are categorized as the TLIB type.

[4]For example, it is reported that Tesla installs NCA battery for its Model S and works with suppliers toward reducing cobalt contained in future chemistries (Azevedo et al., 2018).

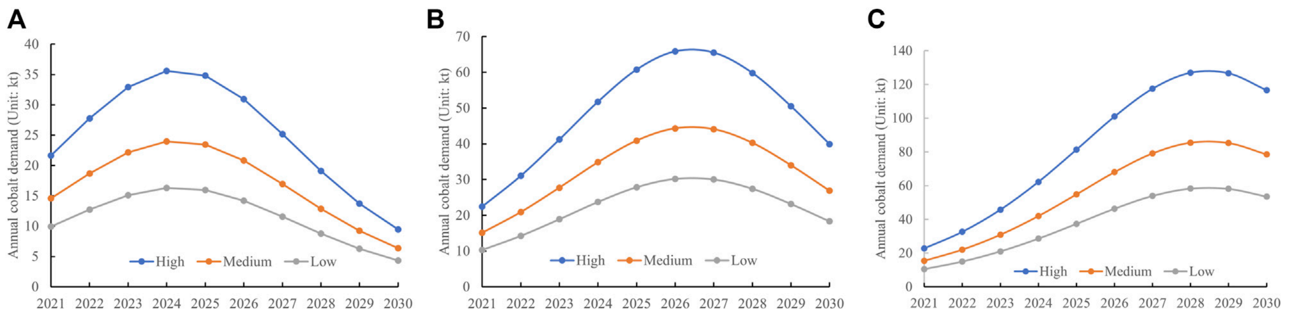

FIGURE 2 | Annual cobalt demand for EVs under different scenarios. **(A)** shows the cobalt demand for the pessimistic market potential scenario; **(B)** is for the baseline market potential scenario; **(C)** is for the optimistic market potential scenario. In the legend, High denotes the high cobalt scenario, Medium denotes the medium cobalt scenario, and Low represents the low cobalt scenario. This figure plots the high scenario of ternary lithium battery market share (70%). Medium and low scenarios are provided in the (**Supplementary Figures S4, S5**).

is likely to transform from cobalt-intensive technologies to fewer cobalt chemistries (Xu et al., 2020). Considering this development trend of the battery mix, we set three cobalt substitution scenarios as follows: a high-cobalt scenario consisting of 70% NMC532, 15% NMC622, 10% NMC811, and 5% NCA; a medium cobalt scenario corresponding to a portfolio of 10% NMC532, 30% NMC622, 50% NMC811, and 10% NCA; and a low cobalt scenario consisting of 90% NMC811 and 10% NCA (Seck et al., 2022). **Table 2** presents all the major assumptions adopted in this study.

2.4 Data Source and Description

The EV annual sales and cumulative sales data (2012–2020) for estimating *p* and *q* are from China Association of Automobile Manufacturers (CAAM, 2021) (see **Supplementary Table S1**). Market potential estimation was based on the projection data of EV sales of SAE-China (2021). Descriptive statistics for the EV data are presented in **Supplementary Table S2**. The annual installed battery capacity to show the fitness of the projected data is provided in **Supplementary Figures S3**. *SI* also provides the BEV and PHEV shares data during the period 2012–2020.

3 RESULTS

3.1 Overview of Cobalt Demand for the EV Sector in China

Figure 2 shows the annual cobalt demand for the EV sector in China during 2021–2030. In each scenario, the demand for cobalt first rises rapidly and then starts to fall. This type of demand curve is closely related to the maturity of the EV market, which is also observed in the case of the Netherlands, one of the newly emerging EV markets (Tang et al., 2021). The differences among these scenarios are in the scales and the turning year of annual cobalt demand (see **Figure 2**), which are significantly influenced by annual EV sales (see more discussions in **Section 3.2**) and the substitution effects (see further discussions in **Section 3.4**).

The cobalt demand will increase until 2026 to the highest requirement of 65.82 kt/year and then begin to decrease for the baseline scenario. For the pessimistic and optimistic scenarios, the highest annual demand of 35.58 kt/year and 126.97 kt/year will occur in 2024 and 2028, respectively. For the growth stage of annual cobalt demand, the compound annual growth rates were 13.25, 19.6, and 23.94% for the pessimistic, baseline, and optimistic scenarios, respectively.

In previous studies related to the projection of annual cobalt demand for EVs in China, Ou et al. (2021) predicted an upper range of 7.17–111.18 kt/year during 2020–2030, Hsieh et al. (2020) reported that China's annual cobalt demand will reach 55.2 kt/year by 2030, and Jones et al. (2020) projected an annual demand of 125 kt/year by 2030. Based on the projected scale of annual cobalt demand, most of the projections of previous studies are within the range of our projections, which, on the one hand, provides a degree of confidence in the modelling framework presented in this paper. On the other hand, there are differences among these studies in the growing trend of cobalt demand that result from the different outlooks of market potentials and different modelling of the EV sales trajectory. Therefore, this study provides a new perspective on the outlook of annual EV sales over the next decade in China.

Our scenario analysis is also different from that of Zeng and Li (2015), who projected that the annual cobalt demand for batteries will increase to 75.7 kt by 2030. There are three key reasons for this discrepancy. First, they estimated the cobalt demand with an average increasing rate of 33.7% for batteries based on linear regression analysis, which implies a growing trend during 2012–2030. Our estimations are based on a nonlinear Bass model that suggests a growth and then a decline in annual EV sales. Second, they investigated the net annual demand by considering the recycling rate, while this study assumes that recycling is a factor that influences supply (Alves Dias et al., 2018) and projects the total cobalt demand. Third, the battery considered by Zeng and Li (2015) is for 3C products that have a shorter lifetime than EVs. The total cobalt requirements used for one unit of the 3C products and one EV are completely different.

Comparing our finding with the cobalt demand of the European Union (EU), the second-largest EV market (IEA, 2020), is meaningful. In 2018, the EU projected that its highest annual cobalt demand may increase to 36.37–123.2 kt/year by 2030 (Alves Dias et al., 2018). The upper value of the range corresponds to its ERTRAC High scenario, which is similar

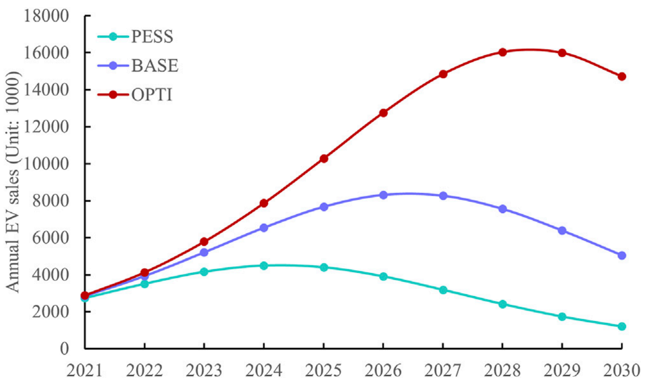

FIGURE 3 | Annual EV sales forecast in China until 2030.

to our optimistic outlook on annual EV sales. The comparison results show that the optimistic outlooks for the annual cobalt demand by 2030 in China and the EU are almost the same. China's EV market started to grow two to three years earlier than that of the EU (IEA, 2020); consequently, its peak cobalt demand occurred earlier. Simon et al. (2015) estimated the cobalt requirement for the EU by 2030, adopting a similar approach to ours; they projected a similar growth curve for cobalt demand–a growth, followed by a fall.[5]

From a global perspective, the annual cobalt demand for EVs will increase to 115–360 kt/year by 2030, depending on the scenario (IEA, 2020; Fu et al., 2020). Based on these projections, our scenario results indicate that China's demand share could account for 8.2%–32%.

3.2 Annual EV Sales in China by 2030 and its Impact

Figure 3 shows that annual EV sales in China are expected to first rise and then fall from 2021 to 2030, suggesting that the predicted scales approach is gradually closer to the targeted market potentials. The growth curves follow the general diffusion characteristics of new products. Along with the massive deployment of EVs and decreasing costs, EV sales are expected to experience a rapid growth. However, as the EV market becomes mature, the growth rate will slow down and gradually converge toward the market potential (Li et al., 2019). The turning year will vary according to the scenario. The pessimistic, baseline, and optimistic scenarios are 2024, 2026, and 2028, respectively. This result indicates that in the most optimistic scenario, China will cease to be the leading driver of the global EV market after 2028.[6]

The highest annual EV sales will be 4.5–16 million units during 2021–2030. Cumulative sales by 2030 is expected to reach 37–111 million units, of which 29.6–88.8 million units will be BEVs and 7.4–22.2 million units will be PHEVs, representing an increase by a factor of 6.7–20 from 5.55 million units in 2020. The differences in EV sales between the scenarios reflect China's determination to achieve the national EV deployment target,[7] which will have a significant influence on the annual cobalt demand. The different projections on the scale and growth curve of annual EV sales differentiate this study from others (Hsieh et al., 2020; Jones et al., 2020; Ou et al., 2021). With the other variables being constant, our results show that, by 2030, the annual cobalt demand in the pessimistic scenario will be 76% lower and that in the optimistic scenario will be 1.92 times higher than the annual cobalt demand in the baseline scenario.

3.3 Annual Installed Battery Capacity and its Impact

The battery capacity installed in the EV sector depends on the scale of EV deployment, the market share of BEVs and PHEVs, and battery capacity requirement per BEV/PHEV. As noted in the Method section, the market shares of BEVs and PHEVs and the battery capacity requirement per EV are assumed to be constant. Therefore, the growth curve of the annual installed battery capacity is similar to that of the annual EV sales (see **Supplementary Figures S3**). The highest annual battery capacity installed is expected to be 248–885 GWh during 2021–2030.

The market share of BEVs is a key factor influencing the annual installed battery capacity, which affects the annual cobalt demand. Many states have set ambitious goals for achieving 100% BEV sales by 2030 (IEA, 2021a; Tang et al., 2021). To determine the response of cobalt demand to the structural change in the EV market in China, we performed a simple sensitivity analysis, assuming 100% BEV sales during 2021–2030. The results indicated that cobalt demand would increase by 19.57% compared with 80% BEV sales, *ceteris paribus*.

The average battery capacity requirement per BEV/PHEV is expected to increase over time as the driving range increases and battery prices decrease (Fu et al., 2020; Tang et al., 2021). The prospective capacity requirement can reach 75 kWh for BEVs and 20 kWh for PHEVs (Fu et al., 2020). Compared with the capacity requirements of 66 kWh for BEVs and 12 kWh for PHEVs, *ceteris paribus*, the annual cobalt demand is expected to increase by 15.94% during 2021–2030.

3.4 Cobalt Substitution Effects

The shrinking market share of TLIBs and the development of less cobalt-intensive cathode chemistries for TLIBs are two technology-substitution mechanisms that can be used to

[5]However, the projection is based on the relatively conservative outlook for EV sales and the relatively aggressive battery mix. Therefore, the scale of their projected cobalt demand is different from (Alves Dias et al., 2018).

[6]According to the Global EV Outlook (2021) recently issued by International Energy Agency, Europe overtook China for the first time with 1.4 million new EV registrations in 2020 (IEA, 2021a).

[7]China is a signatory of EV30at30 campaign, launched at the eighth Clean Energy Ministerial Meeting, and has announced that its new EV sales will account for 20% of its total sales by 2025 (State Council of China, 2020). Our results show that China can achieve this target in the baseline and optimistic scenarios.

reduce the use of cobalt in EV batteries. A higher market share of TLIBs corresponds to higher cobalt demand. Based on our scenario analysis, cobalt demand is expected to decline by 14.29% if the market share of TLIBs decreases by 10%. Currently, in China, LFP batteries are the competitive substitutes because of their lower production costs, better thermal stability, and longer cycle life. Furthermore, the development of CTP technology and blade batteries, introduced in 2020, created a substantial market substitution in 2021.[8] Nevertheless, it is important to understand that the excellent energy density of TLIBs containing a certain amount of cobalt is still more attractive for EV applications than other options (Olivetti et al., 2017). The higher energy intensity of TLIBs is an essential advantage. Additionally, the advantage of the CTP technology in increasing the volume utilization rate of battery packs is ultimately limited. Therefore, the market share of TLIBs is unlikely to be completely replaced in the next decade.

The other substitution effect comes from the development of less cobalt-intensive cathode chemistries. The results of the scenario analysis indicated that the annual cobalt demand in the medium and low cobalt scenario are 21.46 and 54.15%, respectively, lower than that in the high cobalt scenario. In the low-cobalt scenario, with 80 million EV market potential, the highest annual cobalt demand is expected to be 21 kt/year. Developing less cobalt-intensive battery chemistries, such as NMC811 and NCA, is indeed helpful for lowering the pressure on the cobalt supply.

4 CONCLUSIONS AND POLICY IMPLICATIONS

By combining the Bass model and scenario analysis, this study analysed the cobalt demand for automotive electrification in China from 2021 to 2030. The results show that 1) cobalt demand will first rise and then start to fall; the peak annual cobalt demand will reach 35.58–126.97 kt/year during 2021–2030, mainly driven by the annual EV sales. 2) Complete automotive electrification and increasing battery capacity will drive annual cobalt demand to grow by 19.57 and 15.94%, respectively. 3) The demand elasticity of the shrinking market share of TLIBs is 1.43, whereas the battery mix of low-cobalt chemistries can reduce cobalt demand by 54.15% compared with the high-cobalt mix. These results provide a good reference for understanding cobalt demand–supply balance and designing policies to manage this balance.

First, China's cobalt supply is mainly fulfilled by natural mineral mining and cobalt imports. According to USGS (2021), cobalt production in China was 2.5 kt in 2019 and the estimated production in 2020 was 2.3 kt. This implies that domestic production is insufficient to support China's consumption in each of the scenarios presented in this study, although cobalt demand is projected to peak in all scenarios. Consequently, China, in most cases, has to continue importing over 90% of its cobalt demand, especially from the leading global supply source, the DRC, which can supply up to 95 kt annually. To hedge a sudden drop in production or supply crisis contagion (Sun et al., 2021), China should build a dynamic strategic cobalt reserve and encourage domestic companies to establish commercial reserves. Moreover, managing potential risks related to the DRC is another priority for China. Reducing the risks associated with the artisanal mining is one of them. The Chinese central government and the DRC should work together to establish rules for sustainable cobalt production that meet environmental, social, and governance standards. Chinese companies running business in the DRC need to work with their counterparts to develop a tracking system based on blockchain technology to allow the whole cobalt industry chain to achieve a secure and sustainable supply.

Second, considering the substantial impact of cobalt, this study advocates research and development in all prospective battery technologies. As discussed earlier, cobalt-free and low-cobalt chemistries are two substitution mechanisms. From the perspective of a cobalt-free option, the CTP/blade battery using LFP is commercially available, while the other cobalt-free batteries are in its early stage of development. Therefore, they should be treated differently. As a transition technology, the former is competitive. Governments can give this battery technology more credit by dynamically updating the dual-credit policy and thus help in increasing its market share. As for the other cobalt-free batteries, China can co-start a global research initiative with the EU and United States and accelerate its development process to make it more attractive and cost-competitive, which will help free the battery industry from the bottleneck of scarce cobalt resources and ensure a smooth transition to zero-emissions from vehicles. Commercialized technology is now ready for less-cobalt batteries and has entered the pre-stage of industrial-scale production (Kim, 2021). Therefore, policy support is suggested to scale-up production to increase its market share in the battery mix.

Third, scholars treat recycling as a critical solution for the sustainability of cobalt utilization in China (Zeng and Li, 2015; Wang and Ge, 2020). A recent study in China revealed that 3.1 kt of cobalt was recovered from end-of-life LIBs in 2018, which provided 12.8% of the cobalt supply for new LIBs (Liu et al., 2021). Thus, in the future, the potential for recycling is huge, given the magnitude of spent batteries (Wang and Ge, 2020). The recycling rate of end-of-life batteries relies on a national recycling system and mature recycling technologies (Tang et al., 2021). However, the recycling rate of end-of-life LIBs in China is low (Liu et al., 2021) because of the lack of an effective recycling system and early-stage recycling technologies. Therefore, it is highly recommended that governments set mandates and incentives sooner rather than later to establish a collection system for batteries and increase the recycling rate of cobalt-bearing batteries.

[8]In China, the installed battery capacity of TLIBs was 74.3 GWh in 2021, while that of LFP batteries was 79.8 GWh.

This study focuses on the light-duty vehicle and does not consider the electrification of medium- and heavy-duty vehicles, which would be analyzed in the future. Since our focus is on the cobalt demand projection, variables like price, advertising, and policy efforts are treated as blackbox in the Bass model. In the future, a more generalized Bass model could be adopted to study the comprehensive impacts of price and policy efforts on cobalt demand. In addition, this study does not consider the disruptive impact of hydrogen vehicle development on cobalt demand.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

QS: Conceptualization, Methodology, Formal analysis, Visualization, Programming, Writing- original and revised manuscripts.

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Simulation Analysis of Supply Crisis Propagation Based on Global Nickel Industry Chain

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Nickel is a key metal in the low-carbon transition. The industrial chain is a chain network organization system composed of various layers from the initial production of raw materials to the final product sales. The intensified contradiction between supply and demand can easily lead to the problem of resource supply security, and the occurrence of supply shortages will endanger the healthy and orderly development of the whole industrial chain. Therefore, from the perspective of the industrial chain and based on the trade data related to the nickel industrial chain, this study first constructs a multi-layer network model of the nickel industrial chain, and analyzes its trade structure characteristics and the correlation between different layers. It is found that the export policies of resource exporting countries may influence trade structure characteristics. On this basis, a multi-layer network crisis propagation model of the nickel industrial chain is constructed to simulate the impact and its propagation path of Indonesia supply shock on the entire industrial chain. With the increase of supply shock in Indonesia, the impact of crisis gradually concentrates to the downstream. Along the industrial chain, the number of affected countries gradually increases, but the difference in the impact degree gradually decreases. In addition, there are certain differences in countries affected by crisis at different layers of the industrial chain, and the crisis spreads mainly from China and Japan to the countries in midstream and downstream. The research results can provide corresponding policy suggestions for countries involved in the nickel trade.

Keywords: nickel industry chain, simulation, multi-layer network, crisis propagation, Indonesia supply shock

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INTRODUCTION

The Paris Climate Agreement signed in 2015 set climate-change targets, to this end, many countries around the world have made carbon neutral commitments. Vigorously developing electric vehicles is one of the effective ways to achieve carbon neutrality, power battery is an important component in the electric vehicle industry chain, and high-nickel ternary lithium battery is becoming the mainstream, accounting for a gradually increasing proportion. Nickel is listed in the list of 24 strategic minerals by China in 2016, and also listed as a national crisis mineral or strategic mineral of priority concern by the United States, Japan, and other countries. It is mainly used in the fields of steel, nickel-based alloy, electroplating and batteries (Reck et al., 2008; Eggert, 2011). Under the background of carbon peak and carbon neutralization, with the rapid growth of nickel demand in electric vehicle batteries, the sustainable development and utilization of nickel resources have become a global concern (Gulley et al., 2018). Using different scenarios, Elshkaki et al. (2017) calculate that nickel demand will increase by 140–175% by 2025 and 215–350% by 2050. It can be seen that the market demand for nickel resources continues to increase in the future (Alvial-Hein et al., 2021). Although the production rate of nickel is greatly improved compared with that before the last century, mineral resources are limited, and continuous exploitation will eventually lead to exhaustion. The rapid depletion of resources calls for sustainable exploitation and utilization of resources (Mudd, 2010; Lederer et al., 2016). According to the United States Geological Survey (USGS), there are 89 million tons of nickel in the world in 2019, which at current rates of production would last about 37 years. The top three countries with the largest nickel reserves are Indonesia, Australia and Brazil, accounting for 60% of the world's nickel. In recent years, with the development of new energy vehicles, the importance of nickel has been emphasized, so Indonesia has banned nickel exports more than once to improve its industrial structure. Resource export restriction will bring some uncertainty to global resource supply security (Teo, 2017), the shortage of a key strategic resource will endanger the healthy and orderly development of the whole industry chain (Graedel et al., 2015).

The industrial chain is a chain network organization system composed of various layers from the initial production of raw materials to the final product sales. The complex trade relationship of resources in each layer and between layers of the industrial chain forms a multi-layer trade network. As globalization continues to accelerate and countries involved in trade become more and more closely connected, countries around the world are vulnerable to trade disruptions (Liu and Muller, 2013). The industrial chain itself is a complex multi-layer network chain structure, its risks lurk in the industrial chain, always threatening its normal operation and development (Klimek et al., 2015). However, at present, researches based on trade crisis dissemination mainly focus on single-layer networks (Chen et al., 2018; Wang et al., 2018), using the multi-layer network theory to describe and analyze crisis propagation, it can explain the robustness of inter-layer associated networks when they encounter interference or attack, thus providing a scientific basis for further network optimization.

At present, a large number of scholars have begun to study the propagation of crisis communication in multi-layer networks. Danziger et al. (2018) proposed a dynamic dependency framework and used it to study synchronization and propagation processes in multi-layer networks with interaction layers. Gong et al. (2013) constructed an interdependent multi-layer network to analyze the cascading propagation of supply chains. Some scholars have also built a multi-layer copper trading network, using the complex network theory to determine the relationship between the copper raw material trade network and the copper scrap trade network, and understand the impact of China's import ban on the multi-layer copper trading network (Hu et al., 2020). However, from mining to the use of nickel in various industries, all layers of the nickel industry chain are interlinked and interact with each other. When there is a shortage of goods in one layer of a country, it is likely to cause the supply of raw materials in the production of goods in the next layer to be insufficient. Then the output of the next layer will be affected, when the impact exceeds a certain limit, the supply risk of the next layer may be triggered. Therefore, on the one hand, it is necessary to understand the correlation between the upper and lower layers of the industrial chain, and on the other hand, we want to know the impact of problems in a layer on the international trade of the whole nickel industrial chain, so as to provide important reference for the development strategies of nickel-related industries of various countries more macroscopically.

Therefore, considering the frequent occurrence of Indonesia's export restriction policies in recent years, to understand the complex relationship between different layers of the whole nickel industry chain and evaluate the impact of Indonesia's supply shock, this paper analyzes the evolution characteristics of the trade structure of the global nickel industry chain by constructing a multi-layer trade network. Also, a supply crisis propagation model is constructed to simulate the impact of Indonesia's supply shock on the nickel industry chain and the crisis propagation path. The rest of this article is organized as follows. **Section 2** mainly introduces the data and methods, including the construction of network and the construction of the crisis propagation model. **Section 3** mainly analyzes the complex relationship between the multi-layer network of the nickel industry chain and the impact of Indonesia's supply shock. **Section 4** provides the main conclusion and discussion.

DATA AND METHOD

Data

According to the whole nickel life cycle process, this paper divides the nickel industry chain into three layers: upstream, midstream and downstream. The upstream products mainly refer to nickel ore and concentrate and nickel matte, the midstream products mainly include refined nickel and intermediate nickel products, the downstream products are final consumer goods containing nickel. *See* **Table 1** for the Harmonization System Code (HS Code) and nickel content of products involved. Nickel-containing products and nickel-containing coefficients (how much nickel is contained in 1 Kg nickel product) refer to the article of (Nakajima et al., 2018). In this paper, we download and use trade data of all commodities related to the nickel industry chain from 2010 to 2019 from the UN Comtrade database, including import and export flows of countries around the world. The volume of trade is measured in Kg. In this study, some countries with low trade volume are excluded, leaving the trade flows in the top 95% of the total trade volume. However, the elimination of these trade relations and trading countries does not affect the impact on the major trading countries and trade relations, including 186 countries. It should be noted that due to the slight differences in statistical diameters among countries, some inconsistency exists between the statistics reported by a country and their trade partners. Therefore, for unification, the maximum value of the statistics from a reporting country and its partners as the trade value in this paper.

TABLE 1 | Nickel content and HS Code in different layers.

Layers	Nickel content	HS code
upstream	0.015–0.75	2604; 750110
midstream	0.00003–1	282540;282735;283324;381511;720260;750120;7218;7219;7220;7221;7222;7223;7504;7508;7601;7602;7603;7604;7605;7606;7607;7608;7609;7610;7611;7612;7613;7614;7615;7616;731414;732393;732410;740822;740940;741122;750210;750220;750511;750512;750521;750522;750610;750620;750711;750712;750720;850730;850740
downstream	0.00004–0.02	8401;8402;8403;8404;8405;8406;8407;8408;8409;8410;8411;8412;8413;8414;8415;8416;8417;8418;8419;8420;8421;8422;8423;8424;8425;8426;8427;8428;8429;8430;8431;8432;8433;8434;8435;8436;8437;8438;8439;8440;8441;8442;8443;8444;8445;8446;8447;8448;8449;8450;8451;8452;8453;8454;8455;8456;8457;8458;8459;8460;8461;8462;8463;8464;8465;8466;8467;8468;8469;8470;8471;8472;8473;8474;8475;8476;8477;8478;8479;8480;8481;8482;8483;8484;8485;8501;8502;8503;8504;8505;8506;8508;8509;8510;8511;8512;8513;8514;8515;8516;8517;8518;8519;8520;8521;8522;8523;8524;8525;8526;8527;8528;8529;8530;8531;8532;8533;8534;8535;8536;8537;8538;8539;8540;8541;8542;8543;8544;8545;8546;8547;8548;8601;8602;8603;8604;8605;8606;8607;8608;8609;8701;8702;8703;8704;8705;8706;8707;8708;8709;8710;8711;8712;8713;8714;8715;8716;8801;8802;8803;8804;8805;8901;8902;8903;8904;8905;8906;8907;8908;9001;9002;9003;9004;9005;9006;9007;9008;9009;9010;9011;9012;9013;9014;9015;9016;9017;9018;9019;9020;9021;9022;9023;9024;9025;9026;9027;9028;9029;9030;9031;9032;9033;9101;9102;9103;9104;9105;9106;9107;9108;9109;9110;9111;9112;9113;9114

Construction and Characteristic Analysis of Multi-Layer Network

This paper constructs a nickel industry chain multi-layer trade network from 2010 to 2019. The multi-layer trade network includes three layers, namely the upstream trade network, the midstream trade network and the downstream trade network. By using nodes to represent countries and edges to represent trade relations between nodes, the global nickel industrial chain trade network is constructed as $G^t_{L_m} = (V^t_{L_m}, E^t_{L_m})$. t represents a year from 2010 to 2019. L_m (m = 1,2,3) represents each trade layer of the nickel industrial chain, wherein L_1 represents the upstream trade layer of the nickel industrial chain, L_2 represents the midstream trade layer, and L_3 represents the downstream trade layer. The set of countries involved in each layer is defined as $V^t_{L_m} = \{v_1, v_2, \ldots, v_{N^t_{L_m}}\}$, where $N^t_{L_m}$ refers to the number of countries participating in trade in L_m layer in t year. The set of trade relations is defined as $E^t_{L_m} = \{e_{ij}, i, j \in V^t_{L_m}\}$. Here, $e_{ij} = 1$ if country i exports containing nickel products to country j, otherwise $e_{ij} = 0$. In addition, the trade flow in this paper mainly refers to the flow of nickel element. We express the flow of nickel between countries at the layer L_m of the industrial chain as follows:

$$C^{(t,L_m)}_{ij} = \sum\nolimits_{q=1}^{n} \left(W^q_{ij} * p_q\right) \tag{1}$$

Where, n represents the quantity of nickel-containing products in layer L_m, q represents a nickel-containing product involved in layer L_m, W^q_{ij} represents the weight of nickel-containing product q exported from country i to country j, and p_q is the nickel-containing coefficient of product q.

This paper analyzes the dynamic evolution characteristics of global nickel industry chain trade by selecting average weighting degree, density, average clustering coefficient, and average shortest path length. Here, at each layer of the nickel industrial chain, the average weighted degree is used to represent the average trade volume of all participating countries, the density of graphs and the average agglomeration coefficient are used to represent the closeness between participating countries, and the average shortest path length means that through at least how many countries can two countries in the trade network form trade relations.

(1) The average weighted degree

The weighted degree w_i of node n_i displays the sum of imports and exports of country n_i. the greater the value is, the higher its trade volume becomes (Garlaschelli and Loffredo, 2005). The definition is as follows:

$$w_i = \sum\nolimits_{j=1}^{v_N} e_{ij} * w_{ij} + \sum\nolimits_{j=1}^{v_N} e_{ji} * w_{ji} \tag{2}$$

$$\bar{w} = \frac{\sum w_i}{N} \tag{3}$$

Where w_i is the weighted degree of node n_i, and w_{ij} is the weight of edge e_{ij}. $\bar{w}$ represents the average weighted degree of all nodes in this network.

(2) Destiny

Network density (D) is another metric used to measure how tight the relationships between nodes are. In a trade network, the greater the density, the closer the relationship between countries, which is defined as (Fischer and Shavit, 1995):

$$\mathrm{D} = \frac{p}{N(N-1)} \tag{4}$$

Where p represents the number of actual trade relationship in the network, and N represents the number of all countries in the network.

(3) The average clustering coefficient

The clustering coefficient can measure the possibility of trade relationships between two countries that have trade relationships with n_i, and can reflect the closeness of trade relations between countries in the network, with a range of 0–1. It is defined as (Fischer and Shavit, 1995):

$$C_i = 2e_i \Big/ \sum_{j=1}^{N} e_{ij} \left(\sum_{j=1}^{N} e_{ij} - 1 \right) \tag{5}$$

$$\bar{C} = \frac{1}{N} \sum_{i=1}^{N} C_i \tag{6}$$

Where C_i is the clustering coefficient of n_i, e_i represents the real number of trade relations between trading countries of n_i, and $\bar{C}$ is the average clustering coefficient of all nodes in the network.

(4) The average shortest path length

The average shortest path length is the average shortest distance between nodes in the trade network. The smaller the value is, through the fewer transmissions that any two nodes in the network can have a trade relationship. The definition is as follows:

$$L = \frac{1}{N(N-1)} \sum_{i,j} d\left(v_i, v_j\right) \tag{7}$$

Where L is the average shortest path length between nodes in the network, and N represents the total number of nodes in the network.

Topological Correlation Between Different Layers of the Industrial Chain

The relationship between different layers of the industrial chain is complicated and there must be some correlation between layers. Therefore, this paper analyzes the correlation between different layers of the industrial chain from the perspectives of node and edge.

In this paper, the node/edge overlap rate between two layers is selected to reflect the correlation between them. Taking the upstream layer L_1 and the midstream layer L_2 as examples, the definitions are as follows (Hu et al., 2020):

$$on^{(L_1,L_2)} = \frac{V^{L_1} \cap V^{L_2}}{V^{L_1} \cup V^{L_2}} \tag{8}$$

$$oe^{(L_1,L_2)} = \frac{E^{L_1} \cap E^{L_2}}{E^{L_1} \cup E^{L_2}} \tag{9}$$

Where, $on^{(L_1,L_2)}$ and $oe^{(L_1,L_2)}$ represent the overlap of nodes and edges between L_1 and L_2 layers respectively, and V^{L_1} and E^{L_1} represent nodes and edges of L_1 layer respectively.

Node degree refers to the number of edges associated with the node. Node strength is the sum of the weights of the edges connected to the node. To verify whether countries with high node degree or node strength at one layer of the nickel industrial chain also have high node degree or strength at other layers, this paper introduces an indicator:

$$\mu\left(\mathrm{nr}\left(k_i^{[t,L_1]}, \mathrm{t}\right)\right) = \frac{k_i^{[t,L_2]}}{\max\left(k_i^{[t,L_2]}\right)} \tag{10}$$

$$\mathrm{nr}\left(k_i^{[t,L_1]}\right) = \frac{\mathrm{r}\left(k_i^{[t,L_1]}\right)}{N^{[t,L_1]}} \tag{11}$$

Where, $\mathrm{r}(k_i^{[t,L_1]})$ refers to the ranking of country i in the upstream layer of the nickel industry chain in t year, and $N^{[t,L_1]}$ refers to the number of all countries participating in the trade of the upstream layer in t year. Therefore, $\mathrm{nr}(k_i^{[t,L_1]})$ refers to the normalized ranking of node degree of country i in the upstream layer of nickel industry chain. $k_i^{[t,L_1]}$ and $k_i^{[t,L_2]}$ represent the degree of country i in the upstream and midstream layers respectively. The $\max(k_i^{[t,L_2]})$ represents the maximum value of the country degree in the midstream in t year.

For the node strength of a country, its index is defined as:

$$\mu\left(\mathrm{nr}\left(s_i^{[t,L_1]}, \mathrm{t}\right)\right) = \frac{s_i^{[t,L_2]}}{\max\left(s_i^{[t,L_2]}\right)} \tag{12}$$

$$\mathrm{nr}\left(s_i^{[t,L_1]}\right) = \frac{\mathrm{r}\left(s_i^{[t,L_1]}\right)}{N^{[t,L_1]}} \tag{13}$$

Where, $\mathrm{r}(s_i^{[t,L_1]})$ refers to the ranking of strengthening degree of country i in the upstream layer of the nickel industrial chain in t year, and $\mathrm{nr}(s_i^{[t,L_1]})$ refers to the normalized ranking of node strength of country i in the upstream layer. $s_i^{[t,L_1]}$ and $s_i^{[t,L_2]}$ represent the node strength degree of country i in the upstream and midstream layers respectively. $\max(s_i^{[t,L_2]})$ represents the maximum value of node strength degree in the midstream layer in t year.

Construction of Multi-Layer Crisis Propagation Model

Based on the multi-level trade network of the nickel industry chain, this paper constructs a crisis propagation model to simulate the impact of Indonesia's export reduction on the whole nickel industry chain and assumes Indonesia as the source of crisis i. The aim is to explore how this supply crisis will damage all layers of the nickel chain when Indonesia exports decline, how it will affect other countries, and how the crisis spreads from upstream to downstream of the chain. Based on this idea, the risk communication model of the whole industrial chain is simply described as follows:

(1) Assume that the state of all countries in the whole industrial chain is normal, as shown in **Figure 1A**
(2) Assuming that Indonesia is the crisis source country i, Indonesia restricts the export of nickel ore, as shown in **Figure 1B**. If the export volume of crisis source I is reduced by alpha (Occurrence of supply risk, expressed by a reduction in export volume), the reduced export volume is expressed with ΔW, then the existing export volume becomes:

$$W' = (1-\alpha)\mathrm{W} \qquad (\alpha \in [0,1]) \tag{14}$$

$$\Delta W = \alpha \mathrm{W} \tag{15}$$

Where, α is an adjustable parameter, which can be adjusted according to research needs to simulate the influence of trade volume on the whole nickel industry chain in different degrees.

(3) Countries in the upstream trading layer that have a direct trade relationship with Indonesia will be affected, such countries as country D and country B at the upstream layer in **Figure 1C** will continue to spread the crisis to other countries in the upstream layer and the midstream

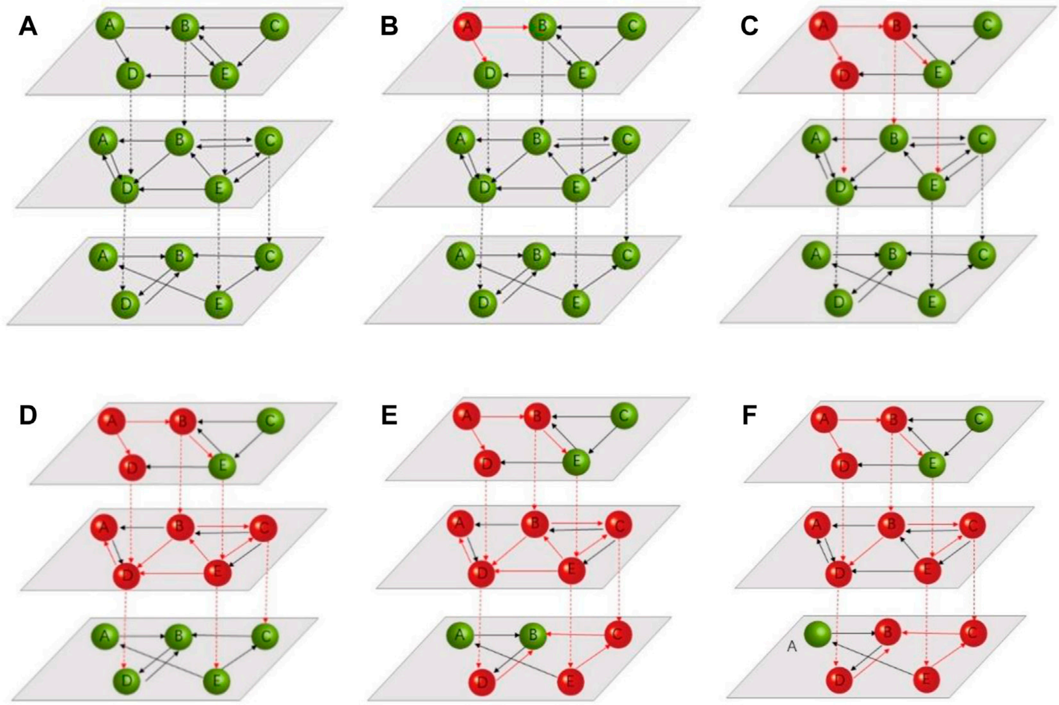

FIGURE 1 | A diagram of crisis transmission **(A)**1,**(B)**2,**(C)**3,**(D)**4,**(E)**5,**(F)**6. Note: Each layer in each subgraph represents each layer of the nickel industry chain. Green and red spheres represent countries involved in trade, green spheres represent normal countries, and red spheres represent affected countries. Solid arrows indicate the flow of trade within layers, and dotted lines indicate the flow of nickel material between layers. A red line indicates a decrease in material flow.

layer. Here, when we judge how the affected countries spread down, there are certain differences in the import and export of nickel resources in different countries, and the degree of risk transmission should be different accordingly (Foti et al., 2013). First, we should judge the import and export volume of the country affected by the risk. If the country is a net exporter, its export decrease is the same as its import decrease. If it is a net importer, it will decrease proportionately. In **Figure 1C**, country B is the crisis-affected country, and its export reduction is calculated by judging whether country B is a net importer or exporter:

$$\Delta W_{BE} = \begin{cases} \Delta W_{IB} & B\ is\ a\ net\ exporter \\ \dfrac{\left(W_{import} - \Delta W_{IB}\right)}{W_{import}} \times W_{export} & B\ is\ a\ net\ importer \end{cases} \tag{16}$$

Where, Where, ΔW_{BE} is the export decrease of country B, ΔW_{IB} is the import decrease of country B. W_{import} and W_{export} are the original import and export volume of country B respectively.

(4) Affected by the reduction of production capacity in the upstream layer, some countries in the midstream layer become the source of crisis transmission, as shown in **Figure 1D**, countries B, D and E in the midstream layer.
(5) As in Step 3, crisis transmission sources B, D, and E in the midstream layer spread the crisis to other countries in the layer and to the downstream layer, as shown in **Figure 1E**.
(6) Similarly, countries C, D and E in downstream of **Figure 1E** become sources of crisis transmission and spread the crisis to other countries in this layer. The simulation is terminated until the trade volume of all countries in the whole industrial chain reaches a stable (**Figure 1F**).

RESULTS AND ANALYSIS

Structural Evolution of Nickel Industry Chain Multilayer Network

To evaluate the development of the global nickel industry chain, this paper studies its evolution characteristics from 2010 to 2019. The analysis shows that the global nickel industry chain development is relatively stable except 2013. Countries and their trade relations have little differences between the upstream and midstream of the industrial chain involved in nickel resource trade (**Figures 2A,B**), while countries and their trade relations are relatively large in the downstream. It is clear that trade countries and trade relations plummeted in 2013. The reason may be that Indonesia has issued seven policies related to banning the export of nickel ore successively in 2013, and it was stipulated in 2012 that the export of raw nickel ore would be banned in 2014. Therefore, major trading countries in downstream of the nickel industry chain increase the import of nickel products related to the downstream for reserve. In addition, as only 95% of the total trade volume is studied in this paper, the vast majority of downstream products are controlled

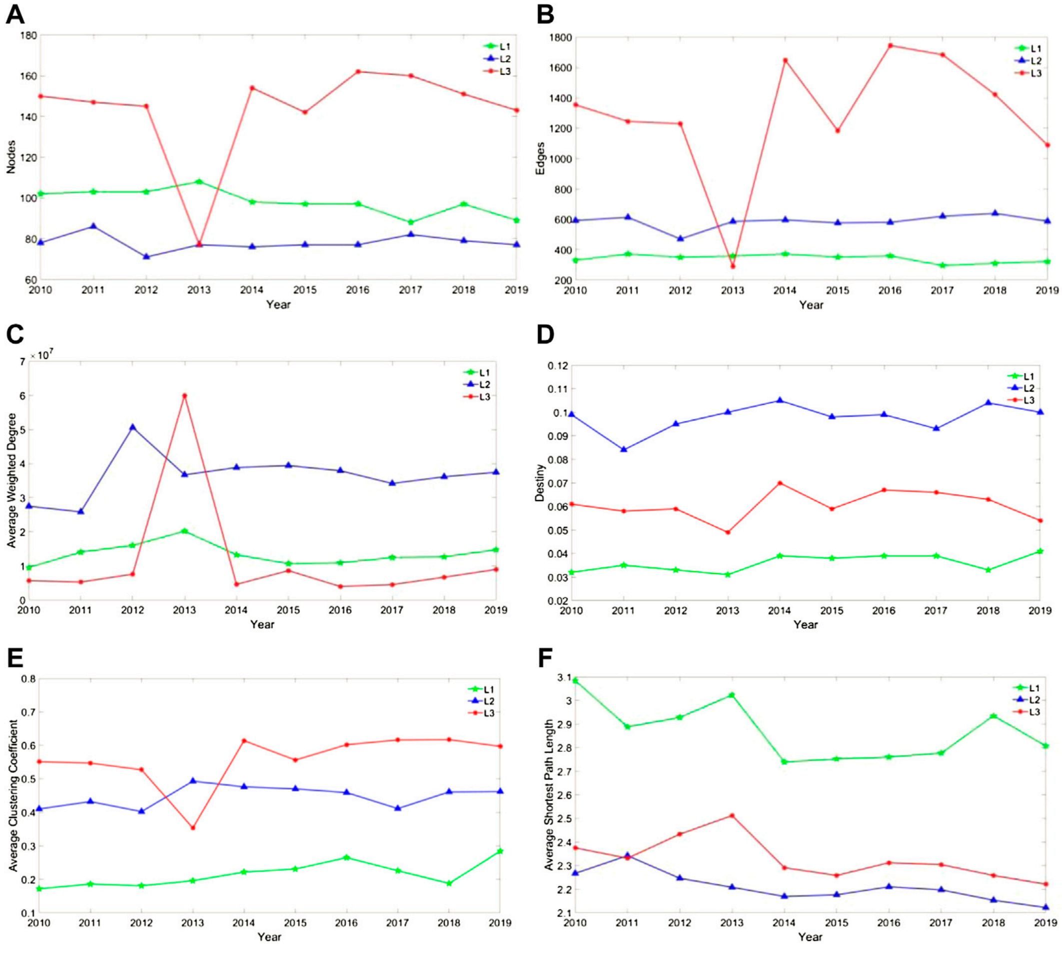

FIGURE 2 | Trade evolution of nickel industry chain trade from 2010 to 2019 **(A)** nodes, **(B)** edges, **(C)** he average weighted degree, **(D)** density, **(E)** average clustering coefficient, **(F)** average shortest path length. Note: L1, L2 and L3 represent the upstream, midstream and downstream of the nickel industry chain respectively.

by a few trading countries, which is also one of the main reasons for the sudden increase in the average weighted degree of downstream nickel industry chain in 2013 (**Figure 2C**). In terms of the tightness of trade relations, **Figures 2D,E** show that the trade relations between countries in the nickel industry chain are relatively close and stable in the past decade, and the trade relations between countries in the upstream layer of the nickel industry chain are the loosest. At any level of the nickel industry chain, at most three countries can form trade relations (**Figure 2F**).

The Correlation Between Nickel Industrial Chain Layers

Figure 3 shows the correlation between layers of the nickel industry chain. As shown in **Figure 3A**, the countries that overlap between layers of the nickel industrial chain have basically remained stable over the past decade. The overlap rate between countries participating in upstream trade and midstream trade is the highest, reaching 72% in 2019, indicating that countries participating in upstream trade of nickel industry chain also actively participated in midstream in 2019. Taking the upstream and midstream of the industrial chain as an example, the horizontal coordinate in **Figure 3B** shows the nodes in descending order of node degree in the trade network of the upstream and shows the degree changes of countries participating in the trade of midstream. The results show that when a country has more trade relations upstream, it tends to establish more trade channels in the midstream of the nickel industry chain. Similarly, most of the countries with higher trade value in the upstream also have higher point strength in the midstream of the nickel industry chain (**Figure 3C**). We also study the correlation between layers of the nickel industry chain from the perspective of national trade relations (edges). **Figure 3D** shows that the overlap rate of trade relations between countries at different layers in the nickel industry chain is basically stable during the decade, among which the overlap rate between the midstream and downstream is the highest. However, compared with the overlap rate of nodes (**Figure 3A**), the overlap ratio of trade relations between layers

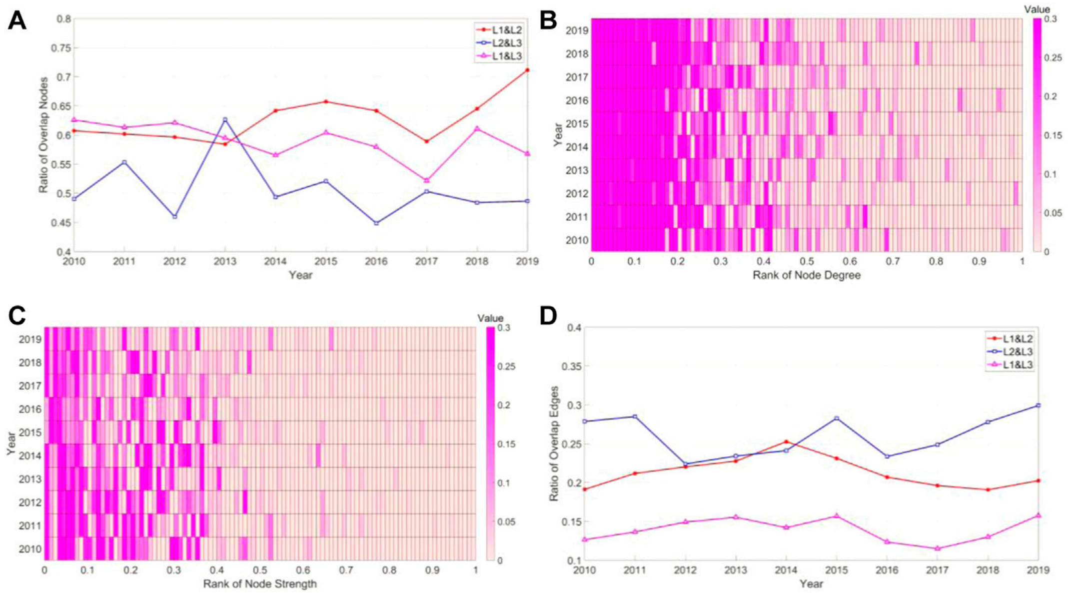

FIGURE 3 | Correlation analysis between layers of nickel industry chain in terms of nodes and edges **(A)** the changes in the proportion of nodes between layers of the nickel industrial chain, **(B)** the changes in degree of standardized nodes in the midstream based on the nodes in the upstream, **(C)** the changes in intensity of standardized nodes in the midstream, respectively, based on the nodes in the upstream, **(D)** the changes in the proportion edges between layers of the nickel industrial chain. Note: For **(B**,**C)**, the abscissa represents the rank of node degree/intensity, and the ordinate represents the year of study. For each year, we first rank them in reverse order of node degree/intensity in the upstream, for each line, we calculate the normalized value of node degree/strength in the midstream through formulas **4**–**7**. The redder the color is, the greater the value is.

TABLE 2 | The impact of upstream supply shocks in Indonesia on the industry chain.

Reduced proportion in Indonesia's exports (%)	Proportion of countries whose imports fell by more than 10 (%)in the upstream	Proportion of countries whose imports fell by more than 10 (%)in the midstream	Proportion of countries whose imports fell by more than 10 (%)in the downstream
10	0	0	0
20	5	0	0
30	13	0	1
40	20	1	2
50	23	12	13
60	25	17	30
70	26	21	47
80	27	29	56
90	27	34	64
100	28	36	67

is relatively low. The reason may be that there is a large gap in the number of trade relations at different layers of the nickel industry chain (**Figure 2B**).

The Impact of Indonesia Supply Shocks

Through the above analysis, we find that there is a certain correlation between layers of the nickel industry chain. Indonesia is a major nickel producer and has had several export bans in recent years. Therefore, using 10-year trade data from 2010 to 2019, this paper constructs a multi-layer crisis propagation model of the nickel industry chain and simulates the impact of the upstream Indonesian nickel resource supply shock on the whole nickel industry chain and how the shock spreads from the upstream to the whole nickel industry chain.

The Overall Impact on the Industrial Chain

The overall impact of Indonesia's export supply shock on the nickel industry chain is analyzed in this paper. By adjusting α in **Formula 1**, we adjust the export supply shock of Indonesia to varying degrees (**Table 2**). The results show that with the increase of supply shock, on the one hand, more and more countries are

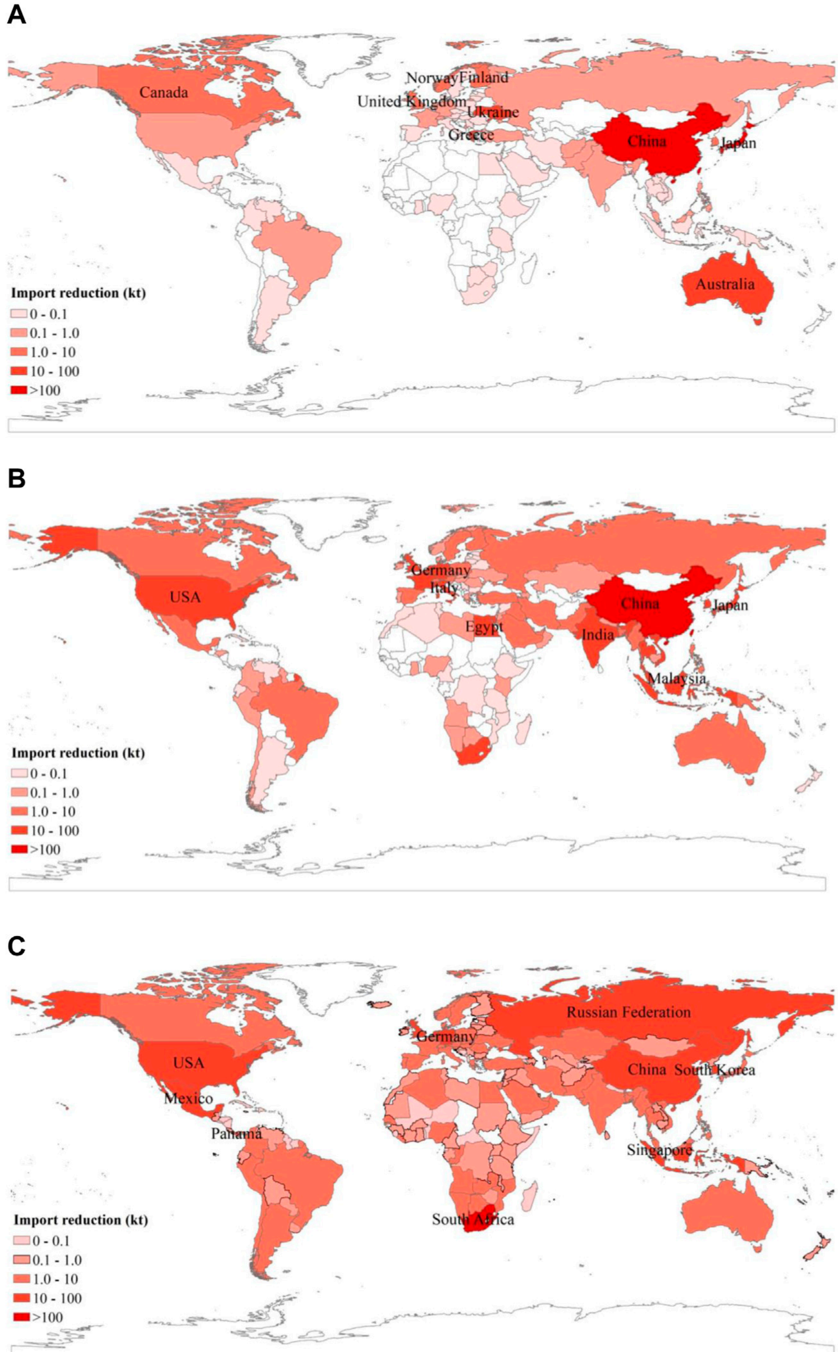

FIGURE 4 | The geographical distribution of the impact degree in countries at different layers of the nickel industry chain **(A)** upstream, **(B)** midstream, **(C)** downstream. Note: The depth of color in the figure indicates the degree of impact. The darker the color, the greater the impact and the greater the import volume reduction. The top 10 most affected countries are marked.

affected at all layers of the industrial chain, and on the other hand, the influence gradually concentrates to the downstream. When Indonesia's exports fall by less than 40%, countries in the upstream are more affected, and those in the midstream and downstream are less affected. When Indonesia's export decreased by more than 50%, the impact gradually concentrated to the downstream, the number of countries affected in the downstream by more than 10% is gradually increasing, and all of them are larger than the proportion of countries affected in the upstream and midstream. When Indonesia's supply exports decrease by 50%, 23% of the countries in the upstream imports decrease by more than 10%, and about 12% of the countries in the midstream

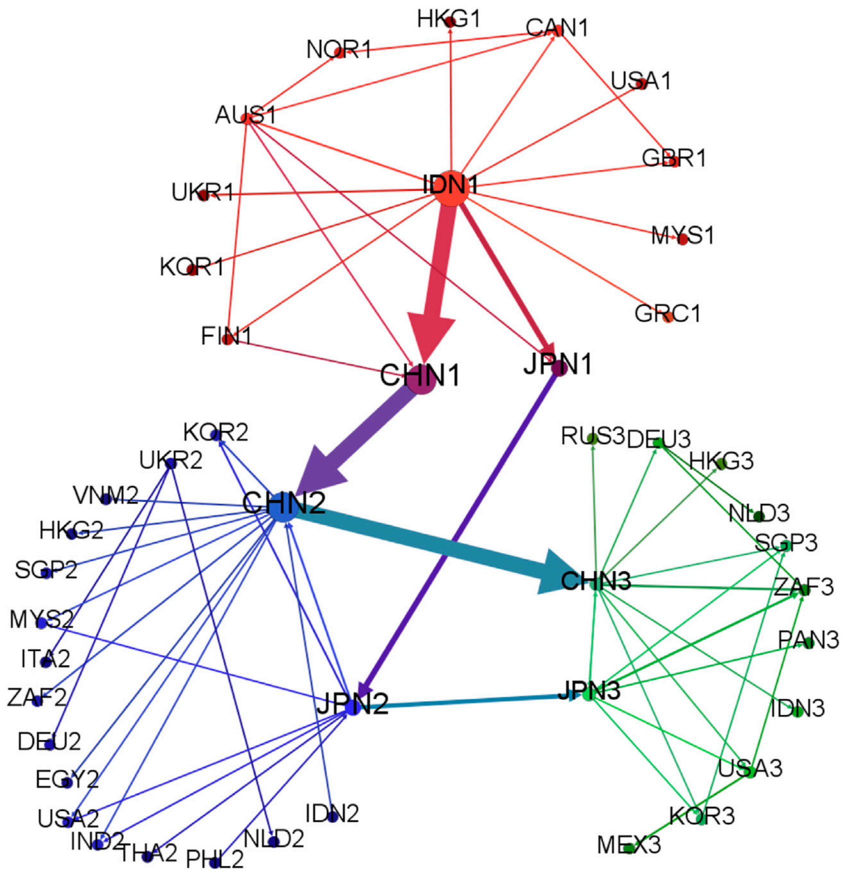

FIGURE 5 | The main route of crisis propagation in the nickel industry chain. Note: the nodes represent countries, the edges represent trade relations between countries, the direction of the arrow represents the direction of trade flow, and the wider the edge, the greater the reduction of nickel material. Red nodes and lines represent the upstream layer of the industrial chain, blue nodes and lines represent the midstream layer, and green nodes and lines represent the downstream layer. The number 1,2,3 following the national abbreviation represents the upstream, middle and downstream of the industrial chain respectively. (*See* **Supplementary Materials** for the country names corresponding to the abbreviations).

and downstream imports decrease by more than 10%, respectively.

Countries Most Affected by Supply Shocks

When there is a supply shock in Indonesia (a 50% reduction in exports), there are also certain differences among countries that are more affected in different layers of the nickel chain (**Figure 4**). Half of the 10 countries most affected in the upstream are in Europe, but China and Japan are the most affected, their import decline is significantly higher than that of other countries, mainly because Indonesia's upstream nickel resources are mainly exported to China and Japan. The 10 most affected countries in the midstream are mainly in Asia and Europe except the USA, with China being the most affected. The downstream countries most affected are South Africa, Mexico, and the USA, so they are the major importers of final consumer goods containing nickel. The overall analysis shows that along the industrial chain, the number of affected countries gradually increases, and the difference of affected degree gradually decreases. China is among the 10 countries most affected at each layer, with Japan, South Korea, Germany and the USA appearing twice.

The Impact of the Crisis Propagation Path

Figure 5 shows the transmission path of the impact of Indonesia's nickel raw material export reduction on the whole industrial chain. The chart shows only the top 20 trade relationships with decreasing trade volume at each layer of the industry chain. Red represents the upstream trading layer of the nickel industry chain. We find that Indonesia mainly transmits the crisis to Japan and China in the upstream layer, while other countries are less affected. The main reason is that resources upstream are all in the hands of a few countries, no matter in the direction of import or export. Indonesia is the main resources producer, while Japan and China are the major resources importers. Blue represents the layer in the middle reaches of the nickel industrial chain. We find that the risk sources in the middle reaches are mainly China and Japan. After the reduction of nickel resources upstream, China and Japan will reduce the production of the midstream and spread the crisis to other countries in the midstream. Green represents the downstream of the nickel industry chain. Similarly, the crisis sources downstream are also China and Japan, which spread the crisis to downstream by reducing the production of downstream products.

DISCUSSION AND SUGGESTIONS

First, we review the evolution characteristics of multi-layer trade networks in the nickel industry chain from 2010 to 2019. The results show that the evolution of the nickel industrial chain is relatively stable from 2010 to 2019, however, the change of export policies of major resource-producing countries can lead to the change of the nickel industrial chain trade pattern. Possibly influenced by various policies related to banning nickel ore exports issued by Indonesia since 2012, countries involved in trade and trade relations between countries plummeted in 2013, while the average trade volume in the downstream soared. At the same time, there are also some differences between the trade networks at all layers of the nickel industry chain, and the trade links between countries participating in the upstream trade are the loosest.

Secondly, we have analyzed the interdependence between industrial chain layers, and the close correlation between the CRM trade network and CWS trade network is identified from the perspective of different structural characteristics determine the close correlation between industrial chain layers from different structural characteristics. In particular, the trade volume and the trade relations between nickel industrial chain layers are highly positive. That is, if a country establishes more trade relations and owns more trade volume in one layer of the nickel industry chain, it generally also has a large number of trading partners and considerable trade volume in other layers. Similarly, if two countries are close at one layer, they tend to establish a tight trade relationship at other layers of the industry chain. In addition, due to the large gap in the number of trade relations between different layers of the nickel industry chain, the proportion of overlapping trade relations between layers is relatively low compared with the overlapping rate of participating countries.

Finally, we build a multi-layer network crisis propagation model for the nickel industry chain to simulate the impact of the upstream supply shock in Indonesia. The results show that with the increase of supply shock in Indonesia, the impact gradually concentrated to the downstream of the industrial chain. By analyzing the impact of Indonesia's supply shock on countries at different layers of the nickel industry chain, it is found that along the direction of the industrial chain, the number of countries affected gradually increases, but the difference of the impact degree gradually decreases. By analyzing the impact transmission path of Indonesia nickel raw material supply shock in the whole industrial chain, it is found that the crisis is mainly spread to the midstream and downstream of the industrial chain *via* China and Japan.

Based on the above analysis, this paper puts forward the following policy suggestions:

(1) Countries like Indonesia and the Philippines, as major exporters of nickel upstream resources, should reasonably regulate their export bans to avoid the sudden interruption of upstream resources leading to the healthy and orderly development of the global nickel industry chain. In recent years, to increase the added value of products and boost the development of the local economy, Indonesia has issued more than one policy to improve the industrial structure by banning the export of nickel ore and has been implementing it in advance. In the high-speed development of new energy vehicles, stainless steel production continues to increase, nickel-iron capacity release is not as expected and other factors intertwined, it is likely to cause nickel prices to rise sharply, resulting in chaos in the trade market.

(2) Countries such as China and Japan must find more ways to ensure the stable supply of upstream resources if they want to guarantee the development of their industrial chain. With few domestic resources, these countries are more than 90% dependent on foreign countries. The promulgation of the ban has caused a considerable impact on their industrial chain. On the one hand, these countries can look for new sources of resources. We know that diversification of trade links can reduce dependence on a single country. Except for Indonesia, the Philippines, which has seen its nickel reserves and grades decline due to heavy exports in recent years, and New Caledonia may be the place to look for an increase in exports. On the other hand, they could invest heavily in Indonesia and other nickel-rich countries and strengthen nickel mining projects with these countries, holding the advantage of high and new technology firmly in hand, maintaining its control over the global industrial chain, so as to avoid the phenomenon of resources being "choked up." In addition, continuing efforts to develop ore extraction technology is also an effective way to alleviate the supply crisis, nickel resources can be recycled more effectively with the improvement of technology.

(3) For all countries, nickel trade should be developed from the perspective of the whole industrial chain. From the above analysis, we know that the trade networks between the industrial chain layers are highly correlated, and the supply shock of the upstream will affect the whole industrial chain. Thus, focusing on a single-layer network will cause some countries to underestimate risks, while others may miss out on opportunities to expand trade. For example, South Africa, which imports a lot of downstream nickel products from China and Japan, should be aware not only of the risks posed by China and Japan but also of the risks they may face.

CONCLUSIONS AND FUTURE WORK

With the rapid growth of the demand for nickel in electric vehicle batteries, the sustainable development and utilization of nickel resources have become a global concern. The industrial chain is a chain network organization system composed of various layers from the initial production of raw materials to the sale of final products. Changes in export policies of some core countries are likely to have a great impact on this system. Each country needs to ensure the safe supply of nickel resources to determine the complex relationships in the industrial chain and understand the impact of export policies. Therefore, based on the complex network theory and the United Nations database, this paper firstly constructs the multi-layer trade networks of the nickel industrial chain from 2010 to 2019, analyzes the evolution characteristics of multi-layer trade structures, and the correlation between different layers. On this basis, a multi-layer trade crisis propagation model of the nickel industry chain is constructed to simulate the supply crisis impact and its propagation path of Indonesia's supply shock. The main results are as follows: *1*) the variation of the export policy of major resource-producing countries is likely to lead to the change of trade pattern of the whole industrial chain. *2*) Each country should gradually improve the construction of its industrial chain. On the one hand, the construction of the "whole industrial chain" can reduce the impact of international factors fluctuations on domestic production activities, on the other hand, it can improve the status of the country in the whole industrial chain. *3*) All countries should develop nickel trade from an overall perspective, pay close attention to all layers of the nickel industrial chain, and understand the position of each country in the industrial chain and the cross-layer relationship between all layers, to establish trade relations more effectively.

This paper builds a crisis propagation model of the nickel industry chain, on the one hand, it can simulate the impact of changes in any link on the whole industry chain, on the other hand, COVID-19 and trade frictions have occurred from time to time in recent years, we also hope that this model can be extended to other key mineral fields. However, this model can draw corresponding quantitative conclusions by studying the impact of risks on different countries, but due to space constraints, this manuscript does not show them. In addition, after the occurrence of crisis, how to adjust the industrial structure of each country is also our next research plan.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

XW and DZ contributed to the conception and design of the study. DZ provided the method and XW completed the first draft of the manuscript. AW contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.919510/full#supplementary-material

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Evolution of the Anthropogenic Gallium Cycle in China From 2005 to 2020

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Gallium is deemed to be a critical mineral given its irreplaceable use in consumer electronics and clean energy technologies. China has become a significant consumer of gallium while also playing a leading role in global gallium production, accounting for more than 90% of the world's primary output in recent years. However, the quantification and evolution of China's gallium cycle is limited until now. This study aims to uncover the dynamic flows and stocks of gallium in China during the period of 2005–2020. The results reveal that: 1) From 2005 to 2020, China's gallium demand increased more than 20-fold, as a result of the booming semiconductor industry and the surging use of gallium in some low-carbon technologies; 2) despite the inefficient recovery issues existed in the production stage, the supply of gallium extracted as a byproduct grew in tandem with the capacity of alumina production, resulting in a significant supply surplus of 948 t by 2020; 3) China exported nearly half of its gallium mainly as raw materials and final products, but still experienced a high reliance on imported gallium-containing intermediate products from abroad, such as integrated circuits; 4) the generations of in-use stocks and end-of-life flows of gallium have accelerated since 2005 and reached about 278 t and 169 t in 2020, respectively. These indicate a large amount of available secondary gallium resource, with nonexistent recycling. The results provide a basis for identifying gallium extraction, use, loss and recycling within its anthropogenic cycle in China, as well as guidance for stakeholders to make future decisions concerning ways to improve resource efficiency and promote sustainable gallium practices from a dynamic material cycle perspective.

Keywords: gallium, material flow analysis, dynamic material cycle, in-use stocks and flows, China

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1 INTRODUCTION

Today, the global energy system is undergoing a dramatic transition from fossil fuels to clean energy in response to the sustainable development goal of combating climate change in line with the Paris Agreement (UNFCCC, 2015). To realize a low-carbon future, many countries have committed to reduce their greenhouse gas emissions to net zero by the middle of this century, which necessitate massive deployment of a wide range of renewable energy technologies such as electric vehicles and battery storage, wind, and solar photovoltaics. Critical minerals have thus played a vital role in the emergence of such clean energy technologies in a decarbonizing world (World Bank, 2020; IEA, 2021). Gallium is an essential scarce metal that has many irreplaceable applications in a variety of industries including aerospace, chemical, medical, military, optoelectronics, telecommunications, and nuclear due to its unique physical and chemical properties (Moskalyk, 2003; Gray et al., 2005). With the accelerating pace of economic development and technological innovation, gallium is becoming one of the most important ingredients for developing key emerging technologies that modern society relies on, such as high-speed wireless communication, energy-efficient lighting, electric vehicles, solar photovoltaics, and wind power (Buchert et al., 2012; Elshkaki and Graedel, 2013; Redlinger et al., 2015). Consequently, gallium consumption has increased rapidly in recent years due to its widening and increasing use in high-tech fields and criticality for the low-carbon transition (Roskill, 2014; U.S. Geological Survey, 2018). Driven by global demand, primary gallium production has grown at a rate of 7% per year on average over the past decades, much faster than most industrial metals (Frenzel et al., 2016). It will almost certainly need to maintain this rate of expansion in order to fulfil the fast-increasing demand for the expanding population and economic growth (Peiró et al., 2013; Frenzel et al., 2017). There are, however, a few countries that possess large reserves of gallium, including China, the United States, Japan, Korea, Germany, and Russia. In particular, China is the world's top producer of gallium, accounting for 96% of the worldwide supply in 2019 (U.S. Geological Survey, 2021). In the view of the high economic importance and concerns about its supply security, gallium is listed as a critical mineral in the European Union (European Commission, 2011, 2014, 2017, 2020), the United States (U.S. Department of Commerce, 2017), Japan (Hatayama and Tahara, 2015), China (CMLR, 2016), and other economies. In this regard, increasing research have been conducted to determine whether future availability of gallium will hinder the sustainable development of its related industries. Academically, recent assessments of metal supply risk and criticality have indicated that gallium is among those critical materials that are vital to domestic economy, susceptible to supply constraints, and facing a problematic substitutability (Nassar et al., 2015; Hayes and McCullough, 2018; Graedel and Reck, 2016; Fu et al., 2018; Yan et al., 2021). However, among the criticality-related indicators adopted, most studies focus on the geopolitically concentrated production and by-product nature as major determinants (Graedel et al., 2015; Ioannidou et al., 2019; European Commission, 2020). While these previous criticality assessments can provide an intuitive comparison among elements, they are limited in reflecting the true level of criticality. This point was proved by Wang et al. (2020) who quantified the flows and stocks of China's europium and found the critically of europium is not as severe as previously assessed due to its decreasing demand. As such, their research suggested that the identification of supply risks should not only be based on indicators such as supply concentration and by-product dependence, but also examine the actual mineral supply situations by tracing the changes through supply chain analysis of critical minerals. A recent study by Løvik et al. (2016) explored the linkage between by-product and host metals and pointed out that future availability of gallium is not limited by geological reserves, but by the production of aluminum. According to their findings, there may be a trade-off between supporting ambitious closed-loop recycling, material efficiency methods, and a potential gallium supply crisis in the future. As a result, more rigorous and thorough information for a holistic and dynamic perspective on the critical mineral's whole supply chain (from production, consumption, loss, stock to end-of-life recycling) is clearly required to address concerns about potential supply shortages, supply security, resource efficiency, and future recycling potential. In order to provide valuable insights on these aspects, it is crucial to quantify the anthropogenic flow of a mineral through each stage of its life cycle, as underlined by many studies (Song et al., 2019; Watari et al., 2020; Zeng et al., 2020; Zhou et al., 2021).

Material flow analysis (MFA) is demonstrated to be an effective tool to provide insights for sustainable resource management by tracking the stocks and flows of minerals in a given temporal-spatial boundary (Chen and Graedel, 2012; Graedel, 2019; Islam and Huda, 2019). This method has been used extensively to explore the supply and demand relation for a number of bulk metals including iron (Li et al., 2018), copper (Zhang et al., 2017), aluminum (Liu and Müller, 2013), nickel (Zeng et al., 2018), lead (Liu et al., 2016), zinc (Meylan and Reck, 2017), and tungsten (Tang et al., 2020). Though there have been numerous studies describing the flows and stocks of critical by-product minerals, such as Lithium (Ziemann et al., 2012; Sun et al., 2018), cobalt (Chen et al., 2019; Sun et al., 2019), chromium (Gao et al., 2022), indium (Werner et al., 2018; Zhou et al., 2021), REEs (Du and Graedel, 2011; Ciacci et al., 2019; Geng et al., 2020), platinum (Rasmussen et al., 2019), and tantalum (Nassar, 2017), existing literature on the life cycle of gallium is limited. A survey of the literature revealed only five MFA studies on gallium. The earliest one was conducted by Yaramadi Dehnavi who developed the first quantification model of gallium flow at global level in the year 2010 from production, consumption to potential recycling (Yaramadi Dehnavi, 2013). Subsequently, a global assessment mainly focused on gallium's extraction, use, and loss as part of its anthropogenic cycle in the year 2011 was provided (Licht et al., 2015). Løvik et al. (2015) performed a comprehensive analysis of the global gallium cycle in 2011, providing detailed statistical data and technical parameters. They further pointed out that to meet the growing gallium demand in the future, there is a need to increase primary production and improve material efficiency across the system. Based on the global framework, Meylan et al. (2017) traced gallium flows in the United States in 2012, but the purpose of their research was to assess the reliability of MFA results by exemplifying flows of three minor metals that are often considered critical. Finally, the latest study by Eheliyagoda et al. (2019) focused solely on predicting the possible end-of-life gallium waste generation in China until 2050 using linear regression and scenario analysis methods. In addition, there have also been a few attempts to track the current availability and potential future supply constraints of gallium (Frenzel et al., 2016; Song et al., 2022). These studies lay the groundwork for a better understanding of the gallium cycle. However, the existing MFAs on gallium provided only static results at the global level and the national scale of the United States, leaving the shifts and dynamics of gallium flows unclear. As the world's largest

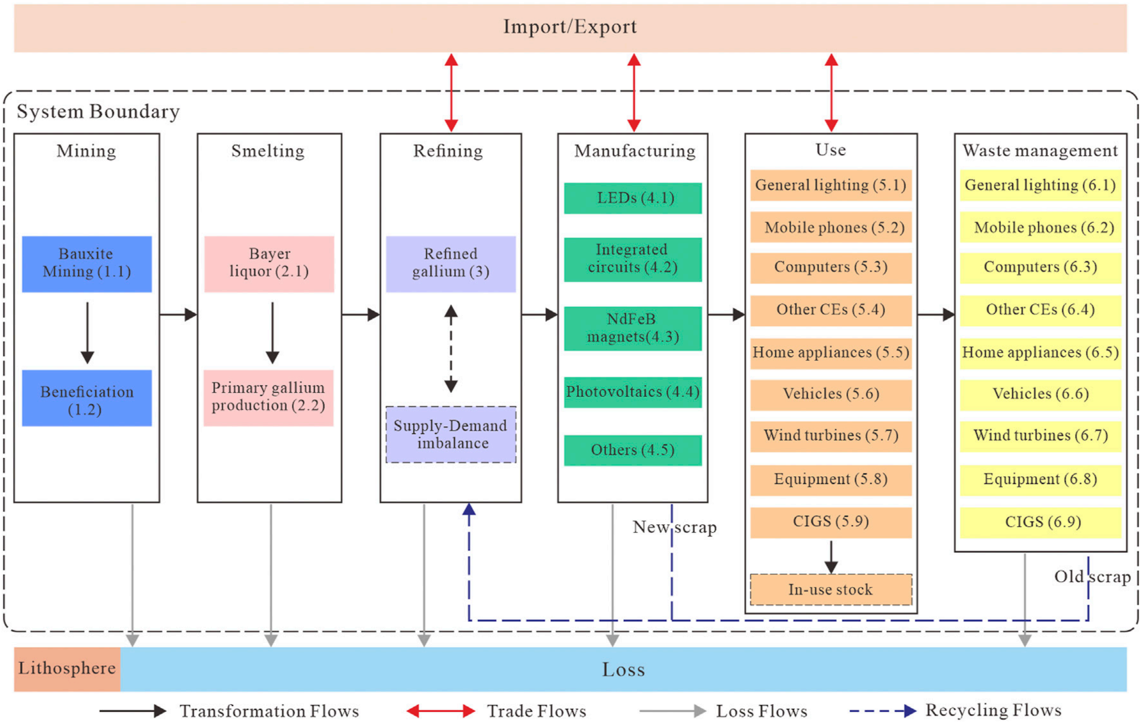

FIGURE 1 | Material flow analysis framework for gallium cycle.

producer and consumer of primary gallium, no comprehensive assessment of China's gallium flows and stocks has been published yet. Therefore, the objective of this study is to use a dynamic MFA method to model the time-varying evolution of gallium flows and stocks through its main life cycle stages over a period of 2005–2020 in China. Our findings may provide valuable insight into China's gallium flow structure and recycling possibilities, assisting decision-making.

As for the remainder of this paper: the MFA framework, accounting method, and data sources are described in **Section 2**. In **Section 3**, we provide results of an overview of the gallium cycle, as well as details on production, consumption and trade trends. Then comes a detailed examination of dynamic shifts in the in-use stock and end-of-life flows, a discussion of the prospective recycling capacity and an evaluation of uncertainty. Finally, **Section 4** draws conclusions and raises policy recommendations.

2 METHODS AND DATA

2.1 System Boundary

Figure 1 depicts the system boundary of this study. The spatial boundary is defined as mainland China excluding Hong Kong, Macau and Taiwan. Due to data availability, the period from 2005 to 2020 is set to be the temporal boundary, which is enough to capture the development and evolution of gallium utilization in modern industry. The entire life cycle of gallium in the anthroposphere can be divided into six principal stages: mining, smelting, refining, manufacturing, use and waste management, as shown in **Figure 1**. Gallium flowing through these stages in commodities include ores, metals, gallium-contained intermediate products, final products, wastes, and scraps.

Gallium is commonly recovered as a by-product from alumina or zinc processing (Schulte and Foley, 2014), but probably the purpose of processing gallium-contained minerals is not to get gallium. More than 95% of China's primary gallium was sourced from bauxite for alumina production via the Bayer process, with the remaining produced from the hydrometallurgical process during the extraction of zinc (U.S. Geological Survey, 2018). Therefore, we mainly concentrate on the gallium extraction in the Bayer process as it represents the major source of gallium in this study. Fly ash from coal combustion in power plants, phosphate ores, and aluminous clay stone and mudstone are also plausible sources (Lu et al., 2017), but this study does not address any of these due to their lack of commercial relevance.

2.1.1 Mining

The model begins with the amount of bauxite exploited from the mine. Since there is no existing information on the exact gallium quantities extracted from the lithosphere, it is possible to estimate the total amount of gallium extracted in the mining stage with gallium concentration in bauxite. However, not all mined bauxite that for alumina production are bound to be used in gallium cycle. Therefore, the gallium input in the bauxite production is calculated bottom-up by using the production of primary gallium, gallium content in bauxite and the recovery rate during the mining process. The amount of gallium recovered from the underground and open-pit mines of bauxite is estimated with an average recovery rate of 90% Ministry of Industry and Information Technology of the People's Republic of China (MIIT), 2013).

2.1.2 Smelting

Bauxite is delivered to the alumina smelter to get by-product gallium via the Bayer process. In the Bayer process, bauxite is dissolved under high temperature in a caustic soda solution, which is the so-called Bayer liquor (Zhao et al., 2012). A portion of gallium clumps in the Bayer liquor, with the rest ending up in a poisonous residue known as "red mud" or in the form of impurities entering the aluminum cycle. Within the Bayer process, the mother liquor containing gallium is recycled in a closed loop. The commonly used method to extract gallium from the Bayer liquor at industrial scale is the ion-exchange resin technology with an average recovery efficiency of 46.5% (Lu et al., 2017).

2.1.3 Refining

The production of 99.99% (4N) pure gallium in the refining stage refers to the primary production, excluding production from scraps. Crude gallium is obtained by smelting and refining of the metal to higher purities (i.e., 6N, 7N) for the electronics industry and communication field is achieved through a combination of methods. At present, high purity gallium is mainly prepared by fractional crystallization and directional crystallization. Considering that the discarded material would be reintroduced in the process chain, the overall yield of purification by crystallization is close to 100% (Yamamura et al., 2007). In the refining stage, there is a stock that fits the characteristics of the Chinese market. The differences between inflows and outflows reflect net changes in stockpiles of refined gallium.

2.1.4 Manufacturing

In the form of metals or gallium-containing compounds, refined gallium is processed to manufacture intermediate products. Common gallium compounds include gallium arsenide (GaAs), gallium nitride (GaN), gallium phosphide (GaP), and copper indium gallium diselenide (CIGS). These are necessary ingredients either for growth of single crystal ingots that would be cut into wafers or for preparing monocrystal film during semiconductor devices production process (Kramer, 1988). As an alloying element, gallium is often added less than 1% of the mass in rare earth magnetic materials for minor improvements of magnetic properties and corrosion resistance (Butcher and Brown, 2014). Low melting point alloys, catalysts, optical glasses, tooth filling materials, and piezoelectric materials are some of the other uses for gallium. The four major gallium-containing industrial uses, which account for more than 90% of gallium usage worldwide and in China, are light emitting diodes (LEDs), integrated circuits (ICs), neodymium iron boron (NdFeB) permanent magnets, and CIGS thin-film photovoltaics (PVs) (Roskill, 2014; U.S. Geological Survey, 2018). The fabrication of GaAs/GaN compound semiconductors, so called wafers, consists of a few microns' thick epitaxial deposition layer on top of the much thicker substrate. GaAs/GaP-based LEDs and ICs are mainly processed on GaAs substrates, while GaN-based LEDs are produced on the substrates of sapphire, silicon carbide (SiC) or silicon. The whole process of semiconductor manufacturing produces a lot of waste due to backgrinding of the substrates, deposition of epitaxial layers, and trimming, etching, and polishing of wafers, a portion of which is recycled as new scrap in closed loop (Izumi et al., 2001; Ho et al., 2006). As for the manufacturing of NdFeB magnets, gallium is often added in a small amount to improve the performance and corrosion stability of magnets, with final material losses of 20–40% (Binnemans et al., 2013). Recycled gallium in the manufacturing stage may be further refined entering the processing chain.

2.1.5 Use

In the use stage, gallium-containing final products are grouped into eight end-use sectors: general lighting, consumer electronics, home appliances, vehicles, general machineries, wind turbines, equipment, CIGS and others. For consumer electronics, they include mobile phones, computers (desktop PCs, laptops and tablets), and other CEs (digital cameras, camcorders, CD/DVD players, car liquid crystal display (LCD) screens and navigation systems); and for home appliances, LCD televisions, washing machines, refrigerators, and air conditioners are included. Ordinary car and new energy automobile are classified into vehicles; equipment include industrial robots and energy-saving elevators.

For this stage estimations, the inflow can be defined as supply of gallium assigned to distinct end products applying a bottom-up method, as shown in **Section 2.2.1**. When finished products approach the end of their useful lives, the gallium incorporated in them is either collected for further treatment or formed into in-use stocks.

2.1.6 Waste Management

The end-of-life products can be theoretically recycled for secondary gallium resources in the waste management stage. Typical recycling techniques, on the other hand, promote the recovery of bulk metals and some precious metals, whereas gallium would wind up in the waste stream and end up in the environment. These gallium-containing wastes will be treated with general waste management such as landfill and incineration. Since there is minimal data on the recycling of gallium-bearing end products, the end-of-life flows are classified as non-recoverable wastes entering the environment.

2.2 Accounting Method

Methods are presented here for calculating the flow and stock of the gallium cycle. Gallium flows of the entire cycle are balanced according to the law of conservation of mass (Brunner and Rechberger, 2017). Accordingly, the total gallium inputs into each stage equals the total gallium outputs, plus any stock changes in this stage. Data for all flows and stocks in this study are expressed in gallium metallic equivalent unless otherwise noted.

2.2.1 Quantification of Domestic Gallium Transformation and Loss

Gallium embedded in mined bauxite from the lithosphere is transformed into metal (refined gallium) and subsequently changed into compounds, processed into intermediate products. These products are further assembled into final products that are used in human society, and are eventually discarded when reaching their service life. The incoming and outgoing flows through each stage of gallium cycle can be calculated using the following equations:

$$F_{x,t}^{in} = F_{x,t}^{production} \times C_x \tag{1}$$

$$F_{x,t}^{out} = F_{x,t}^{in} \times R_x \tag{2}$$

where $F_{x,t}^{in}$ and $F_{x,t}^{out}$ are the inflows and outflows of gallium from stage x in year t (2005–2020), respectively; $F_{x,t}^{production}$ is the production data expressed in either mass or number from stage x in year t; C_x is the gallium content; R_x is the material yield rate of gallium from stage x. Whenever domestic output data are not available, back calculations are conducted using a bottom-up method based on the combination of statistics of final products and relevant coefficients.

The gallium inflows into final products are determined by combining production statistics, market share of Ga-containing products, and gallium content per unit, which is shown in **Eq. 3**:

$$F_{U,t}^{in} = F_{U,t}^{production} \times P_t \times C_U \tag{3}$$

where U refers to the use stage; $F_{U,t}^{in}$ represents the inflow of gallium in end products in year t; $F_{U,t}^{production}$ is the output of Ga-containing end products for the year specified, which is expressed in numbers; P_t is the penetration rate of Ga-containing end products in the market in year t; C_U is the gallium content of each end product.

Using the output data and corresponding material yield rates, losses at different stages of the gallium cycle are directly calculated with **Eq. 4**:

$$F_{x,t}^{loss} = F_{x,t}^{in} \times (1 - R_x) \tag{4}$$

where $F_{x,t}^{loss}$ is the loss of gallium from stage x in year t. Minor dissipative gallium losses into the environment from gallium-containing products are also present in the use stage, which are not addressed in this study.

2.2.2 Calculation of Gallium-Containing Commodities International Trade

According to the life cycle framework of gallium (**Figure 1**), a list of traded commodities is identified, which is shown in **Supplementary Table S1**. Trade flows were estimated by combining the number (or mass) of commodities containing gallium with corresponding content coefficient per commodity (or mass fraction), and market penetration rate, as shown in the following equations:

$$F_{m,t}^{import} = I_{m,t} \times P_{x,t} \times C_x \tag{5}$$

$$F_{m,t}^{export} = E_{m,t} \times P_{x,t} \times C_x \tag{6}$$

where m is the different categories of gallium-containing commodities traded; $F_{m,t}^{import}$ and $F_{m,t}^{export}$ are the quantity of gallium in import and export, respectively; $I_{m,t}$ and $E_{m,t}$ are the amount (in number or mass) of imported and exported gallium-containing commodities, respectively.

2.2.3 Determination of Recycling Flows

For LEDs and ICs, new scraps are generated in two ways: one from the GaAs substrate processing waste, and the other from the semiconductor device manufacturing process, both of which can be recycled internally. On the other hand, the PV processing scrap is also served as possible source of gallium recycling, while gallium is not recycled from the magnets processing scrap. The recycling flows of gallium embedded in new scraps from the manufacturing stage are given by the following equation:

$$F_{m,t}^{recycle} = F_{m,t}^{input} \times (1 - R_i) \times w_i \times \left(1 - R_j\right) \times w_j \tag{7}$$

where $F_{m,t}^{recycle}$ is the recycled gallium from m-category intermediate product in year t; $F_{m,t}^{input}$ is the total gallium flow into m-category intermediate product in year t; R_i is the material yield rate in the production of substrate or sputtering deposition for PV; R_j is the material yield rate in the production of semiconductor device; w_i is the collection rate of substrate production or sputtering deposition scraps; w_j is the collection rate of backgrinding, dicing and polishing scraps from semiconductor device manufacturing.

Considering a lack of statistics for end-of-life gallium in China, the recycling flows of gallium-containing old scraps recycled from the waste management stage cannot be quantitatively obtained.

2.2.4 Estimation of Gallium Stocks

By quantifying the inflow and outflow of the refining stage, we identified a gap in which the outflow is less than the inflow from primary resource and recycled new scrap of gallium. Therefore, we inferred this gap as the stockpile of refined gallium in the light of the mass conservation principle. Stocks in the manufacturing stage are ignored since they are considered stationary over a year (Gao et al., 2022).

In the use stage, the stock is defined as in-use stock referring to the accumulation of materials in the anthroposphere as end-use products (Gerst and Graedel, 2008; Müller et al., 2014). A top-down method is used to determine the in-use stock by quantifying the distinction between input and output flows with **Eqs. 8–10**:

$$S_{m,t} = S_m,t_0 + \sum_{t_0=2005}^{t} \left(F_{m,t}^{in} - F_{m,t}^{out}\right) \tag{8}$$

$$F_{m,t}^{in} = F_{m,t}^{consumption} \tag{9}$$

$$F_{m,t}^{out} = \sum_{k=1}^{lifetime} \left(F_{m,t-k}^{in} \times p_m^k\right) \tag{10}$$

where S_m,t_0 and $S_{m,t}$ refer to the in-use stock of product m in the initial year t_0 (2005) and the specified year t, respectively, and we assume S_{m,t_0} is to be zero; $F_{m,t}^{in}$ represents the flow of gallium from product m into the usage phase in year t; $F_{m,t}^{out}$ represents the obsolete gallium in product m into the waste management phase in year t; $F_{m,t}^{consumption}$ is the consumption of product m in year t, which is the apparent consumption disregarding products manufactured but not marketed; p_m^k is the likelihood that product m will be discarded after k years' lifespan, and it is estimated using the Weibull or the Normal distribution (Melo, 1999). **Supplementary Table S2** lists detailed parameters for each type of commodity in relation to the distribution type, which is used to simulate the creation of end-of-life products.

2.3 Data Sources

Gallium contents are obtained from research reports, research papers, and expert interviews, as shown in **Supplementary Table S1**. Yield rate, loss rate and recycling rate in the mining, smelting, refining and manufacturing stages are derived from the literature and relevant domestic metallurgical standards (see **Supplementary Table S3**). The data for domestic yearly output of 99.99% (4N) pure gallium in the refining stage are obtained from China Nonferrous Metals Industry Association and Antaike's research report. The annual production data of end-use products are primarily obtained from official and industrial sources, including National Bureau of Statistics of China, Department of Consumer Goods Industry, Ministry of Industry and Information Technology, China Automotive Industry Association, and Yearbook of China Electronic Information Industry. The domestic gallium consumption distribution in "Photovoltaics" and "Others" refers to Antaike's report (Li, 2021). Data on international trade comes from the U.N. Commodity Trade Database (UN Comtrade, 2021), which uses 6-digit HS codes, and the General Administration of Customs of the People's Republic of China (GAC) (2005-2016) (2021), which uses 8-digit HS codes. **Supplementary Table S1** shows the relevant HS code for each commodity.

2.4 Uncertainty Analysis

There is an element of uncertainty in the calculation results of this study because of different parameters incorporated into the model. Therefore, the Monte Carlo simulation was conducted to quantify the impacts of uncertainties from different input data on the gallium flows and stocks. There are three levels of uncertainty in the ranges: low, medium, and high. We assumed that the data collected directly from official statistics (e.g., domestic output and international trade) would have low uncertainties with a standard deviation of 2%. For data collected from literatures or through expert interview (e.g., coefficient of gallium-containing products), or mine production of gallium, medium uncertainties were assumed. Based on the actual situation, the standard deviation range is set at 5–10%. Those data of technical parameters during production and processing, and lifetime distribution estimated based on other data were assumed to have high uncertainties with the standard deviation varying from 10 to 15%. The impact of uncertainty on eight major results, including domestic gallium consumption, trade, refined gallium surplus, in-use stock, end-of-life flows, manufacturing loss and new scrap recycling flows are shown in **Figure 10**.

3 RESULTS AND DISCUSSION

3.1 Gallium Cycle

Figure 2A depicts the accumulated gallium stocks and flows along its life cycle in China during 2005–2020. Results show that the total bauxite mined in China was around 745.3 Mt (In physical quantity), with 36,519 t gallium available to be extracted theoretically between 2005 and 2020. As few alumina producers have gallium extraction facilities, exact numbers for the amount of bauxite required to extract gallium are unavailable. Therefore, a bottom-up calculation shows that only 12,660 t of the potential gallium contained in mined bauxite was actually utilized for further gallium recovery, a percentage of 35%. Around 6,583 t gallium flowed into the Bayer liquor, with nearly half of the total extraction ending up in red mud (4,811 t) and entering the aluminum cycle (1,266 t) as an impurity. Over the last 16 years, the total primary production of gallium was 3,061 t, with 3,522 t gallium lost to the environment during refining. Among the refined gallium, about 36% was exported to other countries, while almost 54% was consumed domestically in the form of finished products for diverse end purposes. From a dynamic point of view, the scale of gallium cycles in China grew significantly from 2005 to 2020, as indicated by the flow widths in **Figures 2B–E**. Specifically, from 2005 to 2020, the total mining production, export volume, domestic consumption of gallium increased by more than 20, 8, and 73 times, respectively. These are primarily driven by the large increases in gallium flows to LEDs (from 1 t to 203 t), integrated circuits (from 3 t to 25 t), NdFeB magnets (from 0 t to 88 t), and photovoltaics (from 0 t to 25 t).

It is estimated that there was roughly 948 t gallium surplus stockpiled by the Fanya Metal Exchange or the government, accounting for approximately 31% of the total gallium output. Large material losses occurred in the manufacturing process following primary production, of which LEDs (273 t) dominated, followed by NdFeB magnets (116 t), integrated circuits (80 t), and thin-film PVs (10 t). However, 521 t gallium was recycled as new scraps during the fabrication of semiconductor devices, resulting in an overall recycling rate of about 17%. Despite the fact that considerable amounts of gallium were used to make various intermediate products, only 622 t of gallium entered the use phase, representing a 38% share of the inflow. In addition, 169 t of the cumulative gallium from nine categories of abandoned end-of-life products was estimated to dissipate in landfills or disperse in other material cycles (**Figure 2**).

3.2 Gallium Supply and Demand Pattern

Figure 3 illustrates the supply and demand of gallium in China during 2005–2020, reflecting remarkable changes in the supply chain structure of gallium. China had a small primary production of only 18 t in 2005, most of which was exported, with roughly

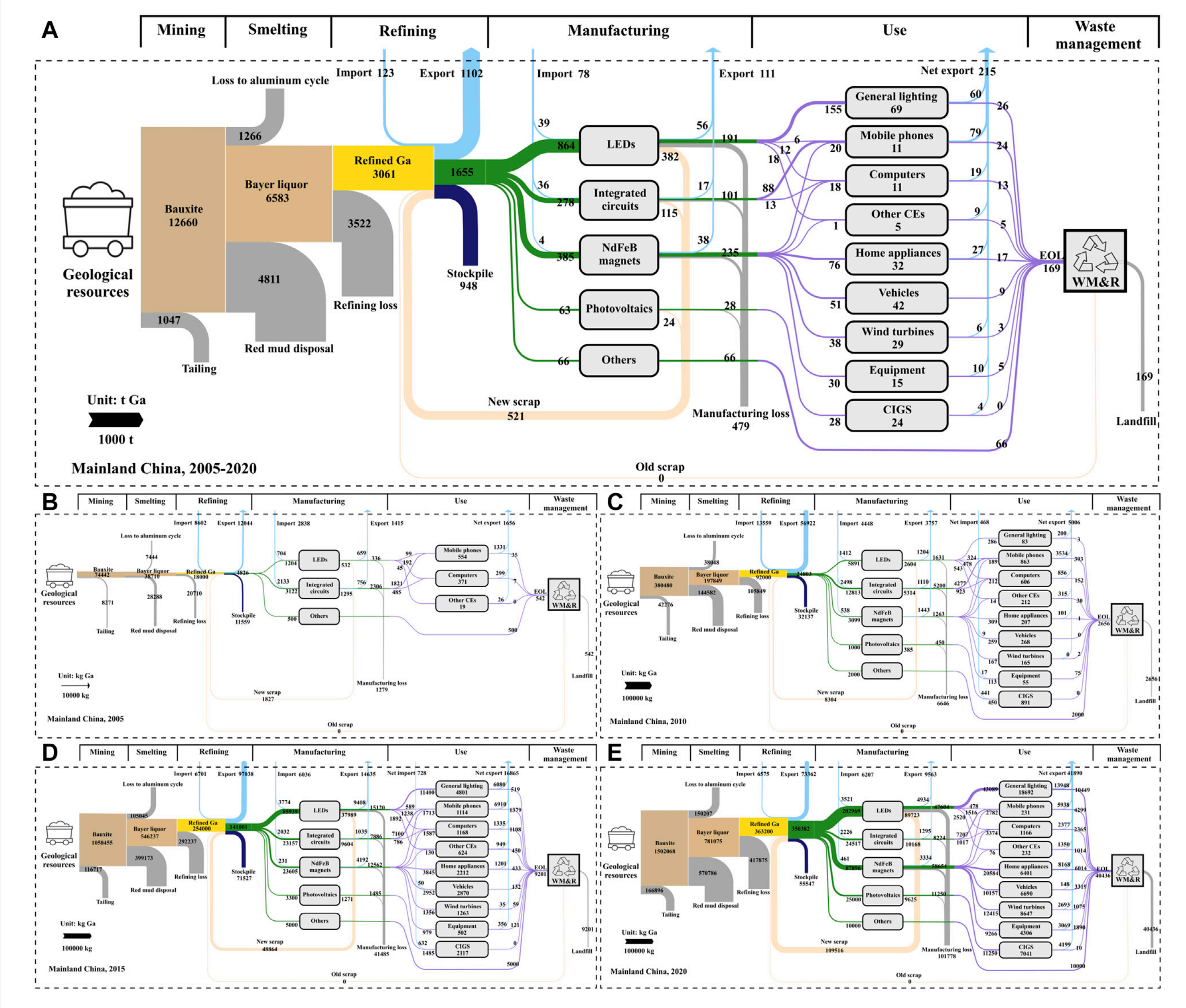

FIGURE 2 | Sankey diagram of **(A)** the accumulated gallium cycle in China during 2005–2020, and four representative 1-year cycles in year **(B)** 2005 **(C)** 2010 **(D)** 2015 **(E)** 2020 (LED: light-emitting diode; CE: consumer electronic; CIGS: copper indium gallium selenide).

27% used to meet domestic demand. From 2010 onward, the production capacity of gallium in China increased rapidly, driven by the continual expansion of domestic alumina production (Li et al., 2021) and the gradual maturation of gallium extraction technologies of some producers. As a result, the mineral supply of gallium also rose dramatically and reached a peak at 282 t in 2012, much exceeding the domestic demand. Because of the growing supply expansions but a modest demand market in the early 2010s (Liu et al., 2014), the gallium supply surplus increased to 509 t by 2012 (**Figure 4A**), which in turn triggered a sharp drop in the market prices of gallium since then. It should be noted that China's gallium production experienced a significant fluctuation between 2012 and 2016 and reached its bottom at 171 t in 2016 (**Figure 3**). Such a fluctuation is primarily caused by the production suspension or reduction of many local enterprises due to the ongoing decline of gallium prices from an average of 4100 CNY/kg in 2011 to 875 CNY/kg in 2017 (**Figure 4B**), which reached a low point in 2016 (790 CNY/kg), lower than the production costs of several enterprises. Overall, the supply of gallium in China has maintained a stable growth and mounted to 363 t in 2020.

On the other hand, owing to the late start of domestic gallium industry, China's gallium consumption has grown much slower than production prior to 2015 (**Figure 3**), which is heavily constrained by downstream industries. In recent years, LEDs rapidly infiltrated the Chinese lighting market (CSSLA, 2016) as they have increasingly become the preferred technology for general lighting due to their energy-saving, cost-effective and environmentally friendly properties (Baumgartner et al., 2011; Nair and Dhoble, 2015). This technology transition from

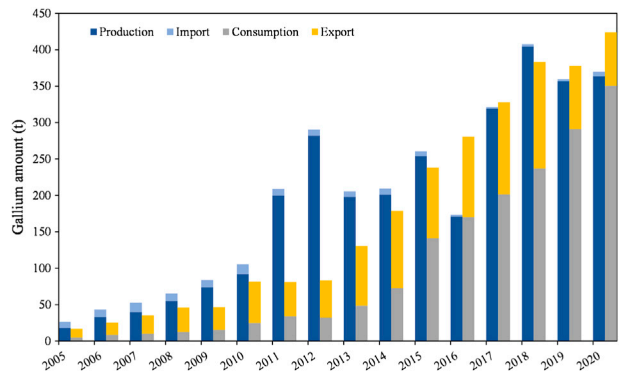

FIGURE 3 | Gallium supply and demand structure in China during 2005–2020.

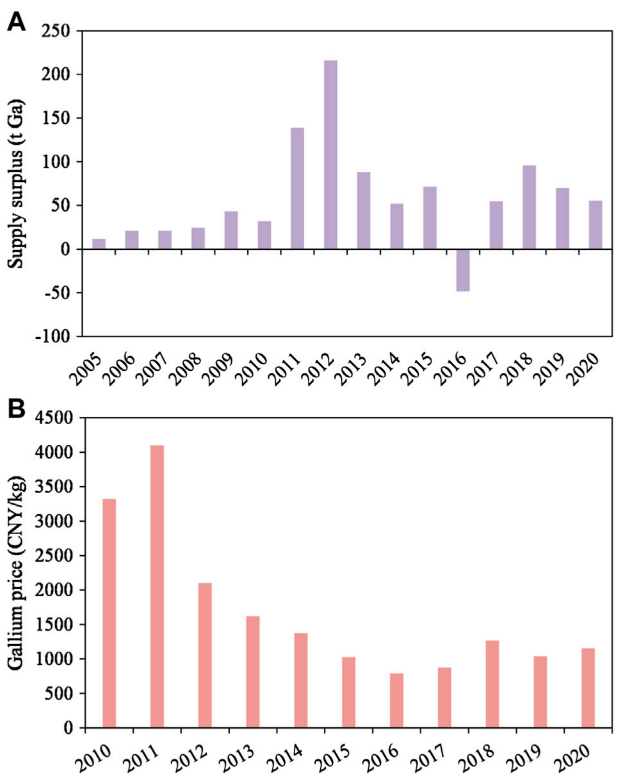

FIGURE 4 | Historical evolution of **(A)** gallium supply surplus, and **(B)** gallium price in China.

traditional lighting sources (i.e., fluorescent lamps) to LEDs stimulated gallium demand by 29 times from 2011 to 2020. Meanwhile, the rising popularity of smartphones and wireless technologies is propelling the market for wider adoption of gallium arsenide technology (Roskill, 2014), which has fueled gallium demand. Moreover, the broadening deployment low-carbon technologies in China, ranging from electric vehicles to wind turbines and solar panels, has also contributed to the soaring demand for gallium in permanent magnets and solar PVs (Guo et al., 2019) by 21 and 25 times from 2011 to 2020, respectively. As shown in **Figure 2**, gallium consumption in China climbed to 350 t in 2020, roughly 73 times that of 2005. During the past 16 years, approximately 70% of China's gallium has been consumed in the semiconductor field (52% in LEDs, and 17% in integrated circuits), with a rising share in NdFeB magnets (23%) and solar PVs (4%). The remaining 4% is attributed to other uses that are not further detailed owing to a lack of data. Driven by the progressive implementation of policies and national strategies, such as "Made in China 2025", "Outline of the 14th Five-Year Plan for National Economic and Social Development", and "Goal for Carbon Peak by 2030 and Carbon Neutrality by 2060" (CASA, 2016; Zhao et al., 2017), gallium demand in China may further rise in tandem with the fast increasing semiconductor industry and clean energy technologies. The growing momentum for gallium demand indicates the significant implications of gallium in global low-carbon transition for the foreseeable future.

3.3 Trades of Gallium-Containing Commodities

Figure 5 depicts the trajectory of China's international trade in gallium-contained commodities between 2005 and 2020. China is a net exporter of gallium products throughout its life cycle and has exported about 49% of gallium to the world. The annual net export of gallium kept growing, peaking at 193 t in 2018, and then showed a downward trend after 2019, with the total net export volume of gallium increasing more than eight-fold during 2005–2020. There was a net export of 33 t gallium embodied in the intermediate products, with gross imports and exports calculated to be 78 t and 111 t, respectively. However, China served as a net importer of gallium-containing intermediate products until 2012 and gradually shifted to a net exporter following its changing role in the global semiconductor manufacturing market (Li, 2016; Grimes and Du, 2022). China mainly exported raw materials (refined gallium) and end-use products. The average annual growth rate of export raw materials and end-use products reached 17 and 26% during 2005–2020, respectively.

As shown in **Figure 6**, China had tight ties with more than fifty countries and regions in terms of exporting gallium-contained products, the majority of which were developed and developing economies. During the study period, Japan is the largest importer of refined gallium (349 t), followed by Germany (175 t), the United States (166 t), the United Kingdom (155 t), and Korea (124 t), while the majority of gallium in intermediate products flowed to China Taiwan, China Hongkong, Korea, India, and Japan. Furthermore, regarding the specific gallium-containing end-use commodities exported, general lighting accounted for the largest proportion (33%), followed by mobile phones (30%), home appliances (10%), computers (7%), and CIGS (7%). It is estimated that China's cumulative net exports of gallium in final products were around 215 t during 2005–2020.

Generally, the upstream mining and refining stages are highly resource-intensive and characterized by high environmental effects and low technological barriers. In contrast, the

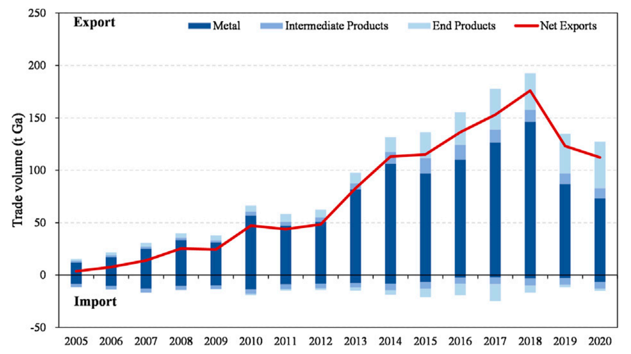

FIGURE 5 | Historical evolution of the trade volume of gallium in China between 2005 and 2020 (Data source: China Customs, UN Comtrade. **Supplementary Table S4** contains the underlying data).

downstream fabrication and manufacturing stage is characterized by tech-intensive product design, manufacturing and packing with high value-added (Tang et al., 2020). It is shown that China accounted for more than 90% of the global primary production of gallium in recent years (U.S. Geological Survey, 2021), which means China produces a high percentage of upstream gallium products that have low value added and are resource-intensive. However, as a net exporter of gallium commodities, China is highly dependent on imports of processed products because of its relatively low share in downstream high value-added and tech-intensive gallium-containing manufactured goods produced domestically. For example, Chinese companies accounted for only 5% of the global market for integrated circuits in 2020 (IC insights, 2021). Even the most advanced Chinese semiconductor companies are much smaller in size and technologically lagging compared to international leaders (Li, 2021). In recent years, the increasing demand for integrated circuits in memory, communication chips, sensors and other high-end fields has promoted the import of integrated circuits in China (Fang et al., 2018). According to customs statistics, during 2005–2020, China's trade deficit of integrated circuits increased year by year and reached a historical peak in 2018 (**Figure 7A**), reflecting China's high dependence on the import of integrated circuits. Moreover, China has been the world's largest consumer of integrated circuits since 2005, but its self-sufficiency rate was only 15.9% by 2020, with the self-sufficiency rate of some cutting-edge integrated circuits (i.e., <10 nm) almost zero (IC insights, 2021). It means that more than 80% of China's high-end integrated circuits rely on imports from other countries and regions, including China Taiwan, Korea, Japan and the United States (**Figure 7B**). It is worth noting that the raw materials used to produce high value-added gallium-containing commodities in these countries and regions are mostly sourced from China as shown in **Figure 6**. Thus, it can be argued that China provides the global economy with high value-added products indirectly through the provision of virgin materials.

3.4 In-Use Stock and End-Of-Life Flows

Gallium in-use stock accumulation is attributed to the discrepancy between the inflows and outflows in the use phase in each year investigated. As illustrated in **Figure 2**, consumer electronics (including mobiles, computers and other CEs) accounted for more than 45% of gallium consumption before 2010 and has always been one of the crucial end-use sectors for gallium. As a result of the continuous growth in demand for

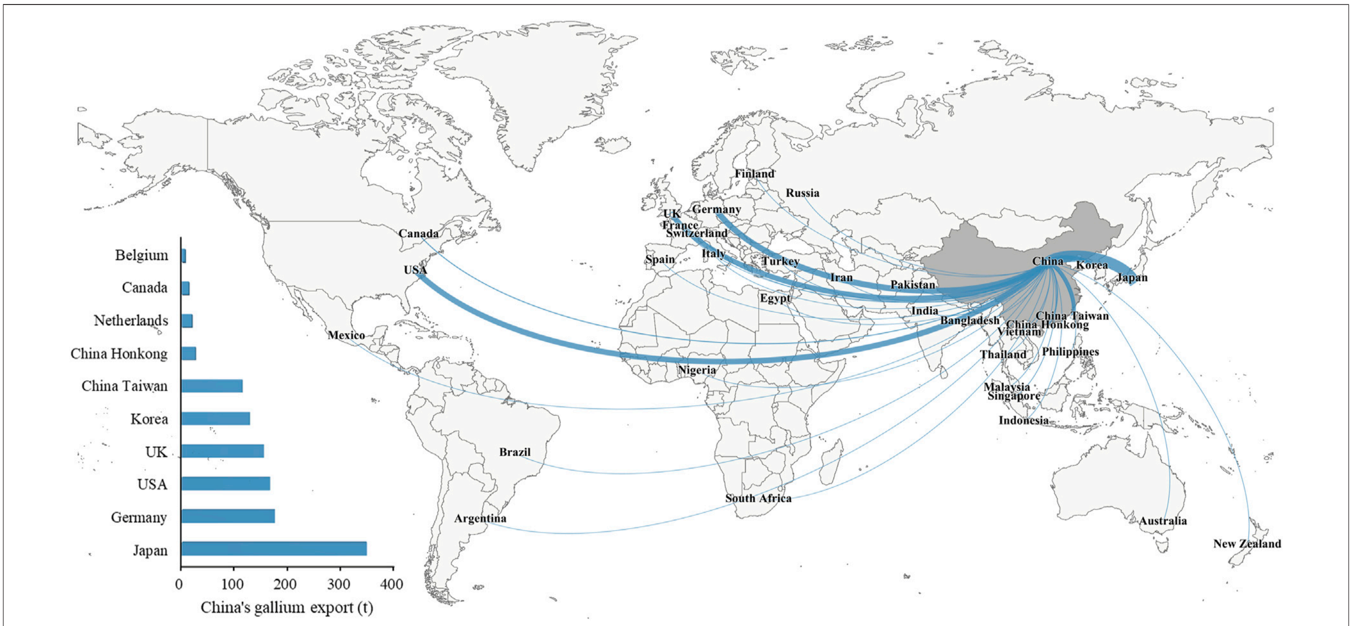

FIGURE 6 | China's accumulated export gallium flows to its key trading partners from 2005 to 2020 (Each flow is proportionate to the volume of gallium exported, and the trade flows under 1 t are not depicted in the graph. Horizontal bars indicate the top ten biggest importers of China's gallium products).

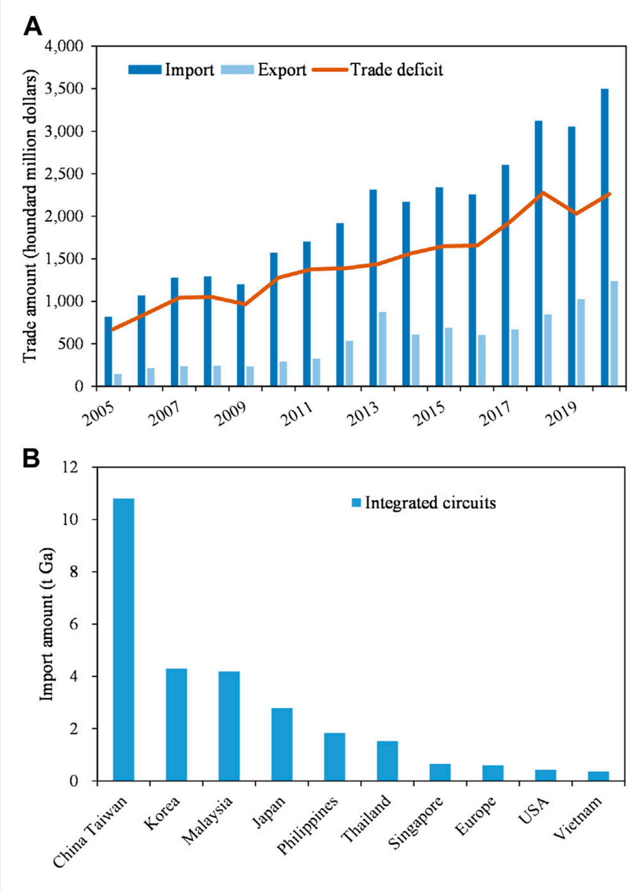

FIGURE 7 | (A) Trade volumes of China's integrated circuits during 2005–2020 **(B)** Key exporters of gallium-containing intermediate products to China during 2005–2020.

energy efficient and low carbon applications, inflows into the general lighting, home appliances, vehicles, and CIGS sectors kept increasing. The accumulated gallium consumption has risen sharply since 2015, reaching around 556 t by 2020 (**Figure 8A**). Meanwhile, the in-use gallium stock expanded 56 times over the research period, with general lighting accounting for the largest share, 35% in 2020, followed by wind turbines (16%), CIGS (13%), vehicles (13%), home appliances (12%), equipment (8%), and consumer electronics (3%). Notably, the net stock accumulation of certain gallium-containing finished products was negative in a given year (**Figure 8B**). For example, the in-use stock of mobile phones declined in 2008, as mobile phones export remained high and the outflow of spent mobile phones was still increasing after reaching their lifespans.

Gallium end-of-life flows from various end-use sectors also increased in lockstep with domestic consumption of gallium. **Figure 9** illustrates that total output of gallium scrap increased by 81% from 0.05 t in 2005 to 169 t in 2020. As the "others" sector are all expected to enter the end-of-life stream for a lack of data, consumer electronics made up the largest share of total old scrap generation (25%), as it has a larger market share and a shorter lifespan (~4 years). The general lighting (15%) was the second largest source of old scarp because of its relatively larger inflow and shorter average lifespan (~6,000 h), followed by home appliances (10%). Although the total amount of gallium end-of life flow grew rapidly in recent years, there is still a long way to go for China's gallium waste management system to achieve efficient recovery of end-of-life gallium considering the current recycling situation (Eheliyagoda et al., 2019).

3.5 Recycling Potential

An overall extraction potential of 24% for gallium was estimated in the mining, smelting and refining stages during 2005–2020, showing a low recovery efficiency of raw gallium. The total losses in these stages amount to 10,646 t, more than three times that of the primary production of refined gallium. During the Bayer process, a substantial quantity of gallium can be found in red mud (45%) or refining loss (33%). These indicate that there is still room for improving recovery in the mining, smelting and refining stages. Improving material output in the production process can significantly boost the total resource efficiency (Zhou et al., 2021; Liang et al., 2022). Notably, a considerable portion of loss occurs in the manufacturing process, including substrate production, wafer fabrication, and manufacturing of semiconductor devices (Licht et al., 2015; Løvik et al., 2015). For example, the utilization of substrate material in gallium arsenide device manufacture is inefficient, with a considerable portion of the initial generated material being wasted during processing (i.e., GaAs wafer grinding, cutting, lapping and polishing). Additionally, the waste streams contain a high concentration of dissolved arsenic, which should be handled as hazardous waste (Izumi et al., 2001; Uryu et al., 2003; Torrance et al., 2010). Therefore, more sustainable manufacturing processes are needed to be developed and adopted to improve material yield in the production processes, as well as reduce the environmental impact of gallium arsenide device manufacture.

It is widely recognized that gallium can be recycled from new scraps generated during the manufacturing of GaAs-based semiconductor devices (Eichler, 2012; Løvik et al., 2015). When it comes to recovering gallium from end-of-life products, however, the current recycling rate is less than 1% (Graedel et al., 2011; UNEP–International Resource Panel, 2011; Ueberschaar et al., 2017). The primary reason for this could be that gallium is frequently present in minute amounts in relevant fragments (e.g., printed circuit board, and LED chip) embedded and glued within the end products, posing technical challenges for recycling as well as the lack of a collecting system to recover metals of interest such as gallium (Eheliyagoda et al., 2019). As gallium has been widely used in electronics, electronic waste is becoming an excellent secondary source of gallium metal. According to previous research, China has become the world's top producer of waste electrical and electronic equipment (Baldé et al., 2017). As a result, numerous studies have focused on recovering gallium from waste electronic devices such as LED lamps, mobile phones, tablets and liquid crystal displays in recent years (Buchert et al., 2012; Cucchiella et al., 2015; Avarmaa et al., 2018; Charles et al., 2020). Many recycling technologies are available for gallium metal in e-waste, including pyrometallurgical processing, hydrometallurgical processing and

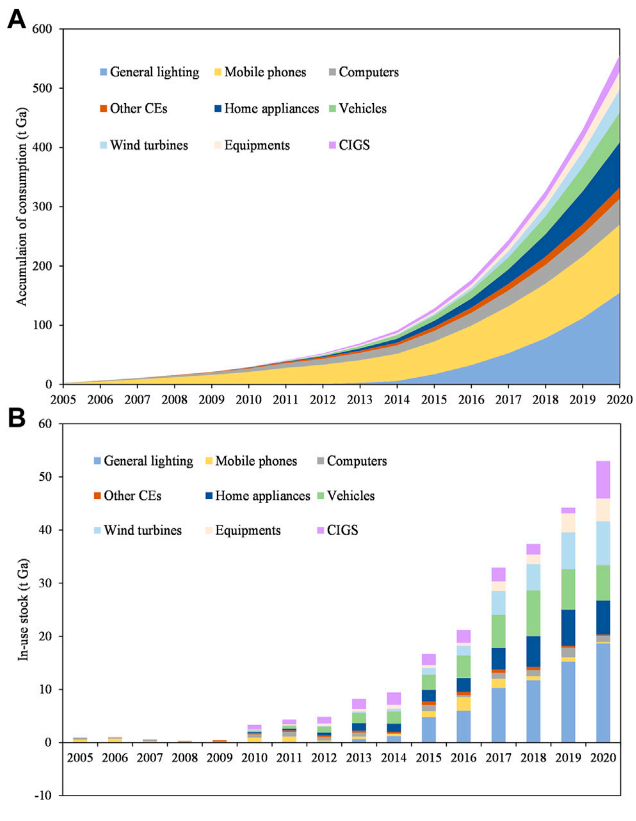

FIGURE 8 | Dynamics of **(A)** accumulation of gallium consumption in China during 2005–2020 **(B)** yearly net increased gallium in-use stock in China during 2005–2020.

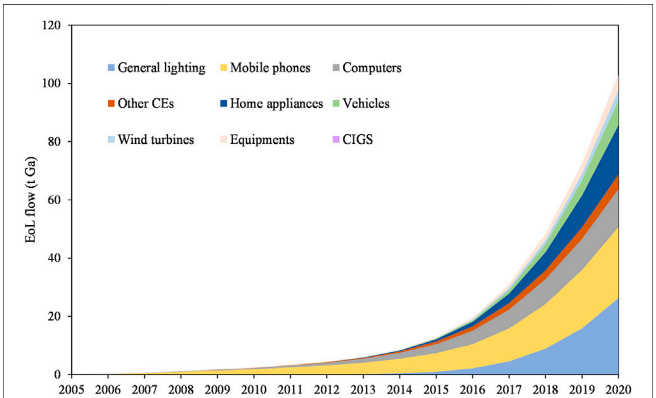

FIGURE 9 | Dynamics of end-of-life gallium flows in China during 2005–2020.

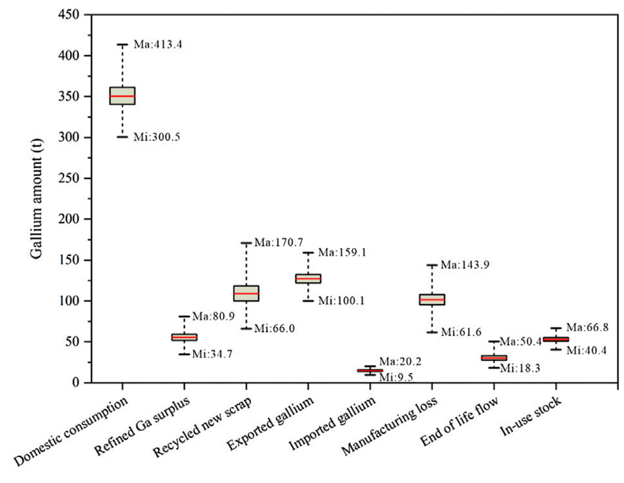

FIGURE 10 | Results of uncertainty evaluation for China's gallium cycle in 2020. (Top line is the maximum value (Ma); bottom line is the minimum value (Mi); box top is the third quartile; box bottom is the first quartile; thick red line in center of the box is the data median).

biohydrometallurgy (De Oliveria et al., 2021). Though these metallurgical extraction techniques for gallium in e-waste can reach recovery efficiencies of more than 90%, they are still in the lab and have a long way to go before commercialization (Swain et al., 2015a, 2015b; Lu et al., 2015; Zhan et al., 2015). Under current industrial waste management practices, when end-of-life gallium-containing products (e.g., waste electronics) are collected, they often wind up in the base metal waste stream (e.g., ferrous metal, copper and aluminum) or for precious metals recovery, without gallium recycled (Fang et al., 2018). In this regard, it is crucial to enhance technologies not only for extracting gallium from primary production and processing wastes, but also for recovery from manufacturing scraps and obsolete products, so as to achieve a circular economy.

Aside from technical impediments to gallium recovery that are very ineffective, a lack of inadequate economic incentives for gallium recycling is also a key challenge. Capturing gallium through improved recycling could be much more expensive than primary resources (Redlinger et al., 2015). Not only that, but the worth of other metals in the same waste end-products might make gallium recovery difficult. To be specific, because neodymium in magnets is currently more valuable than gallium, neodymium recovery from manufacturing wastes is limited, and even from these end-of-life materials is unfeasible (Schulze and Buchert., 2016; Geng et al., 2020; Yao et al., 2021). With the widespread usage of gallium in the magnet industry (**Figure 2**), it is unclear whether recovering gallium from NdFeB manufacturing scraps and end-of-life products would be economically viable in the future. Meanwhile, as solar PVs penetrate more deeply into the market (Grandell et al., 2016), end-of-life recycling of CIGS will also be a significant source of gallium in the future.

3.6 Uncertainty Evaluation

In **Figure 10**, a box plot illustrates the maximum, minimum, median values and quartiles of the uncertainty evaluations results for China's gallium cycle in 2020. For each flow, these data provide a good representation of the uncertainty. Domestic gallium consumption, recycled new scrap and manufacturing loss had higher uncertainty ranges (box heights) than the rest, indicating that these flows were more unpredictable. The reason for this is because the estimation of these flows involves several technical parameters with wider standard deviation range.

Relatively flat boxes indicated lower uncertainties in other flows or stocks, indicating that they had higher concentrations of simulation values. Overall, a high degree of reliability was observed in the uncertainty assessment results.

4 CONCLUSION AND POLICY IMPLICATIONS

This study presents a comprehensive description and analysis of China's gallium flows and stocks between 2005 and 2020, based on a detailed dynamic MFA model. Not only does this research provide information on gallium utilization and recycling possibilities, but also supports policies targeted at increasing resource efficiency. Main conclusions can be drawn as follows:

First, due to domestic capacity expansion, China's primary gallium production is expected to grow 20-fold from 2005 to 2020, making it the world's largest producer. Meanwhile, the gallium consumption grew rapidly to approximately 350 t by 2020. Despite the rapid growth of gallium consumption in recent years, with more than 70% used for making semiconductors, there is still an oversupply of 948 t of refined gallium stockpiled. This indicates a disequilibrium between supply and demand, which is not conducive to the sustained gallium development in the long run. It is therefore imperative to not only steer the upstream production of gallium in a reasonable manner, but also enhance gallium industry by encouraging the downstream use of gallium.

Second, although China has become the world's biggest supplier of raw gallium and exported 1,102 t of unwrought or wrought gallium, it still relies on importing high-end gallium products (i.e., integrated circuits) from abroad, whose raw materials are originally sourced from China. It is possible that the heavy reliance on imports of high-end gallium products will result in an unhealthy development of the domestic gallium industry. Thus, it is urgently needed to improve the advanced integrated circuit processing technology to promote the development of semiconductor industry, which is helpful for enhancing China's position in the downstream gallium industry chain.

Third, results show that the losses amounted to 11,125 t during the study period, among which 10,646 t was attributed to the inefficient mining, beneficiation and refining, while 479 t existed in the manufacturing process, with an overall recycling rate of 17% for the new scraps. Although more efficient recycling can be achieved to some extent, they are still in the experimental stage due to technical and economic limitations. The cumulative in-use gallium stock experienced a boom period during the last decade, reaching about 238 t in 2020. Besides, the total gallium end-of-life flows increased from 0.05 t in 2005 to 169 t in 2020, which suggests a great potential for recycling. However, there is no end-of-life recycling of gallium commercially, reflecting an extremely low utilization efficiency of secondary gallium resources. Therefore, more policies and investment should be given in encouraging cultivation of advanced technologies to improve the system-wide yield efficiency and recovery rate of gallium throughout its whole life cycle. Attention should be paid particularly to semiconductor manufacturing scraps, since they accounted for more than half of gallium processing waste streams, while recycling LED scraps such as obsolete LED lamps and electronics is of equal importance from a long-term perspective.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

HJ: Conceptualization, Methodology, Software, Writing-original draft, review and editing; YZ: Data curation, Methodology; AW: Writing-review and editing, Supervision, Funding acquisition; GW: Conceptualization, Formal analysis; TL: Writing-review and editing; CW: Software, Visualization; WX: Formal analysis; ZM: Formal analysis; PL: Formal analysis.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.944617/full#supplementary-material

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The Impact of Country Risks on the Dependence Patterns of International Cobalt Trade: A Network Analysis Method

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Cobalt is a key resource for the global energy transition, and the differences in the natural endowment of cobalt have led to frequent cobalt trade among countries. This study aims to reveal the dependence patterns of cobalt trade among countries and the impact of country risks (including political and economic risks) on the patterns. First, a cobalt import dependence network (CIDN) and a cobalt export dependence network (CEDN) are established using the network analysis method. Furthermore, this study uses network indicators to reveal the dependence patterns of cobalt trade among countries, and construct diversification indices of trade relations to further analyze the import source risk and the market concentration of cobalt trade. The results indicate that most cobalt importers have a high import source risk, and most cobalt exporters have a high market concentration. Finally, based on the panel regression methods, we reveal an interesting result showing that the dependence patterns of cobalt trade are significantly influenced by country risks. Specifically, on the one hand, for importers, an increase in political risk or economic risk has a negative impact on their dependence patterns of cobalt trade. On the other hand, for exporters, an increase in political risk or economic risk has different effects on their dependence patterns of cobalt trade. This study suggests that countries should pay more attention to the role of country risks in driving the dependence patterns when making cobalt trade policies.

Keywords: cobalt trade, trade dependence, country risks, complex network, panel regression

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1 INTRODUCTION

Against the backdrop of decarbonization of the global economy, cobalt is a crucial resource in the transition from fossil fuels to clean energy. Therefore, cobalt is listed as strategic metal by many countries. As an important primary raw material in industrial production, cobalt is mainly used in many industrial production fields, such as battery electrodes, metallurgy, catalysts and so on (Rachidi et al., 2021; van der Meide et al., 2022). Global growth in demand for electric vehicles is significantly driving cobalt demand, which is likely to increase 37-fold in 2030, judging by the criterion of cobalt demand in 2015 (Jones et al., 2020). The highly concentrated distribution of cobalt resources and the differences in cobalt consumption capacity among countries lead many countries to participate in the global cobalt trade market. The cobalt trade relations among countries form a complex system based on trade dependence between countries. For example, most of the cobalt mines in the world are mined in the Democratic Republic of the Congo (COD), but refined in China (US Geological Survey, 2022). In 2019, China imported 90,600 tons of cobalt ore and concentrate, of which 95.02% came from the COD. In the same year, the COD exported 96,200 tons of cobalt ore and concentrate, 89.49% of which flowed to China. This shows that the import dependence and export dependence of cobalt between the two countries are extremely high. However, the cobalt trade is easily affected by country risks (Sun X. et al., 2019; Liu S. et al., 2020). The unstable national environment could impact cobalt mining and consumption, cobalt transport process, cobalt prices, as well as other related factors, further influencing the economic development of both importers and exporters. Therefore, it is of great significance to explore the dependence patterns of international cobalt trade and the influence of country risks, which could provide references for countries to implement appropriate cobalt trade policies and ensure the aim of energy transformation.

Nowadays, the globalization of the economy and the complexity of international trade relations have become ever more diversified, and numerous scholars have employed network analysis methods to investigate international energy trade (Ji et al., 2014; Xi et al., 2019; Liu L. et al., 2020), agricultural trade (Shutters and Muneepeerakul, 2012; Leem and Won, 2020; Sun et al., 2022b) and mineral resources trade (Liang et al., 2020; Tian et al., 2021; Shi et al., 2022). For the global trade system, the network analysis method can analyze the complicated trade relations among countries and the structural features of the trade network, which help us better perceive the trading system's function (Sun Q. et al., 2019; Sun et al., 2020). The existing studies on cobalt trade mainly focused on the international cobalt trade patterns and the stability of cobalt trade (Chen et al., 2019; Becker, 2021; Shao et al., 2022; Shi et al., 2022). For example, Liu S. et al. (2020) first constructed a cobalt trade network, and in this network, the nodes represented countries, the edges reflected the direction of trade flow and the weight of the edges showed the trade volumes, and then predicted the potential cobalt trade relations. In addition, some studies created cobalt trade networks based on trade dependence. Specifically, combined with trade dependence theory and complex network theory, Zhao et al. (2020) constructed a cobalt trade dependence network to explore the structural characteristics of the dependence network and elaborated the impacts of each country's structural role on cobalt trade prices. Liu H. et al. (2021) explored the overall patterns of global cobalt trade and countries with high trade dependence and identified high-risk countries or regions. Nevertheless, the above-mentioned researches ignored the differences in dependence patterns of cobalt trade between importers and exporters. Cobalt trade is used to boost the economy of exporting countries. Conversely, it is used to meet the energy transition needs of importing countries (Leon et al., 2021; Sun X. et al., 2022). Given that importers and exporters hold varied trade goals and different dependence on other countries in international cobalt trade, it is vital to reveal the dependence patterns of cobalt trade from importers and exporters. On this basis, this study examines the dependence patterns of cobalt trade among countries from the perspectives of importers and exporters, respectively.

Many researches have focused on the influencing factors of international trade (Subramanian and Wei, 2007; Campi and Duenas, 2019; Liu A. et al., 2020). On the one hand, based on the gravity model (Linnemann, 1966; Sun and Shi, 2022), geographical distance (Martinez-Zarzoso and Nowak-Lehmann, 2004), market size (Gopinath and Echeverria, 2004), trade openness (Cavallo and Frankel, 2008), cultural similarity (Kristjansdottir et al., 2020), and exchange rate (Bahmani-Oskooee, 1986; Kang and Dagli, 2018) are identified as significant factors in international trade. On the other hand, using the panel regression methods, Zhang et al. (2021) found that country risks significantly impact energy trade patterns. In terms of mineral resources trade, Zheng et al. (2017) examined the factors influencing the import and export trade of nonferrous metals in China and found that political risk is one of the important factors. Owing to different resource endowments, most cobalt resources are distributed in a few countries with unstable political or economic environments, such as the COD and Cuba (US Geological Survey, 2022). This has directly led to a significant impact on the global supply of cobalt resources (Sun X. et al., 2019; Liu S. et al., 2020). Therefore, country risks may become an important factor influencing the international trade of cobalt. Then, whether country risks have an impact on the dependence patterns of cobalt trade among countries remains to be studied.

In this study, we use the cobalt ore and concentrate trade to represent the cobalt trade. In the cobalt trade, the import dependence of country A on country B is defined as the proportion of the cobalt trade volumes of country A importing from country B in the volumes of country A importing from the world. Similarly, the export dependence of country B on country A is defined as the proportion of the cobalt trade volumes of country B exporting to country A in the volumes of country B exporting to the world. Then, we construct a cobalt import dependence network (CIDN) and a cobalt export dependence network (CEDN) due to the different trading goals of importers and exporters. Based on the network analysis method, this study uses network indicators to reveal the dependence patterns of cobalt trade among countries, and construct diversification indices of trade relations to analyze the import source risk and the market concentration of cobalt trade. Moreover, based on the panel regression method, we explore the impacts of country risks (including political risk and economic risk) on the import and export dependence patterns of cobalt trade. Finally, this study proposes policy implications for countries with different cobalt trade dependence patterns from the perspective of trade security.

Our key contributions are twofold. First, this paper constructs new indicators to examine the diversification of trade relations, including IHHI and EHHI. These indicators provide a close observation of import source risk and the market concentration of cobalt trade. Second, this study is the first to explore the factors influencing cobalt trade dependence relations in combination with network indicators. We mainly reveal the impact of country risk on the pattern of cobalt trade dependence among countries.

The structure of this study is as follows: **Section 2** introduces the data and methodology, **Section 3** presents the results and relates discussions, and research conclusions and policy implications are underlined in **Section 4**.

2 METHODOLOGY AND DATA

2.1 Data

The data of trade flow of cobalt ores and concentrates among 171 countries and regions (hereafter, countries) from 2000 to 2019 are downloaded from UN Comtrade (https://comtrade.un.org/), of which the product code is "HS 2605"[1]. The data of country risks are collected from the International Country Risk Guide (https://www.prsgroup.com/). The GDP and population data are obtained from the World Bank database (https://data.worldbank.org.cn/).

2.2 Methodology

2.2.1 Construction of Cobalt Trade Dependence Network

This study constructs a CIDN and a CEDN. In the networks, nodes represent countries involved in cobalt trade, edges represent the dependence relations of cobalt trade and the direction of the edges is the trade flows. Therefore, CIDN and CEDN are directed and weighted, and the network matrixes are defined as **Eqs 1**, **2** (Sun et al., 2022a).

$$CIDN = (V_{countries}, I_{trade}) = \begin{bmatrix} 0 & \cdots & \cdots & I_{1j} & \cdots & I_{1N} \\ \vdots & \ddots & \ddots & \vdots & \ddots & \vdots \\ I_{i1} & \cdots & \cdots & I_{ij} & \cdots & I_{iN} \\ \vdots & \ddots & \ddots & \vdots & \cdots & \vdots \\ \vdots & \ddots & \ddots & \vdots & \ddots & \vdots \\ I_{N1} & \cdots & \cdots & I_{Nj} & \cdots & 0 \end{bmatrix} \quad (1)$$

$$CEDN = (V_{countries}, E_{trade}) = \begin{bmatrix} 0 & \cdots & \cdots & E_{1j} & \cdots & E_{1N} \\ \vdots & \ddots & \ddots & \vdots & \ddots & \vdots \\ E_{i1} & \cdots & \cdots & E_{ij} & \cdots & E_{iN} \\ \vdots & \ddots & \ddots & \vdots & \cdots & \vdots \\ \vdots & \ddots & \ddots & \vdots & \ddots & \vdots \\ E_{N1} & \cdots & \cdots & E_{Nj} & \cdots & 0 \end{bmatrix} \quad (2)$$

In these above two equations, $V_{countries}$ is node set, and I_{trade} and E_{trade} are edge sets. N is the number of all countries involved in cobalt trade each year. I_{ij} represents the import dependence of country *j* on country *i*, which is defined as **Eq 3**. E_{ij} represents the export dependence of country *i* on *j*, which is defined as **Eq 4**. The values of I_{ij} and E_{ij} are range from 0 to 1. A higher value of I_{ij} indicates a higher import dependence of country *j* on *i*, and a higher value of E_{ij} represents a higher export dependence of country *i* on *j*.

$$I_{ij} = \frac{TV_{ji}}{TIV_i} \quad (3)$$

$$E_{ij} = \frac{TV_{ij}}{TEV_i} \quad (4)$$

In these above two equations, TV_{ji} represents the cobalt trade volumes of country i importing from *j*. TIV_i is the total import volumes of country i from the world. TV_{ij} represents the cobalt trade volumes exporting from country *i* to *j*. TEV_i is the total export volumes from country i to the world. **Figure 1** shows the cobalt trade dependence network in 2019. In the network, the size of the node corresponds to the number of the country's trade partners and the width of the edge corresponds to the extent of import or export dependence between countries.

2.2.2 Measurement Indicators of Trade Dependence Pattern

To measure the dependence patterns of cobalt trade among countries, this study mainly uses network indicators of CIDN and CEDN, and the diversification indices of trade relations constructed on the basis of trade dependence theory and the Herfindahl-Hirschmann index.

(1) The number of trading partners. In CIDN and CEDN, the degree of node i represents the number of cobalt trading partners of country *i*, defined as k_i in **Eq 5**. The degree can be divided into two indicators, including in-degree (ID) and out-degree (OD). The in-degree and out-degree of node i represent the number of cobalt import partners and the number of export partners of country i respectively, defined as k_i^{in} and k_i^{out} in **Eq. 6**, **7** (Bonacich, 1972). If country *i* imports cobalt from country *j*, then $a_{ji} = 1$, meaning that there is an edge pointing from country *j* to country *i*, otherwise $a_{ji} = 0$. If country i exports cobalt to country *j*, then $a_{ij} = 1$, meaning that there is an edge pointing from country i to country *j*, otherwise $a_{ij} = 0$ (Dalin et al., 2012).

$$k_i = k_i^{in} + k_i^{out} \quad (5)$$

$$k_i^{in} = \sum_{j=1}^{N} a_{ji} \quad (6)$$

$$k_i^{out} = \sum_{j=1}^{N} a_{ij} \quad (7)$$

(2) The total trade volumes. In CIDN and CEDN, the total trade volumes (TTV) of country i can be divided into two indicators, including the total import volumes (TIV) and total export volumes (TEV). The calculation methods of these indicators are **Eqs 8–10**. When the value of the TIV of country i is large, it means that the country has a high demand for cobalt. TTV can reflect each country's trade share in the global cobalt trade market.

$$TIV_i = \sum_{j=1}^{N} TV_{ji} \quad (8)$$

[1]This study chooses 2019 as the end year of this study, since they are the latest available data that are not influenced by the big trade shocks like COVID-19 (Sun X. et al., 2022).

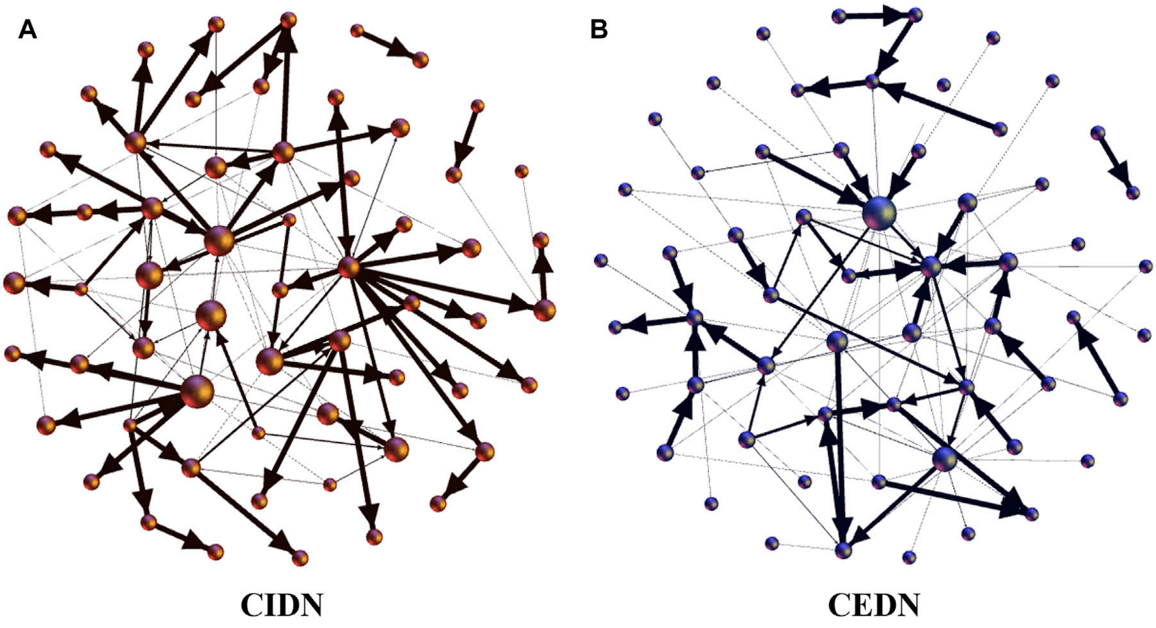

FIGURE 1 | The cobalt trade dependence network in 2019 (**(A)** and **(B)** represent the cobalt import dependence network and the cobalt export dependence network respectively).

$$TEV_i = \sum_{j=1}^{N} TV_{ij} \quad (9)$$

$$TTV_i = TIV_i + TEV_i \quad (10)$$

(3) Betweenness centrality. Betweenness centrality (BC) reflects the ability of countries to control cobalt resources in the network. Its power, as an intermediary in the networks, is expressed by measuring the number of shortest paths through this country in the network (Goh et al., 2003). The calculation method of betweenness centrality of country i shows in **Eq 11** (Freeman, 1977; Boccaletti et al., 2006).

$$BC_i = \sum_{p \neq i \neq q} \frac{\sigma_{pq}(i)}{\sigma_{pq}} \quad (11)$$

In **Eq 11**, σ_{pq} represents the number of shortest paths from node p to node q, and $\sigma_{pq}(i)$ signifies the number of the shortest paths from node p to node q that pass-through node i.

(4) Closeness centrality. The cobalt trade distance of a country to other countries is expressed by measuring the average length of the path established with other countries in the network, which is measured by closeness centrality (CC) (Sabidussi, 1966; Xi et al., 2019). The calculation method of closeness centrality of country i is in **Eq 12** (Freeman, 1978; Boccaletti et al., 2006). The higher the closeness centrality of country i, the shorter the cobalt trade distance.

$$CC_i = \frac{1}{\sum_{i \neq j} d(i,j)} \quad (12)$$

In **Eq 12**, $d(i, j)$ is the number of edges of the shortest path between node i and node j in the CIDN.

(5) Herfindahl-Hirschmann index. To analyze the diversification of trade relations of each country, this study uses Herfindahl-Hirschmann Index (HHI) proposed by Hirschmann and Herfindahl, which value ranges from 0 to 1 (Hirschman, 1964; Rhoades, 1993). The HHI can be used not only to assess the import source risk of cobalt from the perspective of diversification of import relations, but also to measure the market concentration of cobalt trade according to export relations (Achzet and Helbig, 2013; Vivoda, 2019; Althaf and Babbitt, 2021). Thus, based on trade dependence and the Herfindahl-Hirschmann index, this paper constructs the diversification indices of trade relations (THHI). THHI includes the diversification index of import relations (IHHI) and diversification index of export relations (EHHI), defined as **Eqs 13**, **14** respectively. When the $IHHI_i$ is close to 0 in CIDN, it represents a high diversification of import relations and a low import source risk of cobalt in country i, and vice versa. When $EHHI_i$ is close to 0 in CEDN, it represents a high diversification of export relations and a low market concentration of cobalt trade in country i, and vice versa.

$$IHHI_i = \sum_{j=1}^{N} (I_{ji})^2 \quad (13)$$

$$EHHI_i = \sum_{j=1}^{N} (E_{ij})^2 \quad (14)$$

2.3 Variables Analysis

This research selects countries with the total cobalt trade volumes more than 150,000 tons from 2000 to 2019, and due to the availability of the data, 62 countries are selected (referring to **Supplementary Table S1**). The cobalt trade of these countries accounts for over 99% of the global cobalt trade, including 32 importers and 30 exporters. A country that acts primarily as a demander (supplier) with a large amount of cobalt is classified as an importer (exporter)[2] (Zhang et al., 2021).

(1) Independent variables. This study aims at exploring the impact of country risks on the dependence patterns of cobalt trade. Therefore, the country risks act as independent variables. The country risks include political and economic risks, consisting of 12 components and five components respectively[3]. We use **Eqs 15, 16** to adjust the political risk index and the economic risk index. In this study, the higher the values of political and economic risk indices are, the higher the political and economic risks are.

$$\boldsymbol{PolRisk_i} = \sum_{a=1}^{12} (\boldsymbol{maxPolrisk_a} - \boldsymbol{PolRisk_{ia}}) \tag{15}$$

$$\boldsymbol{EcoRisk_i} = \sum_{b=1}^{5} (\boldsymbol{maxEcorisk_b} - \boldsymbol{EcoRisk_{ib}}) \tag{16}$$

In **Eqs 15, 16**, $PolRisk_i$ and $EcoRisk_i$ are the political risk index and economic risk index of the country i respectively. $PolRisk_{ia}$ is the political risk component a for the country i, and $maxPolRisk_j$ is the maximum value of the political risk component a. $EcoRisk_{ij}$ is the economic risk component b for the country i, and $maxEcoRisk_j$ is the maximum value of the economic risk component b.

(2) Dependent variables. Network indicators could provide a clear picture of the dependence pattern of cobalt trade among countries. Therefore, the dependent variables are the network indicators of CIDN and CEDN and the THHI. For importers, we choose the in-degree, total import volumes, closeness centrality and IHHI as dependent variables. For exporters, we choose out-degree, total trade volumes, betweenness centrality and EHHI as the dependent variables (Zhang et al., 2021).
(3) Control variables. On the one hand, since economic development can reflect both demand and supply in a country, the size of the trading partner's economy is generally considered as a major determinant of international trade flows. A higher level of economic development in a country means that it tends to have greater international trade flows. On the other hand, the more population a country has, the greater potential domestic demand it enjoys. Moreover, the population also affects each country's supply and is believed to affect the flow of international trade. Therefore, this study uses GDP and the total population to measure the economic scale and population of each country separately (Zheng et al., 2017; Dong et al., 2018).

TABLE 1 | Variables in the regression models.

Variables	Specific Indicators	Symbols
Dependent variables	In-degree	ID
	Out-degree	OD
	Total import volumes	TIV
	Total trade volumes	TTV
	Betweenness centrality	BC
	Closeness centrality	CC
	IHHI	IHHI
	EHHI	EHHI
Independent variables	Political risk	PolRisk
	Economic risk	EcoRisk
Control variables	GDP	GDP
	Population	Population

2.4 Regression Model

After the above analysis, variables in **Table 1** are selected to establish regression models. Logarithmic processing of total import volumes, total trade volumes, GDP, and the total population are conducted to make the data more stable (Zhang et al., 2021).

This study mainly focuses on the impact of country risks (including political risk and economic risk) on the dependence patterns of cobalt trade. Volatile economic and political environments, such as war, ethnic conflicts and economic depression, could affect the production or consumption of cobalt-related industries in the countries. Meanwhile, increased political and economic risks could also impact cobalt transportation, prices, etc. The aspects mentioned above could affect the cobalt trade between countries and further influence the dependence pattern of cobalt trade among countries. Since there are glaring distinctions in the dependence patterns of cobalt trade between importers and exporters, we construct different regression models. We use **Eq 17** to explore the impact of country risks on import dependence patterns of cobalt trade. Four regression models are constructed using the in-degree, total import volumes, closeness centrality and IHHI as dependent variables Y_{mt} respectively.

$$\boldsymbol{Y_{mt}} = \boldsymbol{\beta_1 PolRisk_{mt}} + \boldsymbol{\beta_2 EcoRisk_{mt}} + \boldsymbol{\beta_3 GDP_{mt}} + \boldsymbol{\beta_4 Population_{mt}} + \boldsymbol{\alpha_m} + \boldsymbol{\varepsilon_{mt}} \tag{17}$$

In **Eq 17**, m represents importers, and t represents year. $\beta_1 - \beta_4$ are the regression coefficients of political risk, economic risk,

[2]The ratio of the sum of cobalt import volumes to the sum of export volumes is calculated for each country from 2000 to 2019, with countries between 0 and 0.9 being exporters and those greater than 1.1 being importers. Each country with a ratio between 0.9 and 1.1 is an importer if the sum of its import volumes ranking in the 50th percentile, otherwise it is an exporter.

[3]Political risk involves 12 components, including the government stability, socioeconomic conditions, investment profile, internal conflict, external conflict, corruption, military in politics, religious tensions, law and order, ethnic tensions, democratic accountability, bureaucracy quality. Economic risk involves five components, including GDP per head, real GDP growth, annual inflation rate, budget balance as a percentage of GDP, current amount as a percentage of GDP. In addition, country risks in the International Country Risk Guide also include financial risk, but the effect of financial risk on dependence patterns of cobalt trade is not significant. Therefore, independent variables do not include financial risk.

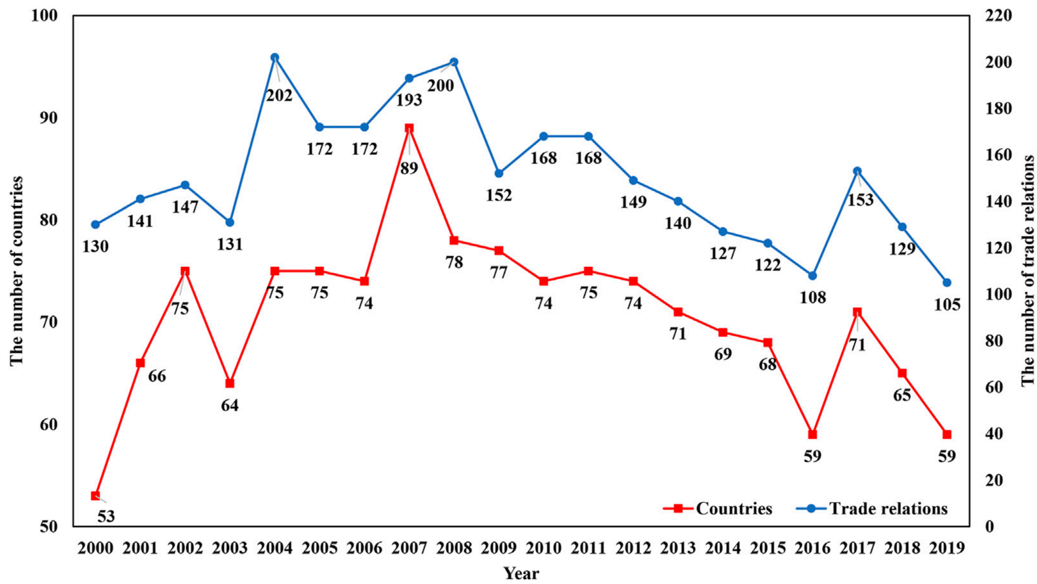

FIGURE 2 | The number of countries and trade relations in CIDN and CEDN from 2000 to 2019.

GDP and total population. α_m is the constant term related to the country, and ε_{mt} is the random variable.

Likewise, **Eq 18** is used to study the impact of country risks on export dependence patterns of cobalt trade. Four regression models are constructed using the out-degree, total trade volumes, betweenness centrality and EHHI as dependent variables Z_{nt}, respectively.

$$\boldsymbol{Z_{nt}} = \boldsymbol{\theta_1 PolRisk_{nt}} + \boldsymbol{\theta_2 EcoRisk_{nt}} + \boldsymbol{\theta_3 GDP_{nt}} + \boldsymbol{\theta_4 Population_{nt}} + \boldsymbol{\alpha_n} + \boldsymbol{\varepsilon_{nt}} \tag{18}$$

In **Eq 18**, n represents exporters. $\theta_1 - \theta_4$ are the regression coefficients of political risk, and economic risk, GDP and total population. α_n is the constant term related to the country, and ε_{nt} is the random variable.

3 RESULTS AND DISCUSSION

3.1 The Dependence Patterns of International Cobalt Trade

3.1.1 The General Evolution Characteristics of CIDN and CEDN

The basic topological structure of CIDN and CEDN can reflect their general evolutionary characteristics. The number of countries and trade relations in CIDN and CEDN are counted, whose evolution trends are shown in **Figure 2**. The number of countries and trade relations follow roughly the same trend over time, and there was an upward trend from 2000 to 2007 and a downward trend from 2007 to 2019.

To analyze the dependence patterns of cobalt trade in detail, we divide the trade relations in CIDN and CEDN into ten groups according to the value of import dependence I_{ij} and export dependence E_{ij} respectively. **Figure 3** shows the percentage of the number of trade relations in each group to the total number of trade relations. In **Figure 3A**, the blue bar means that there was a 62% import dependence with value ranging from 0 to 0.1 in 2000, and the red bar represents that there was a 17% import dependence with the value ranging from 0.9 to 1. Thus, it can be concluded that the percentage of I_{ij} in groups (0, 0.1] and (0.9, 1.0] were higher than other groups from 2000 to 2019. The sum of the percentages for these two groups exceeded 72% each year. In **Figure 3B**, the blue bar means that there was a 54% export dependence with the value ranging from 0 to 0.1 in 2000, and the red bar represents that there was a 22% export dependence with the value ranging from 0.9 to 1. Similar to importers, the percentage of E_{ij} in groups (0, 0.1] and (0.9, 1.0] were higher than in other groups. The sum of the percentages of these two groups exceeded 69% each year. We further analyze the data and find that most countries trade cobalt mainly with a few partners, and their trade volume with other countries is very low. Therefore, the dependence is mainly concentrated in the interval (0, 0.1] and (0.9, 1.0]. The result is similar to Liu H. et al. (2021). For example, in 2019, China's import dependence on COD was 0.95, while its import dependence on the other six import partners was only 0.05. In the same year, the United States had a combined export dependence of 0.99 on Belgium, Brazil, and Germany and a combined export dependence of 0.01 on the other seven export partners.

3.1.2 Import Dependence Patterns of Cobalt Trade

(1) The import volumes

We choose importers with the high import volumes of cobalt, including China (CHN), Zambia (ZMB), Finland (FIN), India (IND), the United Arab Emirates (ARE), Switzerland (CHE), Japan (JPN), and the United Kingdom (GBR). **Figure 4** shows the

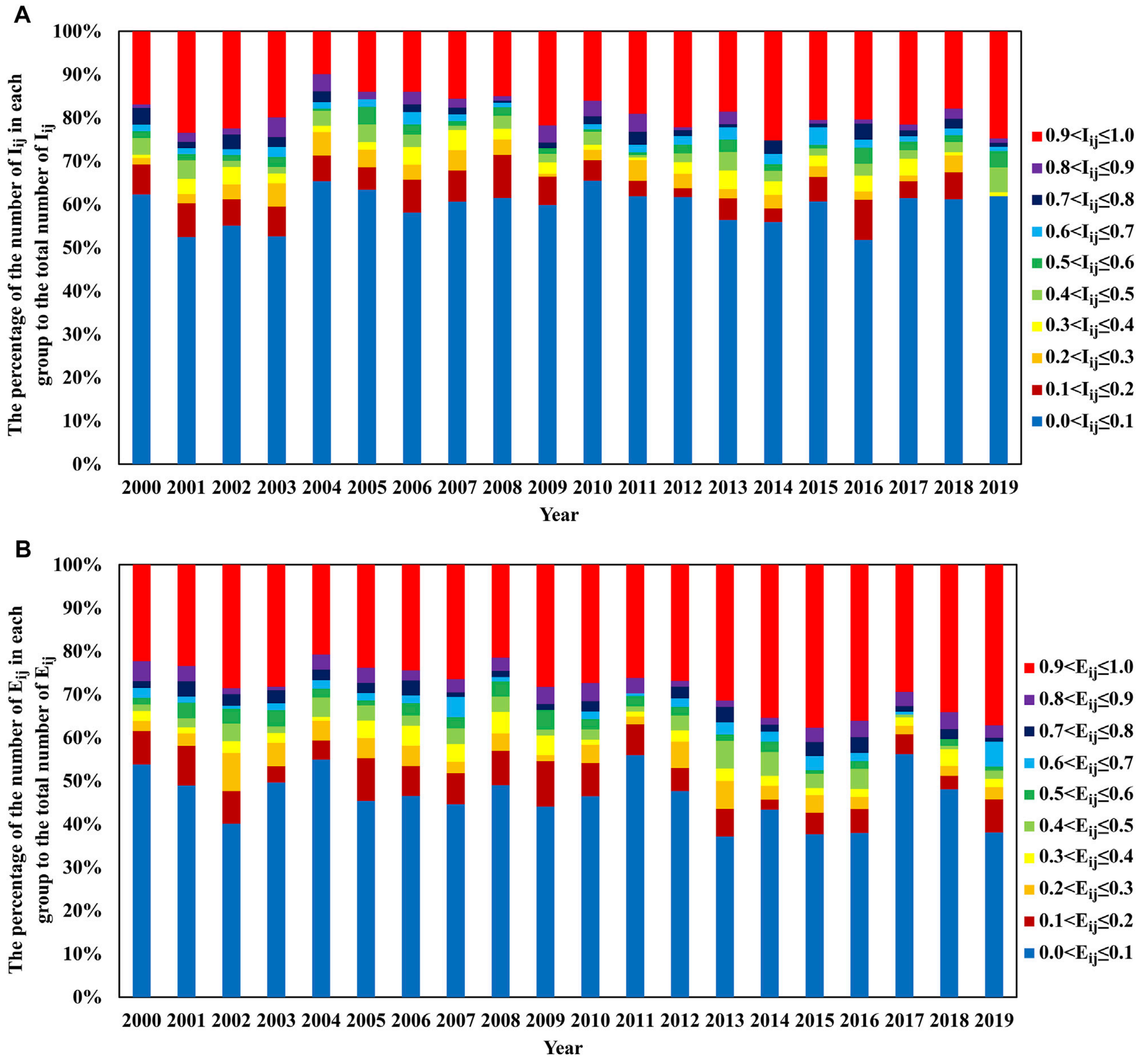

FIGURE 3 | The percentage of the number of trade relations in each group to the total number of trade relations in CIDN and CEDN from 2000 to 2019 (**(A)** reflects the percentage related to import dependence in CIDN, and **(B)** reflects the percentage related to export dependence in CEDN).

percentages of each importer's import volumes of cobalt to the global import volumes. For example, the orange bars indicate China's cobalt import volumes, which accounted for 66% of global import volumes in 2000. The sum of import volumes of these eight importers accounted for 79–99% of the global import volumes each year, indicating that these countries play a decisive role in the global market for cobalt resources demand. Additionally, since 2003, China's import volumes have exceeded Finland's and ranked first in the world, due to China's transformation of its industrial structure to become the world's largest producer of refined cobalt, with global production of refined cobalt being concentrated in China. The result is in line with Zhao et al. (2020).

(2) The role of importers in international cobalt trade

According to the average closeness centrality of each importer from 2000 to 2019, the United Kingdom has the highest average ranking for closeness centrality, which shows that the United Kingdom plays an important role and has the shortest cobalt trade distance with other countries in the trade network. We select the top four countries in terms of average closeness centrality rankings, namely the United Kingdom (GBR), Zambia (ZMB), Spain (ESP) and Belgium (BEL), and their annual rankings of closeness centrality are shown in **Figure 5**. It can be found that the closeness centrality ranking of the United Kingdom fluctuated greatly from 2000 to 2003, as

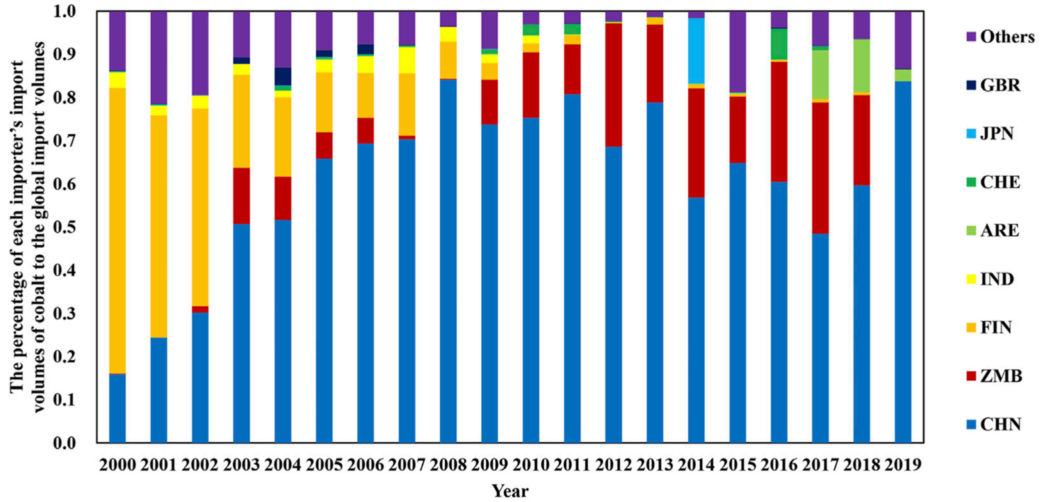

FIGURE 4 | The percentage of each importer's import volumes of cobalt to global import volumes in CIDN from 2000 to 2019.

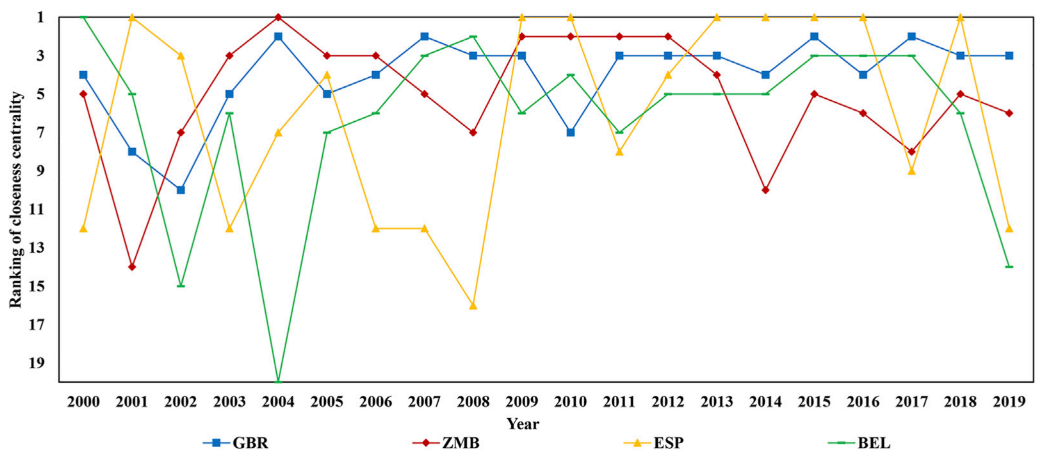

FIGURE 5 | The rankings of closeness centrality from 2000 to 2019.

most of the United Kingdom's import partners were different every year. And it also clearly changed the import dependence between the United Kingdom and other countries. Besides, since 2004 the import partners of the United Kingdom have consisted mainly of the United States, Zambia, Ireland, and Poland, and the United Kingdom has high import dependence on these four countries, which has resulted in a stable closeness centrality ranking for the United Kingdom.

(3) The diversification of import relations

Generally speaking, for cobalt importers, a large number of importing partners may reduce the import dependence on the individual country and the import source risk of cobalt. However, if an importer has lots of importing partners, and most of the cobalt is imported from one country, then it has high import dependence on this partner, causing a high import source risk of cobalt. More specifically, when its import partner with high import dependence suddenly cuts off the supply, the importer will be significantly influenced. To better understand the import source risk of cobalt in each country, we draw a scatter plot between the number of import partners and the IHHI for importers, which is shown in **Figures 6A–E** where the horizontal axis represents IHHI, and the vertical axis represents in-degree. The fitting curve of the scatter plot shows a negative correlation between the number of import partners and the IHHI, which means that the import relationship is more diversified when the importer has more importing partners. It is worth noting that many of the dots are distributed in the bottom right corner, which indicates that most importers have fewer import partners and lower diversification of import relations. Therefore, most importers have a high import source risk of cobalt. Besides, it can be observed that China always acts as an outlier, with a downward trend in its number of import

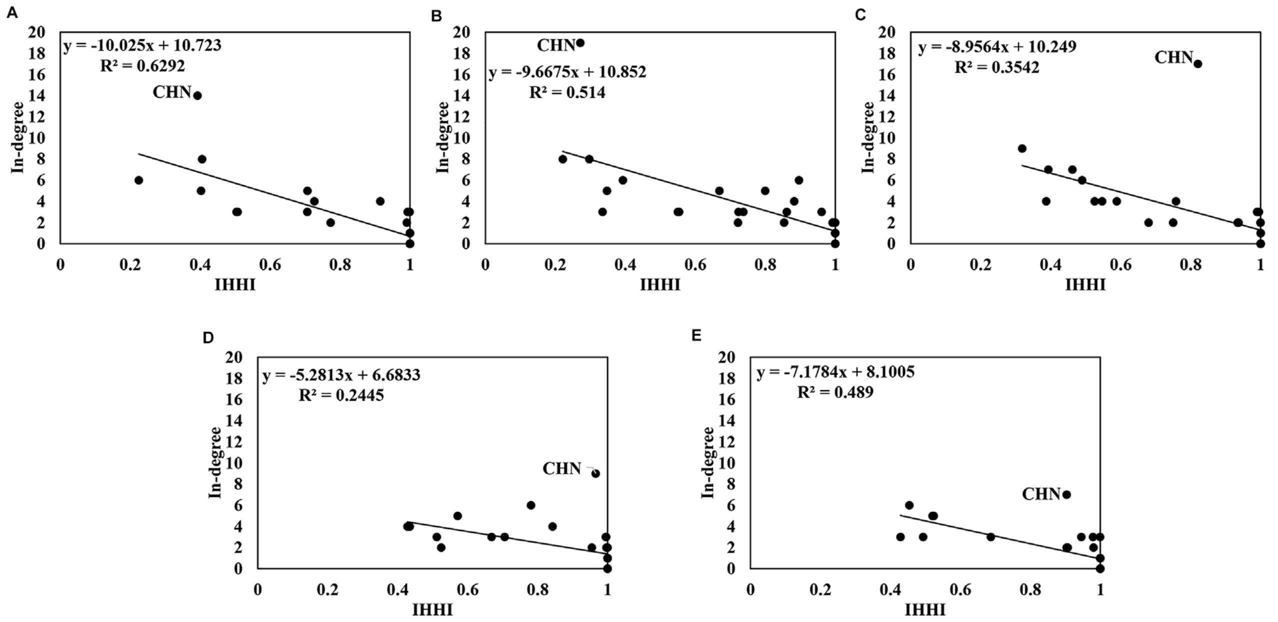

FIGURE 6 | The scatter plot between the number of import partners and the IHHI (**(A–E)** correspond to the years of 2000, 2005, 2010, 2015, and 2019 respectively).

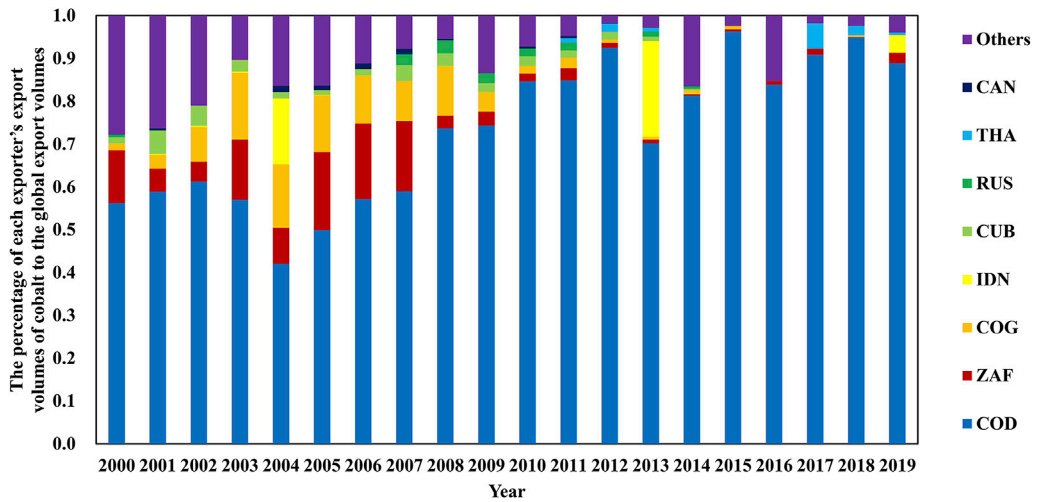

FIGURE 7 | The percentage of each exporter's export volumes of cobalt to global export volumes in CEDN from 2000 to 2019.

partners and an upward trend in the IHHI, which means that its import source risk of cobalt is increasing.

3.1.3 Export Dependence Patterns of Cobalt Trade

(1) The export volumes

Similar to importers, we choose exporters with high export volumes, including the COD, South Africa (ZAF), Congo (COG), Indonesia (IDN), Cuba (CUB), Russia (RUS), Thailand (THA), and Canada (CAN). **Figure 7** shows the percentage of the eight exporters' export volumes of cobalt to the global export volumes. For example, the red bars indicate that South Africa's cobalt export volumes, which accounted for 12% of global export volumes in 2000. The sum of export volumes of these eight countries accounted for 72–98% of the global export volumes each year. Therefore, these eight countries play a decisive role in the global supply market for cobalt resources. In terms of export volumes, the COD has been ranked first in the world, as the country has 46% of the global cobalt resources. In 2018, the COD implemented a new mining law that increased taxes and royalties

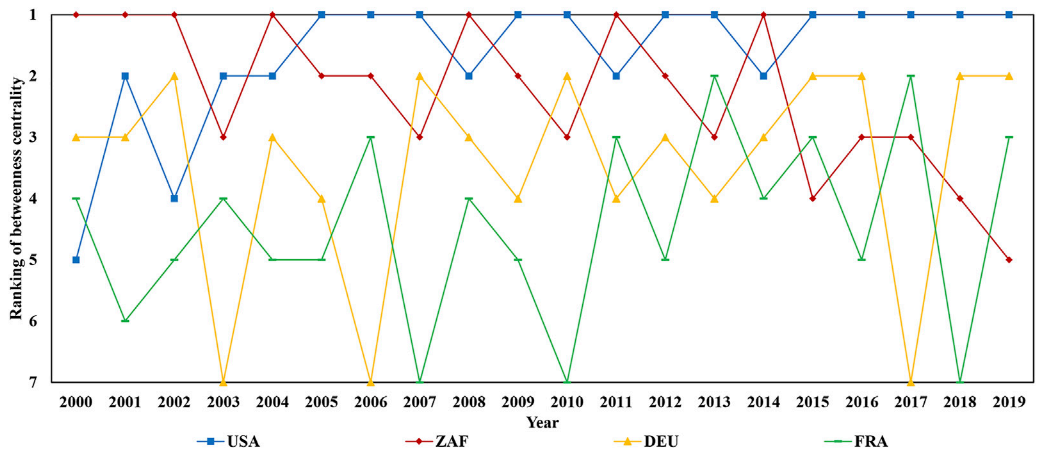

FIGURE 8 | The rankings of betweenness centrality from 2000 to 2019.

for cobalt mining companies and raised the export tax on cobalt resources. This might lead to a significant drop in export volumes from the COD in 2019.

(2) The analysis of the role of exporters

Based on the average betweenness centrality for each exporter from 2000 to 2019, the top four countries, including the United States (United States), South Africa (ZAF), Germany (DEU) and France (FRA) are selected in terms of average betweenness centrality, and the betweenness centrality rankings of these countries in each year are shown in **Figure 8**. It can be found that in most years, the United States and South Africa ranked higher than Germany and France in betweenness centrality, which means that they have a stronger ability to control cobalt resources than other countries and play an important role in the trade network. This is mainly mirrored in the intermediary role of the two countries in the cobalt trade network. Specifically, most cobalt in the United States is imported from South Africa and then exported to many countries in Asia, Europe, and North America. And South Africa mainly imports from Zambia and the COD, and then exports to many countries in Asia and North America. It has led to a high import dependence between these two countries and their many import partners.

(3) The diversification of export relations

Usually, cobalt exporters with many export partners may reduce export dependence on the individual country and reduce the market concentration of cobalt trade. If an exporter has many export partners, but most of the cobalt is exported to one country, then it has high export dependence on this partner, causing a high market concentration of cobalt trade. In this case, when its export partner with high export dependence changes importing sources of cobalt, the exporter will be greatly influenced. Therefore, **Figures 9A–E** shows a scatter plot between the number of export partners and the EHHI for exports, where the horizontal axis represents EHHI, and the vertical axis indicates out-degree. On this basis, three points stand out. First, similar to importers, the fitting curve of the scatter plot shows a negative correlation between the number of export partners and EHHI, which implies that the export relationship is also more diversified when the exporter has more exporting partners. Second, it is important to point out that many of the dots are distributed in the bottom right corner, which means that most exporters have fewer export partners and lower diversification of export relations. Consequently, most exporters have a high market concentration of cobalt trade. Third, with the advantage of a natural port, South Africa has many export partners, but it was the outlier in 2005 and 2010. This might because most cobalt from South Africa is exported to China, which has led to a high export dependence on China, resulting in a high market concentration of cobalt trade.

3.2 The Impact of Country Risks on the Dependence Patterns

3.2.1 Descriptive Statistical Analysis

Descriptive statistics for all variables are shown in **Table 2**. On average, exporters have higher diversification of trade relations, political risk, and economic risk than importers.

3.2.2 The Panel Regression Results

Based on **Section 2.4**, regression models of the relationship between country risks and the dependence patterns of cobalt trade are constructed, and the results are presented in **Table 3**. Columns 1) to 4) are related to importers, and columns 5) to 8) are related to exporters.

(1) The regression results related to importers

The increased political risk of cobalt importers exerts a negative influence on the import dependence patterns of cobalt trade, which is similar to Zheng et al. (2017). An increase in political risk reduces the number of import partners and total

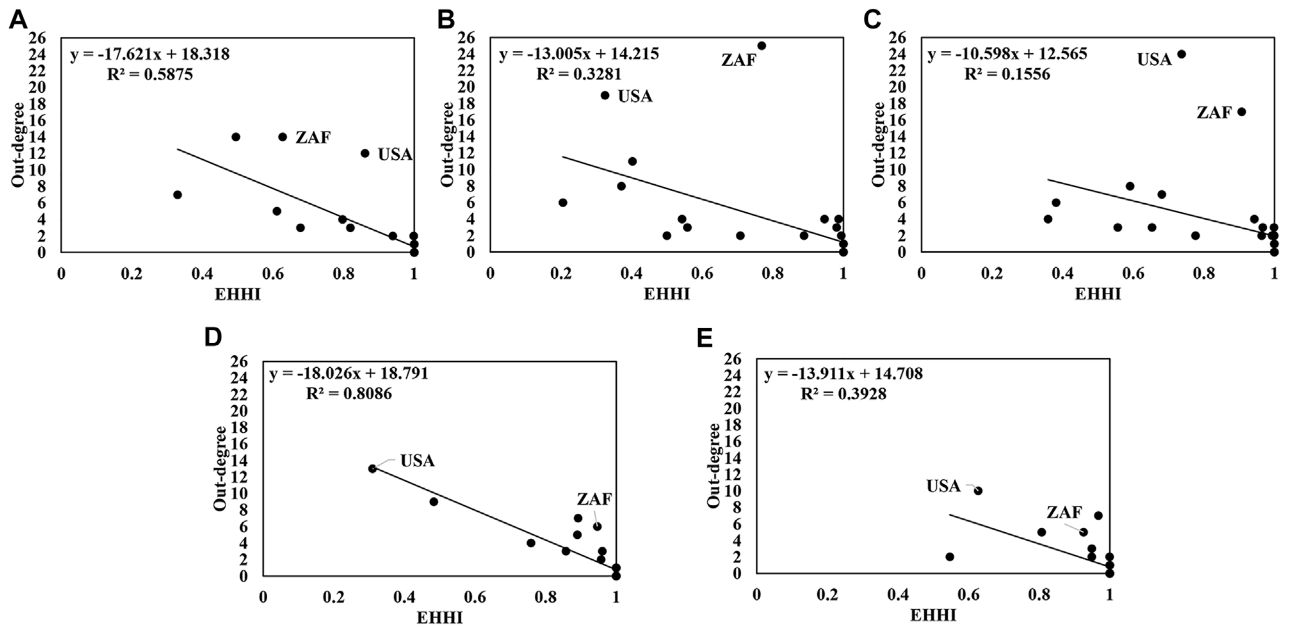

FIGURE 9 | The scatter plot between the number of export partners and the EHHI (**(A–E)** correspond to the years of 2000, 2005, 2010, 2015, and 2019, respectively).

TABLE 2 | Descriptive statistics.

Variables	Importers (640 Observations)				Exporters (600 Observations)			
	Mean	Std.Dev	Min	Max	Mean	Std.Dev	Min	Max
ID	2.6391	3.3276	0	22	1.4267	2.0473	0	14
OD	2.0516	3.1482	0	21	2.6050	4.3081	0	29
TIV	8.1532	6.1368	0.0000	19.6899	4.7110	5.0729	0.0000	17.6656
TTV	9.1314	5.9479	0.0000	19.6918	8.6653	6.0813	0.0000	19.8029
BC	0.0143	0.0300	0.0000	0.2418	0.0122	0.0290	0.0000	0.1750
CC	0.2471	0.2891	0.0000	1.0000	0.2559	0.2547	0.0000	1.0000
THHI	0.8451	0.2314	0.1622	1.0000	0.8889	0.2054	0.1946	1.0000
PolRisk	27.0895	12.0327	3.9167	56.4167	33.0630	15.6088	7.7083	77.5417
EcoRisk	11.7266	5.1253	1.4583	35.9583	13.7348	6.1418	1.5833	50.0000
GDP	26.1859	1.6829	21.8217	30.2899	25.7801	2.0702	21.7517	30.6960
Population	17.0131	1.6688	12.9861	21.0581	17.0173	1.4103	14.0890	19.6095

TABLE 3 | Panel regression results of the country risks to the dependence patterns of cobalt trade.

Variables	Importers				Exporters			
	(1)ID	(2)TIV	(3)CC	(4)IHHI	(5)OD	(6)TTV	(7)BC	(8)EHHI
C	−17.3659***	−7.2587**	−0.7014***	1.9141***	−20.3754***	−3.7768	−0.1559***	1.4670***
PolRisk	−0.0937***	−0.2363***	−0.0054***	0.0075***	−0.0834***	−0.0708**	−0.0005***	0.0033***
EcoRisk	−0.0758**	−0.1203**	0.0014	−0.0011	0.0930***	−0.0749	0.0006**	−0.0019
GDP	0.1133	−0.1985	0.0295**	−0.0136	0.1379	−0.4156	0.0029**	0.0125
Population	1.2029***	1.6706***	0.0179	-0.0531***	1.2284***	1.5587***	0.0059***	−0.0578***

*Notes: *, **and*** represent statistical significance at 10%, 5% and 1% level, respectively.*

import volumes, and meanwhile raises cobalt trade distance and the import source risk of cobalt of importers. High political risk means unstable political rights, poor regulation, and an imperfect legal environment; hence the reasons for the negative impact may be multifaceted. When the domestic political environment of a country is unstable, the instability and cost of trading with the country may grow, which may cause many import partners to stop exporting cobalt to this country. Meanwhile, political crises among importers may bring about warfare, making cargo transportation quite difficult. Besides, a volatile domestic political environment can impair or even interrupt normal production activities in many industries, particularly those heavily relying on imported raw materials, resulting in a lack of demand for cobalt in that country. For importers, cutting-off supply by many exporters and declining domestic demand reduce the number of import partners and total import volumes. This has led to import sources concentrating in a few remaining import partners, resulting in increased import dependence on these countries, which implies an increase in the import source risk of cobalt. For example, in 2018, Japan's political risk increased markedly. This has negatively impacted Japan's dependence pattern of cobalt trade. Specifically, Japan's cobalt trade with countries such as South Africa and Zambia was interrupted. And Japan's import volumes of cobalt decreased by 48,401 tons and its import dependence on the United States increased from 0.19 in 2017 to 0.98 in 2018, which directly contributed to an increase in Japan's IHHI to 0.97. This means that Japan's import source risk of cobalt increased significantly in 2018.

Besides, the increased economic risk of importers negatively impacts the dependence patterns of cobalt trade, reducing the number of import partners and the total import volumes to some extent. High economic risk indicates that the economic society of a country remains unstable. Meanwhile, the country's aggregate demand is full of uncertainty and is often accompanied by depressed and insufficient demand in most consumer and investment markets. An increase in economic risk could lead to insufficient investment in cobalt-related industries and insufficient consumption of cobalt-related products. In addition, economic risks could lead to exchange rate fluctuations, making the trade cost more indefinite. These reasons could lead to a decrease in the total demand for cobalt and the number of import partners. In terms of import dependence, the unstable economic environment of importers does not increase their import dependence on most import partners, and the import source risk of cobalt does not change significantly, either.

As for control variables, the growth of GDP and the total population of importers have a significant positive impact on the import dependence patterns of cobalt trade. The larger the economic scale of the importer, the more direct trade relations it has, which makes cobalt trade distances shorter. As cobalt is widely used in batteries for all types of electronics, the total population of each importer reflects the size of its demand for cobalt. Therefore, the larger the total population of an importer is, the greater the number of import partners and the total import volumes will be. Furthermore, the huge demand for cobalt encourages importers to reduce the import source risk of cobalt by reducing their import dependence on an individual country.

(2) The regression results related to exporters

For exporters, the increasing political risk has a significant negative effect on their dependence patterns of cobalt trade, which is in line with Zheng et al. (2017). An increase in political risk reduces the number of export partners, total trade volumes, and the ability to control cobalt resources, and raises the market concentration of cobalt trade. The security of resource supply is an issue that importers must consider. In general, importers prefer importing resources from countries that have a stable political environment. As cobalt is a strategic mineral resource, importers are more concerned about the geopolitical environment of the supplying countries. The increasing domestic political risk for exporters could cause their partners to switch import sources, directly resulting in a reduction in the number of export partners and total export volumes. This could lead to a concentration of export channels with the remaining export partners and increased export dependence on other countries, increasing the cobalt trade market concentration. For instance, the decline in military risk of the COD in 2015 led to a decline in political risk, which positively impacted the COD's export dependence pattern of cobalt trade. In particular, in 2015, the COD established new trade relations with countries such as Luxembourg, the United Arab Emirates, and the United States. In addition, COD's cobalt trade volumes increased by 65,700 tons, and its export dependence on China and Zambia declined significantly. As a result, the EHHI of the COD declined significantly in 2015, meaning that the country had a lower market concentration of cobalt trade than in 2014.

In addition, the increasing economic risk has a positive influence on the export dependence patterns of cobalt trade, increasing the number of export partners and the exporters' ability to control cobalt resources. For many mineral resource exporters, especially those with mining as their mainstay industry, the export of mineral resources is one of the most important sources of foreign exchange earnings and fiscal revenue. And for a few countries, it is even the main source of fiscal revenue. When a country's domestic economic environment is unstable, the government often makes necessary regulations using fiscal policy. As a result, fiscal revenue and expenditure could become an urgent consideration for the government. To a considerable degree, the government may increase the number of export partners for various mineral resources, including cobalt. This measure could support fiscal revenue, thus improving the unstable domestic economic environment.

For the control variables, GDP and total population positively impact the export dependence patterns of cobalt trade. The total population of an exporter reflects its productivity, and usually the larger the population, the greater the productive capacity. Therefore, for exporters, the higher the total population, the higher the volume of cobalt trade and the higher the number of export partners. An exporter's large cobalt trade volumes could contribute to a reduction in its export dependence on an individual country and reduce the market concentration of cobalt trade. In addition, a greater economic size of the exporter could lead to more trade dependent relations and enhance its ability to control cobalt resources.

4 CONCLUSION AND POLICY IMPLICATIONS

4.1 Conclusion

From the perspective of importers and exporters, this study deploys network indicators to reveal the dependence patterns of cobalt trade among countries, and construct diversification indices of trade relations to further analyze the import source risk and the market concentration of cobalt trade. In addition, based on the panel regression model, the impacts of country risks on the dependence patterns of cobalt trade are explored. The main conclusions are as follows.

(1) In the dependence patterns of international cobalt trade, there is a strong trade dependence between many countries. In the CIDN, most importers have a high import source risk of cobalt. Meanwhile, in the CEDN, most exporters have a high market concentration of cobalt trade. Moreover, the United Kingdom has the shortest cobalt trade distance with other countries in the CIDN. Notably, the United States and South Africa have a stronger ability to control cobalt resources than other countries in the CEDN.

(2) Changes in country risks could considerably influence the dependence patterns of cobalt trade among countries. Specifically, for cobalt importers, the increased country risks have a negative effect on the import dependence patterns of cobalt trade. An increase in political risk could reduce the number of import partners and total import volumes, and raise the import source risk of cobalt. Besides, the increased economic risk could reduce the number of import partners and the total import volumes of importers. For cobalt exporters, an increase in political risk or economic risk has different effects on export dependence patterns of cobalt trade. An increase in political risk could reduce the number of export partners, total trade volumes and the ability to control cobalt resources, and raise cobalt trade's market concentration. In addition, the increased economic risk positively impacts the export dependence patterns of cobalt trade, increasing the number of export partners and the ability to control cobalt resources.

4.2 Policy Implications

Cobalt is an essential primary raw material in industrial production, and its indispensability in battery electrodes makes it a key resource for future energy transitions. Under the background of global economic decarbonization and the scarcity of cobalt resources, we suggest that countries should pay more focus on the cobalt trade. Therefore, it is significant to figure out the dependence patterns of global cobalt trade and the role of national risks in the evolution of different dependence patterns of cobalt trade for formulating cobalt trade policies.

We suggest that cobalt importing countries establish a cobalt reserve system (Shi, 2022). The government could set up a national cobalt reserve scheme, and these reserves could be sold when domestic cobalt supplies run low. Importing countries can also encourage related producers to stockpile cobalt for commercial purposes through financial subsidies. In addition, we suggest that the government develop a cobalt resource monitoring system to track the cobalt's domestic supply (Shi, 2022). These measures could help importers reduce their import source risk of cobalt and mitigate the influence caused by country risks.

For exporting countries, we suggest that they should improve the cobalt trade cooperation system and extend their domestic cobalt industry chain. For trading partners with high cobalt demand, trade relationships could be stabilized by signing long-term resource supply agreements. Furthermore, exporters can export cobalt resources after deep processing or vigorously develop industries such as batteries and new energy vehicles. This could extend the domestic cobalt industry chain. Taking advantage of suitable production environments abroad, exporters could also expand their cobalt trade by establishing cobalt-related multinational companies and engaging in offshore production activities. These measures could reduce market concentration in the cobalt trade and reduce the impact of country risk on exporting countries.

Moreover, countries are suggested to establish cobalt recycling systems and develop new cobalt-free batteries (Zeng and Li, 2015). As the potential for cobalt recovery is enormous, cobalt recycling could be an important source of cobalt in the future (Liu W. et al., 2021). Thus, we advocate that countries should establish comprehensive battery recycling systems and develop proven recycling technologies to improve the efficiency of resource recovery (Wang and Ge, 2020). Besides, due to the scarcity of cobalt resources, the high cost of production is a bottleneck for the development of new energy vehicles. Therefore, countries with large car demand should cooperate to develop prospective and cobalt-free battery technologies.

4.3 Limitations

Due to the limitation of data, the control variables in this study only include economic scale and population. However, many factors could affect the dependence patterns of cobalt trade, such as resource endowment, geographical distance, and trade openness, which will be further investigated in our future research. Besides, cobalt is mainly used in the production of lithium batteries, and the application of lithium batteries is becoming more and more extensive. In future research, we will also consider the international trade in lithium batteries and compare the differences between the cobalt trade and the lithium battery trade.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material** further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SS: Writing–Original Draft, Data Curation, Formal analysis; QS: Conceptualization, Methodology, Writing—Review and Editing

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SUPPLEMENTARY MATERIAL

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Supply chain risks of critical metals: Sources, propagation, and responses

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In the era of globalization, industries of critical metals are organized through the global supply chain. However, the global supply chains have been disrupted since 2020 by the outbreak of COVID-19 and a series of geopolitical crises. To better address the supply chain challenges of critical metals, a review is needed about the sources, propagation, and responses of the supply chain risks. Firstly, this review provides an overview about the research progress in identifying the risk sources and assessing the risks and then proposes a new supply chain framework, categorizing relevant risk factors into upstream risks, middle-stream risks, downstream risks, and general risks, for risk analysis of critical metals. Secondly, this review offers a comprehensive understanding about how the risks propagate horizontally and vertically. Finally, responses such as supply diversification, stockpiling, material substitution, recycling and circular economy strategy, price volatility hedging, and supply chain traceability are reviewed. This survey features the supply chain perspective, overviews on network-based studies, and affirms the urgency and need for further studies on supply chain risks and resilience, which may contribute to a smooth clean energy transition.

KEYWORDS
supply chain, risk, clean energy, network, propagation, critical metals

Introduction

Critical metals usually refer to rare metals, rare disperse elements, and rare earth elements that play irreplaceable and significant roles in new energy industries—from solar photovoltaic and wind turbines to electric vehicles and battery storage (Zhai et al., 2019; IEA, 2021a). Gallium, tungsten, rare earths, bismuth, antimony, magnesium, germanium, vanadium, molybdenum, indium, tin, silver, lithium, niobium, beryllium, nickel, cobalt, chromium, platinum, and copper are recognized as the critical metals for low-carbon technologies (Wang et al., 2021a; Zuo et al., 2021). With the massive and increasing deployment of low-carbon technologies for a net zero emission society, demands for these metals have been increasing significantly and the world is moving from fuel-intensive systems to more material-intensive systems (IEA, 2021b). Against this background, it is important to review the research progress related to these metals.

Nowadays mining, refining, manufacturing, use, and waste management of critical metals are sliced and located across the world, forming various global supply chains of

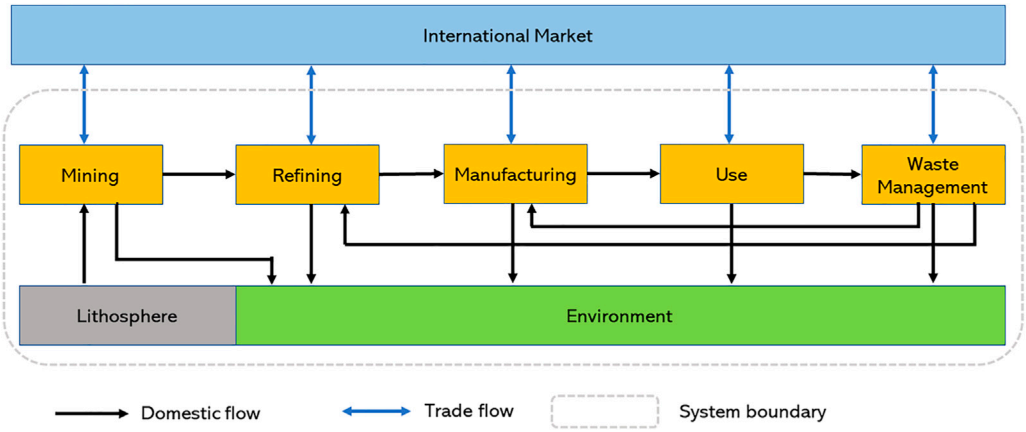

FIGURE 1
Overview of the supply chain of metals. This figure is based on the studies of Muller et al. (2014), Chen et al. (2019), Sun et al. (2019), and Di et al. (2022).

critical metals, as shown in Figure 1. In the supply chain environment, productions are interconnected, and the effective operation of one production stage depends increasingly on the normal operation of the other stages which may be located differently (Ponomarov and Holcomb, 2009). Under this circumstance, disruptions of any stage can be propagated either upstream or downstream. A resilient supply chain of critical metals is therefore of high importance to the global energy transition, which, however, experiences more and more unexpected disruptions.

Since 2020, the global pandemic has pushed governments to adopt various lockdown policies, which seriously affect the operations of global supply chains (Guan et al., 2020), which include those of critical metals. It has been reported that South Africa's lockdown disrupted 75% of the global output of platinum, and Peru's copper-mining activities ground to a halt due to its anti-pandemic policy (IEA, 2020). Besides the pandemic crisis, the global supply chains of critical metals were hit unexpectedly by the Russia–Ukraine event in 2022. Russia is responsible for 10.69% of global production of nickel and 4.4% of global production of cobalt (USGS, 2021), this geopolitical crisis made the market worry about the supply availability from Russia, and prices of nickel and cobalt have undergone high volatilities accordingly. Crises that occurred in the mining stage of the supply chain have disturbed downstream significantly. It is reported that prices of power lithium-ion batteries and electric vehicles have spiked (IEA, 2022). The pandemic crisis and frequent geopolitical events highlight that maintaining resilient supply chains of critical metals is an urgent issue to be addressed, and its related studies have become the global frontiers and hot topics (Ibn-Mohammed et al., 2021). This review aims to provide an overview on the research progress achieved in identifying and assessing supply chain risks, analyses of the propagation of risks, and responses to supply chain risks of critical metals.

Many reviews have been carried out on critical metals. Achzet and Helbig (2013) and Schrijvers et al. (2020) reviewed the methods to determine raw material criticality. Watari et al. (2020) emphasized the research progresses on the long-term outlook and sustainability of 48 metals. Wang et al. (2021a) did a review on the nexus between low-carbon energy and critical metals. Swain and Mishra (2019) summarized the various processes developed for the separation of rare earths and transition metals from secondary resources. Miao et al. (2022) provided an overview on the critical metal recycling associated with global power lithium-ion batteries. Using CiteSpace, an increasingly applied tool for scientometrics reviews, Zuo et al. (2021) and Wang et al. (2019) analyzed the research clusters, cooperation networks, and burstiness for strategic mineral resource security and resource recycling industry. Nevertheless, we currently lack a picture of the progress on the supply chain risks of critical metals. The absence of such review impedes our comprehensive understanding of supply chain resilience of critical metals, which in turn could possibly mislead the policy-decision makings for clean energy transitions. This review is related to the review by An and Li (2022) who emphasized various interactions in the industrial chains at the macro and micro levels. This review, different from theirs, focuses on the supply chain risk sources, propagation of the risks, and responses to the risks and thus makes a contribution to building a resilient supply chain of critical metals.

The remainder of this review is organized as follows: Section 2 introduces risks identification and assessment; Section 3 presents the propagation of risks in the global supply chain networks of critical metals; Section 4 discusses responses to the supply chain risks, followed by the last section of conclusion.

2 Identifying risk sources and assessing risks

2.1 Supply risks in criticality assessment

In the field of criticality assessments of metals, supply risk is a key component, as shown in Eq. 1 (Graedel et al., 2012; Graedel et al., 2015). Identifying and assessing the supply risks thus become the starting points to assess the criticality (Achzet and Helbig, 2013).

$$Raw\,material\,criticality = supply\,risk \times vulnerability \times environmental\,risk \tag{1}$$

In an overview of the raw material supply risks, Achzet and Helbig (2013) summarized that there are 20 indicators to evaluate the supply risks, namely, country concentration, country risk (social and political factors), depletion time, by-product dependency, company concentration in mining corporations, demand growth, recycling potential, substitutability, import dependence, commodity prices, exploration degree, production costs in extraction, stock keeping, market balance, mine/refinery capacity, future market capacity, investment in mining, climate change vulnerability, temporary scarcity, risk of strategic use, and abundance in the Earth's crust. Besides these conventional risks, trade risk, natural disasters, logistic restrictions, resource competition, and ore concentration are newly added indicators (Klimek et al., 2015; Hao et al., 2018; Schrijvers et al., 2020; Althaf and Babbitt, 2021). Some scholars also propose the thermodynamic rarity dimension of raw materials. That is, if a material is obtained in energy-intensive ways and is scarce in nature, it is thermodynamically rare (Calvo et al., 2018). Relevant studies using these indicators are listed in Supplementary Table S1.

Due to the various economic structures and resource endowments, different economies have adopted differentiated methods to assess supply risks. For example, in the European Commission (EC)'s supply risk assessment, the supply risk is measured as a product of supply concentration, import reliance, governance performance, trade adjusted parameter, and substitution index (European Commission, 2017; Blengini et al., 2020), as expressed by Eq. 2:

$$SR = \left[(HHI_{WGI,t})_{GS} \cdot \frac{IR}{2} + (HHI_{WGI,t})_{EU sourcing} \cdot \left(1 - \frac{IR}{2}\right) \right] \cdot (1 - \rho) \cdot SI \tag{2}$$

where SR denotes the supply risk, HHI is the Herfindahl–Hirschman Index to proxy for country concentration, WGI is the scaled World Governance Index to proxy for country governance, t is the trade adjusted parameter, GS is the global supplier countries mix, $EU sourcing$ is the actual sourcing of the supply to the European Union, IR is the import reliance, ρ is the recycling rate, and SI is the substitution index related to supply risk.

In the supply risk evaluation framework of the United States, the National Research Council identified five supply risk sources, namely, demand growth, thin markets, production concentration, by-product production, and recycling. Based on this research, the United States Department of Energy (DOE) developed a weighted index for evaluating supply risk, in which 40% is given to basic availability of metals, 20% to political, social, and regulatory factors, 20% to producer diversity, 10% to competing technology demand, and 10% to codependence to other markets. The United States framework was later developed by Graedel et al. (2012), which differs medium-term risks from long-term risks.

Low-carbon technologies have been massively deployed in China, and some of them have the largest market size in the world (e.g., electric vehicles). To develop a criticality assessment for the Chinese context, Yan et al. (2021) analyzed three types of supply risks, i.e., sustainability risk, reliance risk, and tolerance risk, in identifying the critical metals for China, as given in Eq. 3:

$$SR = SI \cdot IR \cdot (1 - \rho) \cdot HHI_{WGI} \tag{3}$$

The illustrated cases show that not all these indicators are utilized in each assessment of the supply risks. The selection of indicators depends on the goal and scope of the relevant research; accordingly, there is no unified assessment of supply risks and the lists on critical metals are varying (Helbig et al., 2021). It is noteworthy, however, that among the 26 used indicators for supply risks, country/company concentration, country risk, depletion time, by-product dependency, and demand growth are the most frequently chosen indicators for evaluating supply risks (Achzet and Helbig, 2013; Schrijvers et al., 2020). It has been pointed out by Watari et al. (2020) that demand-related risks, social and environmental risks induced by the growing demand for metals, spatial divergence, and circular economy strategies should be further studied. They also held that life cycle assessment and the input–output model are the potential tools that better monitor the supply risks, which is closely related to the supply chain concept. Therefore, it has been suggested that a supply chain perspective be adopted for analyzing the supply risks in later criticality assessments.

2.2 From supply risks of single stage to supply chain risks

From the perspective of a supply chain, the supply risks can be categorized into four groups, namely, upstream risks,

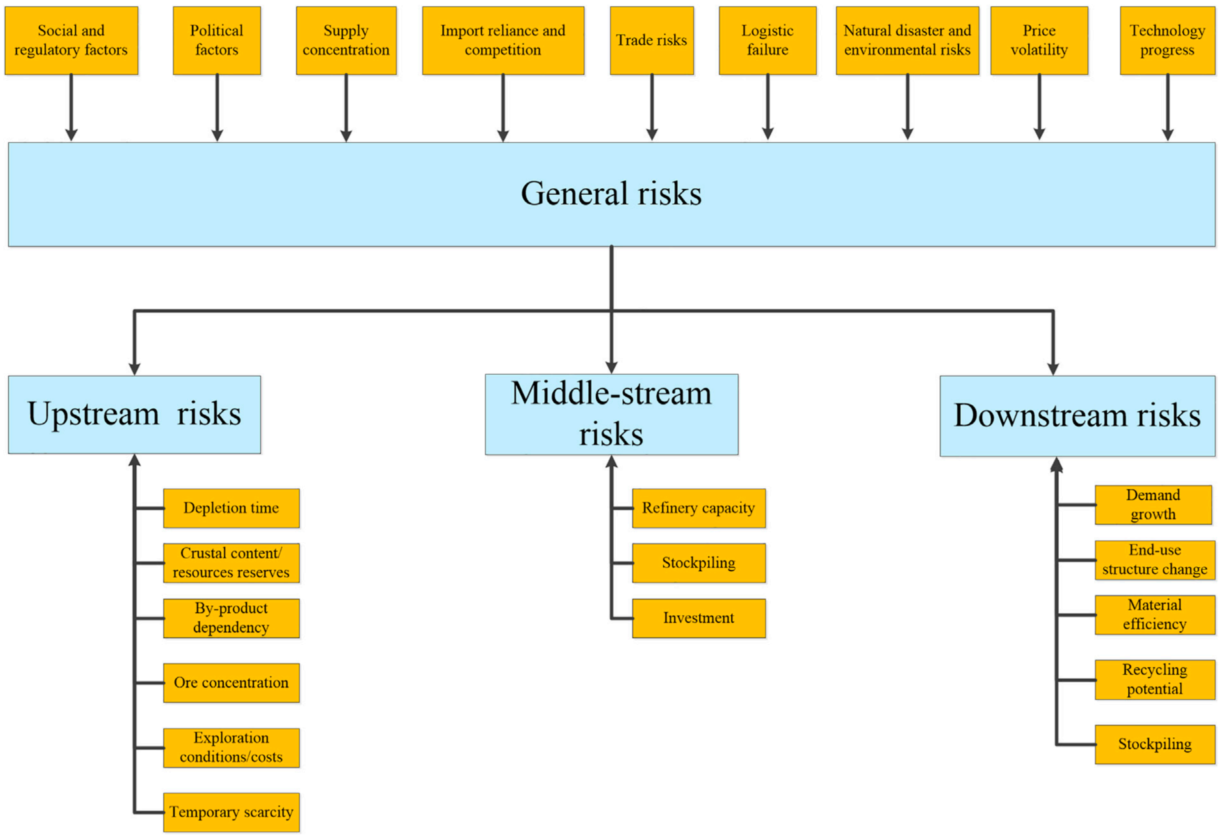

FIGURE 2
Framework for the supply chain risk assessment.

middle-stream risks, downstream risks, and general risks, as shown in Figure 2. The general risks are the disruptions that could occur at any stage of the supply chain. This perspective could provide a more holistic view about the supply chain risks of critical metals and a better understanding of the existing supply risk studies. Most existing studies on the supply risks of critical metals focus on the upstream risks, and only a few analyze the potential bottlenecks in middle-stream, downstream (Schrijvers et al., 2020), and the whole supply chain.

Shocks in the middle-stream and downstream, however, should be fully acknowledged. For the shocks to the middle-stream, the supply chain of metals is seriously affected due to China's processing role in the global production network (Dente and Hashimoto, 2020). Disruption to the downstream could be positive or negative. For example, the end-use structure change could significantly affect the supply–demand balance of materials and cause supply risks in the upstream (Zeng and Li, 2015). Recycling from the end-of-life products also deserves attention (Fu et al., 2019; Rasmussen et al., 2019). In addition, evidence shows that there are a few countries that participate in the whole chain and own global influences (Shi et al., 2022). Ignoring the potential disruptions in the key countries impedes the effective management of supply chain risks. Acknowledging these shortcomings, the European Commission exercised a double-stage supply risk assessment for the first time (Blengini et al., 2020), and van den Brink et al. (2020) examined the supply chain risks for cobalt. Yan et al. (2020) developed a supply resilience assessment framework that includes upstream and downstream factors for the Chinese lithium-ion battery industry.

There are four theoretical tools to analyze the supply chain risks. The first is the material flow analysis (MFA), which is widely used in analyzing the material cycles of metals in the anthroposphere (Muller et al., 2014). Since MFA can trace the flow volume along the whole supply chain of metals, the derived results can be used as parameter inputs (especially the trade-related factors) to the supply risk analysis and better monitor the risks. Nuss and Blengini (2018) developed a model combining criticality assessment and MFA for the European Union. Sun et al. (2020) discussed the supply chain risks for manganese. The second is the multiregional input–output (MRIO) model, which can reveal indirect risks through the input–output linkages between sectors across the world. In this context, Nansai et al. (2015) proposed a global mining risk footprint of critical metals, and Nansai et al. (2017) highlighted the role of primary processing in the supply risks of critical metals. The third one is system dynamics proposed and developed by Forrester (1994) and has been adopted for the rare earth supply chain disturbance (Sprecher et al., 2015) and tantalum supply chain risk (Mancheri et al., 2018). The last tool is complex network analysis, which is an effective and widely used tool for analyzing the interactions between the actors and structures of the resultant complex systems (Barabasi and Albert, 1999; Newman, 2003). Klimek et al. (2015) developed network-based indicators for trade risks. Based on the global copper trade network, Li et al. (2021) innovatively introduced betweenness, an indicator for reflecting the position and resource control capability of one country in the trade network, into the supply chain risk analysis.

3 Propagation of risks in global supply chain networks of critical metals

There are several terminologies for the propagation of risks in the academic literature, which include risk diffusion (Basole and Bellamy, 2014), cascading failures, ripple/domino effect (Dolgui et al., 2018), supply chain disruption propagation (Scheibe and Blackhurst, 2018), and risk contagion (Paltalidis et al., 2015). These terms may be applied in different fields. For example, risk diffusion is closely related to the epidemiological models (Zhao et al., 2018); cascading failures and ripple/domino effects are often used by scholars in complex network studies (Ash and Newth, 2007; Xia et al., 2010); and risk contagion is a widely used term related to the systemic risk studies in the financial literature (Gai and Kapadia, 2010; Elliott et al., 2014; Jackson and Pernoud, 2021). Nonetheless, the essence of these terminologies is the same, i.e., referring to the propagation of both endogenous and exogenous risks from one node to the other nodes (Basole and Bellamy, 2014) and generating an amplified impact in the system (Ojha et al., 2018). Failure nodes, propagation links, and amplified impact are three core elements for the definition of the propagation of risks. The risk/shock propagation, therefore, can be defined as the process that failure nodes amplify their impact through various channels. Trade links, input–output linkages/supply–customer relations, and price correlations are the most common propagation channels.

The global supply chains of critical metals are complex systems that contain various economic and financial connections. These connections provide various channels for shock/disruption of one node to propagate to its directly connected nodes, which then propagate their crises to the other connected nodes. This process continues until the disruption effects are absorbed totally by the chain or all the nodes in the supply chain are jeopardized. The propagation process in the global supply chain of critical metals is essentially the same as the virus-spreading phenomenon, which has been widely analyzed by network-based models (Newman, 2002; Pastor-Satorras et al., 2015). Due to trade links and price correlations being the most studied channels, this review mainly summarizes the current status of these two fields.

3.1 Propagation of shocks in single-layer trade network

Systemic trade-related risks have been widely acknowledged (Klimek et al., 2015). The resource trade network consists of nodes and links (An et al., 2014; Zhong et al., 2014). In the context of international trade, for example, if country A imports cobalt minerals from country B, then there is a link between A and B. The trade links thus provide a channel for crisis contagion (Lee et al., 2011). By constructing a trade network of critical metals and applying the network metrics, Wang et al. (2018) and Sun et al. (2022) firstly identified the systemic importance of economies for the graphite trade network and cobalt trade network, respectively. Then they established cascading failure models and analyzed the propagation processes caused by the failures of systemic importance economies. It is found that GDP and export volume affect the scope of the influence (Wang et al., 2018), and indirect links play a key role in the propagation process (Sun et al., 2022). The main contribution of these studies is that they provide a model framework to identify the propagation paths and understand the systemic impacts of epicenter economies. There are many cases where more than two materials are required to produce one good. For example, cobalt, lithium, and nickel are the necessary materials to produce lithium-ion battery and are called joint consumption products (Shammugam et al., 2019). To analyze the shock of technology progress affecting the trade of joint consumption products, Shao et al. (2022) constructed a cobalt–lithium trade network and simulated the structural changes under trade weight preference and trade country preference scenarios.

Besides the disruptions that happened in the upstream, Wu et al. (2021) designed a non-dominated sorting genetic (NSGA-II) algorithm to identify the key countries and trade relations in the stability of the lithium carbonate trade network, which enriches the understanding of potential supply risk propagation paths in the trade network of middle-stream products. As for the risk propagations in the downstream of the supply chain, disruptions spreading caused by node failure and link interruption in the lithium-ion battery trade network (Hu et al., 2021) and pandemic-related disruption contagion in the solar panel trade network (Wang et al., 2021b) have been studied and both are based on single-layer networks. All these

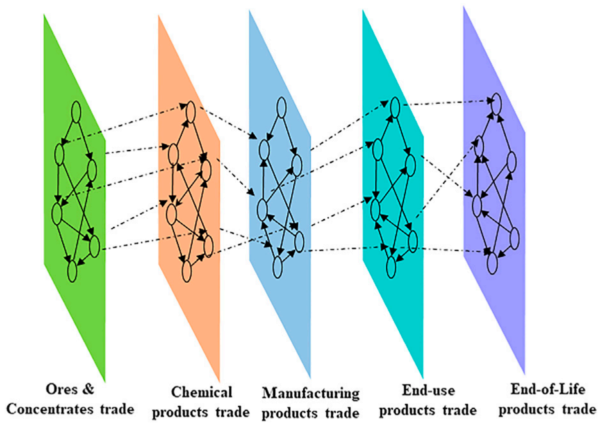

FIGURE 3
Illustrated multiplex trade network of metals.

studies only focus on the geographic disruption propagations, ignoring the propagation along the whole global supply chain.

3.2 Propagation of disruptions in multiplex trade network

From the perspective of a multiplex network, mining, refining, manufacturing, consumption of end-use products, and waste management of the supply chain are different layers (Shi et al., 2022), as illustrated in Figure 3. In each layer, countries exchange goods through international trade, forming a single-layer network. Single-layer networks connect *via* global input–output linkages, forming an interdependent multiplex network. In this interdependent multiplex network, the failure of nodes in the mining stage leads to failure of the dependent nodes in middle-stream or downstream layers, which in turn may cause further damage to the first network, leading to cascading failures and possibly catastrophic consequences (Gao et al., 2014). To design resilient supply chains of critical metals, we should understand how vulnerability is affected by such interdependences.

Through investigating the interdependencies between the copper raw materials–trading network and its waste-trading network, Hu et al. (2020) analyzed the direct and indirect impacts of China's restrictive scrap imports on the global copper multiplex network. It should be noted that their multiplex shocks model only contains two stages of the supply chain and implies research gaps for future studies. With the development of lithium-ion batteries containing high nickel elements, more attention is being paid to the supply chain of nickel. Wang et al. (2022) developed a multilayer network crisis propagation model to simulate the disruption spreading in the global nickel industry chain.

3.3 Price volatility spillover/transmission

Price volatility is also recognized as an important risk, which significantly affects the supply–demand balance, trade dependence structure (Zhao et al., 2022), investment decisions, and other sectors of the economic system (Sun et al., 2018; Sun et al., 2019). Understanding the price volatility spillovers is helpful in hedging the price risks. From the perspective of a single-layer network, price volatility spillovers are transmitted horizontally and occur at different levels, from firms, commodities, markets, sectors, countries, to time, which have been studied intensively. Guo et al. (2019) examined simultaneously the price transmissions across countries and cross products in the middle-stream of the steel industrial chain. An et al. (2020) constructed a network model and analyzed the dynamic volatility spillovers among bulk mineral commodities, such as cobalt, nickel, and copper. Li et al. (2021) analyzed the dynamic joint impacts of gold and oil prices on the copper price. These studies feature the combination of econometric modeling and network analysis. Using a firm's high-frequency data, Zheng et al. (2021) studied the asymmetric connectedness and dynamic spillovers between renewable energy and rare earth markets in China. Zhou et al. (2022) investigated the spillovers from China's rare earths stock prices to its trading partners. Considering the substitute effect of clean energy, a series of studies have been conducted to examine the spillover effects of fossil energy prices on clean energy metal prices (Shao and Zhang, 2020; Hammoudeh et al., 2021; Niu, 2021; Shao et al., 2021; Chen et al., 2022). There are also studies examining the price volatility links between the rare earth market and financial market (Reboredo and Ugolini, 2020; Bouri et al., 2021; Song et al., 2021).

From the perspective of the supply chain, price volatility is transmitted vertically. The vertical transmission can be further categorized into forward vertical transmission, backward vertical transmission, and bidirectional transmission. In a study on the dynamic relationship between primary and scrap prices, Xiarchos and Fletcher (2009) found that scrap prices do not improve the long-run interpretation of primary prices of copper, lead, and zinc, which, however, exist in the short run. In recent years, network-based transmission models are developed to reveal the sources, receptors, hubs, media, paths, and motifs of price spillovers. Related studies have been examined in the steel supply chain (Liu et al., 2019; Qi et al., 2020) and rare earth supply chain (Jia et al., 2021).

4 Responses to supply chain risks

The responses to the supply chain risks are essential to improve supply chain resilience, which is defined as "the capacity to supply enough of a given material to satisfy the demands of society, and to provide suitable alternatives if insufficient supply is available" (Sprecher et al., 2015). On the supply side, the diversity of supply and increasing stockpiling are proposed to improve supply chain resilience of critical metals; on the demand side, improving material efficiency and developing material substitution are advocated (Sprecher et al., 2015; Sprecher et al., 2017; Mancheri et al., 2018). Recycling and circular economy strategies are also widely promoted (Hua et al., 2020; Zeng and Li, 2021).

4.1 Responses on supply side

Supply diversification. More sources of raw materials are helpful in reducing damages caused by disruptions. Using rare earths as an illustrated case, with increasing alternative supplies from Australia and the United States, the HHI of rare earths has decreased from 0.68 in 2017 to 0.43 in 2019, which could potentially decrease to 0.34 (Althaf and Babbitt, 2021). This result highlights that diversifying supply could substantially reduce the risks from supply concentration. Besides expanding sources, increasing domestic mineral extraction could also effectively alleviate the supply risk of raw materials (Yan et al., 2020). Currently, the mostly advocated diversity of supply is about the diversified ores supply. It should be noted, however, that the availability of domestic mining and extraction technologies is the prerequisite for domestic production. In addition, supply diversification comes at the cost of regulatory limits, high social and environmental risks, high economic costs, etc. (Althaf and Babbitt, 2021). Furthermore, from the supply chain perspective, the supply diversification in the upstream is not enough. It is argued that investment in all stages of the chain can realize true resilience, which is unfortunately against the basic law of comparative advantages that drives globalization.

Increasing stockpiling. Stockpiling is a short term and effective tool to hedge supply disruption and price hikes (Sun et al., 2022) and can be applied to any stage of the supply chain. A critical issue of stockpiling is the feedback loop through the price mechanism (Sprecher et al., 2015). When a supply disruption occurs, emergency stockpiling by actual needs and speculation activities will drive up the demand and price, which in turn lead to pessimistic expectations about supply and more stockpiling. On the contrary, releasing inventories will increase the supply and ease the market, which in turn negatively influences the price. How does this price mechanism interact with the stockpiling behavior in the field of critical metals? There are few studies in this regard to date.

Recycling and circular economy strategy. Supply diversification and stockpiling cannot sufficiently mitigate the supply chain's risks. The supply chain is a closed loop, and in the reverse supply chain/circular value chain, old scrap/waste can be redesigned, reused, remanufactured, and recycled/urban-mined, therefore, recycling and circular economy strategy are treated as a sustainable solution to reduce the supply chain risks (Zeng and Li, 2015; Hua et al., 2020; Baars et al., 2021; Zeng and Li, 2021; Miao et al., 2022). It is estimated that there are 0.21–0.52 million tons (Mt) of lithium, 0.10–0.52 Mt of cobalt, and 0.49–2.52 Mt of nickel contained in the global end-of-life batteries (Xu et al., 2020). Using dynamic material flow analysis, Wang and Ge (2020) estimated China's urban cobalt mines could reach 78,800–186,500 tons. At the city level, the urban mines are estimated to be in the range of 300–500 kilotons from 2015 to 2050 in Hong Kong SAR of China, and the economic potential will be 2 billion US dollar each year (Kuong et al., 2019). Taking full advantage of these recycling potentials requires clear recycling targets, public education, a comprehensive recycling system at the national scale, abundant treatment capacities, mature recycling technologies, recycling-oriented design strategies, cost competitiveness, and effective fiscal incentives (He et al., 2020; Wang and Ge, 2020; Tang et al., 2021; Mao et al., 2022; Shahjalal et al., 2022). However, these are still at a very early stage in the context of the global battery industry (Tang et al., 2021; Mao et al., 2022). Global efforts are called for studying these aspects to promote the economic and sustainable recycling strategies.

Supply chain traceability. Social and environmental risks draw more and more attention, for example, the artisanal mining in the Democratic Republic of the Congo (Nkulu et al., 2018). To reduce related risks, it is suggested to establish a supply chain traceability system (Shi, 2022). Due to the advantages of decentralized control, security, traceability, and auditable time-stamped transactions (Shi and Sun, 2020; Omar et al., 2022), blockchain is proposed as a tool for supply chain traceability in the mineral industry and critical success factor for this type of tracing system are discussed (Hastig and Sodhi, 2020). Despite the benefit of high traceability, blockchain applications are energy intensive, which is against the development trend of sustainability (Jiang et al., 2021; Biswas et al., 2022). This trade-off needs more studies in the future for promoting a traceable supply chain for the metal industry.

4.2 Responses on demand side

Material substitution. Price hikes of critical metals have determining influence on material substitution (Mancheri et al., 2018). With the increasing prices of raw materials, many studies have suggested developing alternative technologies as substitutions to cope with the supply chain disruptions (Olivetti et al., 2017; Alves Dias et al., 2018; IEA, 2021a). For example, the nickel manganese cobalt (NMC) chemistry has evolved from cobalt intensive to less cobalt intensive, and the annual cobalt demand in the medium and low cobalt scenarios are 21.46 and 54.15%, respectively, lower than that in the cobalt intensive chemistry (Shi, 2022). This case shows that material substitution can reduce the supply chain risks to some extent. However, the decrease of cobalt use accompanies the increase of nickel, which in turn drives up nickel supply risks. In addition, due to the expected massive deployment of low-carbon technologies, supply strains are still there even with material substitution (Gourley et al., 2020).

Hedging price volatility. Buyers and sellers can use long-term contracts to negotiate a stable price for a specific period and stabilize profits/costs (Mancheri et al., 2018). Besides the long-term contracts, the market players are suggested to make full use of modern financial tools, such as futures and options. Establishing long-term cooperation between suppliers and customers along the supply chains and adopting integrated operation strategies are also effective ways to hedge price volatility.

5 Conclusion

To better address the supply chain challenges of critical metals in the era of frequent disturbance, this article reviews the studies on the sources, propagation, and responses of supply chain risks of critical metals. Based on the literature review on these three aspects, the following issues are proposed to be further studied in the future.

Firstly, to better identify and assess the risks in the criticality assessment of metals, there are more studies to be conducted in a new holistic framework of supply chain risks. This new framework should not only focus on the specific risks in the upstream, middle-stream, and downstream but also on general risks along the whole supply chain. Besides this conceptual framework, building a comprehensive database is required for this type of risk assessment. As for the potential direction of empirical studies, scholars could perform a holistic risk assessment for a particular metal, cobalt, for example, or they could carry out a holistic assessment for joint-metals, cobalt–lithium–nickel, for instance, or do comparison studies of risk assessments and thus better understand the criticality of the corresponding metals. The material flow analysis, multiregional input–output model, systemic dynamics, and complex network theory are potential tools to address these issues.

Secondly, the propagation of trade-related risks and price volatility are intensively examined, and we have a comprehensive understanding of how the risks propagate in a single-layer network. Nonetheless, there is still a lack of enough understanding about the supply chain vulnerability caused by the interdependences between different stages of the supply chain. In addition, the vertical transmissions of price risk, which include forward vertical transmission, backward transmission, and bidirectional transmission, should be further explored. Multiplex network could be a useful tool for these explorations. Interdisciplinary studies that combine the multiplex network, econometric modeling, multiregional analysis, etc., also deserve a try since they may provide flexible and comprehensive solutions to these issues in the future.

Thirdly, to respond effectively to the supply chain challenges, there are short-term measures like stockpiling and price hedging and long-term approaches like recycling and circular strategy. In the future, more studies should be done to investigate supply chain diversification rather than diversification of one stage. In addition, more quantitative models those include the price factor, recycling, and technological breakthrough are worthy of attention due to rapid clean energy transition and the nature of metal scarcity. As for the recycling of critical metals, studies on the cost of recycling and its influencing factors are few but deserve academic investigations. Supply chain traceability supported by blockchain has also become an emerging frontier topic. It should be noted that there are trade-offs in every response approach, which deserves more studies in the future.

Author contributions

XS: conceptualization, methodology, formal analysis, writing—original draft and revision.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.957884/full#supplementary-material

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Review of the input-output network and its application in energy and mineral industries

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Nowadays, it has become a widespread consensus to deal with global warming through carbon emission reduction among mainstream scientists in the world. As the main battlefield and main force to achieve carbon peak and carbon neutrality, the energy and mineral industries play a crucial role. At the same time, as the basic industries provide energy and raw materials, the energy and mineral industries and other industries form a complex and integrated economic system with each other through input-output correlation. It can provide scientific reference for policymakers and market investors to quantitatively reveal the overall structure of the industry and deeply analyze the role and position of energy and mineral industries in it. Combining the input-output analysis with the complex network theory, the input-output network is a set of theoretical methods with strong theory and application to describe the industrial association structure both between economies and within them, and a powerful tool for studying linked character between energy and mineral industries and related industries, carbon emission, environmental protection and so on from the perspective of physical economics. Based on document analysis, this paper introduces the concept and theoretical basis of the input-output network and energy and mineral industries, and then systematically expounds the research status of the input-output network from several dimensions such as data source, research object, and research question. Finally, the paper summarizes research methods, research objects, and application scope of the input-output network, points out the weak links, and prospects some future development directions in energy and mineral industries.

KEYWORDS
input-output network, carbon neutrality, object, question, prospect

1 Introduction

The industry is the result of the social division and the continuous development of productivity, which comes into being and develops with the emergence and development of the social division. The industrial association is one of the basic relationships in economic activities, specifically referring to the extensive, complex and close economic and technological links among various industries (Suga, 2001). Energy and mineral industries provide energy and raw materials for various economic sectors and the national defense industry, playing an important supporting role in the development of many industries such as manufacturing, construction, and chemical industry. At the same time, energy and mineral industries also need to consume a large amount of energy and mineral resources from upstream industries, which has a huge impact on energy consumption, carbon emissions, and the environment. The evidences above indicate that energy and mineral industries have high degree of industrial mutual relation. Especially under the background that it has been widely agreed by all countries in the world to cope with global warming through carbon reduction, there is important theoretical and practical significance to study scientifically the correlation between industries and reveal the role and status of energy and mineral resources.

The input-output model is mainly used to track the direct and indirect supply-demand relationship between various industrial sectors in the economic system, which has a powerful function in the calibration of the economic structure characteristics at the industrial level and the interaction with energy, mineral resources, emissions and other environmental factors (Lenzen et al., 2012; Jetashree et al., 2021; Tian et al., 2022). The concept of complex system and complex network can be traced back to the 1990s (Fan et al., 2014; Interdonato et al., 2020). Later, the complex network theory is widely applied to the field of industrial economics and resource and environmental management by the input-output network.

As a technology combining input-output analysis and complex network theory, the input-output network model is dedicated to studying the specific relationship structure (McNerney, 2009; He et al., 2017; Mundt, 2021), key industries, and industrial clusters among industries (Theodore, 2017; Piccardi et al., 2018; Giammetti et al., 2020), which plays a unique role in discussing the role of energy and mineral industries in the industrial pattern, predicting industrial development and simulating policy effects.

However, the research about the input-output network and its application in energy and mineral industries is still in its infancy. Many scholars discuss industrial association based on the idea of the complex network. Terminologies such as input-output network, industrial complex network, and industrial connection network are scattered in current literature. But there is no clear definition of its connotation, application range, and research paradigm for the input-output network. Therefore, this paper intends to review of the input-output network, and its application in energy and mineral industries, summarize research progress, and finally prospect its future development direction on this basis based on a systematic analysis of existing literature.

2 The concept connotation of input-output network and energy and mineral industries

2.1 Input-output network

The idea of industrial association can be traced back to the Economic Table, which is used to study the trade relations between industries by the founder of the French classical political economy Quesnay (1785). In 1936, Leontief established the input-output model to quantitatively describe the relationship among all industries in America, which thus became the basic method to measure industrial relation (Leontief, 1936). In 1958, Hirschman put forward the concepts of forward relation and backward relation, and applied industrial relation to the study of regional economic strategy for the first time (Hirschman, 1958), which evolved into the Hirschman Benchmark studying key industries and economic development strategy.

Traditional tools based on IO models play an important part in exploring economic structures, such as structural path analysis (SPA) and linkage analysis. SPA is about estimating the contributions of separate paths to particular sectors (Defourny and Thorbecke, 1984; Li et al., 2020; Liu et al., 2022). Linkage analysis goes one step further by studying the effect of the upstream and downstream on the entire economy (Lenzen and Murray, 2010). However, when employing these tools, few treat an economy as a complete, particular system in the IO literature (Xu and Liang, 2019).

Complex network theory developed from graph theory and network theory, which can be traced back to the Konigsberg Bridge Problem proposed by the Swiss mathematician Euler (1735) in the 18th century. Relevant concepts such as complex system and complex network appeared formally in the 1990s. These complex systems such as power network, transportation network, and so on in real life, can be modeled as complex networks. Similar to above networks, the input-output network is also the complex network, in which nodes represent industries or sectors and links represent physical production flows, money flows, or some unique relation between industries or sectors. The input-output network is not only a form of data representation, but also a means of scientific research.

The idea of using network theory to study economic structure is put forward earlier by Slater et al. (1978), who used the maximum flow minimum cut algorithm to identify production and consumption communities in the American input-output table of the year 1967. Based on the network of relatedness between products, or "product space", Hidalgo et al. (2007) studied how the structure of the product space affects a

TABLE 1 Energy and mineral industries in the main input-output data in the world.

Database	National bureau of statistics of China	WIOD	EORA26	OECD	FIGARO
Energy and mineral industries	Mining and washing of coal	Mining and quarrying	Mining and Quarrying	Mining and quarrying, energy producing products	Mining and quarrying
	Extraction of petroleum and natural gas				
	Mining and processing of metal ores			Mining and quarrying, non-energy producing products	
	Mining and processing of nonmetal and other ores			Mining support service activities	
	Processing of petroleum, coking, processing of nuclear fuel	Manufacture of coke and refined petroleum products	Petroleum, Chemical and Non-Metallic Mineral Products	Coke and refined petroleum products	Manufacture of coke and refined petroleum products
	Manuf. Of non-metallic mineral products	Manufacture of other non-metallic mineral products		Other non-metallic mineral products	Manufacture of other non-metallic mineral products
	Manufacture of metal products	Manufacture of fabricated metal products, except machinery and equipment	Metal Products	Fabricated metal products	Manufacture of fabricated metal products, except machinery and equipment
	Basic metals	Manufacture of basic metals		Basic metals	Manufacture of basic metals

country's pattern of specialization. The term "input-output network" first appeared in the report of McNerney (2009) on the economic structure of major countries in the world. Since then, terms such as industrial complex network, input-output network and industrial associated network have appeared in domestic and foreign literature, whose essence is to discuss the problem of industrial association from the perspective of the complex network (Blochl et al., 2011; Rodrigues et al., 2016; Sun et al., 2018; Yang et al., 2021).

2.2 The concept and connotation of energy and mineral industries

Energy and mineral industries refer to the related industrial sectors in which people treat nature as the object of labor to obtain natural resources, such as the coal industry, the oil industry, and the salt industry through mining and logging and other means. In this paper, energy and mineral industries can be defined in a narrow sense and a broad sense, respectively. In a narrow sense, energy and mineral industries refer to the mining, smelting, and products related to energy and mineral resources in the input-output table, which has the same basic meaning as the energy and mineral industries mentioned above, which can be thought of as its quantitative expression (Table 1). In a broad sense, it is no longer confined to the inherent classification of the input-output table, and can be the whole industrial chain covering the production, supply, storage, sales and trade of energy and mineral resources between different regions.

There list energy and mineral industries in the main input-output databases of the world in Table 1, which can be seen that it basically covers all the main industries in the upstream, midstream and downstream of the production-trade-consumption of energy and mineral resources.

As for Mining and Quarrying, different from WIOD, EORA26 and FIAGRO, it is subdivided into Mining and washing of coal, Extraction of petroleum and natural gas, Mining and processing of metal ores, Mining and processing of nonmetal and other ores in the database from the National Bureau of Statistics of China, and Mining and quarrying, energy producing products, Mining and quarrying, non-energy producing products and Mining support service activities for OECD. As to Smelting and processing, Manufacture of basic metals appears in all the databases except EORA 26. As to Products, it is subdivided into Fabricated metal products and Petroleum, Chemical and Non-Metallic Mineral Products in all databases.

3 Data sources of the input-output network

The main source of data for the input-output network is the input-output table. The input-output table, also known as the department balance sheet, is a balance sheet that reflects the relationship between industries and the balanced proportion in a certain period. As shown in Table 2, Quadrant I reflects the economic and technological linkage between industries, which is the basic part of the table and the main part of input-output

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TABLE 2 The basic pattern of the input-output table.

act	Intermediate demand	Final demand	Output
Intermediate input	I (X_{ij})	II(Y_i)	X_i
Primary input	III(N_j)		
Input	X_j		

TABLE 3 The five typical multi-regional input-output tables in the world.

Name	Compilation institution	Number of countries	Number of industries	Time sequence	Latest version
WIOD	European Union	43 (28 + 15)+RoW	56	2000–2014	2016
EXIOBASE	European Union	44 (28 + 16)+5RoW	163	1995–2011_2022	V3.8.1
EORA	Australia	189 + RoW	26–429	1990–2015	Full Eora
		189 + RoW	26	1990–2015	Eora26
OECD	OECD	66 (38 + 28)+RoW	45	1995–2018	2021
FIGARO	European Union	29 (27 + 2)+RoW	64	2010–2019	2018

network construction. Quadrant II reflects the final use of products in each industry; Quadrant III reflects the primary distribution of national income; Quadrant IV reflects the redistribution of national income, which may sometimes be omitted because the redistribution process it illustrates is incomplete.

From a regional perspective, it can be divided into global, national and regional levels for the input-output table. Input-output analysis, originally derived from the national input-output table, is a quantitative description of the economic structure of a single country. The expansion and extension of the national input-output table to other national economies is the global input-output table, while the detailed deepening of the national input-output table to regional economies is the regional input-output table, which can refer to single or multiple domestic regional economies or national economies. National input-output tables are generally compiled by national statistical offices, for example, China's National Bureau of Statistics[1] and Bureau of Economic Analysis, and the United States Department of Commerce[2] may regularly release national input-output data. Input-output tables of a single region are generally compiled and published by provincial and municipal statistical departments.

Compared with the input-output tables of a single economy, the joint input-output tables of multiple economies are particularly complex due to the addition of regional dimensions. Most of them are compiled and published by third parties based on official data of each country/region and international/inter-regional trade data (Lenzen et al., 2012; Stadler et al., 2018; Zheng et al., 2020). As an extension of interregional input-output analysis in the international field, the international input-output analysis began in the 1960s. Japan's Institute for Development Economics (IDE) first tried to compile input-output tables for six international regions, including North America, Europe, Oceania, Latin America, Asia and Japan. At present, there are five most typical international input-output databases, namely WIOD[3], EXIO[4], EORA[5], OECD[6] and FIGARO[7] (Table 3).

As mentioned above, Quadrant I of the input-output table is the core part of the table, also known as the intermediate matrix, where the detailed breakdown of production (consumption) sectors is listed. The industry sector or product classification standards of the intermediate matrix are mainly taken from the fourth edition of the International Standard Industry Classification of All Economic Activities (ISIC) or its derivatives. The ISIC is an international benchmark classification of productive economic activities whose main purpose is to provide a set of activity categories that can be used to compile statistics on such activities. Since the first edition of ISIC is adopted in 1948, most countries in the world have

1 https://data.stats.gov.cn/easyquery.htm?cn=C01
2 https://www.bea.gov/industry/input-output-accounts-data
3 https://www.rug.nl/ggdc/valuechain/wiod/
4 https://www.exiobase.eu/
5 https://www.worldmrio.com/
6 https://www.oecd.org/sti/ind/inter-country-input-output-tables.htm
7 https://ec.europa.eu/eurostat/web/experimental-statistics/figaro

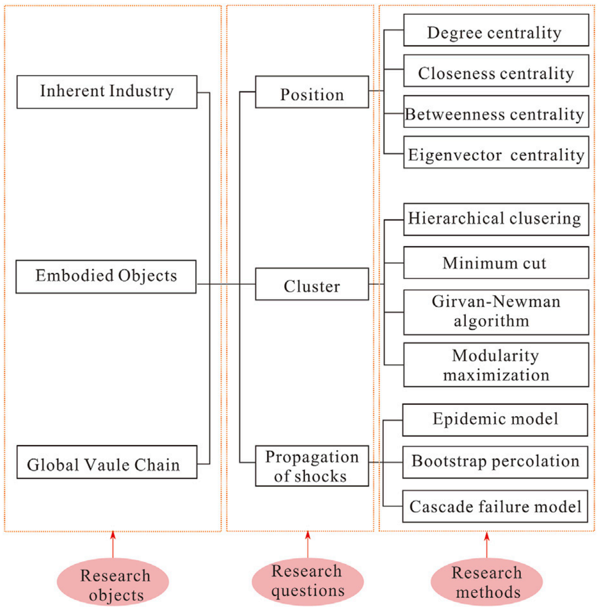

FIGURE 1
Research objects, questions and methods of the input-output network.

adopted The ISIC or formulated their own national classifications based on the ISIC.

It is worth mentioning that major databases also publish satellite accounts of input-output data, covering socio-economic and environmental accounting data. Socioeconomic accounts generally include data on employment, capital stock, total output and addedvalue in relevant industries in each country. The environmental account provides data on industrial energy consumption, land use, material consumption, carbon emissions, and atmospheric emissions. Satellite accounts provide researchers with a unique tool to analyze the socio-economic situation and the environmental impact of economic activities from an industrial perspective.

4 Research status analysis

4.1 Research objects

Through the screening and comprehensive analysis of relevant literature, it is found that the relevant research objects of the input-output network at home and abroad are mainly divided into three categories, namely the inherent industries in the input-output table, embodied objects, and global value chain (Figure 1). Note that the application of input-output network in the field of energy and minerals mainly focuses on the analysis of embodied objects, which will be discussed in Section 4.3.

4.1.1 Inherent industries in the input-output table

The inherent industry sectors in the input-output table are the initial research objects of the input-output network. Researchers use input-output data to construct a complex network with the industry as the point and the input-output relationship as the edge, and analyze the network topology and even the temporal evolution characteristics based on concepts such as degree distribution, weight distribution, and network path length. James et al. (2013) discussed the characteristics of industrial association of 45 economies by the OECD database, and found that edge weight of input-output network follows typical Weibull distribution, and industry size follows exponential distribution. Liang et al. (2016) expanded the index analysis range of point degree and edge weight in the input-output network (total output, final demand and added value, etc.), and further tested the influence of different input-output data selection on the scale characteristics of the input-output network.

At the same time, many scholars directly use the input-output network model to identify key industries and industrial communities, and discuss the transmission mechanism of risk shock among industries. Blochl et al. (2011) selected and compared the key industries of each country in the OCED database by random walk centrality and counting betweenness. Cerina et al. (2015) identified industrial communities worldwide by the WIOD database, and found that the division of communities was still based on countries or geography as the main dividing factor. There were two large groups in the world production system, the European group and the North American group, with Germany as the core (countries in the Far East were temporarily absent). Wang et al. (2021) constructed multiple input-output networks from 2007 to 2012 for the selection of key industries and associations by China's multi-regional input-output table, and found that the provinces covered by industrial associations were less and less, while the key industries were mostly distributed in Guangdong Province, Jiangsu Province and many other coastal provinces in Southeast China.

4.1.2 Global value chain

Global value chain is one of the recent research hotspots in the field of the input-output network. In recent years, the progress of science and technology and the reduction of trade barriers have promoted the formation of the global value chain (Gereffi et al., 2005; Grossman and Rossi-Hansberg, 2008). Nowadays, the global value chain has covered most economies in the world and become a link connecting the economies of all countries in the world. Its development has brought unprecedented development opportunities and challenges to all participants in the global value chain.

At present, the research of global value chain mainly focuses on two aspects: value chain accounting and the impact of global value chain on industrial economy. The input-output model can clearly reflect the relationship between production and consumption of products in various countries or regions and among various departments by the checkerboard pattern, and is currently the mainstream tool for tracking product flow and global value chain (Piccardi et al., 2018). Los et al. (2015) constructed an input-output model based on the global multi-regional input-output table from 1995 to 2011, and found that the value chain was increasingly internationalized except for the temporary pause caused by the 2008 financial crisis. Johnson and Noguera (2012) provided a method using input–output and trade data to compute bilateral trade in value added, and verified there are significant differences between value added and gross trade flows. Antras et al. (2012) put forward an indicator to measure the industry "upstreamness" (or. average distance from final use), which is an industry-level measure of relative production-line position. Xing et al. (2021) built a global industrial value chain network model by the international input-output data, and analyzed the correlation, hierarchy, and robustness of economic development indicators and system structure measurement indicators of countries or regions from the perspective of physics and economics. The functions and positions of economies in global value chain were discussed from national, inter-national and international levels.

The development and spatial-temporal evolution of global value chain directly promote the continuous growth of industrial transfer, thereby affecting industry upgrading. Tian et al. (2019) proposed a different approach including eight indicators in factor analysis to examine the multidimensionality of industrial upgrading. A group of scholars believe that the global value chain specialization could reduce production costs, improves productivity, and then promoted industrial upgrading (Bhagwati et al., 2004; Baldwin and Robert-Nicoud, 2014; McWilliam et al., 2020).

4.2 Research questions and methods

The research about the input-output network focuses on the identification of industrial position, the selection of industrial clusters, and the propagation mechanism of shocks in the network (Figure 1). The input-output network mainly conducts correlation and hierarchical analysis of economic development indicators and system structure measurement indicators from the perspective of econophysics. Its ideological core is the complex network theory, so its main research issues are similar to those of mainstream complex networks.

4.2.1 The position of industry

The identification of industrial position is one of the most primitive and nuclear research problems in the input-output network. The input-output network is a typical heterogeneous network with scale-free characteristics. Different nodes and links play different roles in network propagation, and key nodes have more influence on network structure and information transmission than other nodes (Zhou et al., 2019; Jiang and Wang, 2020).

Intuitively, the closer you are to the center of the network, the more important the node is, which is called node centrality. The main indexes to measure node centrality in the network include degree centrality (Sigler et al., 2021; Li et al., 2022), closeness centrality (Dekker, 2005), betweenness centrality (Stolz and Schlereth, 2021), and eigenvector centrality (Figure 1).

4.2.2 The cluster of industry

The cluster of industry is another major hotspot in the field of input-output networks coupled with the identification of industrial position. Nodes in the complex network tend to form clusters and exhibit cluster characteristics. The existence of cluster structure also reflects the heterogeneity of the complex network. It is generally believed that the connections between nodes within a cluster are relatively dense, while the connections between nodes in different clusters are relatively sparse (Leicht and Newman, 2008; Chen et al., 2009; Li et al., 2013). At present, there are four kinds of mainstream algorithms, i.e. Hierarchical clustering (Defays, 1977), Minimum cut (Newman, 2004), Girvan-Newman algorithm (Girvan and Newman, 2002), and Modularity maximization (Newman, 2004) for cluster selection.

In recent years, scholars often start with the structural attributes of input-output networks, study industrial position and industrial clusters simultaneously, and explore the correlation between industries (Theodore, 2017; Wang et al., 2021). In terms of time and space, with the enrichment of input-output data and the improvement of input-output data in multiple regions, relevant research has also developed from the original single-year and single-region research to multi-year and multi-region research (Cerina et al., 2015; Piccardi et al., 2018; Xu and Liang, 2019).

4.2.3 Propagation of industry

Propagation of industry belongs to the category of complex network dynamics and is an extension of network topology. Since being introduced into the input-output network, it has attracted great attention immediately. With the rapid development of economic globalization and network information technology, the dependence and restriction relationship between industries continuously strengthen, and the world's economies form an inseparable network relying on their respective crisscrossed industries. The disturbance of economic shock to industrial sectors will produce a butterfly effect, which will have a profound impact on the global economic system. Therefore, research on the propagation path and dynamic mechanism of shocks in the input-output network is the basis for effective risk control, and the establishment of an appropriate transmission model can accurately predict economic development and simulate policy effects. At present, network dynamic models are effective in simulating the chain reaction of potential supply risks, such as the epidemic model, bootstrap percolation, and cascade failure model (Figure 1).

The research on the impact of shocks on the economic system is mainly qualitative in the early stage, and the research questions mainly focus on whether micro-impact from specific industrial sectors can lead to significant total fluctuation in the economic system. Initially, the conventional wisdom in macroeconomics was that when aggregate output was concentrated around its mean, particular shocks would dissipate quickly and have a significant effect on the economic system. With the introduction of the input-output model, especially the complex network theory, the majority of scholars have demonstrated that the micro impact will have a significant impact on the entire economic system by building models between the structure of various industrial networks and aggregate fluctuation (Carvalho, 2009; Acemoglu et al., 2012; Harvey and O'Neale, 2020).

With the development of complex network theory, it is possible to explore the relationship between micro shock and aggregate fluctuation in a semi-quantitative or even quantitative way. The construction of the complex network model and the setting of network indicators can quantify the contribution of shocks to the total output volatility of specific industries (Ando, 2014) and measure the propagation of shocks (Li et al., 2014; Grazzini and Spelta, 2015), and the process of long-term and short-term diffusion effects of industrial sectors (Xing et al., 2016). Later, based on previous qualitative and quantitative studies, scholars begin to explore the influencing factors of the transmission range of micro shocks (Contreras and Fagiolo, 2014), and the reasons for the changes in the vulnerability of the economic system to microshocks (Distefano et al., 2018). Further, the macroeconomic impact of microeconomic shocks is decomposed into pure technological effect and allocative efficiency effect (Baqaee and Farhi, 2020).

4.3 Application of input-output network in energy and mineral resources

In recent years, with the occurrence of the global issues such as ecological imbalance, environmental pollution, and resource shortage, the research objects of the input-output network gradually expand from the inherent industries to resources and environment, namely embodied objects.

4.3.1 Embodied objects

Embodied objects in this paper specifically contain embodied energy, embodied minerals, embodied emissions and embodied water, etc. (Table 4), corresponding to the satellite account in the input-output table mentioned in Section 3. Embodied analysis, derived from the embodied energy first proposed at the 1974 Meeting of the International Federation of Advanced Research Institutions (IFIAS) Energy Analysis Working Group, refers to the total amount of direct and indirect resource consumption or pollution emissions and labor occupation in the production of goods or services (IFIAS, 1974; Brown and Herendeen, 1996). The accounting of embodied objects, which covers all historical information of products or services from producer to consumer, can provide a more systematic perspective for the economic accounting of various industrial sectors (Baral and Bakshi, 2010; Duarte et al., 2018).

4.3.2 Data

The extended input-output model is the mainstream method of embodied accounting from a macro point of view. The extended input-output table is the basis of embodied analysis based on the complex network. In the development of the extended input-output table, environmental factors can be directly included in the input-output table as a separate production industry (Leontief, 1970). More often, the associated effects of various production activities in the input-output table can be calculated by building the extended input-output table with the associated coefficients (such as CO_2 emission intensity, resource consumption intensity, etc.). Relevant studies are summarized in Table 4. Currently, satellite accounts of the major input-output databases now contain a growing variety of objects. For example, EXIOBASE alone contains five types of carbon emissions, 2 types of hidden water, and 4 types of substance use lists. Moreover, they are all multi-region input-output models.

4.3.3 Methods

The emission/consumption intensity of embodied objects is shown as Eq. 1

$$q = h(\hat{x})^{-1}(I - A)^{-1} \quad (1)$$

Where, the column vector x refers to the total output of each sector. The row vector h refers to the satellite account row vector of total emission/consumption of each sector. The hat () refers to diagonalizing the vector. $(I - A)^{-1}$ refers to the Leontief inverse, it means the sector output driven by a unit of terminal consumption.

The flow of embodied objects between industrial sectors is expressed in Eq. 2

$$E_{ij} = q_i{}^{*} x_{ij} \quad (2)$$

Where, q_i refers to the emission/consumption intensity of embodied objects in the sector i. x_{ij} refers to the input from sector i to sector j.

A complex network consists of nodes and edges that link the nodes, as in Eq. 3

$$G = (N, E) \quad (3)$$

Where, G represents a complex network. N denotes the set of nodes in the network. E represents the set of edges in the network. An

TABLE 4 Summaries of related research on the.

Research perspectives	Research objects	References
Climatic environment	Carbon emission	Wiebe et al., 2012; Chen and Chen, 2013; Jiang et al., 2019a; Jiang et al., 2019b; Lv et al., 2019; Ma et al., 2019
	PM 2.5	Wang et al., 2017b; Gao et al., 2020; Yang et al., 2018
Natural resources	Energy	Chen et al., 2018; Chen and Chen, 2013; Xia et al., 2016
	Minerals	Jiang et al., 2018; Liang et al., 2020; Wang et al., 2017a; Wang et al., 2019; Zhang et al., 2022
	Water	Chen et al., 2012; Distefano et al., 2018; Yang et al., 2021
Social economy	Global value chain	Piccardi et al., 2018; Xing et al., 2021

element E_{ij} of matrix E indicates the direct and indirect input from sector i to sector j required to produce unitary output of sector j.

4.3.4 Hotspots

Carbon emission is one of the most important hotspots in the field of embodied analysis. The greenhouse effect caused by carbon emission is a global environmental problem that hinders the sustainable development of the human economy and society. The transfer of carbon emissions in quantified trade has become a topic of widespread concern in academia and the public. The environmental extended input-output method can be used to quantitatively divide the actual place where carbon emission is generated and the final consumption place that drives carbon emission (Wiebe et al., 2012). Scholars combine the complex network theory with the input-output analysis to build a hybrid network model of interregional carbon flow. Based on quantifying direct and embodied carbon emission, the main processes and key industries of trans-regional carbon transfer can be determined (Chen, 2016; Lv et al., 2019). Identify the role of countries in the process of carbon transfer (Jiang et al., 2019b), and then discuss its driving factors (Jiang et al., 2019a). If multiple years of data are available, multiple embodied carbon emission networks can be constructed to explore their temporal structure characteristics and key industries (Ma et al., 2019).

At the same time, based on the extended input-output table, a large number of scholars also use the input-output method and the complex network theory to target $PM_{2.5}$ (Wang et al., 2017b; Yang et al., 2018; Gao et al., 2020), energy (Chen and Chen, 2013; Xia et al., 2016; Chen et al., 2018), minerals (Wang et al., 2017a; Jiang et al., 2018; Wang et al., 2019; Liang et al., 2020; Zhang et al., 2022), water (Chen et al., 2012; Distefano et al., 2018; Yang et al., 2021), and so on (Table 4). Research orientations mainly focus on the discussion of network structure and the identification of key industries and industrial communities as well as the driving mechanism.

5 Summary and prospect

This paper draws the following conclusions by clarifying the existing literature:

(1) In terms of application scope, previous scholars first directly used the single-regional input-output (SRIO) model for research work, such as the national input-output table and provincial input-output table. Later, the multi-regional input-output (MRIO) model came into being and was more widely used in the study of cross-border trade and related issues. However, all countries in the world have different degrees of spatial differences. Such differences not only come from differences in natural endowments and geographical conditions of different regions within a country, but also differences in development level and industrial structure. The existing multi-regional input-output tables are mostly input-output databases between countries, which are weak in decomposition and extension at the provincial level. As a result, it is easy to ignore the heterogeneity of provinces in the target country in terms of economic endowment, geographical location, development stage, and industrial structure. Therefore, the decomposition and extension of the existing multi-regional input-output table to the sub-regional level are one of the preconditions to expanding the input-output network research work in the future.

(2) In terms of research objects, previous studies may be implemented to explore network attributes and industry associations from the perspectives of the whole industry pattern, or just a single industry in the input-output table, such as manufacturing, finance, construction, or embodied objects (embodied energy, embodied mineral, embedded emissions). But overall, research objects of the input-output network are still relatively limited, such as the implications of GVC for energy and materials sectors, footprint family. Therefore, there is a lot of space to explore both the inherent industries in the input-output table and the objects in the extended input-output table.

(3) In terms of research methods, the input-output network initially focuses on the mining of key industries and industrial communities in economic networks, and then use the information transmission

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model in the complex network to discuss the transmission process and dynamic mechanism of shocks. However, complex network theory is something broad and profound, and a large number of related models and analytical techniques (such as degree rank, path search, robustness, machine learning, transmission dynamics, etc.) are not fully applied to the study of the social and economic system. Meanwhile, to mine the economic implications of such dense weighted and directed networks, many algorithms also need to be improved combined with the practical significance to the research of the social economic system thought and method.

(4) In terms of energy and mineral industries, the current research mainly focuses on energy and a few mineral resources such as rare earth, etc. For critical energy minerals and bulk minerals such as iron, copper, and aluminum, the research efforts are relatively weak either because of the difficulty of obtaining data or the lack of attention. In addition, research on the role and status of the inherent energy and mineral industries in the input-output table, such as mining, smelting, and products industry, as well as the temporal evolution characteristics of the regional and even global industrial pattern, also needs to attract people's attention.

Since the emergence of the input-output network, research methods, research objects, and application scope have been greatly expanded, but it is still in the initial stage on the whole. The future research on the input-output network may have more research objects, more diverse research methods, and more applications.

Author contributions

LW and LJ contributed to the conception and design of the study. HM provided the method and LW completed the first draft of the manuscript. LJ and WB contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Tracing of lithium supply and demand bottleneck in China's new energy vehicle industry —Based on the chart of lithium flow

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With the rapid development of China's new energy vehicle industry, the supply security of lithium resources is crucial. To ensure the healthy development of the new energy vehicle industry and the security of supply of key mineral resources, it is necessary to accurately determine the supply and demand pressure of lithium resources and their sources. This study analyzes the lithium stock and flow at the end of the new energy vehicle chain by constructing a material flow analysis framework for the new energy vehicle industry and compiling a lithium resource flow table for the new energy vehicle industry, and the results show that 1) the supply and demand pressure on lithium resources in China is increasing year by year, and the external dependence of lithium resources has reached 75% in 2019; 2) China's domestic lithium battery production and consumption accounted for nearly 70% of the lithium consumption in various industries, of which 60% of the lithium batteries were assembled on new energy vehicles, and the net outflow of lithium exceeded more than the lithium consumption of new energy vehicles in 2019. The lithium consumption of new energy vehicles was more than five times that of the previous year. Insufficient supply of domestic lithium ore, lithium inventory, and import and export are the key reasons for the pressure on lithium supply and demand in the new energy vehicle industry; 3) By the end of 2019, the cumulative scrap lithium batteries in new energy vehicles contain about 10,000 tons. The lithium accumulated in new energy vehicles has 26,500 tons. These results provide a theoretical basis for policy recommendations to ensure the healthy development of the new energy vehicle industry and to promote international cooperation in the development, utilization, and recycling of lithium resources.

KEYWORDS

new energy vehicles, lithium battery, the chart of lithium flow, material flow, lithium supply and demand bottleneck

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1 Introduction

As one of the most important strategic emerging minerals, lithium is widely used in battery energy storage, glass ceramics, grease, air treatment, metallurgy, medicine, and other fields. It is a key industrial raw material for the current and future (Xing et al., 2015). Due to the rapid development of the new energy vehicle industry, the high dependence of lithium-ion batteries on lithium resources has further accelerated the development of lithium resources. According to the statistics of the Lithium Industry Branch of the China Nonferrous Metals Association and related research institutions, the global lithium demand from 2015 to 2019 increased from 162 thousand tons to 297 thousand tons, with an average annual growth rate of 16.4%. However, the global lithium resources are relatively limited. As of 2020, the global lithium ore reserves are estimated to be 128.28 million tons (lithium carbonate equivalent), which are mainly distributed in Argentina, Bolivia, Chile, Australia, China, and other countries. China's lithium ore reserves are 8.1 million tons (lithium carbonate equivalent), accounting for 6.31% of the world (Wang et al., 2021).

China is the world's largest producer and seller of new energy vehicles and a consumer of lithium resources. In 2020, sales of new energy vehicles will reach 1.367 million units, accounting for 42% of global sales. In 2019, China's lithium resource consumption was 186 thousand tons (LCE) (Dai et al., 2019), which accounted for 60% of global lithium resource consumption. Although China's lithium resources are relatively abundant, there are problems such as poor resource quality and difficult development. The current development scale of lithium resources is not large and relies heavily on imports (Ju and Zhao, 2018). According to the "New Energy Vehicle Industry Development Plan (2021–2035)," the sales of new energy vehicles in China will account for about 20% of the total sales of new vehicles by 2025. With the continuous improvement of global status, the demand for lithium resources will increase sharply in the future development of the new energy vehicle industry. In the post-epidemic era, global uncertainty and instability have further increased, and China's lithium resource supply may face greater uncertainty in the future. In order to actively respond to the supply and demand risks of lithium resources, it is currently necessary to accurately grasp the sources and causes of lithium supply and demand pressures in the new energy vehicle industry.

In recent years, material flow analysis methods have been applied in the fields of emerging mineral resources such as lithium, cobalt, nickel, indium, rare Earth elements, etc.(Liu et al., 2021). This method has played an important role in the analysis of international trade, consumption space, waste recycling, and environmental impact of emerging minerals (Shinkuma and Nguyen Thi Minh, 2009). Saskia Ziemann and others established the first global lithium flow model including production, manufacturing, and use, which laid the foundation for later lithium flow analysis (Ziemann et al., 2012; Ziemann et al., 2018a; Ziemann et al., 2018b). At present, the research on lithium material flow has covered the world, various regions, and countries, and the research methods include static material flow, dynamic material flow, element material flow, mixed model including material flow analysis, etc. However, most studies are still based on the traditional bulk mineral material flow analysis framework to examine the material flow of emerging minerals. In contrast, there will be a certain amount of loss in the process of lithium resources from mining, processing into raw materials, and then entering commodities. The material flow analysis results based on bulk minerals cannot accurately describe the real lithium flow in the new energy vehicle industry. In addition, due to the high price, small volume, speculative, and other characteristics of lithium, the lithium resources and lithium raw materials that are mined and refined at a certain time cannot be completely consumed at that time. But most of the current research did not take into account the analysis of lithium inventories and lithium losses. At present, new energy vehicles have gradually grown into the largest application field of lithium batteries, and new energy vehicles have also become key areas of lithium material flow research. Rapid development and its high dependence on lithium batteries will accelerate the consumption of lithium resources (Hao et al., 2017), and the spatial distribution of lithium resources and international trade will lead to lithium supply and demand risks (Hu et al., 2021). However, in these studies new energy vehicles are only one part of the lithium material flow (Richa et al., 2014), and they do not consider the lithium flow in the whole industry chain of new energy vehicles (Univ et al., 2016; Shafique et al., 2022), nor can they describe the changes and risks (Chang et al., 2009; Gaines, 2014; Song et al., 2019) of lithium material flow caused by changes in new energy vehicles. Although dynamic material flow analysis can analyze the material flow in the system at different times, and can also realize the connection of material flow within the system at the same time, it is still difficult to solve the connection and comparison of material flow between time and systems. Therefore, from the perspective of three-dimensional chain, time, and space, this paper constructs the lithium flow analysis framework of the new energy automobile industry, compiles the dynamic lithium flow table of the new energy automobile industry, and sorts out the stock and flow of lithium resources at each chain end of the new energy automobile industry, analyzes the key sources of lithium supply and demand pressure in the new energy vehicle industry, and provides reference for the compilation of other key mineral resource flow tables.

2 Methodology of material flow analysis and framework

Material Flow Analysis (MFA) follows the law of conservation of mass, analyzes the flow of materials by linking resources, paths, intermediate processes, and the final destination of materials, and traces the source and path of material flow in a

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specific system and sinks (Islam and Huda, 2019). As an important tool for material management analysis (Brunner and Rechberger, 2016), MFA has been widely used in the fields of resource management, waste management, environmental management, and sustainable development (Kiddee et al., 2013). Material flow analysis methods can be divided into two categories: material flow analysis of economic system and element flow analysis. Material flow analysis of economic system is the study of the total amount and structure of matter in a system within a certain time and space range, regardless of the internal material flow and element flow in the system. The research object of the analysis is a specific element, monomer or compound. Based on the law of conservation of mass, it tracks and investigates the material flow trajectory in a certain space-time system, and then obtains data on the circulation and waste discharge of each link during the flow of the material throughout its life cycle. A large number of studies have successfully examined the material flows of bulk minerals such as steel (Davis et al., 2007; Park et al., 2011; Pauliuk et al., 2012), copper (Gloser et al., 2013; Wang et al., 2018), aluminum (Chen et al., 2008; McMillan et al., 2010; Liu and Muller, 2013) and zinc (Meylan and Reck, 2017) in various countries around the world using material flow analysis methods (Sun et al., 2019).

2.1 Scope of the study

New energy vehicles are powered by unconventional energy. Lithium batteries are divided into two categories: primary lithium batteries and secondary lithium batteries. Secondary lithium batteries include lithium-ion batteries and all-solid-state lithium batteries. Lithium-ion batteries are composed of positive electrode materials, negative electrode materials, electrolytes, diaphragm, and auxiliary materials such as ultra-thin copper foil and aluminum foil. The positive electrode materials mainly include lithium cobaltate, lithium manganate, lithium nickelate, ternary materials (lithium nickel manganese cobalt) and lithium iron phosphate, the negative electrode materials are mainly graphite, graphitic fiber materials, etc., and the electrolyte is composed of solvent, lithium salt (LiFL6), and additives. The new energy vehicles mentioned in this study are electric vehicles equipped with lithium-ion batteries, and three types of new energy vehicles are selected as pure electric vehicles, hybrid electric vehicles, and fuel cell electric vehicles. The spatial boundaries of the system are defined as China and outside China. Although new energy vehicles have been promoted and used in China since this century, it was not until 2012 that China's new energy vehicle production and sales exceeded 10,000 units, and only after 2014 did they begin to be developed on a large scale. Due to the limitation of data availability, the time boundary was chosen to be 2014–2019. In this paper, new energy vehicles are composed of plug-in hybrid electric passenger cars, plug-in hybrid electric special vehicles, pure electric passenger cars, pure electric special vehicles, and fuel cell vehicles. The battery is composed of lithium iron phosphate lithium battery, lithium manganate lithium battery, lithium cobalt oxide lithium battery, and ternary material lithium battery.

2.2 Analytical framework for lithium flow

2.2.1 Lithium material flow in the new energy vehicle industry

In this study, the lithium material flow in the new energy industry chain was analyzed based on the element flow analysis method. The new energy vehicle industry is a collection of economic activities carried out around the design, research and development, production, sales, maintenance and repair, scrap and dismantling of new energy vehicles. The focus of the research is to analyze the production (consumption) links directly related to lithium resources in the new energy vehicle industry chain. The new energy vehicle industry chain is centered on the manufacture of new energy vehicles, and the upper end includes lithium battery production, lithium raw material mining and extraction, lithium battery material production, and other links, the lower end of the new energy vehicle use, scrap, recycling, and other links. According to the flow process and important links of lithium element in the new energy vehicle industry chain, the new energy vehicle industry chain is divided as follows (see Figure 1 for details).

2.2.2 Lithium flow meter for the new energy vehicle industry

The lithium material flow of the new energy vehicle industry has three attributes of chain, time, and space. "Lithium" can flow along the three dimensions of chain, time, and space. From the perspective of the entire life cycle of the industry, "lithium" flows in sequence following the industrial chain, and the flow of lithium is one-way and cyclic. From the perspective of time, the new energy vehicle industry chain needs to span different periods. Generally speaking, lithium mineral mining, lithium raw material production, lithium battery material production, lithium battery production, and even new energy vehicle manufacturing can be completed within the same period. The consumption of energy vehicles and the reuse of retired lithium batteries take a very long time, and the time required for the recycling, dismantling, and recycling of lithium resources of scrapped lithium batteries is also relatively long. From a spatial point of view, the lithium material flow in the new energy vehicle industry involves the country (region) and other countries (regions), and can be divided into two categories: domestic and foreign. The inflow of lithium from the foreign new energy vehicle industry to China is lithium import. On the contrary, it is lithium export.

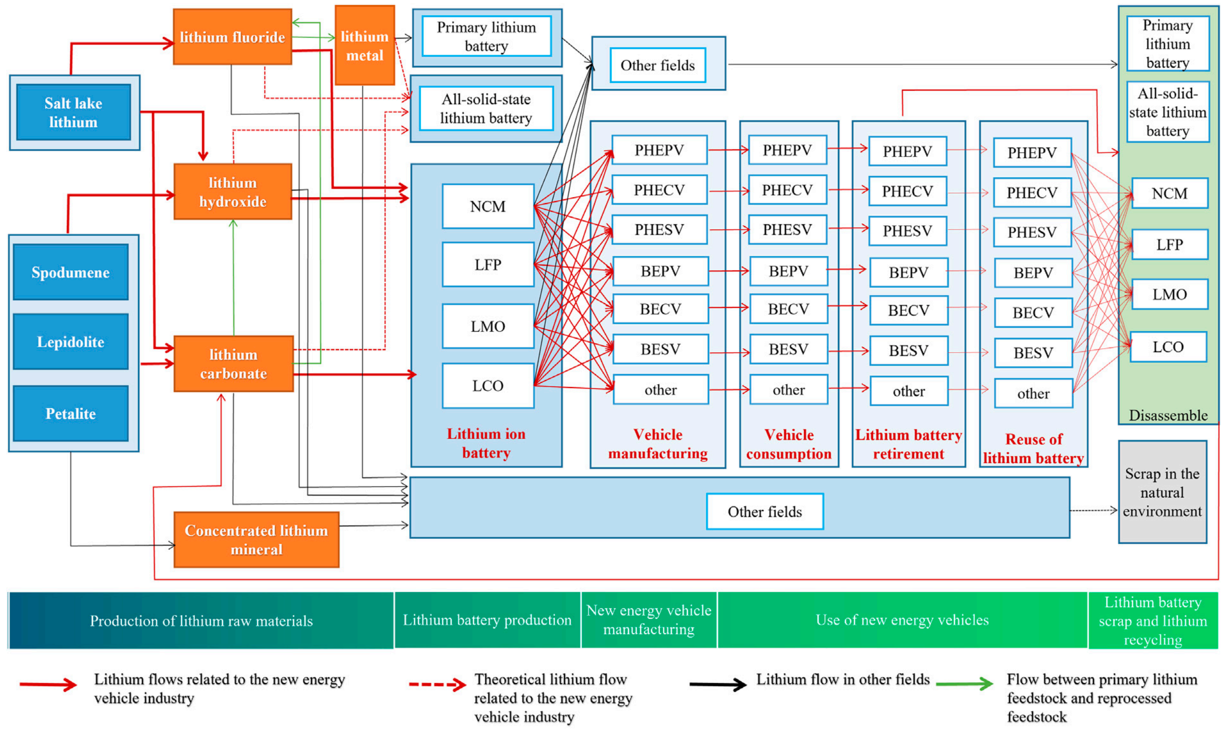

FIGURE 1
"Lithium" flow under the new energy vehicle industry chain.

Lithium-containing brine in salt lakes is bulky and difficult to transport. Brine cannot flow between countries. Scrap lithium batteries have potential environmental risks, and scrap lithium batteries should not flow between countries. The "lithium" (materials, products) in the production raw materials of a certain link in the domestic new energy automobile industry chain added the "lithium inventory" and "lithium import" that flowed in the previous cycle minus the "lithium export", are the "lithium" stock on the link in this country.

In a certain period (usually 1 year), the lithium stock at the end of a certain industrial chain of new energy vehicles in the country may not all enter the next production stage, and the difference is the inventory, which will flow into the industrial chain of the next period and even other periods. Although lithium has inter-period lithium flow (stock) in various industries of new energy vehicles, generally speaking, the lithium stock of new energy vehicle manufacturing and its previous industrial chains in a certain period is not much different, and the lithium stock at each chain end is also not much. In comparison, there are more lithium stocks at the consumption end of new energy vehicles involved in a certain period (including the retirement and reuse of assembled lithium batteries), and the lithium stocks at this time include the lithium stocks on all new energy vehicles that are still in consumption and use. The same is true for the lithium stock at the scrap and recycling end of lithium batteries, which involves the lithium on all lithium batteries scrapped from new energy vehicles. To sum up, the lithium flow of the new energy vehicle industry in a certain period not only includes the sequential flow of the lithium stock in the production link of the new energy vehicle in the current period, but also includes the lithium stock of all the new energy vehicles in use during this period, that is, the lithium stock in different periods intertemporal flow. (See Figure 2).

According to the above division of the new energy vehicle industry chain, the lithium material flow analysis framework of the new energy vehicle industry, and based on the lithium existence form and flow process at each industrial chain end, determine the nodes and flow directions of each industrial chain end, and compile the new energy vehicle industry of lithium flow meter standard template. The flow meter can measure the flow and stock of lithium resources in the new energy vehicle industry, and also include the flow direction and flow information of lithium resources.

2.3 Model assumptions

Considering uncontrollable factors, the following assumptions are made: 1) The lithium battery and the vehicle produced in the year were consumed and put into

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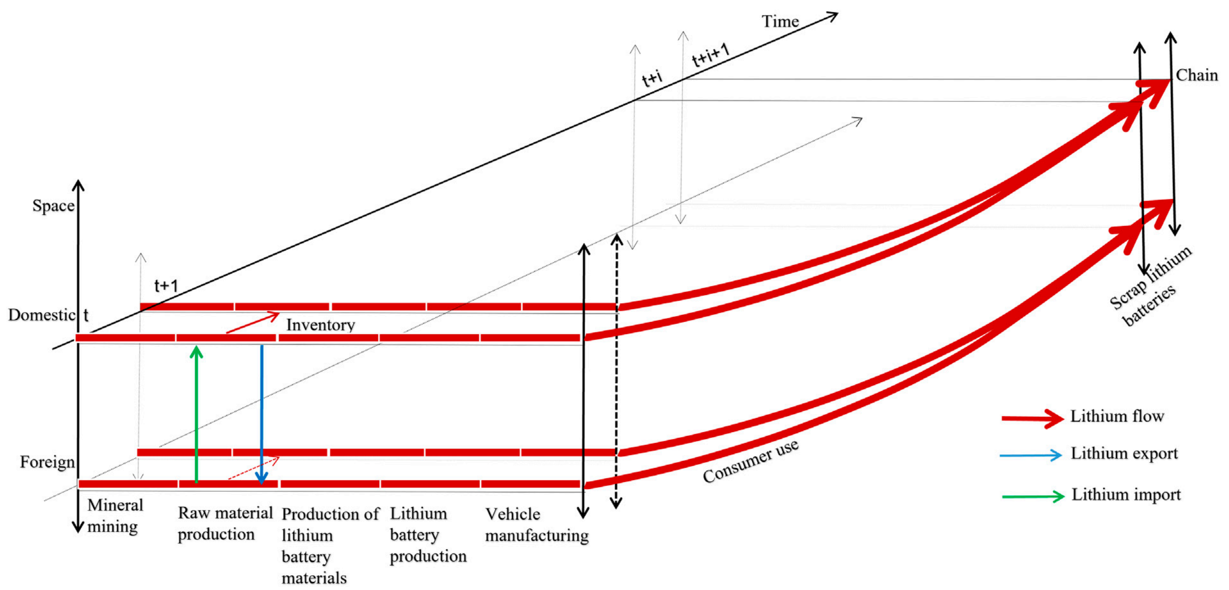

FIGURE 2
Basic framework of lithium material flow in the new energy vehicle industry.

use; 2) The demand and consumption of lithium batteries in new energy vehicles, 3C, and energy storage industries are consistent. The lithium consumption of battery products in China from 2014 to 2019 is consistent with the total demand for lithium-ion batteries in the corresponding industries, and the relevant data are consistent. 3) Domestic and foreign new energy vehicles, lithium battery production technology level, all kinds of lithium battery unit storage lithium consumption intensity are consistent; 4) The performance of new energy vehicle industry is consistent with that of lithium batteries applied in 3C and energy storage fields, and the lithium consumption intensity of unit power storage is the same.

2.4 Data sources

The production information data of new energy vehicles and the production information data of assembled lithium batteries are from the "Energy Saving and New Energy Vehicle Yearbook," refer to the "Vehicle Purchase Tax Exemption" and "Enjoy Vehicle and Vessel Tax Reduction and Exemption" jointly issued by the Ministry of Industry and Information Technology and the State Administration of Taxation to supplement the missing data of new energy vehicle model information. The historical lithium consumption data of China's lithium batteries, pharmaceuticals, glass ceramics, lubricants, and other products; China's demand for lithium batteries for new energy vehicles, 3C products, and energy storage comes from Shanghai Nonferrous Metals Network (SMM).

2.5 MFA methodological setup

2.5.1 Lithium extraction stage

Lithium mining enterprises excavate lithium ore and lithium-containing brine (lithium-rich minerals) from mines and salt lakes (seawater). The calculation formula of lithium flow during the extraction stage of lithium ore is as follows,

$$MLF_t = \left(ML^{dp}_{t,ore} + ML^{dp}_{t,brine}\right) + \left(ML^{im}_{t,ore} - ML^{ex}_{t,ore}\right) + \left(ML^{im}_{t,bine} - ML^{ex}_{t,brine}\right) + \gamma_t \tag{1}$$

Eq. 1, MLF_t is t annual lithium ore extraction stage of lithium flow. $ML^{dp}_{t,ore}$, $ML^{dp}_{t,brine}$ are t annual domestic extraction of lithium ore and lithium-bearing brine in lithium resources. $ML^{im}_{t,ore}$, $ML^{im}_{t,bine}$ are t annual imports of lithium ore, lithium-bearing brine in lithium resources. $ML^{ex}_{t,ore}$, $ML^{ex}_{t,brine}$ are t annual exports of lithium ore, lithium-bearing brine in lithium resources. γ_t is t annual lithium ore, lithium-bearing brine (lithium-rich minerals) inventory.

2.5.2 Lithium battery raw material production stage

Part of the lithium raw materials have entered the field of lithium battery production, and other parts have entered the production fields of glass ceramics, grease, polymers, metallurgy, and other industries. According to the proportion of the domestic lithium battery industry production demand for lithium to the production demand for lithium in all industries, the demand for lithium in domestic production can be calculated. The calculation formula of lithium flow at the production end of lithium raw materials can be as follows,

$$RmLF_t = \frac{TLBC_t}{TLBC_t/TDL_t} + \sum\left(RmL^{im}_{t,0} - RmL^{ex}_{t,0}\right) + \delta_t \quad (2)$$

In Eq. 2, $RmLF_t$, $TLBC_t$ are t annual lithium flow of lithium raw material production end, lithium consumption of domestic lithium battery production. TDL_t is t annual lithium consumption of domestic production of all industries. $RmL^{im}_{t,0}$, $RmL^{ex}_{t,0}$ are t annual lithium content of imported lithium raw materials and exported lithium raw materials. δ_t is t annual lithium raw material production stage lithium inventory and loss.

2.5.3 Lithium battery production side

First, according to the vehicle type of the new energy vehicle, the type of lithium battery assembled and its power storage information, the unit vehicle storage power of each type of new energy vehicle is calculated.

$$PRE^m_t = \sum_{i=1} pre^{i,m}_t \times amv^{i,m}_t \Big/ \sum_{i=1} amv^{i,m}_t$$
$$m = PHEPV, PHECV, PHESV, BEPV, BEVV, BESV, FCEV \quad (3)$$

In Eq. 3, PRE^m_t is the unit vehicle storage power of t annual m type of new energy vehicle, $pre^{i,m}_t$ and $amv^{i,m}_t$ are the vehicle storage power and the number of vehicles in i information of m type of new energy vehicle in the year t, respectively.

$$PRE^n_t = \sum_{j=1} pre^{j,n}_t \times amv^{j,n}_t \Big/ \sum_{j=1} amv^{j,n}_t$$
$$n = LFP, LMO, LCO, NMC \quad (4)$$

In Eq. 4, PRE^n_t is the unit vehicle storage capacity of t annual assembly n type lithium battery new energy vehicle. $pre^{j,n}_t$ and $amv^{j,n}_t$ are the vehicle storage capacity and the number of vehicles in the j information of the t annual assembly n type lithium battery new energy vehicle, respectively.

Secondly, according to the output of new energy vehicles and the power storage per unit vehicle, the total power storage of new energy vehicles is calculated.

$$TRE^m_t = PRE^m_t \times TMV^m_t$$
$$m = PHEPV, PHECV, PHESV, BEPV, BEVV, BESV, FCEV \quad (5)$$

In Eq. 5, TRE^m_t, PRE^m_t, and TMV^m_t are the total power storage capacity of new energy vehicles of the t year assembly m type, the power storage capacity per unit vehicle, and the number of vehicles, respectively.

$$TRE^n_t = PRE^n_t \times TMV^n_t, n = LFP, LMO, LCO, NMC \quad (6)$$

In Eq. 6, TRE^n_t, PRE^n_t, and TMV^n_t are the total storage capacity of lithium battery new energy vehicles of the t annual assembly n type, the storage capacity per unit vehicle, and the number of vehicles, respectively.

TABLE 1 Lithium consumption intensity of lithium batteries by type in China, 2014–2019.

Year	LFP	LMO、LCO	NMC
2014	0.156	0.280	0.280
2015	0.148	0.256	0.256
2016	0.140	0.231	0.231
2017	0.133	0.207	0.207
2018	0.129	0.189	0.189
2019	0.126	0.186	0.186

Unit: kg/kwh.

Finally, according to the total storage capacity of lithium batteries assembled in new energy vehicles and the total consumption of lithium in the new energy vehicle industry, the lithium consumption intensity of lithium batteries is calculated.

$$PLC_t = TLC_t/TRE_t \quad (7)$$

In Eq. 7, PLC_t and TLC_t are respectively the lithium consumption intensity and lithium consumption per unit of storage capacity of lithium batteries assembled in new energy vehicles in t year.

Combined with the actual production technology of lithium batteries in China, the structural decomposition method is used to set the lithium consumption intensity of lithium iron phosphate, lithium manganate, lithium cobaltate, and ternary material lithium batteries in China from 2014 to 2019 (See Table 1).

2.5.4 A model for measuring lithium consumption at the production end of new energy vehicle lithium batteries

The calculation formula of lithium consumption of various types of new energy vehicles is as follows,

$$TLC^m_t = PLC^m_t \times PRE^m_t \times amv^m_t \quad (8)$$

In Eq. 8, TLC^m_t, PLC^m_t, PRE^m_t, and amv^m_t are the t annual assembly m type lithium consumption of new energy vehicles, the lithium consumption intensity per unit of stored electricity, the unit of vehicle storage, and the number of vehicles, respectively.

$$TLC^n_t = PLC^n_t \times PRE^n_t \times amv^n_t \quad (9)$$

In Eq. 9, TLC^n_t, PLC^n_t, PRE^n_t, and amv^n_t are the t annual lithium assembly n type consumption of assembled lithium-ion battery new energy vehicles, the lithium consumption intensity per unit of stored electricity, the unit of vehicle storage, and the number of vehicles, respectively.

2.5.5 Model for measuring lithium consumption at the production end of lithium batteries

The calculation formula of lithium flow at the production end of lithium battery is as follows,

$$TLF_t = \frac{TLC_t}{(VLBC_t/TLBC_t)} + (LBC_t^{im} - LBC_t^{ex}) + \beta_t \quad (10)$$

In Eq. 10, TLF_t is the t annual lithium flow at the production end of lithium batteries. $VLBC_t$, $TLBC_t$ are the t annual consumption of lithium batteries in the new energy vehicle industry, and the consumption of lithium batteries in all industries. LBC_t^{im}, LBC_t^{ex} are the t annual lithium content of imported lithium batteries, and the lithium content of exported lithium batteries, β_t is the t annual inventory of lithium batteries.

According to the import and export of lithium primary batteries, the total number of lithium batteries accounted for the proportion of the total number of lithium batteries assembled in new energy vehicles, and the above measurement of lithium consumption of lithium batteries assembled in new energy vehicles, we can measure the import and export of lithium primary batteries and lithium ion storage batteries in lithium content.

$$\begin{aligned}(LBC_t^{im} - LBC_t^{ex}) = TVLC_t \Big[&\left(TLW_t^{\text{primary battery im}}/TLW_t^{\text{monomer}}\right) \\ &- \left(TLW_t^{\text{primary battery ex}}/TLW_t^{\text{monomer}}\right) \\ &+ \left(TLW_t^{\text{Storage battery im}}/TLW_t^{\text{assembly}}\right) \\ &- \left(TLW_t^{\text{Storage battery ex}}/TLW_t^{\text{assembly}}\right)\Big] \quad (11)\end{aligned}$$

The lithium consumption of the lithium battery production of new energy vehicles calculated above is the lithium flow rate of the lithium battery production side, that is, $TLF_t = TLC_t$. In Eq. 11, $TVLC_t$, $TLW_t^{\text{primary battery im}}$, $TLW_t^{\text{primary battery ex}}$, $TLW_t^{\text{Storage battery im}}$, $TLW_t^{\text{Storage battery ex}}$, TLW_t^{monomer}, and TLW_t^{assembly} are the t annual lithium flow rate of the new energy vehicle industry on the lithium battery production side, and the primary battery. Import volume, primary battery export volume, storage battery import volume, storage battery export volume, lithium monomer volume assembled by new energy vehicles, and lithium assembly volume assembled by new energy vehicles.

2.5.6 New energy vehicle production end

According to the ratio of the import and export of new energy vehicles to domestic production, the import and export flow of lithium in the industry and the net inflow of lithium are calculated.

$$TVLF_t = \sum TVLF_t^m \left\{1 + \left[\left(\frac{amv_t^{m,im}}{amv_t^m}\right) - \left(\frac{amv_t^{m,ex}}{amv_t^m}\right)\right]\right\} \quad (12)$$

In Eq. 12, $TVLF_t^m$, $amv_t^{m,im}$ and $amv_t^{m,ex}$ are the t annual consumption of lithium by new energy vehicles assembly m type and the number of vehicle imports and exports.

2.5.7 The consumer side of new energy vehicles

The lithium stock of the new energy vehicle consumer side in that year is the lithium stock of the new energy vehicle in the current state of use minus the lithium recovery potential formed by the retired lithium battery that year.

$$TVLS_t = \sum (TVLF_{n,mt} - TVLFs_{n,m}) \quad (13)$$

In Eq. 13, $TVLS_t$ and $TVLFs_t^{n,m}$ are the t annual lithium stock of new energy vehicles and the amount of lithium scrap produced by the lithium battery of the assembly n type lithium battery m type new energy vehicle.

2.5.8 The end-of-life end of lithium batteries assembled in new energy vehicles

When the power storage performance of the lithium battery assembled in the new energy vehicle drops below 80%, the lithium battery will no longer be able to be used in the new energy vehicle and it needs to be retired (scrapped).

Calculation method for retired lithium battery in new energy vehicle assembly. The two-parameter Weibull distribution model was used to estimate the amount of lithium resource decommissioning of new energy vehicles in each year. Comprehensively consider the cycle times and charging times of lithium batteries, refer to existing research results (Zheng et al., 2022), China's mandatory automobile scrapping indicators, technical standards and maximum mileage, and other factors, as well as new energy passenger cars, passenger buses, and special vehicle power batteries equipped with different lithium batteries. The maximum retirement age shall be treated as 1.3 times the average retirement age. According to the maximum years of lithium batteries installed in different new energy vehicles, the corresponding retirement time probability distribution of lithium batteries is calculated as Table 2 shows.

Lithium recycling mainly comes from lithium batteries that are directly scrapped and lithium batteries that are scrapped after secondary use. Considering the actual situation in China, only a small part of lithium batteries retired before 2018 have been used in cascade, and only a small part of lithium batteries have been used in cascade after 2018. This paper will no longer measure the lithium recovery potential of this part. According to the lithium battery retirement probability of new energy vehicles and the calculated lithium content of new energy vehicles, the lithium recovery potential of retired lithium batteries of new energy vehicles is calculated.

$$TVLFs_t = \sum\sum (TVLF_t^{n,m} + \alpha_t) \quad (14)$$

In Eq. 14, $TVLF_t^{n,m}$ and α_t are the t annual lithium recovery potential of retired lithium batteries for new energy vehicles and the retirement probability of new energy vehicle lithium batteries for the m type of assembled n lithium battery.

TABLE 2 Set values for the maximum years of retirement of new energy vehicles in China, 2014–2019.

	Lithium iron phosphate	Lithium manganate	Lithium cobaltate	Ternary materials
Passenger cars	10	6	9	8
Bus	5	2	2	3
Special purpose vehicle	5	2	3	3

Unit: year.

2.5.9 Lithium loss

The flow of lithium in the new energy vehicle industry chain is affected by factors such as production technology and technical level. Lithium loss occurs in some production links. Lithium loss mainly occurs in the production process of lithium ore raw materials and cathode materials. At present, the relevant technical parameters show that China's lithium minerals are mainly lithium ore (Tian et al., 2020; Zhang et al., 2020), the lithium recovery rate in the production of lithium carbonate and lithium hydroxide is 90%, and the lithium recovery rate in the production of cathode materials is 98%, that is, there is a 12% loss of lithium in the whole production process of lithium raw materials. Theoretically, the lithium element will be lost in the production of lithium batteries, assembly and even the assembly of new energy vehicles. The lithium in the scrap lithium battery can not be completely recycled, but the loss is small, this paper is no longer considered (Kamran et al., 2021).

3 Results

3.1 Lithium extraction

China's external dependence on lithium mines is high and continues to increase. The mining of concentrate and brine has been increasing year by year, and the extraction of domestic lithium resources has increased from 4.014 thousand tons in 2014 to 12.631 thousand tons in 2019. Among them, the lithium extracted from brine has increased from 1.989 thousand tons in 2014 to 6.692 thousand tons in 2019. However, this still cannot meet the domestic demand for lithium resources. The import of lithium raw materials continues to increase, and the external dependence of lithium salt production raw materials has rapidly increased from 67% in 2014 to 75% in 2019. (See Supplementary Table S1).

3.2 Lithium battery raw material production

China is a net outflow country of lithium raw materials and lithium battery materials, and has made positive contributions to the global supply of lithium raw materials and lithium battery materials. In 2019, the net outflow of lithium from the lithium raw material end in China was 4.679 thousand tons, of which 8.062 thousand tons was net through lithium hydroxide, and lithium carbonate, lithium fluoride, and lithium iron phosphate were the net inflow raw materials. China is a net inflow country in terms of lithium battery materials, and in 2019, a net inflow of 1.004 thousand tons of lithium through lithium battery materials. Overall, in 2019, China had a net outflow of 3.675 thousand tons of lithium through lithium raw materials and lithium battery materials, while before 2018, on the contrary, China was a net inflow country in this regard. (See Supplementary Table S2).

The consumption of lithium in various industries in China has grown rapidly year by year, from 9.137 thousand tons in 2014 to 21.938 thousand tons in 2019. The average annual growth rate of lithium consumption has reached 19%. Among them, the proportion of lithium consumption in lithium battery industry has increased from 57% in 2014 to 69% in 2019 (see Supplementary Table S3).

3.3 Lithium battery production

The new energy vehicle industry has gradually grown into the industry with the largest demand for lithium batteries. In 2019, the lithium content of lithium batteries in China's new energy vehicles was 9.06 thousand tons, which accounted for 60% of the total domestic lithium battery consumption. In 2014, this proportion was only 13%. The lithium batteries assembled in new energy vehicles are mainly ternary material batteries and lithium iron phosphate batteries. In 2019, the lithium content of these two types of lithium batteries was 6.348 thousand tons and 2.548 thousand tons respectively. (See Supplementary Table S4, S5).

The number of lithium batteries China provides to the world continues to grow rapidly. In 2019, China had a net outflow of 7.9 thousand tons of lithium through the import and export of lithium batteries. In 2018, the net outflow of lithium was only 3.271 thousand tons. In 2014, the net outflow of lithium was 11 tons. Most of the net outflow of lithium was achieved through lithium battery imports and exports, and the import and export of lithium batteries alone was very small. (See Supplementary Table S5).

(1) Lithium ore extraction stage

Inventory at the beginning of the year	Domestic mining	Imported ore	Lithium loss	Year-end inventory
46466	12631	38544	4448	44632

(2) Lithium raw material production stage

Production of lithium raw materials					Lithium raw material consumption			
Domestic	Import	Export	Lithium loss	Recycle and reuse	Lithium battery	Glass ceramic	Grease	Medicine
44739	6147	10649	913	371	28153	4017	2036	737

(3) Lithium battery production stage

Lithium battery production	Domestic	28153			
	Import	29401			
	Export	42515			
Domestic consumption of lithium batteries	Energy storage	1076			
	3C	4904			
	New energy vehicles	9060			
		NMC	LFP	LCO	LMO
		6347	2548	71	94

(5) New energy vehicle lithium battery scrap and lithium recovery stage / (4) New energy vehicle manufacturing stage

	Completely scrapped by the end of the year	Recyclable at the end of the year	Year-end balance	Balance at the beginning of the year	Consumption of the year	NMC	LFP	LCO	LMO	Subtotal	
PHEPV	10	3	1639	1256	396	379				379	Domestic
PHECV	83	21	125	187	42		7	8	27	42	Domestic
PHESV	0	0	1	0	1	1				1	Domestic
BEPV	87	22	14782	8924	5967	5820	255		3	6078	Domestic
BECV	2050	512	7757	8491	1828		1722	63	43	1828	Domestic
BESV	939	235	2139	2606	707	146	548		13	707	Domestic
FCV	0	0	41	16	25	1	16		8	25	Domestic
Total	3169	793	26484	21480	8966	277					Import
						371					Export
						8966					Inventory

Unit: ton

FIGURE 3
New energy vehicle industry lithium material flow meter in 2019.

3.4 New energy vehicle production, new energy vehicle consumption

The consumption of lithium in the production stage of new energy vehicles continues to grow rapidly. The consumption of lithium in domestic new energy vehicle production increased rapidly from 655 tons in 2014 to 90.6 million tons in 2019, with an average annual growth rate of 83%. Among them, the main force of lithium consumption is the production of pure electric passenger cars and pure electric buses. In 2019, the lithium required for domestic production of pure electric passenger cars and pure electric buses accounted for 67% and 20% of the total, respectively. However, the net inflow of lithium through imported new energy vehicles is less than 100 tons, and the lithium stock on the consumption side of new energy vehicles is roughly equal to the lithium stock on the domestic production side. (See Supplementary Table S6).

3.5 New energy vehicle lithium battery end-of-life

Passenger cars have the longest retirement (scrap) years. In 2020, the retired (scrapped) lithium batteries of plug-in hybrid electric vehicles and pure electric passenger vehicles will contain about 346 tons of lithium; passenger cars and special vehicles have a shorter service life. In the early stage, the amount of scrapped is relatively large. In 2020, the retired (scrapped) lithium battery of pure electric buses will contain about 2.571 thousand tons of lithium; At present, most new energy vehicles are directly scrapped after the lithium batteries are scrapped. In the future, the amount of lithium battery replacement generated by the retirement (scrapped) of lithium batteries in new energy vehicles will increase rapidly, which will increase the demand for lithium resources. China's new energy vehicles retired lithium batteries have less echelon utilization. In 2020, the retired

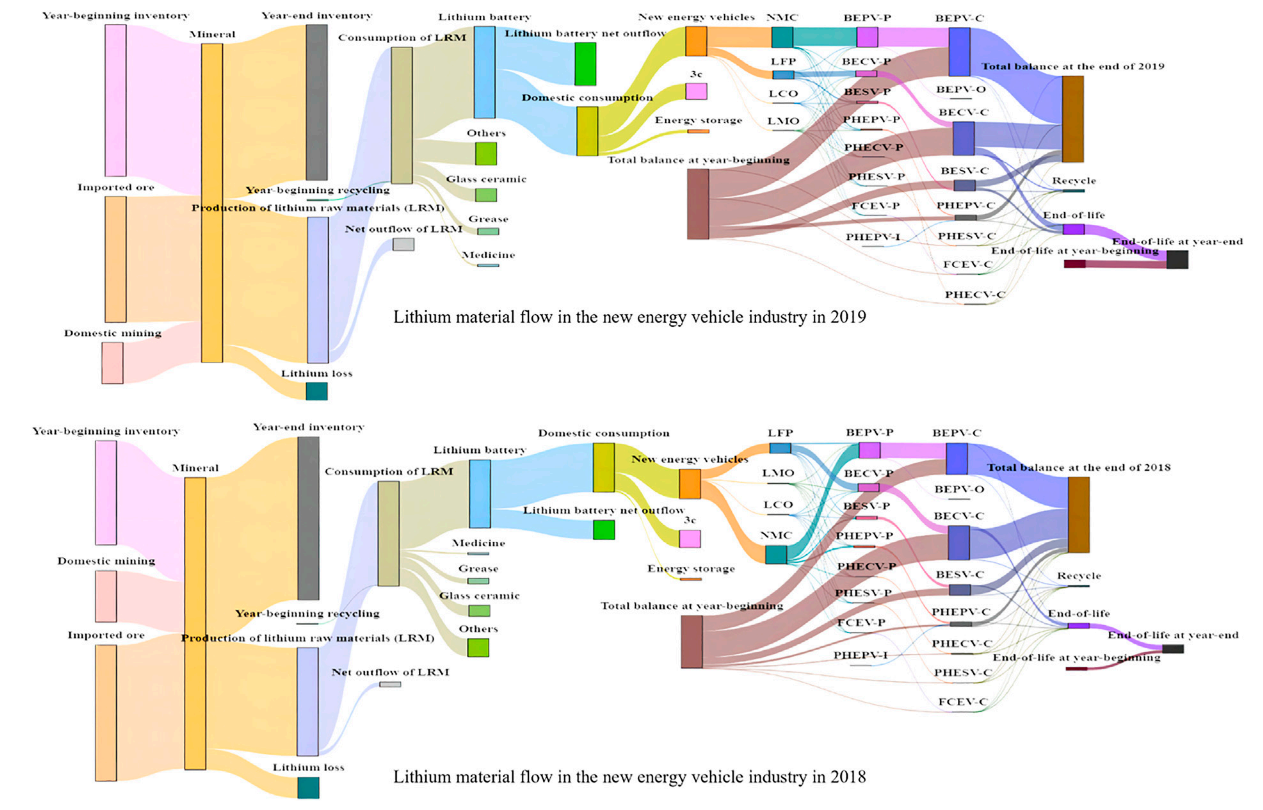

FIGURE 4
Lithium material flow in the new energy vehicle industry in 2018–2019.

lithium batteries will be used in other industries and the lithium batteries will contain less than 800 tons of lithium (See Supplementary Table S7, S8).

3.6 Preparation of lithium flow chart and table for new energy vehicles

According to the existing status and stock of lithium in the new energy vehicle industry chain from 2014 to 2019, the flow table and flow chart of lithium resources in China's new energy vehicle industry can be compiled, as shown in Figures 3-6.

4 Discussion

Insufficient supply of domestic lithium resources is a key bottleneck for the pressure of lithium supply and demand in China's new energy vehicle industry. According to the British Geological Survey report, China's lithium reserves account for about 8% of the world's reserves (BGS, 2016), which is relatively abundant, but 78% of China's lithium reserves are distributed in the Qinghai-Tibet region, which exists in the form of salt lake resources. The development of lithium resources is difficult and costly, especially the challenges such as salt lake mining are difficult to overcome. The extraction of spodumene and lepidolite resources also faces the same problem. At the same time, the development of lithium resources is subject to environmental restrictions such as energy consumption standards, fluorine emissions, and solid waste emissions, further limiting its mining capacity. In 2019, the total domestic production of lithium resources in China was only 12.631 thousand tons. Although it has increased significantly compared with 4.014 thousand tons in 2014, China's lithium consumption of 9.137 thousand tons in that year is still significantly insufficient. The domestic supply capacity of lithium resources is limited. Under the "dual carbon" goal, China's future demand for lithium in the new energy vehicle industry will continue to maintain rapid growth, and the pressure on supply and demand of lithium resources will continue to increase in the future.

The import and export of related products is also an important source of lithium supply and demand pressure in the new energy industry. China's new energy vehicle industry is actively integrating into the global industrial chain and value chain. China has exported

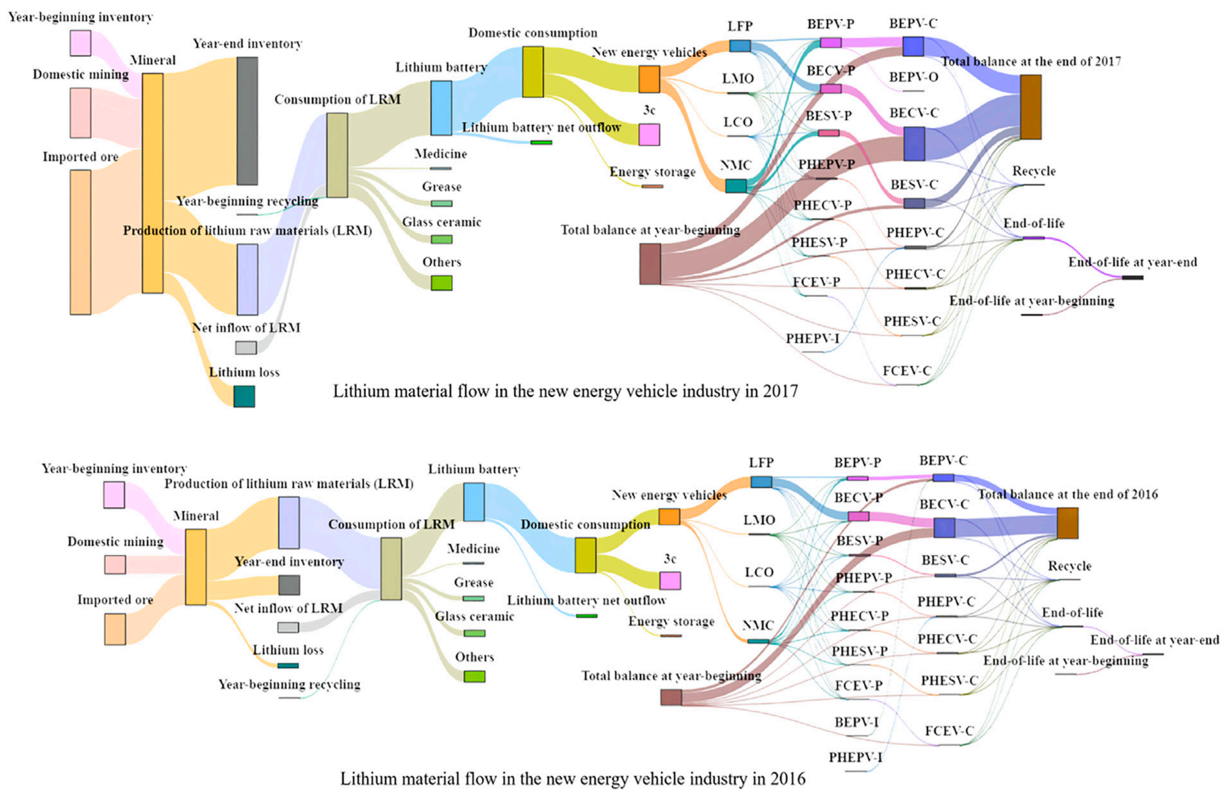

FIGURE 5
Lithium material flow in the new energy vehicle industry in 2016–2017.

a large amount of lithium hydroxide, lithium hexafluorophosphate, lithium metal and other lithium raw materials and lithium battery materials to foreign countries. In 2019, China passed lithium raw materials, lithium battery materials, lithium batteries, and the total net outflow of lithium from new energy vehicles is about 11.669 thousand tons, while the domestic consumption of lithium produced by new energy vehicles in 2019 is only 9.06 thousand tons. With the advancement of China's lithium battery and new energy vehicle production technology, China will contribute more lithium battery raw materials, materials, lithium batteries, and new energy vehicles to the world in the future, which will further increase the supply and demand pressure of lithium resources in the new energy industry.

The global lithium ore market has a strong monopoly, and the price of lithium ore fluctuates greatly. The lithium inventory brought by these factors is the main source of lithium supply and demand pressure in China's new energy vehicle industry. At present, the global concentration of lithium ore resources is relatively high, and lithium ore resources are mainly in the hands of a few global mining groups. According to data provided by Roskill, in 2017, 80% of global lithium production capacity and 85% of lithium production came from Talison Lithium, SQM, Reed Ind. Mins 11 other manufacturers. The overly concentrated market structure is likely to cause collective market conspiracy and abnormal fluctuations in lithium ore prices. Since 2016, the global "lithium" price began to grow rapidly. Although it began to drop sharply after 2018 (Wang, 2020), the global "lithium" price will increase rapidly in 2021. The drastic changes in the price of lithium raw materials have not only caused price pressure on the downstream manufacturers of new energy vehicles, but also caused huge pressure on the raw material supply of various manufacturers in the industrial chain. Inventory has become a common choice for many raw material manufacturers to avoid risks.

In order to ensure the safe supply of lithium resources required by the new energy vehicle industry in China and even in the world, the following main suggestions are put forward around the key links, main pressures and future development trends of lithium material flow in the new energy vehicle industry.

First, in order to guide the healthy development of the lithium resource market, industry organizations such as professional key mineral industry associations and lithium mining industry alliances can be established, which can help further develop and publish information to strengthen industry

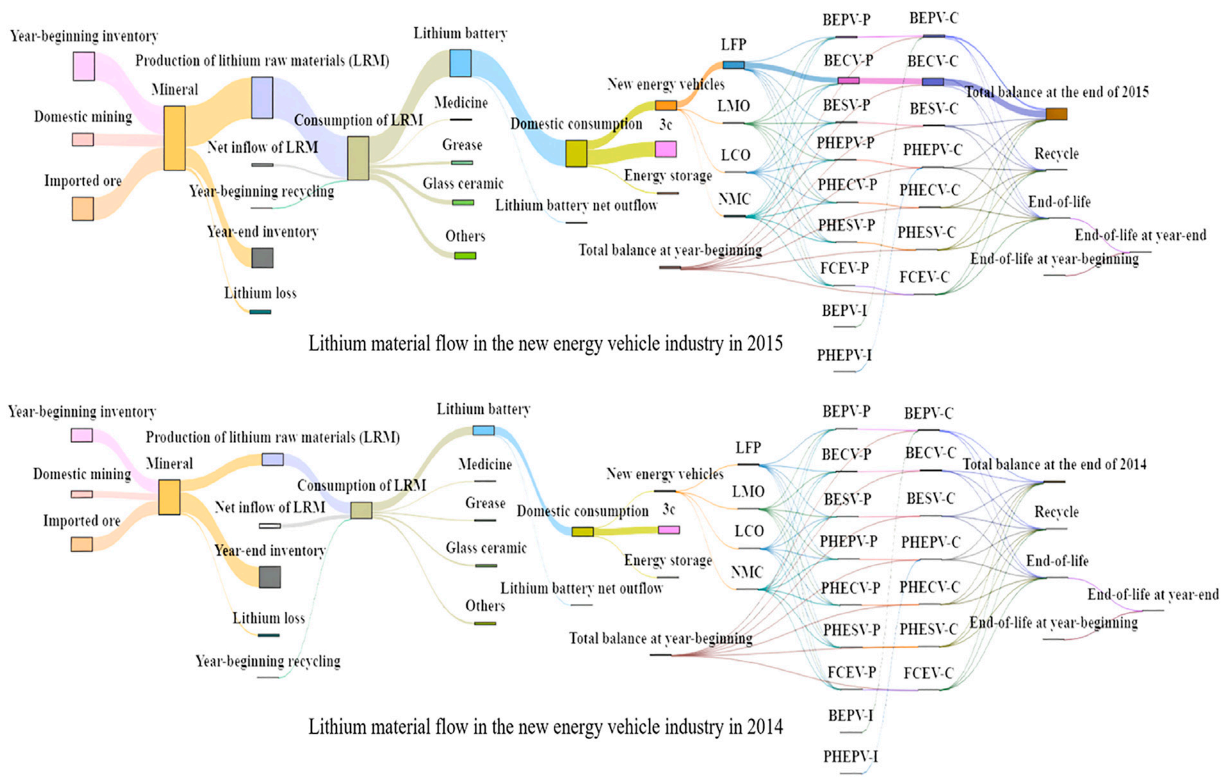

FIGURE 6
Lithium material flow in the new energy vehicle industry in 2014–2015.

standards, industry information, and development plans. At the same time, this can also effectively inhibit vicious inventory and vicious market competition behavior. In addition, it is necessary to strengthen the market information monitoring and statistics of lithium resources, lithium raw materials, and their related products. It is also important to strengthen the data monitoring, data analysis, and risk control of key aspects of lithium material flow for new energy vehicles. When formulating competition norms for the key mineral industry, it is necessary to center on lithium and strictly control the disorderly development of the industry.

Second, international cooperation in lithium resource development is also important. For China, we need to promote cooperation with South America, Africa, the Belt and Road, and other regions on the development of lithium mineral resources. At the same time, international cooperation in the whole industrial chain of lithium, lithium raw materials, lithium materials, lithium batteries, and new energy vehicles is also essential. Only in this way can we improve China's voice and influence in global lithium resource development and market operation, and further participate in global lithium mineral resource exploration and development research.

Third, we need to pay attention to technological innovation. Innovative research on key technologies for lithium battery production, lithium extraction from salt lakes, lithium extraction from ores, and lithium battery resourcing is very important. The joint efforts of global scholars can help break through the technical bottleneck of lithium extraction from lithium ore more quickly. In addition, solid fuel cells and hydrogen energy development and application are equally important. Reducing the dependence of new energy vehicles on lithium resources is a key measure to ease the pressure of lithium supply and demand. In order to give full play to the full life value of lithium, more efforts are needed in research to extend the life length of various lithium products. For example, retired lithium batteries from new energy vehicles can be encouraged for safe stepwise utilization in other industries (wind power, photovoltaic energy storage).

Finally, we need to pay attention to the construction of lithium resource recovery system. With the increasing amount of lithium resources at end-of-life, in order to improve the efficiency of lithium resources recycling, we can encourage the lithium resources recycling system to change from government-driven to market-led, so that enterprises engage in lithium battery recycling, storage, and disposal. The problems faced by lithium battery resources, such as economy of scale and transportation cost, also need to be taken seriously. We need to combine the spatial layout of the lithium battery material industry with the scientific and reasonable layout of the lithium battery resource industry. We should implement different lithium battery recycling policies and give financial support to small and medium-sized cities, remote areas, and ecological environment fragile areas.

5 Conclusions

In this article, the flow and stock of lithium resources in China's new energy vehicle industry were analyzed using the material flow analysis method, and a new energy industry lithium material flow table for this industry in 2019 and a lithium material flow diagram for this industry from 2014 to 2019 were completed. In summary, the following main conclusions can be obtained.

The technical performance and structural changes of lithium batteries assembled in new energy vehicles will affect their consumption of lithium. Although the lithium consumption intensity of lithium batteries produced in China continues to decline, the lithium battery storage required for new energy vehicles to assemble lithium batteries continues to increase, and the structure of lithium batteries for new energy vehicles has gradually changed from lithium iron phosphate batteries to ternary batteries. Material battery transformation, these changes affect the lithium consumption of the new energy vehicle industry.

The lithium battery and new energy vehicle industries have gradually become the main force of lithium resource consumption. In 2019, China's domestic lithium battery production and consumption consumed 15.04 thousand tons of lithium, accounting for 29% of the total lithium output at the lithium mineral end and 69% of the total domestic lithium consumption of lithium raw materials. Domestic new energy vehicle production consumes 9.06 thousand tons of lithium through lithium batteries, which accounts for 18% of the total lithium output at the lithium mineral end, and 60% of the lithium consumption required for domestic production of lithium batteries.

The supply and demand pressure of lithium resources in China's new energy vehicle industry mainly comes from lithium batteries, new energy vehicles, import and export, and inventory. In 2019, China's net outflow of lithium through the import and export of lithium batteries, lithium battery raw materials, materials and new energy vehicles accounted for 23% of the domestic lithium raw material consumption. The cumulative domestic lithium inventory is more than twice the lithium consumption of various industries in that year, and more than five times the lithium consumption of new energy vehicles.

New energy vehicles are an important lithium mineral that cannot be ignored. As of 2019, the lithium stock accumulated in new energy vehicles is about 26.484 thousand tons. More and more lithium batteries will be retired and scrapped from new energy vehicles in the future. From 2014 to 2019, the accumulated lithium content of retired (scrapped) lithium batteries is about 6.92 thousand tons. In 2020, the accumulated lithium content of retired (scrapped) lithium batteries will reach 10.721 thousand tons, which is the threshold value for enterprises to recycle and reuse lithium batteries. It is also an important node for China to formulate lithium battery recycling policies.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

LZ: data curation, writing original draft, writing review, and editing. GC: resources, writing original draft, writing review, and editing. LL: methodology, resources, writing original draft. YH: methodology, resources, writing original draft. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.992617/full#supplementary-material

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Game evolution and simulation analysis of power battery recycling in China under conflicting supply and demand of critical metals

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A great demand for lithium, cobalt, nickel, and other critical metals by power batteries has been increasing with the explosive development of the new energy industry, which further exacerbated the contradiction between the supply and demand of critical metals. In addition, two key factors, including an imbalance of government reward and punishment and a low degree of cooperation between manufacturers and recycling enterprises, have hindered the recovery and utilization of critical metals in power battery with the expansion of the power battery recycling market. A three-party evolutionary game model, including power battery manufacturers, third-party recycling enterprises, and the government, was constructed in this study to analyze the evolutionary stability of the strategy selection of each participant. Also, the influence of each factor on the three-party strategy selection and verifying the reliability of the results through simulation were also discussed. The results show that 1) both government incentives and punishments are beneficial for promoting cooperation between power battery manufacturers and recycling enterprises. The cost of cooperation will be the key factor affecting power battery recycling. 2) Increasing the probability of cooperation is an effective way to ensure the increase in income of both parties after cooperation. Further suggestions, including the establishment of a dynamic reward and punishment mechanism by the government and strengthening the cooperation to cope with the continued tight supply of critical metals by the manufacturers and recyclers, were also put forward in this research.

KEYWORDS

critical metals, recycling, cooperation, tripartite evolutionary game model, simulation analysis

Introduction

The development of energy vehicles (EVs) is an effective way to achieve carbon emission reduction and carbon neutrality (Li et al., 2022). As an important component of EVs, power batteries are crucial to the manufacturing and development of EVs. Critical metals such as lithium, cobalt, and nickel, as essential constituents of active cathode materials and anode active materials of power batteries, have become indispensable raw materials in power battery manufacturing (Gu et al., 2017). By 2030, China's lithium-ion battery (LIB) demand for lithium, cobalt, and nickel will be 11 times, 9 times, and 62 times higher than that in 2020, respectively (Shafique et al., 2022), and the tight supply and demand situation for critical metals in China is expected to intensify in the future. Power battery will enter the end-of-life stage after their capacity decays to a certain level, and recycling of retired power batteries can effectively increase the supply of key materials and reduce the initial production cost of power batteries (Idjis and Costa, 2017). In addition, battery recycling and reusing will achieve a win-win situation for both resource recovery and environmental protection impact, compared to new battery manufacturing (Gu et al., 2018). It will become increasingly important as lithium batteries increase (Alipanah et al., 2021). It is expected that by 2025, recycled lithium in China will account for 9% of the total lithium supply from lithium batteries and cobalt will account for nearly 20% (Pagliaro and Meneguzzo, 2019), which will go some way to alleviating the tight supply and demand for critical metals in power battery production.

Government supervision plays a major role in power battery recycling. On the one hand, a rational design of the layout, pricing strategy, and utilization to the power battery recycling industry is the key to realizing the efficient use of recycled power batteries (Lyu et al., 2021). On the other hand, supervision and subsidies for power battery recycling, gradient utilization, and resource reuse recycling systems are important to realize resource recycling (Tang et al., 2019; Liu and Wang, 2021; Wang, 2022). Lack of supervision will lead to the occurrence of corporate fraud and other situations. The Chinese government has introduced a series of regulations to guide and regulate the recycling of used batteries (Sun et al., 2021). Nevertheless, there are still phenomena such as regulatory imbalances and unsound recycling networks, which seriously hinder the healthy development of recycling market and incur huge environmental governance costs (He and Sun, 2022).

The cooperation cost is also one of the factors that both production enterprises and recycling enterprises must be considered when cooperating. Although extended producer responsibility (EPR) policies hold producers responsible for the entire life cycle of their products (Lindhqvist, 2000), especially the recycling and disposal of products designated by consumers as no longer useful (Gaur et al., 2022), producers usually cannot completely rely on their own power to achieve waste recycling. According to Gu et al. (2016), subjects involved in waste recovery can be divided into hawkers, collection stations, distributors, and middlemen, of which middlemen are second-level recyclers, and the other three are directly connected with consumers and belong to first-level recyclers (Chi et al., 2011). Although the number of recycling enterprises is very large, most of which are small and medium-sized enterprises, no special recycling network has been formed (Wang and Wu, 2017). Both power battery manufacturers and recycling enterprises need to pay a certain cost to seek recycling cooperation. For recycling enterprises, capabilities with high dismantling capabilities and strong technical have to pay less such costs. Power battery manufacturers can achieve win-win cooperation by signing risk-equivalent contracts and establishing advantages in the recycling power battery recycling market (Zhu and Yu, 2019). For recyclers, the amount of investment under different investment models and the recycling rate will also influence its decisions (You et al., 2014).

There are many studies on various aspects of power battery recycling, such as policies and regulations on power battery recycling (Xu et al., 2017; Choi and Rhee, 2020; He and Sun, 2022), power battery recycling subjects (Schultmann et al., 2003), recycling channels (Chuang et al., 2014; Tang et al., 2018), and recycling mode (Hong and Yeh, 2012). Game theory is simulated decision interactions among rational decision-makers by using mathematical methods and has many applications in political science, economics, and sociology (Fang et al., 2021). Compared with traditional engineering methods, game theory pays more attention to the social and personal behaviors of stakeholders (Yuan et al., 2022). Luo et al. (2019) used a dynamic game to optimize subsidy policy for autonomous vehicles. Gu et al. (2021) constructed a game model of the impact of government subsidies on the utilization of electric vehicle batteries from the perspective of the closed-loop supply chain. Li X. et al. (2020) conducted an evolutionary game analysis on the behavior of the main participants in the electric vehicle battery deposit refund scheme launched by the Shenzhen Municipal Government of China. Li J. et al. (2020) built a non-cooperative game model that considers the battery recycling rate and consumers' environmental awareness and includes three game subjects, namely, EVs manufacturers, fuel vehicle manufacturers, and the government, and further verify the efficiency of dual credit policy over subsidy one. Using an evolutionary game model among consumers, EVs manufacturers, and the government under the EPR system, He and Sun (2022) found that the government's dynamic reward and punishment mechanism encourage consumers and 97% of EVs enterprises to participate in power battery recycling; the cost of recycling is the biggest influencing factor that hinders the recycling of power batteries by EVs manufacturers, and the change of recycling price of third-party recycling enterprises will affect the development of recycling industry.

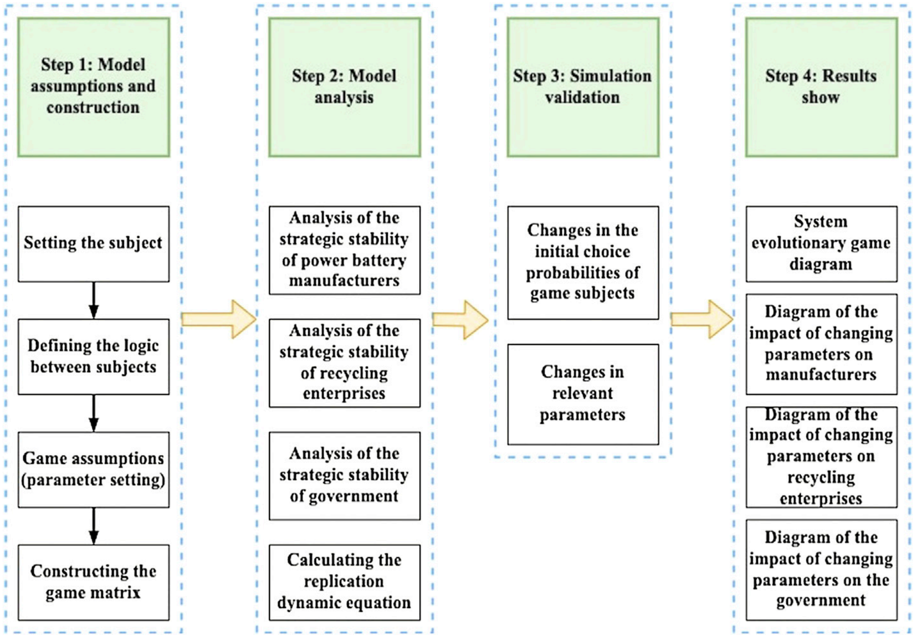

FIGURE 1
Framework for studying the evolution of a tripartite game for recycling critical metals in power batteries.

There are many literatures on government policy research, but there is a lack of research on the design of power battery recycling network at the enterprise level (Wang et al., 2020). In order to improve the efficiency of power battery recycling and the utilization rate of recycled power batteries, it seems difficult to rely only on the government, and the roles and interactions between different players must be considered (Kong et al., 2020). Specifically, the cooperation between recycling enterprises and power battery stakeholders can promote a mutually beneficial win-win situation (Ding and Zhong, 2018; Sopha et al., 2022). Therefore, it is necessary to study the cooperation between interest groups in the battery recycling industry in China (Zhou et al., 2007).

In summary, this study structures an evolutionary game model of three responsible parties in the power battery recycling chain to address 1) the influence of the initial selection probability of production enterprises, recycling manufacturers, and the government on the evolutionary game process and results in power battery recycling. 2) The impact on the game subject is analyzed from the perspectives of cooperation cost, supervision cost, and the amount of rewards and penalties; furthermore, the mitigation effect of power battery recycling on the supply shortage of critical metal resources is analyzed. Compared with previous studies, the model scenario of this study is more practical and the analysis of the scenario is richer. First, this study considers the participation willingness of both power battery manufacturers and recycling enterprises; second, the model of three-party game is introduced to analyze the evolution process of the three-party game under the reward and punishment mechanism. Third, this study introduces the optimization behavior of the dynamic reward and punishment mechanism for the three game subjects. Finally, this study analyzes the influence of key factors on group behavior and provides policy suggestions for power battery recycling to alleviate the supply shortage of critical metals. This can help policy makers to make better policies and help alleviate the tight supply and demand situation of critical metals. The rest of the article is structured as follows: *Section 2* constructs a three-party evolutionary game model, *Section 3* provides a stability analysis of the game subjects, *Section 4* conducts simulations, and the last section gives conclusions and policy recommendations.

Tripartite evolutionary game modeling

Research framework

This study adopts the evolutionary game method for research, and the specific research framework (Figure 1) can be obtained as follows: first, the game model is hypothesized based on the actual situation, including determining the game subject, setting the game relationship between the subjects and the parameters in the game relationship, and constructing the pure strategy game matrix.

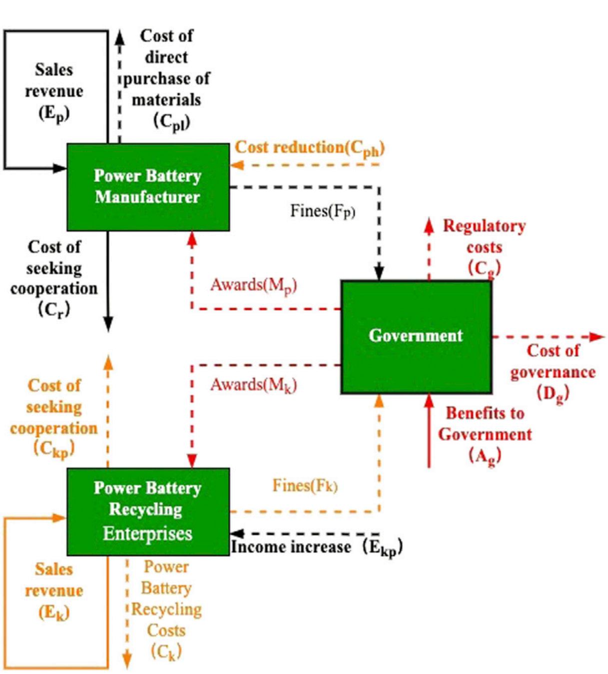

FIGURE 2
Evolutionary game model among power battery manufacturers, recycling enterprises, and government.

Second, we analyzed the stability of game models and evolutionary stable strategy (ESS), including the calculation of the dynamic replication equation under different pure game strategies, phase diagram of strategy evolution, and Jacobian matrix of the stable system. Third, the model parameters are assigned to the actual situation, and a simulation analysis is carried out to observe the influence of the change in the initial selection probability of the subject and the change in related parameters on the evolution process of all parties in the evolutionary game. Finally, the related results are described by images.

Game model assumption

The reduction in the supply of critical metals has exacerbated the tension of the contradiction between supply and demand, resulting in increased production costs for power battery manufacturers. The government has strengthened its supervision of power battery recycling enterprises, which makes it difficult for them to sell recycled power batteries to unqualified enterprises. Under the guidance of the government, power battery manufacturers and third-party recycling enterprises are willing to cooperate and spend some cost to seek cooperation. Therefore, the government, power battery manufacturers, and recycling enterprises are the main participants of power in battery recycling.

Based on the aforementioned scenarios, this study constructs a three-party evolutionary game system (Figure 2) and puts forward the following reasonable assumptions:

Assumption 1: The power battery manufacturer is participant 1, the third-party recycling enterprise is participant 2, and the government regulatory department is participant 3. The three parties are rational subjects with limited participation, and the choice of strategy gradually evolves over time and stabilizes at the optimal strategy. This study only considers the scenario that power battery manufacturers and recycling enterprises cooperate to recycle power batteries. Power battery manufacturers are not directly involved in power battery recycling. Third-party recycling enterprises do not include manufacturers.

Assumption 2: The strategy space for power battery manufacturers is $\alpha = (\alpha_1, \alpha_2) =$ (using recycled power batteries, not using recycled power batteries), the probability of choosing α_1 is x, and the probability of choosing α_2 is $1 - x$, $x \in [0, 1]$. The strategy space for the third-party recycling enterprises is $\beta = (\beta_1, \beta_2) =$ (cooperation, non – cooperation), the probability of choosing β_1 is y, and the probability of choosing β_2 is $1 - y$, $y \in [0, 1]$. The strategic space for the government regulatory department is $\gamma = (\gamma_1, \gamma_2) =$ (strict supervision, loose supervision), the probability of choosing γ_1 is z, and the probability of choosing γ_2 is $1 - z$, $z \in [0, 1]$.

Assumption 3: The production cost of power battery manufacturer is C_{pl}. Power battery manufacturers can choose to cooperate with third-party recycling enterprises and purchase their recycled power batteries from third-party recycling enterprises through cooperation. The cost of power battery manufacturers seeking cooperation is C_r. The cost of recovering critical metals from the recycled power battery is lower than the cost of buying from the market, and the use of recycled power batteries reduces the production cost of power battery manufacturers to a certain extent. This part of the cost is C_{ph}. The operating income of the power battery manufacturer is E_p. Under the strict supervision of the government, the power battery manufacturer actively seeks to cooperate with third-party recycling enterprises, the government will reward M_p. Otherwise, the negative behavior of power battery manufacturers will be punished, and the punishment amount is F_p.

Assumption 4: The cost of the third-party recycling enterprises is C_k, and the income is E_k. If under the guidance of government policies, the additional income obtained by the resale of recycled waste power batteries to power battery manufacturers for processing is E_{kp}, and the government award is M_k. If they are handed over to unqualified enterprises or hoarded and disturbed market prices, they will be fined F_k by the government.

Assumption 5: When the government regulates recycling behavior, the regulatory cost that the government pays is C_g. When power battery manufacturers and third-party recycling enterprises reach cooperation, the market price remains stable,

TABLE 1 Game matrix of mixed strategies.

		Third-party recycling agency	Government regulator	
			Strict supervision z	Loose supervision 1-z
Power battery manufacturer	Use recycled power batteries (x)	Intention to cooperate (y)	$E_p - C_{pl} + C_{ph} - C_r + M_p$ $E_k - C_k + C_r + M_k$ $-C_{kp} + E_{kp}$ $-C_g - M_p - M_k + A_g$	$E_p - C_{pl} + C_{ph} - C_r$ $E_k - C_k + C_r - C_{kp} + E_{kp}$ A_g
		Intention not to cooperate (1-y)	$E_p - C_{pl} - C_r$ $E_k - C_k - F_k$ $F_k - D_g - C_g$	$E_p - C_{pl} - C_r$ $E_k - C_k$ A_g
	No recycled power batteries are used (1-x)	Intention to cooperate (y)	$E_p - C_{pl} - F_p$ $E_k - C_k$ $F_p - D_g - C_g$	$E_p - C_{pl}$ $E_k - C_k$ A_g
		Intention not to cooperate (1-y)	$E_p - C_{pl} - F_p$ $E_k - C_k - F_k$ $F_k + F_p - D_g - C_g$	$E_p - C_{pl}$ $E_k - C_k$ A_g

the recycling industry develops healthily, the contradiction between the supply and demand of critical metals will be alleviated, and the government will gain social benefits A_g. Otherwise, any party is unwilling to cooperate, the contradiction between the supply and demand of critical metals in the market will further intensify, and the price of power battery will continue to rise. The government needs to consume manpower and material resources to renovate the market, and the cost of this part of governance is D_g. When the government loose supervision, if the power battery manufacturer and the third-party recycling enterprises do not reach cooperation, because the government cannot know the strategic choice information of the enterprise and the third-party recycling enterprises, the government regulatory department will not reward or punish. The means of government regulation mainly include setting up supervision agencies, setting recovery prices, public financial subsidies, penalties, rewards, sales tax, production tax, and setting up licensing systems.

According to the aforementioned assumptions, the mixed strategy game matrix of the power battery manufacturer, third-party recycling enterprises, and government can be obtained, as shown in Table 1.

Evolution model construction and stability analysis

In this section, we calculate the mathematical expectations and probabilities of the strategic choices of power battery producers, recycling enterprises, and governments, and the factors that influence the evolution of the game between the parties can be obtained and analyzed.

Strategy stability analysis of power battery manufacturers

The mathematic expectation that power battery manufacturers using recycled power batteries E_{11}, the mathematic expectation that power battery manufacturers not using recycled power batteries E_{12} and the average mathematic expectation $\overline{E_1}$ are as follows:

$$E_{11} = yz\left(E_p - C_{pl} + C_{ph} - C_r + M_p\right) + y(1-z)\left(E_p - C_{pl} + C_{ph} - C_r\right) + (1-y)z\left(E_p - C_{pl} - C_r\right) + (1-y)(1-z)\left(E_p - C_{pl} - C_r\right), \quad (1)$$

$$E_{12} = yz\left(E_p - C_{pl} - F_p\right) + y(1-z)\left(E_p - C_{pl}\right) + (1-y)z\left(E_p - C_{pl} - F_p\right) + (1-y)(1-z)\left(E_p - C_{pl}\right), \quad (2)$$

$$\overline{E_1} = xE_{11} + (1-x)E_{12}. \quad (3)$$

The dynamic replication equation of the power battery manufacturer's strategy selection is as follows:

$$F(x) = \frac{dx}{dt} = x\left(E_{11} - \overline{E_1}\right) = x(x-1)\left[\left(M_p y + F_p\right)z + C_{ph}y - C_r\right]. \quad (4)$$

The first derivative of x can be obtained by the following:

$$\frac{d(F(x))}{dx} = (1-2x)\left[\left(M_p y + F_p\right)z + C_{ph}y - C_r\right], \quad (5)$$

making

$$G(y) = \left(M_p y + F_p\right)z + C_{ph}y - C_{gr}. \quad (6)$$

According to the stability theorem of the ordinary differential equation, the probability of power battery production enterprises choosing to use recycled batteries in a stable state must satisfy $F(x) = 0$ and $\frac{d(F(x))}{dx} < 0$. $\frac{\partial G(y)}{\partial y} = M_p z + C_{ph} > 0$, so $G(y)$ is a monotonically increasing function with respect to y. When $y = y^* = \frac{C_r - F_p z}{zM_p + C_{ph}}$, $G(y) = 0$, $\frac{d(F(x))}{dx} \equiv 0$, unable to determine stabilization strategy; when $y < y^*$, $G(y) < 0$, $\frac{d(F(x))}{dx}|_{x=0} < 0$, $x = 0$ is ESS; when $y > y^*$, $G(y) > 0$, $\frac{d(F(x))}{dx}|_{x=1} < 0$, $x = 1$ is ESS.

As shown in Figure 3, V_1 represents the willingness of the power battery manufacturers to use the recycled power battery, and the probability that the power battery manufacturers are unwilling to use the recycled power battery can be expressed as V_2. The volumes of V_1 and V_2 are calculated as follows:

$$V_2 = \int_0^1 \int_0^1 \frac{C_r - F_p z}{zM_p + C_{ph}} dzdy = -\frac{F_p}{M_p} + \left[\frac{C_r}{M_p} + \frac{F_p C_{ph}}{M_p^2}\right] ln\left(1 + \frac{M_p}{C_{ph}}\right), \tag{7}$$

$$V_1 = 1 - V_2 = 1 + \frac{F_p}{M_p} - \left[\frac{C_r}{M_p} + \frac{F_p C_{ph}}{M_p^2}\right] ln\left(1 + \frac{M_p}{C_{ph}}\right). \tag{8}$$

Corollary 1: The willingness of power battery manufacturers to use recycled power batteries V_1 is negatively correlated with the benefits brought by using recycled power batteries C_{ph}, positively correlated with government rewards M_p and punishments F_p, and negatively correlated with the cost of seeking cooperation C_r.

Proof 1: Calculate the first partial derivative of each influencing factor according to the formula V_1. It is possible to obtain $\frac{\partial V_1}{\partial C_r} < 0$, $\frac{\partial V_1}{\partial M_p} > 0$, $\frac{\partial V_1}{\partial C_{ph}} > 0$, $\frac{\partial V_1}{\partial F_p} > 0$. Therefore, an increase in M_p, C_{ph} and F_p or a decrease in C_r will increase the probability that power battery manufacturers will seek to use recycled batteries.

Corollary 1 shows that it is important to ensure that manufacturers can make enough profit from using recycled power batteries. The government can increase the reward amount M_p and the punishment amount F_p to increase the willingness of the producer enterprises to use recycled power batteries V_1. The cost of seeking cooperation with recycling enterprises C_r restricts the willingness of power battery manufacturers to use recycled power batteries V_1.

Stability analysis of third-party recovery enterprises

The mathematic expectation that third-party recycling enterprises intend to cooperate with power battery manufacturers E_{21}, the mathematic expectation that third-party recycling enterprises unintended to cooperate with power battery manufacturers E_{22} and the average mathematic expectation $\overline{E_2}$ are as follows:

$$\begin{aligned} E_{21} &= xz(E_k + C_r + M_k - C_k - C_{kp}) + x(1-z)(E_k + C_r - C_k - C_{kp}) \\ &+ (1-x)z(E_k - C_k - C_{kp}) + (1-x)(1-z)(E_k - C_k - C_{kp}), \end{aligned} \tag{9}$$

$$\begin{aligned} E_{22} &= xz(E_k - C_k - F_k) + x(1-z)(E_k - C_k) \\ &+ (1-x)z(E_k - C_k - F_k) + (1-x)(1-z)(E_k - C_k), \end{aligned} \tag{10}$$

$$\overline{E_2} = yE_{21} + (1-y)E_{22}. \tag{11}$$

The dynamic replication equation of the power battery manufacturer's strategy selection is as follows:

$$F(y) = \frac{dy}{dt} = y\left(E_{21} - \overline{E_2}\right) = y(1-y)\left[(M_k x + F_k)z + C_k x - C_{kp}\right]. \tag{12}$$

The first derivative of y can be obtained by the following:

$$\frac{d(F(y))}{dx} = (1-2y)\left[(M_k x + F_k)z + C_k x - C_{kp}\right], \tag{13}$$

making

$$J(z) = (M_k x + F_k)z + C_k x - C_{kp}. \tag{14}$$

According to the stability theorem of ordinary differential equations, the probability of the third-party recycling enterprises choosing cooperation in a stable state must meet $F(y) = 0$ and $\frac{d(F(y))}{dy} < 0$. $\frac{\partial J(z)}{\partial x} = E_{zk}z + E_{k2} > 0$, so $J(z)$ is a monotonically increasing function with respect to x. When $z = z^* = \frac{C_{kp} - C_k x}{F_k + xM_k}$, $J(z) = 0$, $\frac{d(F(y))}{dy} \equiv 0$, it is unable to determine the stabilization strategy; when $z < z^*$, $J(z) < 0$, $\frac{d(F(y))}{dy}|_{y=0} < 0$, $y = 0$ is ESS, and when $z > z^*$, $J(z) > 0$, $\frac{d(F(y))}{dy}|_{y=1} < 0$, $y = 1$ is ESS.

As shown in Figure 4, V_1 represents that recycling enterprises are unwilling to cooperate with power battery manufacturer, and the probability of cooperation can be expressed as V_2, calculate the volumes of V_1 and V_2 as follows:

$$V_1 = \int_0^1 \int_0^1 \frac{C_{kp} - E_{kp}x}{F_k + xM_k} dxdz = -\frac{E_{kp}}{M_k} + \left[\frac{C_{kp}}{M_k} + \frac{E_{kp}F_k}{M_k^2}\right] \ln\left(1 + \frac{M_k}{C_{kp}}\right), \tag{15}$$

$$V_2 = 1 + \frac{E_{kp}}{M_k} - \left[\frac{C_{kp}}{M_k} + \frac{E_{kp}F_k}{M_k^2}\right] \ln\left(1 + \frac{M_k}{C_{kp}}\right). \tag{16}$$

Corollary 2: The probability of third-party recycling enterprises choosing cooperation V_2 is positively correlated with government rewards M_k, punishments F_k and increased benefits of cooperation E_{kp}, negatively correlated with the cost of seeking cooperation C_{kp}.

Proof 2: Calculate the first partial derivative of each influencing factor according to the formula. V_1. It is possible to obtain $\frac{\partial V_1}{\partial C_{kp}} < 0$, $\frac{\partial V_1}{\partial M_k} > 0$, $\frac{\partial V_1}{\partial E_{kp}} > 0$, $\frac{\partial V_1}{\partial F_k} > 0$. Therefore, an increase in M_k, E_{kp} and F_k or a decrease in C_{kp} will lead to a rise in the probability of third-party power battery recycling enterprises seeking cooperation.

Corollary 2 indicates that the government should play the role of bridge and build a cooperation platform between power battery manufacturers and third-party recycling enterprises through the guidance of the government. The government should increase the rewards M_k and punishments F_k for third-party recycling enterprises, that is, to reward the

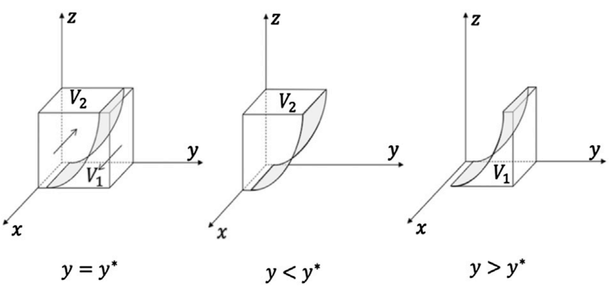

FIGURE 3
Phase diagram of power battery manufacturing enterprises strategy evolution.

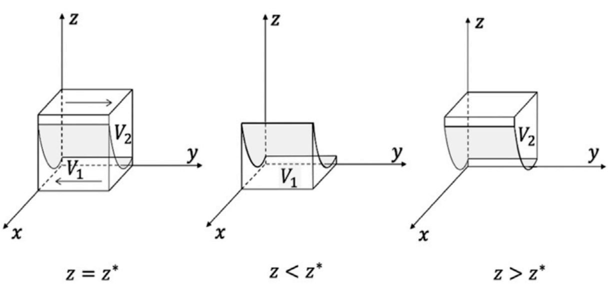

FIGURE 4
Phase diagram of recycling enterprises strategy evolution.

recycling enterprises that carry out recycling cooperation according to law and increase the punishments for the illegal behaviors of the recycling enterprises, so as to increase the willingness of third-party recycling enterprises to cooperate V_2. Power battery manufacturers should adopt the strategy of high price recycling to increase the cooperation income of recycling enterprises E_{kp}. The cost of recycling enterprises in seeking cooperation with manufacturing enterprise C_{kp} restricts their willingness to cooperate V_2.

Stability analysis of government

The mathematic expectation that power battery manufactures using recycled power batteries E_{31}, the mathematic expectation that power battery manufactures not using recycled power batteries E_{32}, and the average mathematic expectation $\overline{E_3}$ are as follows:

$$\begin{aligned}E_{31} &= xy\left(-C_g - M_p - M_k + A_g\right) + x(1-y)\left(F_k - D_g - C_g\right)\\&+(1-x)y\left(F_p - D_g - C_g\right) + (1-x)(1-y)\left(F_p + F_k - D_g - C_g\right),\end{aligned} \tag{17}$$

$$E_{32} = xy\left(A_g\right) + x(1-y)\left(-D_g\right) + (1-x)y\left(-D_g\right) + (1-x)(1-y)\left(-D_g\right), \tag{18}$$

$$\overline{E_3} = zE_{31} + (1-z)E_{32}\,. \tag{19}$$

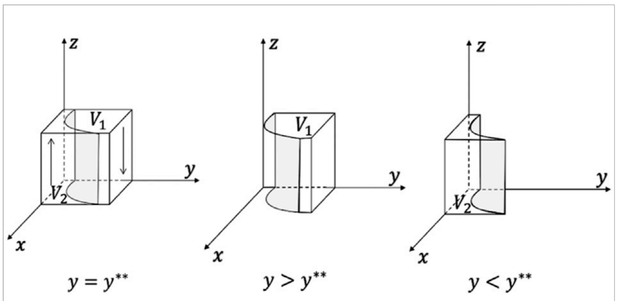

FIGURE 5
Phase diagram of government strategy evolution.

The dynamic replication equation of the power battery manufacturer's strategy selection is as follows:

$$\begin{aligned}F(z) = \frac{dz}{dt} = z\left(E_{11} - \overline{E_1}\right) = z(1-z),\\\left\{\left[\left(D_g - M_k - M_p\right)x - F_k\right]y + F_p x + F_p - D_g + F_k - C_g\right\}.\end{aligned} \tag{20}$$

The first derivative of z can be obtained:

$$\frac{d(F(z))}{dz} = (1-2z)\left\{\left[\left(D_g - M_k - M_p\right)x - F_k\right]y + F_p x + F_p - D_g + F_k - C_g\right\}, \tag{21}$$

making

$$H(y) = \left[\left(D_g - M_k - M_p\right)x - F_k\right]y + F_p x + F_p - D_g + F_k - C_g\,. \tag{22}$$

According to the stability theorem of ordinary differential equations, the probability of strict government supervision in a stable state must meet $H(y) = 0$ and $\frac{d(F(z))}{dz} < 0$. $\frac{\partial H(y)}{\partial y} = (D_g - M_k - M_p)x - F_k < 0$, $H(y)$ is a monotonically decreasing function with respect to y, when $y = y^{**} = \frac{F_p + F_k - F_p x - C_g}{x(M_p + M_k) + F_k}$, $H(y) = 0$, $\frac{d(F(z))}{dz} \equiv 0$, unable to determine stabilization strategy; when $y < y^{**}$, $H(y) < 0$, $\frac{d(F(z))}{dz}|_{z=1} < 0$, $z = 1$ is ESS; when $y > y^{**}$, $H(y) > 0$, $\frac{d(F(y))}{dy}|_{z=0} < 0$, $z = 0$ is ESS.

As shown in Figure 5, V_2 represents the probability of government strengthening supervision, the probability of loose supervision can be expressed as V_1, and the volumes V_1、V_2 are calculated as follows:

$$\begin{aligned}V_2 = \int_0^1\int_0^q \frac{F_k + F_p - F_p x - C_g}{x\left(M_p + M_k\right) + F_k}\,dxdz = -\frac{F_p}{M_p + M_k}\\+\left[\frac{F_k + F_p - C_g}{M_p + M_k} + \frac{F_K F_p}{\left(M_p + M_k\right)^2}\right]\ln\left(1 + \frac{M_p + M_K}{F_K}\right),\end{aligned} \tag{23}$$

$$V_1 = 1 + \frac{F_p}{M_p + M_k} - \left[\frac{F_k + F_p - C_g}{M_p + M_k} + \frac{F_K F_p}{\left(M_p + M_k\right)^2}\right]\ln\left(1 + \frac{M_p + M_K}{F_K}\right). \tag{24}$$

Corollary 3. The probability of the government's strict supervision V_2 is positively correlated with the amount of the

TABLE 2 Stability analysis of equilibrium points of the three-party evolutionary game system.

equilibrium	Eigenvalues of the Jacobian		Stability conclusion	Conditions
	$\lambda_1, \lambda_2, \lambda_3$	Symbol		
$E_1 = (0,0,0)$	$-C_{kp}, -C_r, F_k + F_p - C_g$	$(-,-,\times)$	Not sure	A
$E_2 = (1,0,0)$	$C_r, E_{kp} - C_{kp}, F_k - C_g$	$(+,+,-)$	Instability point	
$E_3 = (0,1,0)$	$C_{kp}, C_{ph} - C_r, F_p - C_g$	$(+,+,-)$	Instability point	
$E_4 = (0,0,1)$	$F_k - C_{kp}, F_p - C_r, C_g - F_k - F_p$	$(\times,\times,-)$	Not sure	B
$E_5 = (1,1,0)$	$C_r - C_{ph}, C_{kp} - E_{kp}, -C_g - M_p - M_k$	$(-,-,-)$	ESS	C
$E_6 = (1,0,1)$	$C_r - F_p, C_g - F_k, E_{kp} - C_{kp} + F_k + M_k$	$(\times,\times,+)$	Instability point	
$E_7 = (0,1,1)$	$C_{kp} - F_k, C_g - F_p, C_{ph} - C_r + F_p + M_p$	$(\times,\times,+)$	Instability point	
$E_8 = (1,1,1)$	$C_r - C_{ph} - F_p - M_p, C_{kp} - E_{kp} - F_k - M_k, C_g + M_p + M_k$	$(-,-,+)$	Instability point	

(A: $F_k + F_p < C_g$, B: $F_k < C_{kp}$, $F_p < C_r$, C: $C_r < C_{ph}$, $C_{kp} < E_{kp}$, $\times$ indicates symbol uncertainty).

TABLE 3 Parameter values for each stage in the evolutionary game model.

Parameters	C_{pl}	C_{ph}	E_p	C_r	F_p	M_p	C_k	E_k	E_{kp}	M_k	F_k	C_{kp}	C_g	A_g	D_g
Value	130	60	150	30	50	15	8	30	11	2	3	5	20	30	10

government's rewards M_p and punishments F_p for power battery manufacturers; it is positively correlated with the reward amount M_k and punishment amount F_k of third-party recycling enterprises; it is negatively correlated with government rewards for power battery manufacturers and third-party recycling enterprises $(M_p + M_k)$ and negatively correlated with government regulatory costs C_g.

Proof 3: Calculate the first partial derivative of each influencing factor according to the formula of V_1, $\frac{\partial V_1}{\partial (M_p + M_k)} < 0$, $\frac{\partial V_1}{\partial F_p} > 0$, $\frac{\partial V_1}{\partial C_g} < 0$, $\frac{\partial V_1}{\partial F_k} > 0$. An increase in F_k, F_p and $(M_p + M_k)$ or a decrease in C_g will increase the probability that a power battery manufacturer will seek to use recycled batteries.

Corollary 3 shows that the greater the punishment degree of the government to manufacturer F_p and recycling enterprises F_k, the more conducive to government supervision. The greater the reward degree of the government to the production enterprises M_p and the greater the reward degree of the recycling enterprises M_k, the more unfavorable the implementation of government supervision. The government needs to strictly control the cost of supervision C_g, which is not conducive to the implementation of government supervision.

Stability analysis of ESS

According to Lyapunov's first rule: all eigenvalues of the Jacobian matrix have negative real parts, then the equilibrium point is asymptotically stable. If at least one of the eigenvalues of the Jacobian matrix has a positive real part, the equilibrium point is not stable. Make $F(x) = 0$, $F(y) = 0$, $F(z) = 0$, the equilibrium point of the system can be obtained: $E_1 = (0,0,0)$, $E_2 = (1,0,0)$, $E_3 = (0,1,0)$, $E_4 = (0,0,1)$, $E_5 = (1,1,0)$, $E_6 = (1,0,1)$, $E_7 = (0,1,1)$, $E_8 = (1,1,1)$. The stability analysis of the Jacobian matrix and equilibrium point of the three-party evolutionary game system (Table 2) is shown as follows:

$$J = \begin{bmatrix} J_1 & J_2 & J_3 \\ J_4 & J_5 & J_6 \\ J_7 & J_8 & J_9 \end{bmatrix} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix},$$

$$= \begin{bmatrix} (1-2x)\left[(M_p y + F_p)z + C_{ph} y - C_r\right], & x(1-x)(M_p z + C_{ph}), & x(1-x)(M_p y + F_p), \\ y(1-y)(M_k z + E_{kp}), & (1-2y)\left[(M_k x + F_k)z + C_k x - C_{kp}\right], & y(1-y)(M_k x + F_k), \\ z(1-z)\left[(D_g - M_k - M_p)y + F_p\right], & z(1-z)\left[(D_g - M_k - M_p)x - F_k\right], & (1-2z)\{\left[(D_g - M_k - M_p)x - F_k\right]y + F_p x + F_p - D_g + F_k - C_g\}, \end{bmatrix} \quad (25)$$

Corollary 4: When $C_r < C_{ph}$ and $F_{p'} C_{kp} < E_{kp}$ and $F_{k'}$ $(F_k + F_p) > C_g$, there is only one ESS in the system: $E_5 = (1,1,0)$; when $F_k < C_{kp'} F_p < C_{r'} (F_k + F_p) < C_g$, there are three ESS in the system: $E_1 = (0,0,0)$, $E_4 = (0,0,1)$ and $E_5 = (1,1,0)$.

Corollary 4 shows that when the following conditions are met, the evolution of the strategy combination is stable at E_5 (using recycled power battery, cooperation, loose supervision): (1) the cost reduced by the manufacturer when using recycled power battery C_{ph} is greater than the cost of the power battery manufacturer seeking joint renting C_r; (2) the punishment

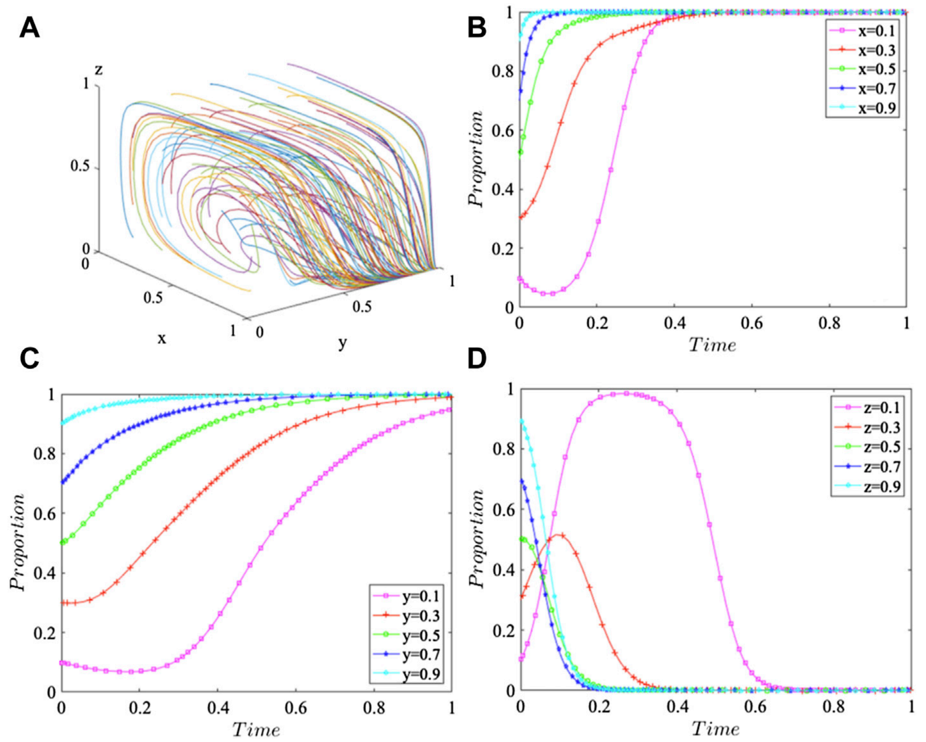

FIGURE 6
Results of three parties with different initial selection probabilities. **(A)** Results of ESS with different initial selection probabilities, **(B)** evolutionary game results of power battery manufacturers under different initial selection probabilities, **(C)** evolutionary game results of recycling enterprise under different initial selection probabilities, **(D)** evolutionary game results of government under different initial selection probabilities.

imposed by the government on the manufacturer F_p is greater than the cost of the power battery manufacturer seeking joint renting C_r; (3) when the third-party recycling enterprises cooperate with power battery manufacturers, the increase of enterprise income E_{kp} is greater than the cost of third-party recycling enterprises seeking external cooperation C_{kp}; (4) when the third-party recovery agencies do not cooperate, the government's punishments F_k is greater than the cost of the third-party recovery agencies seeking cooperation C_{kp}; (5) the sum of fines imposed by the government on power battery manufacturers and third-party recycling enterprises $F_k + F_p$ is greater than the cost of government supervision C_g.

Simulation analysis

In order to intuitively observe the dynamic evolution of the behavior of the three stakeholders in the power battery recycling model and verify the validity of the aforementioned analysis, the model parameters were assigned and simulated based on Corollary 4. The parameters are assigned according to Lander et al. (2021) and the actual situation. Table 3 illustrates the initial game values of the three stakeholders.

Each parameter value in Table 2 satisfies the stability conditions, and 50 groups of different initial strategy points of x, y and z are randomly generated to verify that the equilibrium point $E_5 = (1, 1, 0)$ is the stable equilibrium point in the dynamic system. The different colored lines in Figure 6A show the evolutionary process of the three-way evolutionary game. They finally converge to E_5. The results of the evolutionary game show that no matter what the initial strategies of each party are, when the constraint conditions of Inference four are satisfied, $E_5 = (1, 1, 0)$ is the ESS of the system, which effectively validates the analysis results mentioned before. Regardless of whether the government strictly regulates or not, power battery manufacturers and recycling enterprises will cooperate on power battery recycling as the supply and demand contradiction of critical metals continues to intensify.

Compared with the evolution process of power battery manufacturers and third-party recycling enterprises, it takes a long time for third-party recycling enterprises to reach E_5 with the same initial probability selection. For both production

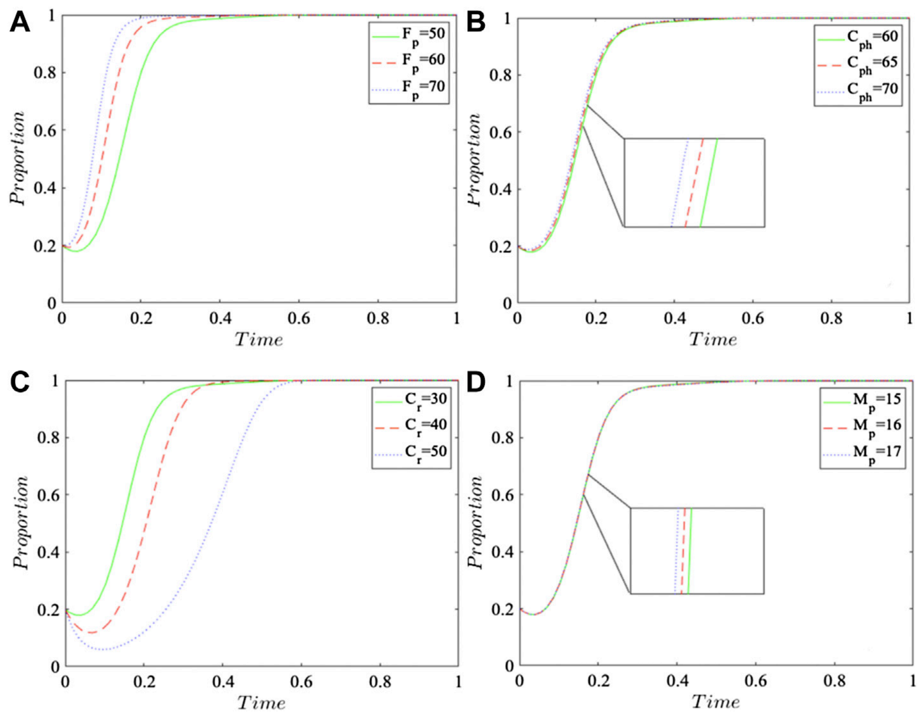

FIGURE 7
Influence of changing parameters on power battery manufacturers. **(A)** Impact of changes in the amount of punishment, **(B)** impact of changes in profits from using power batteries, **(C)** impact of changes in collaboration costs, **(D)** impact of changes in the amount of reward.

enterprises and recycling enterprises, the increase in initial selection probability will speed up the process to reach E_5 (Figures 6B,C). For the government, it can be observed that when the probability of choosing strict supervision is 0.1 and 0.3, the initial evolution direction changes toward strict supervision and then becomes loose supervision. After the initial probability exceeds 0.3, the evolution direction continues to evolve in the direction of loose supervision (Figure 6D).

To analyze the cost saved by enterprises, the government's rewards and punishments for enterprises, and the impact of cooperation cost changes on power battery manufacturers, assign 50, 60, and 70 to F_p; assign 60, 65, and 70 to C_{ph}; assign 30, 40 and 50 to C_r; assign 15, 16 and 17 to M_p, observation of the replication dynamics equations of production firms evolving 50 times over time under the same initial selection probability.

With the amount of government reward M_p, the punishment F_p and the use of recycled power batteries to reduce costs for enterprises C_{ph}, the process for the evolutionary game to reach E_5 becomes faster (Figures 7A,B,D), which indicates that power battery manufacturers are more willing to use recycled power batteries. The change in power battery use intention F_p has a stronger effect on the change. The increase in cooperation cost of power battery manufacturers C_r has a restraining effect on the willingness to use power battery, which is shown as with the increase in cooperation cost C_r, the process for the probability curve to reach E_5 becomes slower and presents a trend of continuous expansion (Figure 7C). This indicates that the inhibiting effect of increasing the cost of cooperation C_r on producers' willingness to use recycled power batteries is more pronounced than the promoting effect of increasing the fine F_p on producers' willingness to use recycled power batteries. Therefore, higher cooperation costs C_r are the main obstacle to the cooperation between production enterprises and recycling enterprises.

To analyze the increased sales revenue after cooperation, the government's rewards and punishments, and seek the impact of changes in cooperation costs on recycling enterprises, assign 5, 6, and seven to C_{kp}; assign 2, 4, and six to M_k; assign 11, 12, 13 to E_{kp}; assign 3, four and five to F_k, observation of the replication dynamic equations of the recycling enterprises evolving 50 times over time under the same initial selection probability.

When the government reward amount M_k, punishment amount F_k and increased revenue from cooperation E_{kp} increase, the process for the probability curve to reach E_5 becomes faster (Figures 8B–D). This means that it takes less time for third-party recycling enterprises to make cooperative decisions. By comparison, it is found that the curve in Figure 8A is more affected by variable changes, indicating that the third-party recycling enterprises pay more attention to the increased income after cooperation E_{kp} when making decisions. As the cost

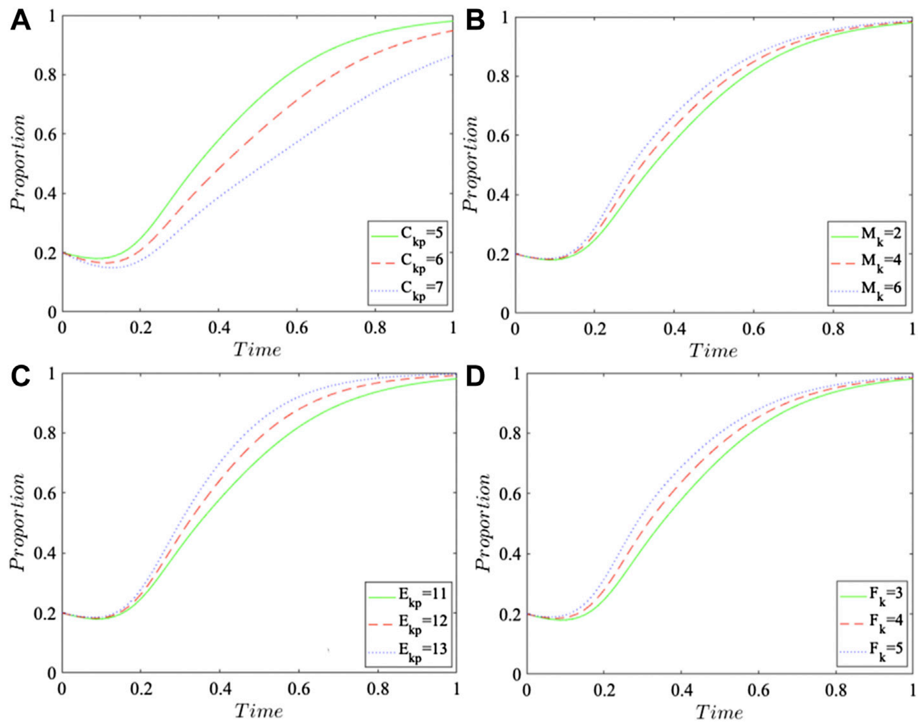

FIGURE 8
Influence of changing parameters on third-party recycling enterprises. **(A)** Impact of changes in collaboration costs, **(B)** impact of changes in the amount of reward, **(C)** impact of changes in profits in increase profits, **(D)** impact of changes in the amount of punishment.

of seeking cooperation C_{kp} increases, the willingness of third-party recycling enterprises to cooperate decreases. Like the graphs of power battery manufacturers, the increase in cooperation cost C_{kp} has a greater impact on the willingness of third-party recycling enterprises to cooperate relatively to the change in other parameters.

To analyze the effects of increasing government regulatory cost C_g, government rewards M_p and punishments F_p for power battery manufacturers, and government rewards M_k and punishments F_k for recycling enterprises on government selection strategies, assign 20, 25 and 30 to C_g; assign 2, four and six to M_k; assign 15, 25 and 35 to M_p; assign 3, six and nine to F_k; assign 50, 60 and 70 to F_p. observation of the replication dynamic equations of the government evolving 50 times over time under the same initial selection probability.

With the increase in M_p, F_p, M_k, and F_k, the probability curve can evolve to E_5 faster and is more obvious in the middle of the game than in the early and late stages (Figures 9B–E). The government's willingness to strictly regulate acts as a disincentive. Especially as government decisions evolve toward lighter supervision, the increase of M_p, F_p, M_k and F_k have an increasingly pronounced effect on the impetus for lenient government supervision. When the government's regulatory cost C_g increases, it has a dampening effect on the government's decision regardless of whether the government's regulatory intention is strict or loose, and the probability curve takes significantly longer to reach E_5. This indicates that changes in government regulatory cost C_g have a greater impact on the government's evolutionary game (Figure 9A).

The aforementioned simulation results show that, under the assignment conditions of Table 2, the system only has one combination of evolutionarily stable strategies (use recycled power battery, cooperation, loose supervision), which is consistent with the conclusion of inference 4. The simulation results are consistent with the analysis results, which have certain practical guiding significance for the development of the critical metal recycling market.

Conclusion and policy recommendations

With the rapid growth of the demand for EVs critical metals and the continuous contradiction between the supply and demand of critical metals, the efficient recycling of power batteries plays an increasingly prominent role in alleviating the tight supply of critical metals and protecting the environment. As stakeholders, the production manufacturers,

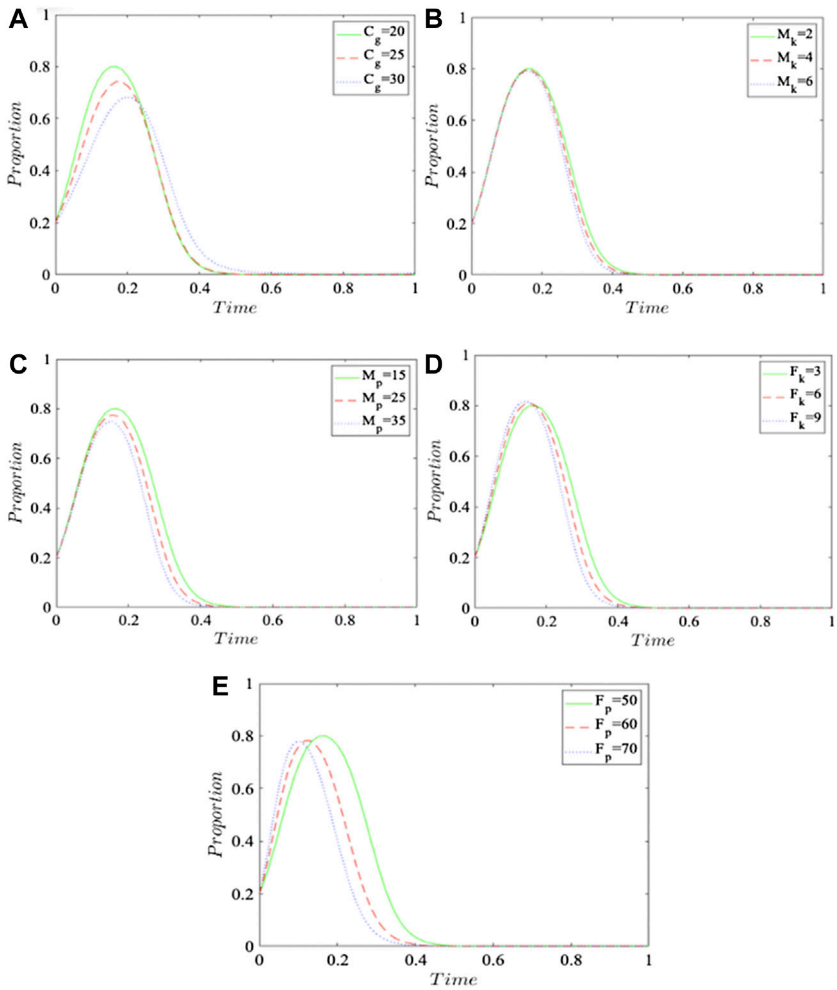

FIGURE 9
Influence of changing parameters on the government. **(A)** Impact of changes in monitoring costs, **(B)** impact of changes in rewards for recycling enterprises, **(C)** impact of changes in rewards for power battery manufacturers, **(D)** impact of changes in punishments for recycling enterprises, **(E)** impact of changes in punishments for power battery manufacturers.

recycling enterprises and the government have a great impact on this process. Therefore, this study considers the impact of recycling cooperation between power battery manufacturers and recycling enterprises under government supervision on the contradiction between the supply and demand of critical metals used in power battery production, and constructs a three-party evolutionary game model between them. The stability of each strategy choice, the system stability, and the influence of each factor on the main body of the game are analyzed. The effectiveness of the results is verified by simulation. The main conclusions and policy recommendations are included as follows:

(1) The initial probability of selection strategy does not change the decision only affects the process of E_5. When the probability of strict supervision is low at the beginning, the government will prefer to change from strict supervision to loose supervision. When the probability of strict supervision is high at the beginning, the willingness for strict supervision will gradually decrease with the increase in the number of games and finally stabilize to loose supervision. Regardless of the initial selection probability, the choice intention of the manufacturer and the recycling institution can evolve toward E_5. Power battery manufacturers are more affected by a tight supply of critical metals than third-party recyclers. Regardless of whether a power battery manufacturer's initial willingness to use recycled batteries is strong, their strategy has evolved to E_5 faster than third-party recycling enterprises. The government should pay more attention to the willingness

of third-party recycling enterprises to cooperate with power battery manufacturers and crack down on their illegal distribution channels, which could improve the supply shortage of critical metals.

(2) The effective way to promote cooperation between power battery manufacturers and recycling enterprises is to ensure an increase in both sides' income after cooperation. In the case of a shortage of critical metals in the power battery production process, power battery manufacturers must increase the use of recycled power battery to reduce the consumption of primary resources to reduce the manufacturing cost of power battery. For production enterprises, it is better to suggest that the government strengthen market supervision rather than spending much on negotiating with third-party recycling enterprises. Recycling enterprises need to appropriately increase recycling efforts and technical input according to their own economic conditions. With the expansion of the recycling scale and the increase in government subsidies, recycling enterprises need to choose appropriate development strategies according to their own conditions. Continuing to increase cooperation is a good development direction for recycling enterprises to increase profits while maintaining the same cost.

(3) Government rewards and punishments are conducive both to promote cooperation between power battery manufacturers and recycling enterprises and to encourage the recovery and utilization of critical metals. The cost of cooperation between both parties will be the key factor affecting the recovery of power battery. The government should pay close attention to the trend of the recycling market, increase the communication between manufacturers and recycling enterprises, and do a good job of publicizing policies to reduce the cost of cooperation so that both sides can gain certain benefits under the cooperation mode. The government needs to pay attention to the cost changes of market supervision and adjust the rewards and punishments mechanism according to the constant changes in the market. Static rewards and punishments mechanism will lead to rigid behavior patterns of participants in power battery recycling. Dynamic rewards and punishments will make power battery manufacturers more actively participate in recycling. Government rewards for power battery manufacturing enterprises cannot be too high, and the optimal battery recycling rate may be reduced by increased government rewards. In both model analysis and simulation analysis, government subsidies for power battery recycling enterprises and third-party recycling enterprises play a positive role in the decision-making of both parties. Relevant studies also show that government subsidies for manufacturers and third-party recycling enterprises promote the closed-loop development of the supply chain of EVs. The intensity of subsidies is the issue that the government needs to focus on when making policies. In the setting of the punishment amount, the punishments for noncooperation of third-party testing enterprises should be higher than that of power battery manufacturers.

Future work

This study only considers the game behavior among the three players of power battery recycling under the premise of bounded rationality and does not consider the influence of consumer behavior and other parameter changes on power battery production. Therefore, expanding the system boundary, combining system dynamics with game theory to draw more quantitative conclusions, and introducing consumers as game subjects will be our next research direction.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, SG and GL; methodology, SG and YW; software, SG; validation, SG and GL, and XG; formal analysis, SG; investigation, SG and GL; resources, SG; data curation, SG; writing—original draft preparation, SG; writing—review and editing, SG, GL, and XG; visualization, SG and YW; supervision, GL and XG; project administration, GL; funding acquisition, GL. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Volatility research of nickel futures and spot prices based on copula-GARCH model

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Nickel, an essential strategic emerging mineral in China, plays a vital role in promoting the development of the new energy vehicle industry and protecting the security of energy resources. However, the linkage between international and domestic nickel futures markets and the spot market is increasing. It is necessary to analyze and study the correlation characteristics and influence mechanisms to help investors avoid risks and judge the market situation which will improve the risk control ability and promote the steady development of the domestic market. Therefore, from the perspective of international and domestic markets and based on the yield sequence of the nickel futures prices and the spot prices, the study first discusses the characteristics of the volatility aggregation effect and asymmetries of the nickel futures and spot prices. Second, select an appropriate GARCH model to fit the marginal distribution sequence of the yields. Third, use the Copula function to connect the financial time series to find the correlation. The results indicate that the Copula-GARCH model can better fit the tail correlation between nickel futures market and spot market. Finally, we put forward policy recommendations for strengthening and improving the domestic nickel futures market, actively participating in the international competition mechanism, and preventing and controlling the risk of market price fluctuations.

KEYWORDS

Copula-GARCH model, price volatility correlation, LME nickel futures market, SMM nickel futures market, nickel spot market

Introduction

For the first time, mineral and power security were discussed at the Political Bureau of the CPC Central Committee meeting on 18 November 2021, elevating mineral security to the status of a national strategy. First, a long-term stable supply of mineral resources must be guaranteed. Second, we must prevent wildly fluctuating mineral resource prices. The market supply, psychology, finance, trade, and other elements to encourage the metal nickel futures prices have varied drastically. Nickel is an essential new energy mineral. The London Metal Exchange (LME) nickel price once again passed the $100,000/ton mark on 10 March 2022, hitting its most significant historical level. The SMM Nickel also followed LME nickel's lead at that time. However, despite being nickel-poor, China is the largest consumer of nickel resources all over the world. According to Antaike statistics, China's nickel dependence on foreign nations will reach an all-time high of 85% in 2020, indicating that China's nickel dependence has been above 80% since 2015. Due to China's extensive reliance on imported nickel resources, the local nickel price is greatly influenced by the price of nickel in other countries. To better understand the international and domestic nickel markets, increase the security of the supply of nickel from mines, and ensure the long-term steady and healthy growth of the Chinese nickel period spot market, it is helpful to study the correlation between domestic nickel period spot price and international nickel futures price.

The Copula function is suitable for analyzing the correlation between variables. Scholars mainly use it to study the correlation between multiple financial markets. (Sklar 1959) first proposed using the Copula function to connect the marginal distribution of multivariate joint distribution function variables to realize the analysis of complex correlation. Next, Nelson 1999) systematically summarized the theory of Copula function and its basic properties. Using the Copula function for correlation risk analysis has gradually become a standard. Although domestic research started late, it has made some achievements. The research scope mainly focuses on the correlation between the stock markets (Feng et al., 2016), stock market and crude oil price (Zhu et al., 2016; Liu and He 2020); the model can also be used to measure the comprehensive risk of China's carbon financial market (Wang et al., 2022) and analyze the correlation between exchange rate correlation and economic fundamentals (Gong et al., 2022). Presently, the research on the correlation of capital market is mainly focused on the domestic market, and there is less research on the correlation between international and domestic markets. However, with the development of the Chinese capital market, the correlation between international and domestic markets is closer, and the research on the correlation between domestic and international markets is becoming more and more critical. Therefore, this paper uses international and domestic perspectives as an entry point for research.

The GARCH model can accurately simulate the change of volatility of time series variables which enables people to grasp the risk fluctuation more accurately. For example, the volatility of crude oil prices is predicted based on the relevant GARCH model, which improves the forecasting ability of crude oil futures volatility (Klein et al., 2016; Wu et al., 2019; Verma et al., 2021); in addition, the correlation GARCH model can be used to study the relationship between emerging markets and stock market volatility (Nathani et al., 2022). Therefore, the GARCH model has excellent performance in price volatility and risk prediction. But there is less research on the nickel market based on the GARCH model, this paper decides to use it to study the nickel futures market and the spot market to make a contribution to the research in this field.

In the application of the Copula-GARCH model, scholars mainly used it to analyze the correlation between stocks, bonds, crude oil, and other markets. For instance, the Copula-GARCH model can be used to analyze the dependence of financial assets (Jondeauel 2006; Yu 2018); the model can also be used for the correlation analysis of the Shanghai, Hong Kong and Shenzhen Stock Exchanges. After the implementation of the Shanghai-Hong Kong Stock Connect policy, the tail correlation coefficient between Shanghai Stock Exchange Index and Hang Seng Index increased significantly. The daily yield sequences of the Shanghai and Shenzhen stock markets have a strong correlation and symmetry. When the Shanghai and Shenzhen stock markets fluctuate sharply, the synergistic effect of the yield sequences of the two markets will be significantly enhanced (Hou et al., 2019; Shi et al., 2021). At the same time, some scholars used the model to study the correlation and risk spillover effect of the stock market and found that the financial return series has the characteristics of time-varying fluctuations, high peaks and thick tails (Tang 2014; Wang 2017). Based on the Copula-GARCH model, some scholars have studied the correlation between the financial and real estate markets in mainland China and Hong Kong. The study showed a correlation between the financial and real estate markets in mainland China and Hong Kong (Sui et al., 2019); and some scholars based on the model and the empirical analysis of the Istanbul Stock Exchange, analyze the correlation between oil price and the stock market. The results show that all stock market returns and oil price changes are positively correlated, and there is a weak dependence structure between Istanbul Stock Exchange and Brent crude oil price (Ayse 2019; Kouki et al., 2019).

The Copula-GARCH model is also applied to other aspects. Some scholars studied the hedging effect based on the Copula-GARCH model, it is found that the margin of stock index futures and the exchange rate will have a certain impact on the hedging effect (Guo et al., 2017; Yu et al., 2019; Zhu et al., 2020). The Copula-GARCH model also plays an important role in the study of the interdependence between oil prices and exchange rates. The study shows that there is a mutual relationship between two variables which helps to diversify risks and achieve inflation targeting. (Aloui et al., 2013; He et al., 2019, Thai Hung; Ngo 2019), and some studies have evaluated the conditional dependence structure of commodity futures markets based on the Copula-GARCH model, and the analysis shows that there are significant differences in the correlation between commodity futures (Just et al., 2020). In addition, Quantile causality and the DCC Copula-GARCH method are used to analyze the causal relationship between exchange rate and real estate price in boom and bust markets, the study shows that there is a greater causality between house prices and exchange rates in the booming market compared to the bust market (Woraphon et al., 2022).

Through the research of nickel futures and spot prices, it is found that nickel futures have a certain price discovery

TABLE 1 Statistical descriptions.

Indicators	The spot price	SMM nickel	LME nickel
mean	0.000478	0.000476	0.000482
Median	0.000447	0.000309	0.001203
Maximum	0.222480	0.193107	0.147819
Minimum	−0.251253	−0.163705	−0.226485
Standard deviation	0.018964	0.018015	0.019518
Skewness	−0.030132	0.439762	−0.643440
Kurtosis	39.68985	22.27301	21.56791
J-B	96,698.38	26,737.99	24,884.75
Probability	0.000000	0.000000	0.000000

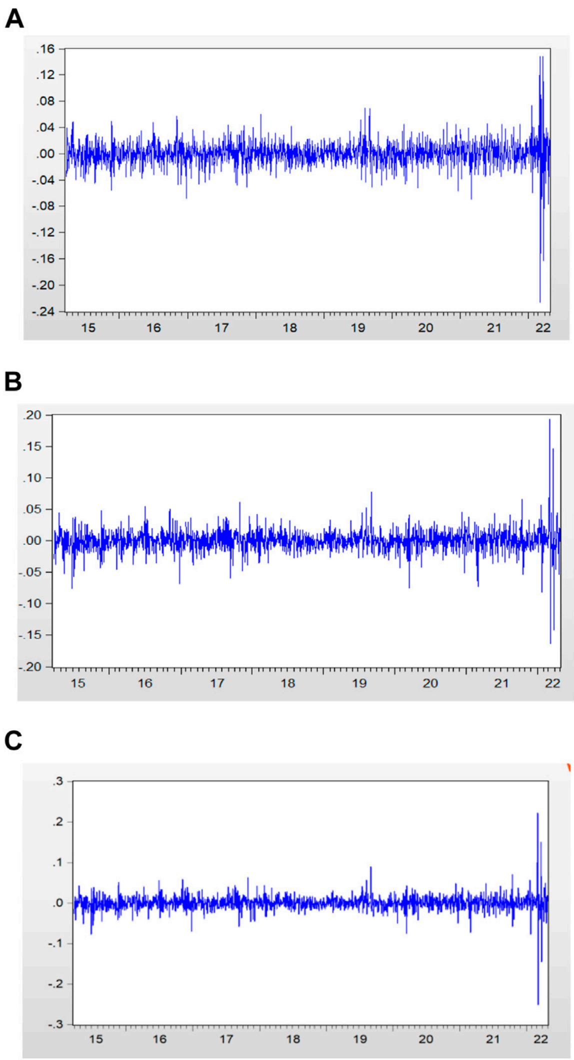

FIGURE 1
Time sequence diagram of yield series **(A)** LME Nickel, **(B)** SMM Nickel, **(C)** The spot price.

function. Based on the Johansen cointegration test and wavelet coherence analysis, the researchers compared the price discovery efficiency of Chinese non-ferrous metal futures and found that nickel futures price could guide spot price to a certain extent (Yu 2019); and then, based on the distributed lag model, the study analyzed the network evolution of the linkage effect between nickel futures and spot prices which shows that the change in spot prices is caused by the change in nickel futures prices (Dong et al., 2019). Making full use of the price discovery function of nickel futures is beneficial to Chinese investors to avoid the risk in time and realize hedging. The COVID-19 pandemic has had a huge impact on traditional energy manufacturing, with geopolitical risks in the low frequency band, unprecedented impacts on economic policies and stock volatility of oil prices plummeting (Nwosa Philip Ifeakachukwu, 2021; Zhu et al., 2021; Zhang et al., 2021; Sharif et al., 2020; Adedeji Abdulkabir et al., 2021). But to some extent, it has also promoted the development of new energy industries. Research on new energy minerals has gradually become a hot topic.

In conclusion, the research on the correlation of financial time series in the existing literature tends to focus on stocks, bonds, crude oil and other fields, while there are fewer studies on the correlation of new energy minerals (such as lithium, cobalt and nickel). However, new energy minerals have been widely concerned with the advancement of global "carbon neutrality" in recent years. Since last year, the soaring price of nickel futures has exposed China to price and supply security risks. Therefore, it is necessary to effectively avoid market risks by analyzing the correlation of nickel price fluctuations.

What's more, this paper discusses the correlation between the nickel futures market and spot market from international and domestic perspectives, which overcome the shortcoming that previous studies only considered domestic market or international market. Besides, this article adopts the method of combining the GARCH model and the Copula function to build the Copula-GARCH model to describe the correlation between international and domestic markets. This method not only overcomes the limitations of selecting a single model in previous studies but also can better portray the nonlinear relationship between the series from the perspective of probability. This research is of great significance for regulating the domestic market risk, providing a basis for prognosis in the context of the current international market form, and avoiding systemic risk.

Theoretical model

The Copula-GARCH model is mainly used to analyze multivariate financial time series' correlation and

TABLE 2 ADF stationarity test results.

Model	The spot price	SMM nickel	LME nickel
t-Statistic	−32.45816	−31.57072	−32.35210
Prob	0.0000	0.0000	0.0000

distribution characteristics. In this paper, the GARCH model is used to describe the conditional marginal distribution of each yield series, and the Copula function is used to link the financial time series. It is to convert the obtained conditional edge function by probability integration, and the Copula function connects the new series to depict the correlation relationship between them. The definition of the GARCH-t model and the Copula function as follows.

Construction of marginal distribution model

The conditional distributions of financial time series predominantly present peaks, thick tails, time-varying, and skewed characteristics. The t-distribution can perfectly describe these characteristics, and the GARCH model can describe the series' volatility. Generally, the GARCH (1,1) model can be used to fit the time-varying and volatility of each financial time series. The t-GARCH (1,1) model is expressed as follows:

$$\begin{cases} X_i = \mu + \varepsilon_t \\ h_t = \varpi + \alpha\varepsilon_{t-1}^2 + \beta h_{t-1} \\ \sqrt{\dfrac{\nu}{h_t(\nu-2)}} \bullet \varepsilon_t | I_{t-1} \sim t(\nu) \end{cases} \tag{1}$$

Where μ refers to the mean of the return R_t; h_t stands for the conditional variance of ε_t; $\alpha \geq 0$ $\beta \geq 0$; $t(\nu)$ Represents the standard t-distribution with degrees of freedom ν . The yield R_t is a function of X_t , R_t and X_t It is identically distributed.I_{t-1} is the set of $t-1$ moment information.

The construction of EGARCH model

The expression of the EGRACH model, which is used to characterize the asymmetry of fluctuations. The model is as follows:

$$\ln(h_t) = \alpha_0 + \sum_{j=1}^{p} \beta_j \ln(h_{t-j}) + \sum_{i=1}^{q} \left[\alpha_i \left| \frac{\varepsilon_{t-i}}{\sqrt{h_{t-i}}} \right| + \phi_i \left| \frac{\varepsilon_{t-i}}{\sqrt{h_{t-i}}} \right| \right] \tag{2}$$

Where if $\varphi_i \neq 0$, it indicates that the volatility has asymmetry, and when $\sum_{i=1}^{q} \varphi_i > 0$, it indicates that the volatility induced by the price increase information is larger than that caused by the price fall.

Construction of copulas connect function

Selecting the bivariate Gaussian-Copulas function and the bivariate t-Copulas function describe the serial correlation. The distribution and denisity function of the bivariate t-Copulas function are respectively defined as follows:

$$C(u, v; \rho) = \int_{-\infty}^{\varphi(u)} \int_{-\infty}^{\varphi^{-1}(v)} \frac{1}{2\pi\sqrt{1-\rho^2}} \exp\left[\frac{-(r^2+s^2-2\rho rs)}{2(1-\rho^2)}\right] drds \tag{3}$$

$$c(u, v, \rho) = \frac{1}{\sqrt{1-\rho^2}} \exp\left[-\frac{\varphi^{-1}(u)^2 - 2\rho\varphi^{-1}(u)\varphi^{-1}(v) + \varphi^{-1}(v)^2}{2(1-\rho^2)}\right] \bullet \exp\left[-\frac{\varphi^{-1}(u)^2 + \varphi^{-1}(v)^2}{2}\right] \tag{4}$$

TABLE 3 EGARCH model results.

Sample	Model	α	β	ϕ	ν	AIC
The spot price	EGARCH-norm	−0.5487	0.2027	0.0804	--	−5.436412
	EGARCH-t	−0.7340	0.1447	0.0829	3.8537	−5.565518
	EGARCH-GED	−0.04037	0.0196	−0.0040	1.1292	−5.497412
SMM Nickel	EGARCH-norm	−0.5526	0.1978	0.0726	--	−5.476351
	EGARCH-t	−0.7271	0.1586	0.0763	3.9374	−5.582004
	EGARCH-GED	−0.6352	0.1713	0.0739	1.1228	−5.581715
LME Nickel	EGARCH-norm	−0.2670	0.1204	0.0515	--	−5.298359
	EGARCH-t	−0.2386	0.0863	0.0487	5.3807	−5.353075
	EGARCH-GED	−0.2511	0.0998	0.0523	1.2685	−5.354638

TABLE 4 Parameter estimation and test results of the marginal distribution model.

Sample	Model	μ	ω	α	β	v	AIC
The spot price	GARCH-norm	−0.0353	3.35E-05	0.1324	0.7517	--	−5.433411
	GARCH-t	−0.0483	267E-05	0.0624	0.8434	3.8554	−5.562050
	GARCH-GED	−0.0326	3.14E-05	0.0875	0.7915	1.0833	−5.558206
SMMNickel	GARCH-norm	0.5722	3.06E-05	0.1227	0.7648	--	−5.471804
	GARCH-t	−0.0535	2.70E-05	0.0709	0.8335	3.8961	−5.580138
	GARCH-GED	−0.0335	2.87E-05	0.0891	0.7969	1.1195	−5.578870
LME Nickel	GARCH-norm	−0.0427	2.42E-05	0.0862	0.8356	--	−5.298346
	GARCH-t	−0.0471	2.05E-05	0.0541	0.8791	5.4553	−5.353008
	GARCH-GED	−0.0479	2.18E-05	0.0664	0.8609	1.2726	−5.353572

Where u, v refers to the daily returns in the futures and spot markets; ρ is the parameter of interest, $\rho \in (-1, 1)$. φ^{-1} is the inverse function of the standard normal distribution function.

The distribution and density function of the bivariate t-Copula function with a degree of freedom v can be expressed as:

$$C(u, v, \rho, k) = \int_{-\infty}^{t_k^{-1}(u)} \times \int_{-\infty}^{t_k^{-1}(v)} \frac{1}{2\pi\sqrt{1-\rho^2}} \left[1 + \frac{s^2 + t^2 - 2\rho st}{\lambda(1-\rho)^2}\right]^{-\frac{k+2}{2}} dsdt \tag{5}$$

$$c(u, v, \rho, k) = \rho^{-\frac{1}{2}} \cdot \frac{\Gamma\left(\frac{k+2}{2}\right)\Gamma\left(\frac{k}{2}\right)}{\left[\Gamma\left(\frac{k+1}{2}\right)\right]^2} \cdot \frac{\left[1 + \frac{t_{k=1}^{-2}}{k}\right]^{\frac{k+1}{2}} + \left[1 + \frac{t_{k=2}^{-2}}{k}\right]^{\frac{k+1}{2}}}{\left(1 + \frac{y_t' \rho^{-1} y_t}{k}\right)^{\frac{k+2}{2}}} \tag{6}$$

Where t_k^{-1} is the inverse of the one-dimensional t-distribution function with a degree of freedom $y_t = (t_k^{-1}(u, t), t_k^{-1}(v, t))$.

Empirical analysis

Data selection and statistical description

To examine the futures and spot price fluctuations of nickel association, this article selects the London Metal Exchange (LME) and Shanghai Nonferrous Metals Mesh (SMM) nickel daily closing prices as the domestic and international nickel futures prices, the domestic nickel daily market prices as the nickel spot price, with a sample period of 1 April 2015, to 29 April 2022, a total of 1722 sets of daily nickel price data. $\{P_t\}$ is defined as a market index daily closing price, $\{q_t\}$ is defined as the daily market price, $\{R_t\}$ *is* defined as $R_t = ln\frac{p_t}{p_{t-1}} \times 100\%$ or $R_t = ln\frac{q_t}{q_{t-1}} \times 100\%$.

As can be seen from the data in Table 1, the means of the three yield sequences are relatively small and greater than 0, the skewness is less than 0 and the kurtosis is greater than 3. We can find that the yield sequences have left skewness, and the series has the phenomenon of "sharp peak and thick tail." The probability values are all less than 0.05, indicating that the null hypothesis that the series follows normal distribution is rejected. That is to say, the LME Nickel and spot yield series do not follow the normal distribution, and the J-B statistic values are both large, which further indicates that the distribution of the yield series is not normal.

Since the GARCH model can better reflect the conditional heteroscedasticity of the data that does not follow the normal distribution, and can reflect the characteristics of the peaks and thick tails of the sequences. Therefore, it is appropriate to use the GARCH model for fitting the sequences in this paper. The time series of the yield series is shown in Figure 1. By observing the time series, it can be found that the yield series of domestic and international nickel futures have significant characteristics of volatility aggregation effect.

Construct GARCH and EGARCH models

First, the stationarity of the return series is examined using the ADF unit root test (Table 2), and the findings indicate that all three series are stationary. The yield series residuals are next examined for autocorrelation; if the null hypothesis is rejected, autocorrelation is assumed to exist in the series. The three sequences' residual terms were subjected to the ARCH-LM test, which revealed that all of the p-values for the F-statistic and LM statistic were less than 0.05, showing that the sequences showed conditional heteroscedastic properties. Therefore, the standard normal model, the T model, and the GED model with thick-tailed distribution are employed to investigate the aggregation and asymmetries of the return series of the LME price, the SMM price and the spot price. The outcomes of GARCH(1,1)-t and EGARCH(1,1)-t chosen for the return series of the LME Nickel, the SMM Nickel and the spot price, are displayed in Tables 3, 4 based on the AIC criterion.

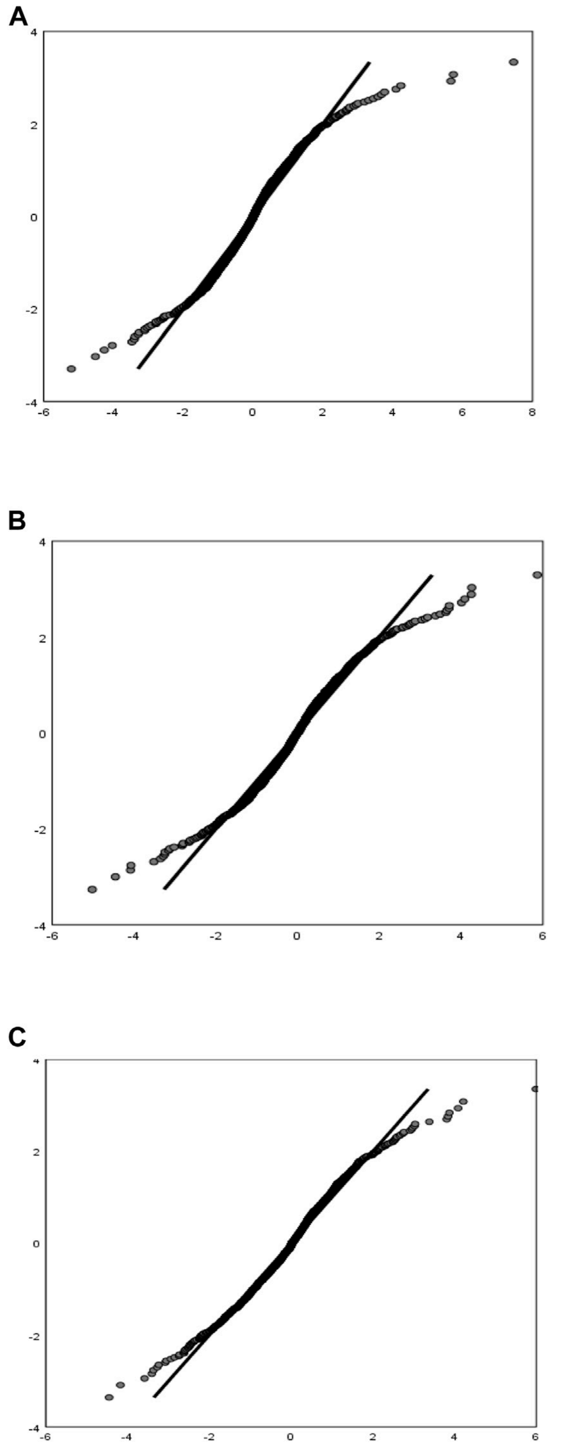

FIGURE 2
Q-Q diagram of the fitting degree of the conditional marginal distribution mode **(A)** LME Nickel yield series, **(B)** SMM Nickel yield series, **(C)** The spot price yield series. Note: The horizontal axis represents the quantile of the normal distribution. The vertical axis represents the quantile of the series of yields after a first-order difference.

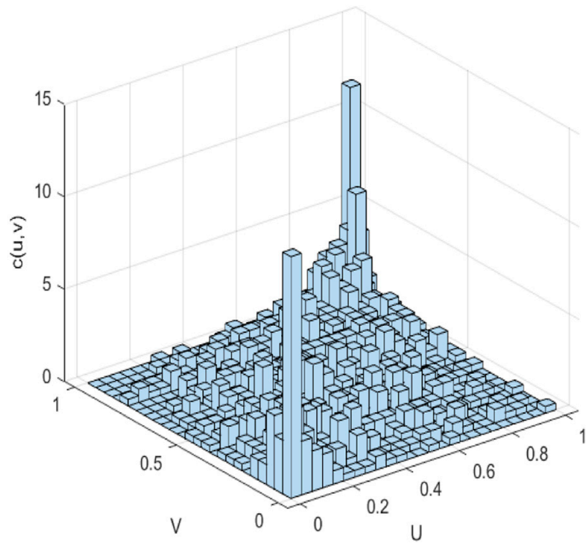

FIGURE 3
Bivariate frequency histogram of daily yield series in LME Nickel and the spot price. Note: The indicator U is the edge distribution of LME Nickel futures. The indicator V is the edge distribution of the spot price. C (U,V) represents a joint distribution fuction.

GARCH marginal distribution model selection and parameter estimation

According to earlier research, the Copula-GARCH model is frequently used to examine the correlation properties of financial time series, so in this paper, conditional marginal distribution is carried out using the GARCH model. By altering the probability integral of the normalized residual sequence, a new sequence is generated. Finally, as shown in Figure 2, the quantile comparison diagram of the matching T-distribution and the distribution of residual sequence are both drawn. The quantile figure demonstrates intuitively how well the aforementioned model fits the marginal distribution.

Selection of copula function and parameter estimation

Correlation between the london metal exchange nickel futures market and the spot market

After determining the respective marginal distributions, the bivariate frequency histograms (Figure 3) of the joint distribution function (U, V) consisting of the marginal distribution functions of the series of LME Nickel futures and spot price returns were obtained by processing with Matlab software.

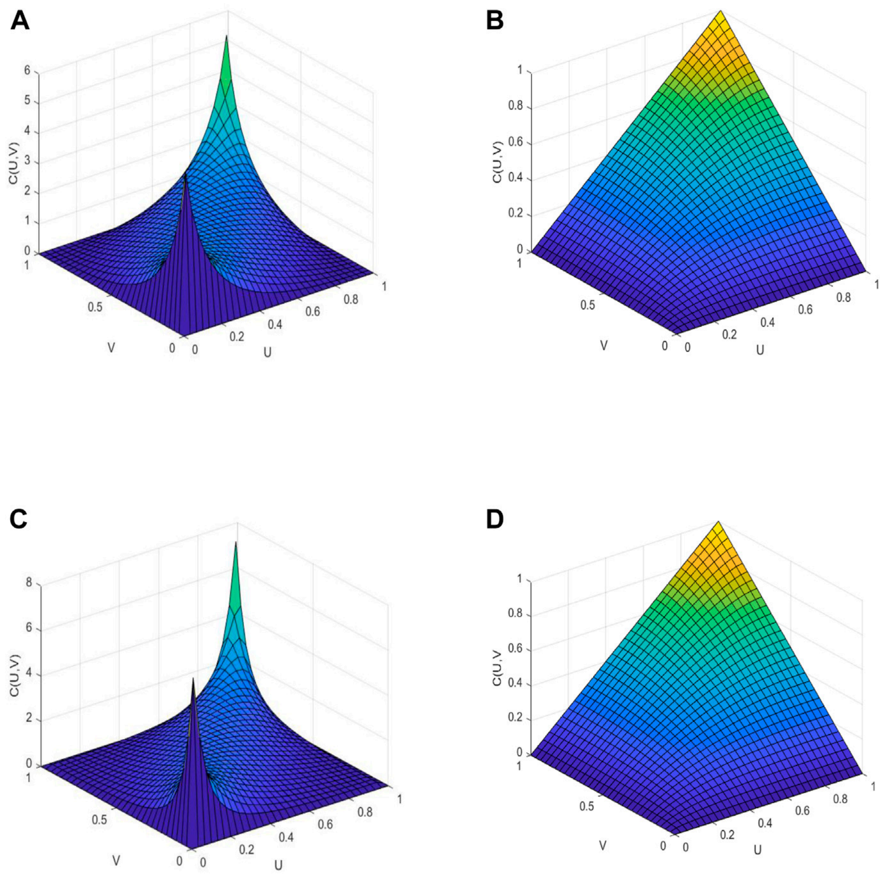

FIGURE 4
Bivariate density function and bivariate distribution fuction of the Gaussian-Copula function and the t-Copula function **(A)**bivariate Gaussian-Copula density function, **(B)**Bivariate Gaussian-Copula distribution function, **(C)**bivariate t-Copula density function, **(D)**Bivariate t-Copula distribution function.

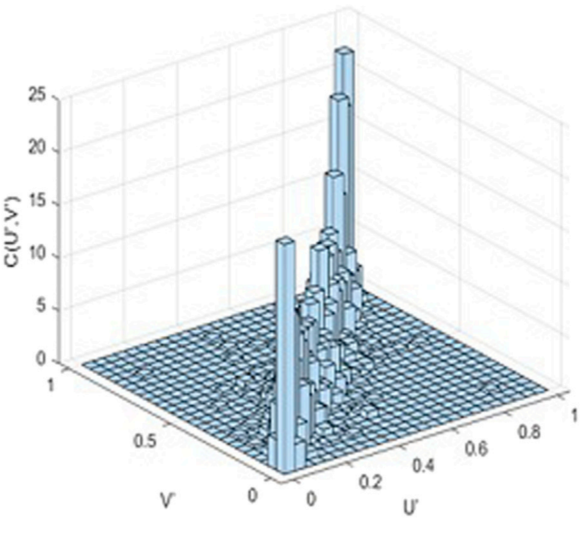

FIGURE 5
Bivariate frequency histogram of daily yield series in SMM Nickel and the spot price. Note: The indicator U' is the edge distribution of LME Nickel futures. The indicator V' is the edge dis tribution of the spot price. C (U', V') represents a joint distribution fuction.

TABLE 5 Estimated values of relevant parameters of the Copula model.

Parameter	Gaussian-copula	t-Copula
The parameter value	0.5356	0.5310 $k = 4.0100$
Kendall rank correlation coefficient	0.7722	0.7694
Spearman rank correlation coefficient	0.5590	0.5729
Euclidean distance	0.1948	0.1530
AIC	1356.9665	1012.8134
BIC	1382.7714	1038.6183

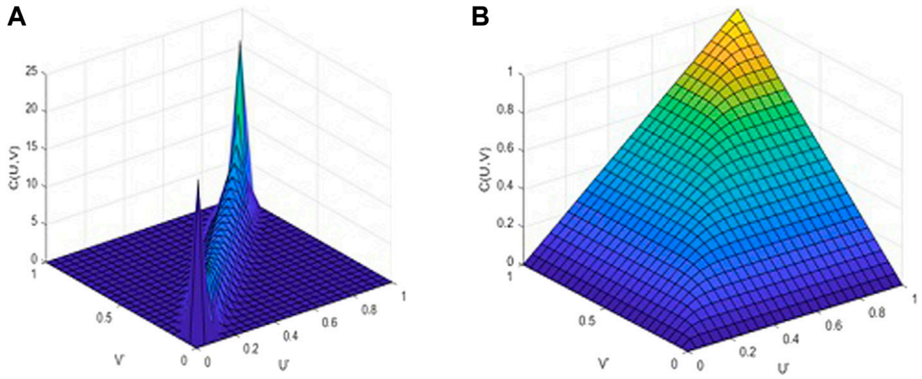

FIGURE 6
Bivariate density function and bivariate distribution fuction of the t-Copula function **(A)** bivariate t-Copula density function, **(B)** Bivariate t-Copula distribution function.

According to the histogram, it can be shown that the joint density function (U, V) has a significant density in the upper and lower tails. The density of the lower tail is moderately more significant than the density of the upper tail. In contrast, the tails of the two markets are strongly correlated and have a comparatively symmetric tail, demonstrating that the probability of the two markets having a low or high level at the same time is higher, and the joint density function (U, V) also known as the Copula function, has a symmetric tail. According to the image characteristics of the Copula function, it can initially be determined to select the bivariate Gaussian-Copula function and the bivariate t-Copula function that depict the tail symmetry relationship. The density function and distribution function of the bivariate Gaussian-Copula function and the bivariate t-Copula function are displayed in Figure 4.

It can be intuitively seen from the density function plot that the data exhibit noticeable symmetric features, demonstrating that both the bivariate Gaussian-Copula function and the bivariate t-Copula function can better capture the correlation characteristics between the two series. Among them, the bivariate t-Copula function has thicker tails and is more responsive to changes in the tail relationship between variables, and can better capture the tail correlation between the two markets compared with the bivariate Gaussian-Copula function. The distribution function images of both functions reveal conical shapes. Nevertheless, the bivariate t-Copula function selection as the most appropriate Copula function by the image alone still lacks basis, so further accurate analysis with relevant data is necessary.

In order to select the best Copula function to describe the dependency structure of the variables from the two functions, this article uses the AIC information criterion to estimate the function parameters. First of all, the normalized residual sequences obtained by the above conditional edge distribution is transformed by probabilistic integral transformation to two new sequences. Then, use the bivariate Gaussian-Copula function and the bivariate t-Copula function to describe the correlation between new sequences, and the analysis results are displayed in Table 5.

The fitting degree can be directly compared according to the Euclidean distance minimum rule, but in order to more accurately select the Copula function with the best fitting degree, this paper uses the AIC information criterion and BIC information criterion of different Copula functions for comparison. According to the AIC and BIC information criteria, the smaller the value, the better the fitting effect.

TABLE 6 Estimated values of relevant parameters of the Copula model.

Parameter	Gaussian-Copula	t-Copula
parameter value	0.0416	0.0333 $k = 1.5817$
Kendall's rank c orrelation coefficient	0.2445	0.2203
Spearman's rank correlation coefficient	0.0457	0.0574
Euclidean distance	0.1041	0.0817
AIC	57,364.1219	8341.1849
BIC	57,389.9269	8366.9899

As shown in Table 5, the value of the Euclidean distance, AIC and BIC of the Gaussian-Copula function is the largest, which means that the bivariate Gaussian-Copula function fits less than the bivariate t-Copula function. Meanwhile, the Kendall coefficient and the Spearman coefficient of the 0.7694 and 0.5729 respectively, and the coefficients are all positive, indicating that there is a strong nonlinear and positive correlation between the new sequences. It can be seen from Figure 4 that the tail correlation of the two yield series is larger than zero, which indicates that the price surge or sudden drop in the international nickel futures market will have a significant impact on the domestic nickel spot market. Above all, according to the AIC information criterion, the bivariate t-Copula function has a better fitting effect on the correlation between the yield series of the LME Nickel futures price and the spot price.

Correlation between the shanghai nonferrous metals mesh nickel futures market and the spot market

After determining the marginal distribution functions of the yield series of SMM Nickel and spot prices, bivariate frequency histograms (Figure 5) of the joint distribution function (U′, V′) composed of their marginal distribution functions are plotted.

It can be visualized from the bivariate frequency histogram that the joint distribution function (U′, V′) has a symmetric tail relationship with a more significant density in the upper and lower tails, which means that the probability of both markets having a lower and higher level at the same time is higher. Consequently, the bivariate Gaussian-Copula function and the bivariate t-Copula function can be selected to describe the correlation between the series of futures and spot yields. The normalized residuals of the two series are reconstructed by probability integration to obtain two new series, and then the correlation between the new series is evaluated, and the results are displayed in Table 6.

We can intuitively see that the value of the Euclidean distance, AIC and BIC of the bivariate t-Copula function are all less than the relevant parameter values of the bivariate Gaussian-Copula function, indicating that the bivariate t-Copula function has a better fitting effect. At the same time, the value of the Kendall coefficient and the Spearman coefficient is positive, showing that the new sequences have a strong nonlinear and positive correlation. If the price of the domestic nickel futures market rises, the price of the nickel spot market will rise synchronously. The density function and distribution function of the bivariate t-copula function as shown in Figure 6.

The above analysis selects the bivariate t-Copula function to depict the correlation between domestic and foreign nickel futures markets and the spot market. The values of the correlation measures of the bivariate t-Copula function are all positive, and the density function plots of the bivariate t-Copula functions of nickel futures and spot prices all exhibit a symmetrically distributed positive correlation pattern with thick tails and symmetric front-to-back concavity in the middle, demonstrating that the bivariate t-Copula function is sensitive to changes in the tail relationship between random variables and can well capture the tails between the two markets correlation. There is a strong synergistic effect between the two markets, and they display the same increase and decline to some extent. When the price of one index changes sharply, the price of the other will likewise change the same way in a short period of time.

Conclusion and policy implications

Conclusion

Affected by geopolitical conflicts, emergencies and carbon neutrality, the demand and competition for new energy minerals will increase, and China will face a certain degree of price and supply risks. At the beginning of 2020, the COVID-19 epidemic caused the price of mineral products to drop continuously. On 26 March 2020, the SMM Nickel futures price fell to 91,700 yuan per ton, the lowest since 2019, and the spot price fell by 11.21% simultaneously. After the outbreak of the Russian-Ukrainian conflict on 24 February 2022, the nickel futures price soared and broke through the $100,000 per ton on

March 10. The price was so high that the LME was forced to suspend nickel trading. As the largest consumer of nickel, the soaring price of international nickel futures inevitably had a serious impact on the domestic market. The SMM nickel prices was affected by the linkage mechanism between internal and external markets, the futures price rose by the daily limit and the premium rate exceeded 100%. The spot price reflected in the short term and continued to rise for 2 days, breaking the new high of 310,000 per ton, with an increase of 46.86%. This event reflects the synergy between the nickel futures market and the spot market, which means that the soaring price of nickel futures will lead to the same rise of the domestic nickel spot price. Nickel futures prices are closely related to the global economic conditions, investors can use the linkage between the futures market and the spot market to hedge, avoid the price risk of the spot market and achieve the expected profit. China should reasonably arrange nickel futures and spot trading according to the needs of domestic economic development, reserve and release nickel ore from the national perspective, and timely adjust nickel supply to push up or stabilize nickel prices.

In this paper, the correlation between domestic and foreign nickel futures and spot markets is researched by constructing the Copula-GARCH model, based on the yield series of daily nickel prices from 1 April 2015, to 29 April 2022, for empirical analysis. Firstly, the GARCH (1,1)-t model is embraced to estimate the marginal distribution of each return series. The Copula function is constructed to depict the correlation between the markets, and lastly, the AIC information criterion is employed as an evaluation index to test the fitting effect of the model and select the most appropriate Copula function. The following conclusions can be drawn.

(1) The yield series of LME nickel, SMM nickel and spot price has an ARCH effect, the characteristics of peak, thick tail, fluctuation aggregation and random walking characteristics. They rise steadily and the fluctuation range gradually increases, reflecting the rapid changes of the capital market and the sustainability of price fluctuations. Market investors can make reasonable investment decisions by predicting the fluctuation trend of the nickel futures prices.
(2) The GARCH(1,1)-t model and the EGARCH(1,1)-t model better explain the fluctuation aggregation characteristics and asymmetric characteristics of nickel price series, and the GARCH(1,1)-t model has a good fit effect on the edge distribution of the series, and the GARCH model and the Copula function can fit well.
(3) The bivariate t-Copula function fits the yield sequence of the international and domestic nickel futures markets and the spot market well, indicating that the futures market and the spot market have a symmetrical tail correlation relationship which is a positive correlation. That is to say, the market has a synergistic effect. Empirical analysis found that the density function of the bivariate t-Copula function has a thicker tail. The thicker the tail, the greater the probability of extreme yields.

Recommendations

To make reasonable decisions, the analysis of the linkage mechanism between domestic and foreign nickel markets plays a vital role in the investors' systematic analysis and risk analysis. To improve the global discourse power of China's nickel market and ensure the smooth and orderly operation of the market, the following recommendations are proposed:

First, strengthen and improve the domestic nickel futures market

China's nickel futures were listed and traded in 2005, and the development of its relevant legal system and transaction mechanism is relatively lagging behind. Due to the strong correlation between the LME and the SMM, the relevant outstanding systems and operating mechanisms of foreign countries can be learned to improve the relevant legal system and trading operation mechanism based on the current situation and characteristics of the Chinese nickel futures market. The first point is to improve the current future regulations and relax the restrictions on overseas futures trading, which is conducive to Chinese trading enterprises to carry out hedging transactions on the international market, and facilitate producers and operators to transfer spot market risks to achieve lock-in costs and achieve expected profits and encourage Chinese capital to enter the international capital market to improve China's discourse power in international nickel futures pricing. The second point is that domestic exchanges should enrich the types of futures hedging tools to meet the market demand better, The selection of futures hedging tools can learn from those outstanding tools in the LME and those suitable for the China nickel futures market, which can better meet the market demand. In this way, the risk of nickel industry chain-related enterprises can be reduced, the scale of the futures market can be expanded, the trading volume of futures can be increased, and sufficient capital can be obtained to increase the discourse power of Chinese nickel futures in the international market.

Second, actively participate in international competition mechanisms

(1) Actively participate in the formulation of international futures policies. It can be concluded from the above research that LME Nickel futures market is strongly correlated with the SMM Nickel futures market and the spot market. Therefore, the domestic nickel futures and spot market is influenced not only by relevant policies at home but also by relevant policies abroad. Therefore, China should

actively participate in the formulation of international futures policy, refer to international futures policy, and timely adjust relevant policies of our futures market which can provide fair competition conditions and a suitable environment for the development of the nickel market and gradually improve the discourse power of nickel pricing in China.

(2) Encourage domestic and foreign enterprises to participate in international competition actively. We should actively encourage enterprises to adopt risk exploration, acquisition of the stake in mines, sign long-term supply contracts, participate in the international market, strengthen foreign exchange and cooperation, implement diversified imports ways, and prevent our nickel market from relying heavily on exporting countries. In this way, we can improve the discourse power of the China's nickel market and gradually reduce the influence of international nickel market price fluctuation on China's nickel market prices.

Third, prevent and control the risk of market price fluctuations

(1) Improve the information disclosure mechanism of nickel futures products. Relevant regulatory authorities and exchanges should improve the nickel futures information disclosure mechanism. Futures information disclosure mechanism. Due to the strong correlation between the LME and the SMM, the information disclosed includes relevant information on domestic and foreign nickel futures products. We should improve the efficiency of information acquisition at home and abroad, ensure the truth and accuracy of the information, and improve the nickel futures price warning mechanism. In this way, the relevant information will be made transparent, the negative impact caused by the asymmetry of market information will be reduced, and the trading will be more rational, to improve the anti-risk ability of China's nickel futures market and make China's nickel futures market more autonomous and independent.

(2) Strengthen the popularization of professional knowledge of nickel futures traders. The relevant departments of nickel futures shall train the traders of nickel futures, popularize the relevant professional knowledge, attract more traders with professional knowledge to enter the market, promote the relevant traders of the nickel futures market to trade rationally, and give full play to the function of risk avoidance and price discovery of the futures market.

(3) Improve the market risk control system. While improving futures hedging tools and expanding the trading scale, we should also pay attention to risk control and management and establish and improve the risk control system at different levels, and risk prevention and control should include international and domestic risk prevention and control. The futures supervision department should make full use of market information at home and abroad to monitor risks, establish and perfect risk management systems and risk monitoring systems, and let relevant systems play a corresponding role in risk management. The futures exchange should make use of the risk early warning system. According to the information conveyed by international and domestic nickel futures markets, we should take corresponding risk prevention and control measures to prevent and resolve risks in timely manner to avoid excessive transmission of foreign risks to the domestic market.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

SH put forward the main research points; SH, YL, ML, and DQ completed manuscript writing and revision; YL and ML completed simulation research; ML and DQ collected relevant background information; SH, YL, ML, and DQ revised grammar and expression. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Global antimony supply risk assessment through the industry chain

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Antimony is a type of critical metal for the energy transition. The antimony industry chain is distributed among the major developed and developing countries around the world. With the development of clean energy technology, the demand for antimony in photovoltaic and energy storage fields will increase significantly. Considering the significant changes in the global demand for antimony products and the serious supply shortage, people should pay more attention to the supply risk of related products of the antimony industry chain. In this paper, we propose a new integrated index to evaluate the supply risk of antimony industry chain related products, including Herfindahl Hirschman index, global governance index, human development index, global innovation index, and betweenness centrality in complex networks. Meanwhile, seven commodities in the antimony industry chain are selected for empirical analysis from 2011 to 2019. The results show that countries with high supply risks of the industry chain upstream include Canada, France, Germany, India, Japan, Thailand, and the United Kingdom. And, Australia, India, Japan, Thailand, and Vietnam are with high supply risks in the midstream of the industry chain. Meanwhile, Canada, India, Japan, and Thailand are with high downstream supply risks. Some countries, like China, the United States, and Germany, play a core role in different sectors of the industry chain. International competitive relations of countries have caused a high supply risk of products related to the antimony industry chain. The supply risk of the antimony industry chain shows that countries must strengthen industrial division and cooperation to maximize their interests. It is suggested to take the country-specific measures to mitigate supply risks, including establishing national inventories of critical materials, overseas investment, strengthening the guidance of industrial policies, and accelerating infrastructure construction.

KEYWORDS

antimony, industry chain, supply structure, supply risk, ensemble index

1 Introduction

Antimony is a non-renewable and valuable mineral with a wide range of industrial applications. Antimony is mostly used in the production of fire retardants, of which 20% is used in the manufacture of alloy materials, sliding bearings, and welding agents in batteries. Antimony also has many other uses. For example, antimony can form alloys with lead for various purposes, and the formed alloys are much higher in hardness and mechanical strength than antimony. Antimony can be used to make stabilizers and catalysts, as well as clarifiers. Antimony acetate can be used as a catalyst in the chemical fiber industry, and antimony chloride can be used in medicine. High purity antimony can be widely used in high-tech industries to produce semiconductors, far-infrared devices, and electric heating devices.

The unbalanced geographical distribution of antimony resources leads to differences in antimony resource types and reserves for different countries/regions. Specifically, the political instability and insufficient economic and social conditions in some mining countries pose a potential threat to antimony supply. In addition to political, economic and social factors, the technical impact on mining and metallurgical processes has also attracted more public attention. All these factors threaten the supply of related products of the antimony industry chain. Therefore, it is necessary to evaluate the supply risk of antimony industry chain related products.

Previous studies have focused on the criticality and supply risks of key metals, such as the reports from the United States National Research Council (Committee On Earth Council, 2008) and the US Department of energy, the assessment issued by Yale University and the EU study (Graedel and Nassar, 2015; Nuss et al., 2016). These studies define the metal supply risk based on various factors, such as consumption time based on production and reserves, recovery rate, market balance, substitutability, etc., These studies are mainly based on four main factors, namely geological availability, mining governance and policy stability, global market concentration and environmental sustainability.

However, as far as we know, the international trade and supply risks of related products of the antimony industry chain have received little attention so far. Most of the existing antimony research mainly focuses on the recycling of secondary antimony (Chancerel et al., 2013; Dupont et al., 2016; Anderson et al., 2019) and antimony substitutes (Henckens et al., 2016; Liu and Qiu, 2018). Some scholars have studied the trade flow of antimony ore in some specific countries.Chu et al. (2019) measured the import and export of antimony ore in China from 2006 to 2016. Adopt a complex network method to quantitatively analyze the evolution of international antimony ores trade patterns from 1993 to 2019.

We have not found any scholars that have studied international trade and supply risks of related products in the antimony industry chain. We believe that the two main reasons may have led to the neglect of trade in products related to the antimony industry chain in the past. One reason is that antimony is far less valued than other key metals (such as lithium, cobalt, nickel, and rare Earth) before it is widely used in clean energy. Another reason is that China has been the world's Antimony mining center for decades, accounting for more than half of the world's antimony production during the research period. However, these two situations have changed in the past decade. Antimony is becoming a clean energy metal, which has a wide application prospect in solar photovoltaic power generation and solar cells. With the decline of domestic antimony ore production, China's import volume is also rising. Therefore, it is necessary to study international trade and supply risks of related products in the antimony industry chain.

The existing research has laid a solid foundation for analyzing the opportunities and challenges of the future development of the antimony industry. However, there is a lack of quantitative analysis of the trade status and supply risks of related products in the antimony industry chain. For important mineral resources with complex industry chains, supply risks should be comprehensively identified in the whole antimony industry chain. In the face of the current situation of rapid development of technology and industry, such an assessment becomes more important for those countries that hope to gain a firm foothold in the global antimony market in the future. To fill this research gap, this study quantitatively describes the current situation of the global antimony industry chain, systematically identifies the supply risks of related products in the antimony industry chain, and evaluates the import structure and risks of antimony-related products in 12 countries including Japan, China, and the United States from 2011 to 2019. The results show that there are significant supply risks in the global antimony industry chain, especially in the upstream antimony ore. This study has an in-depth understanding of the supply risk of commodities in the antimony industry chain. The full text is divided into five parts. After the introduction, these methods will be introduced in the next section. Then, it analyzes the current situation of the antimony industry chain and the supply risk of key commodities. On this basis, relevant policy recommendations are put forward. The last section summarizes the whole study.

2 Method and data

2.1 System definition

Given the high degree of globalization of the antimony industry chain, this study selects 12 countries accounting for 80% of the global antimony product trade volume as the spatial boundary, and they are all major participants in the global antimony industry chain. The time boundary is set from

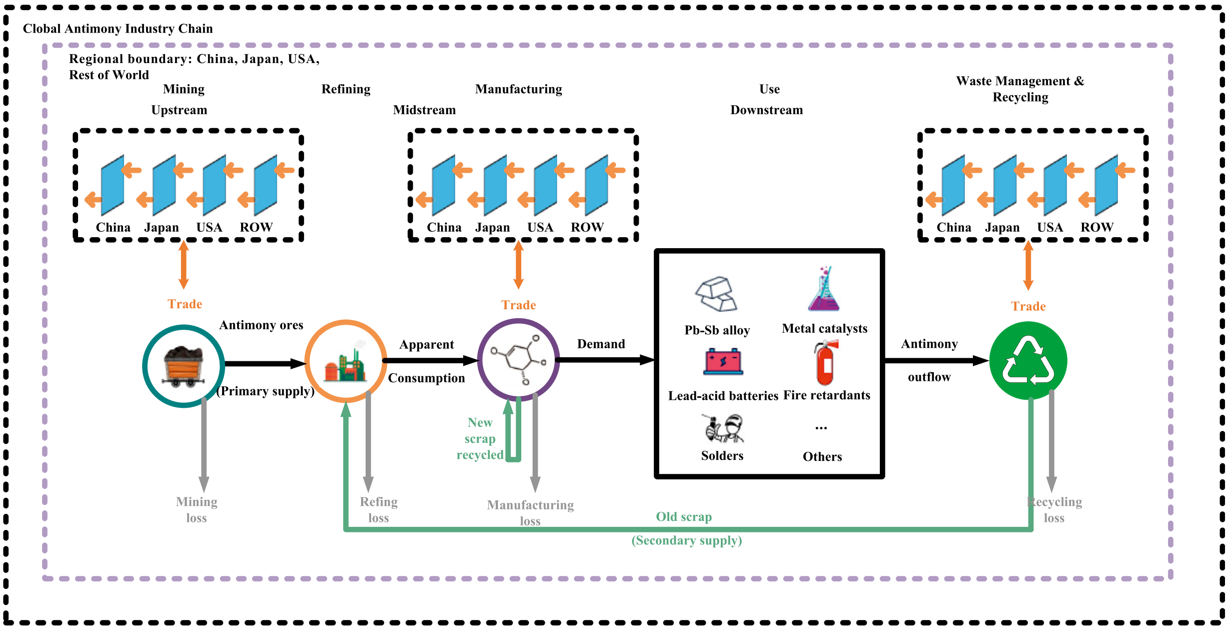

FIGURE 1
System definition of the antimony industry chain.

2011 to 2019. This period was chosen to reflect the latest state of the antimony industry chain.

The main processes in the antimony industry chain are shown in Figure 1. The industry chain can be divided into three main stages, namely antimony raw ore (upstream), antimony intermediate products (midstream), and antimony terminal products (downstream). In the upstream stage, Stibnite is the main source of antimony, and antimony mainly exists in Stibnite in nature. In the midstream stage, Antimony oxide is the main intermediate product of antimony. For the downstream stage, Pb-Sb alloy, lead-acid batteries, solders, fire retardants, and metal catalysts are the end products of antimony. The main use of antimony is to use its oxide (antimony trioxide) in the manufacture of refractory materials. Pb-Sb alloy is corrosion-resistant and is the preferred material for the production of vehicle and marine battery electrode plates; Antimony alloys with tin, aluminum, and copper have high strength and excellent wear resistance. They are excellent materials for manufacturing bearings, bushings, and gears. High purity antimony and antimony metal compounds (indium antimony, silver antimony, gallium antimony, etc.,) are also ideal materials for the production of semiconductors and thermoelectric devices. Among them, the antimony used in the production of fire retardants accounts for about 60% of the total consumption of antimony. The antimony consumed in the manufacture of alloy materials, sliding bearings, and welding agents in batteries accounts for about 20%, and the consumption of the other aspects is about 20%.

2.2 Indicators

Supply risk refers to the probability of material supply interruption. Market concentration is widely used by economists and government regulators to describe supply risk. The research and development of antimony resources related technologies have a decisive impact on the supply of related products of the entire antimony industry chain. The government governance ability and social and economic development of the main exporting countries have a great impact on the supply of antimony resources. Some countries which are located in the important position of the antimony resource trade path controlled the supply lifeline of antimony resources. Therefore, the supply risk of antimony industry chain related products is analyzed from five aspects: market concentration, government management ability, social stability, technological innovation and trade control ability.

Market concentration. The Herfindal Hirschman index reflects the market concentration of the industry. The index is widely used in the market position and safety analysis of mineral resources in individual countries (Li et al., 2021; Gamarra et al., 2022; Xun et al., 2022; Yamamoto et al., 2022; Zhang et al., 2022). This study uses the HHI index of the global antimony product import (export) market to reflect the structural layout of the corresponding market. The theoretical value of HHI is between 0 and 1. The larger the index, the higher the market concentration. The lower the index, the lower the market concentration. Market concentration reflects the monopoly degree of the market. Markets with high concentration are usually dominated by a few countries, and markets with low concentration are more competitive.

$$HHI = \sum_{i=1}^{n} (S_i)^2 \tag{1}$$

where S_i represents the market share of the country (region) i, and n represents the number of trading countries (regions).

Government's management ability. WGI is a comprehensive indicator used to measure the six dimensions of governance of more than 200 countries and regions from 1996 to 2018, including Voice and Accountability (VA), Political Stability and Absence of Violence (PV), Government Effectiveness (GE), Regulatory Quality (RQ), Rule of Law and Control of Corruption (RC) (Henri, 2019; Gamarra et al., 2022). The range of all sub-indicators is from −2.5 (bad governance performance) to 2.5 (good governance performance). In these dimensions, PV has a significant correlation with the stability of the supply structure. For demonstration purposes, scale this value to 0e1 using Eq. 2.

$$WGI_{scale} = 0.2 \times WGI + 0.5 \tag{2}$$

Social stability. The social and economic development of antimony exporting countries (importing countries) affects the global supply of antimony products. The human development index (HDI) released by the United Nations Development Programme is a widely accepted standard to measure the social and economic development of countries since 1990. We calculate the social stability level of global antimony product supply according to the human development index of major exporting (importing) countries (Ebrahimi Salari et al., 2022; Zheng and Wang, 2022).

Technological innovation. Technological progress has a positive impact on the supply of antimony, especially the recovery and reuse technology of antimony. The global innovation index (GII) is an annual ranking jointly established by the world intellectual property organization, Cornell University, and the European School of business administration in 2007. It measures the performance of more than 120 economies in the world in innovation capacity (Hu et al., 2022; Jahanger et al., 2022; Kamguia et al., 2022; Lee and Wang, 2022). We use GII to measure the level of technological innovation in various countries. This indicator ranges from 0 to 100. For demonstration purposes, scale this value to 0e1 using Eq. 3.

$$GII_{scale} = 0.01 \times GII \tag{3}$$

Trade control. The control of each country (region) over cobalt resources is not only reflected on the terminal countries (regions) of resource flow, but also in the countries (regions) on the resource flow path that have an important impact on the overall material flow. Therefore, this study uses the betweenness centrality in complex networks to measure the trade control power of a country (region). Betweenness centrality refers to the number of shortest paths through a specified node (Chen et al., 2018; Wang et al., 2019; Chen et al., 2020; Chen et al., 2021; Zhang et al., 2021; Zheng et al., 2022). The higher the betweenness centrality is, the stronger the node's control over the whole network is (Dong et al., 2020; Liang et al., 2020; Liu et al., 2020; Liu et al., 2022). The variable g_{jk} represents the number of shortest paths between country j and country k, and $g_{jk}(i)$ represents the number of shortest paths between country j and country k through country i. Variable BC_i is the betweenness centrality of country i. The calculation method is as follows:

$$BC_i = \sum_{j<k} \frac{g_{jk}(i)}{g_{jk}} \tag{4}$$

The supply risk index (SRI) measures the relative interruption probability of different import combinations in a country, which is calculated by Eq. 5 (Xun et al., 2021). The index takes into account not only the import dependence and trade impact of the country, but also the political and technological environment of different importing countries. The higher the SRI, the higher the identifiable supply risk.

$$SRI_i = HHI_i{}^*(1 - WGI_{i,scale}{}^*\mathrm{HDI}_i{}^*GII_{i,scale})^*(1 - BC_i) \tag{5}$$

where SRI_i is national trade risk index for country i.

TABLE 1 International trade of commodities in the antimony industry chain.

Commodity	Quantity unit	Customs code
Antimony ore (AO)	kilograms	261710
Antimony oxide (AOX)	kilograms	282580
Pb-Sb alloy (PSA)	kilograms	780191
Lead-acid batteries (LAB)	kilograms	850710
Solders (SO)	kilograms	381090
Fire retardants (FR)	kilograms	291990
Metal catalysts (MC)	kilograms	381512

2.3 Data sources

The data of this study is the trade data of products related to the antimony industry chain. Trade data comes from the United Nations commodity trade statistics database. Trade data include all import and export flows between countries and regions within the system boundary, and the unit of the trade volume is the kilogram.

Based on the three stages of the antimony industry chain, this study selected seven antimony-containing commodity trade volumes in 2011, 2013, 2015, 2017, and 2019. The upstream includes antimony ore (AO). Antimony in the

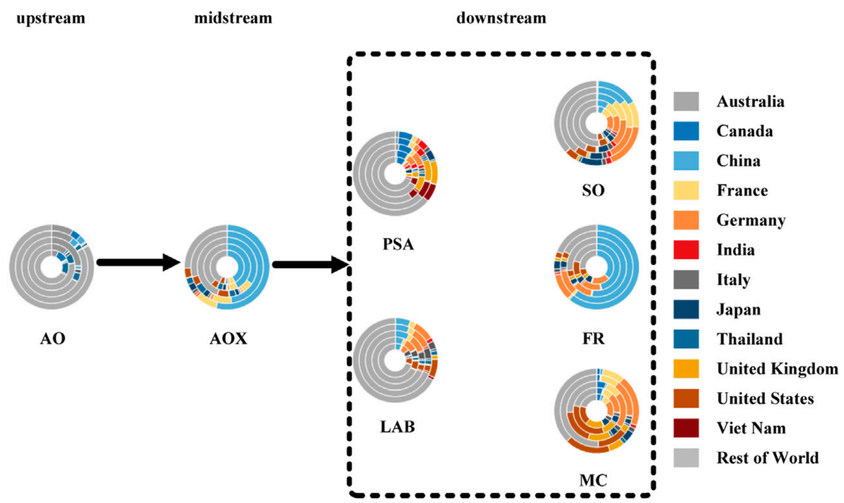

FIGURE 2
Supply structure in the global antimony industry chain.

middle reaches mainly exists in the form of an oxide (AOX). Downstream antimony-containing products include Pb-Sb alloy (PSA), lead-acid batteries (LAB), solders (SO), fire retardants (FR), and metal catalysts (MC). According to the HS code of commodities, these commodities are further divided into three categories: minerals, chemicals, and final products. The corresponding HS code is shown in Table 1.

3 Results

3.1 Analysis of supply structure of global antimony industry chain

The supply structure of key commodities in the global antimony industry chain from 2011 to 2019 is shown in Figure 2. In the upstream stage, due to the continuous fluctuation of Australian AO production, the supply structure of AO has also changed greatly in the past 9 years.

In the midstream stage, the supply structure of AOX has not changed significantly from 2011 to 2019. The main supplier is China. Due to the rapid growth of China's production, China has become a major source of AOX imports for all countries in the world.

In the downstream stage, the supply structure of LAB and SO has not changed significantly from 2011 to 2019. The main suppliers of PSA have changed greatly from 2011 to 2019, and their supply structure has been adjusted accordingly. From 2011 to 2019, the supply of FR in China maintained a steady growth. As for MC, the United States and Germany continue to maintain a high market share.

3.2 Supply risks in the antimony industry chain for representative countries

Figure 3 shows the import structure and risks of Germany, France, Italy and United Kingdom from 2011 to 2019. Germany, France, Italy and United Kingdom belong to European countries with similar economic environment and government system. The import structure and supply risk of antimony industry chain related products are similar.

As far as Germany is concerned, in all stages of the antimony industry chain, there is a supply risk for commodities in the upstream stage. From 2011 to 2019, more than 88% of AO was imported from a single country, resulting in a high SRI. The supply risk of commodities in the middle and lower reaches is low and relatively stable. The SRI of AOX, FR, and MC are all maintained at about 0.15, while the SRI of PSA, LAB and the SO is relatively low, only about 0.07.

In the antimony industry chain of France, the supply risk, mainly exists in the upstream stage. The import structure of AO is relatively concentrated, and more than 60% of AO is imported from a single country, which leads to a high SRI. In the middle and lower reaches stage, the import structure remained relatively stable from 2011 to 2019, and the import share fluctuated slightly. The SRI of PSA, SO and MC increased in fluctuation. The SRI of PSA and FR decreased slightly. The supply risk of LAB is relatively low and stable, and there is little change in SRI value from 2011 to 2019.

In Italy's antimony industry chain, supply risks mainly exist in the upstream stage. The import structure of AO is centralized, and more than 70% of AO is imported from a single country. In the middle and downstream stages, the supply risk of each commodity is relatively low. From 2011 to 2019, the supply

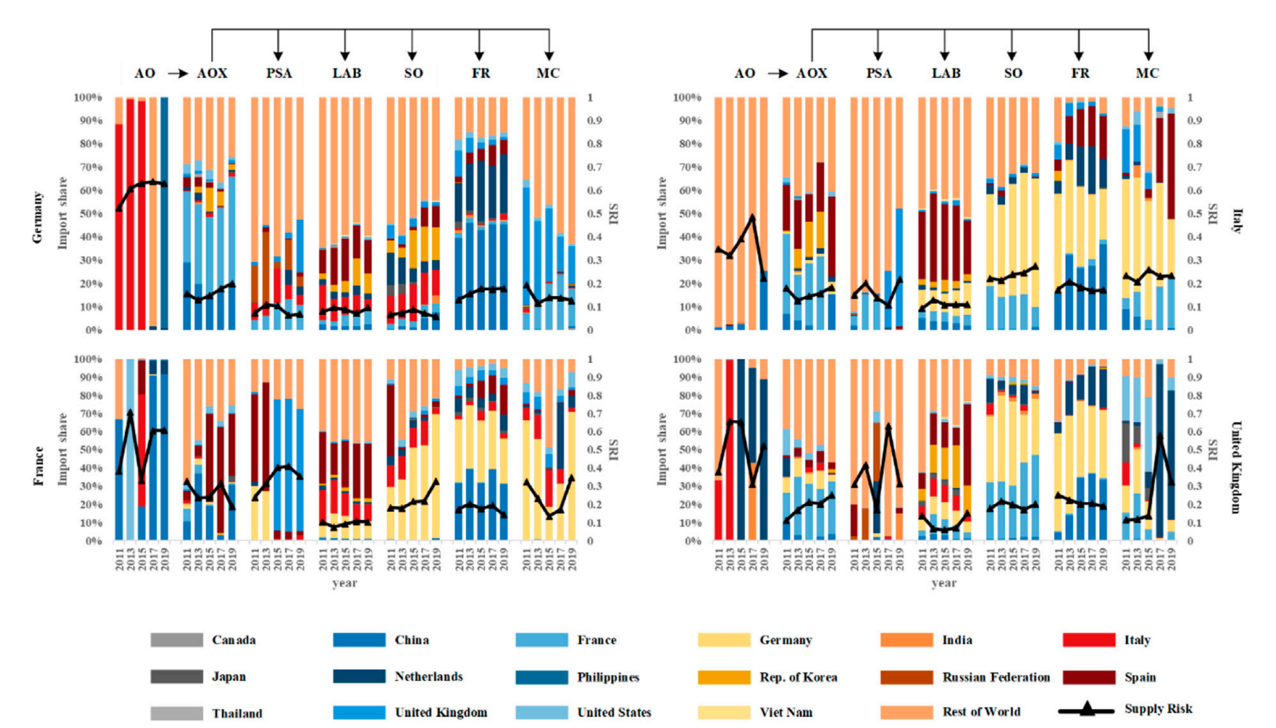

FIGURE 3
Import structures and risks of key commodities in the antimony industry chain in Germany, France, Italy and United Kingdom.

risk of AOX, LAB, FR, and MC is relatively stable. The SRI of AOX, LAB, FRs, and MC is about 0.18, 0.09, 0.17, and 0.23 respectively. The supply risk of PSA and SO in the downstream stage is rising in fluctuation. From 2011 to 2019, the SRI of PSA increased from 0.15 to 0.22, and the SRI of SO increased from 0.22 to 0.27.

In the UK's antimony industry, from 2011 to 2019, supply risks mainly lie in commodities in the upstream stage, PSA, and MC on the downstream stage. In the upstream stage, the import structure of AO is relatively concentrated, and the import share is constantly changing, resulting in SRI fluctuations at a high level. The supply risk of AOX in the midstream stage gradually increased due to the gradual reduction of import sources, and the SRI increased from 0.11 in 2011 to 0.25 in 2019. In the downstream stage, the import structure of PSA and MC is constantly changing, the SRI of PSA remains relatively stable in fluctuations, and the SRI of MC rises in fluctuations. The supply risk of LAB and SO in the downstream stage from 2011 to 2019 is relatively stable. The import structure of the FR has gradually changed from centralized to decentralized, resulting in a decrease in SRI from 0.25 in 2011 to 0.19 in 2019.

Figure 4 shows the import structure and risks of Australia, Canada, and the United States from 2011 to 2019. For Australia, Canada, and the United States, the whole antimony industry chain is relatively complete, but the supply risk of AO, AOX, and FR is relatively high.

In Australia's antimony industry chain, supply risks mainly exist in commodities in the upstream and midstream stages and PSA in the downstream stage. By weight, most AO is imported from a single country, resulting in a high SRI of more than 0.6. As the main producer of AO is China, the vast majority of AO is imported from China, resulting in a high SRI. From 2015 to 2019, the import mix of PSA changed, and the import share from Thailand decreased by about 15%. The less centralized import structure has reduced SRI by 14% in these 3 years. Due to the relatively stable import structure and import share, the SRI of LAB and SO does not fluctuate much. From 2011 to 2019, the share of FR imported from China increased by about 10%, which led to a small increase in SRI. As the import structure of MC changed in 2019, the import sources decreased, and Japan became the main import source country, resulting in a sharp rise in SRI.

As far as Canada is concerned, in all stages of the antimony industry chain, there are supply risks for commodities in the upstream stage and PSA in the downstream stage. In the upstream stage, the supply structure of AO is the most concentrated. Since 2013, more than 80% of AO has been imported from a single country, which leads to higher supply risks. Due to the fluctuation of supply share, the SRI of AO first decreased by 15% from 2013 to 2019, and then rose to a higher level. The supply risk of PSA is similar. Due to the change of import structure, SRI first fell sharply, then rose sharply and

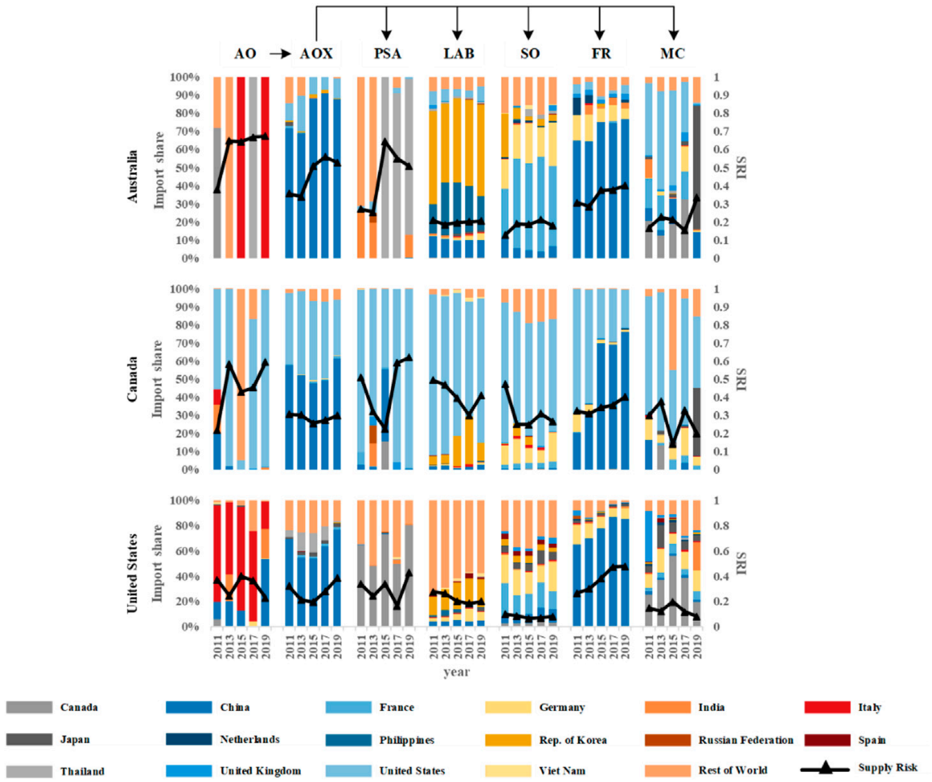

FIGURE 4
Import structures and risks of key commodities in the antimony industry chain in Australia, Canada, and the United States.

remained at a high level. Due to the fluctuation of import share, the SRI of LAB and MC are also fluctuating. In the middle and downstream stages, the supply risk of AO, SO and FR is significantly lower than that of upstream commodities.

As far as the United States is concerned, in all stages of the antimony industry chain, there are supply risks for commodities in the upstream and midstream stages, PSA and FR in the downstream stage. In the upstream and midstream stages, the import structure and import share have been changed from 2011 to 2019, resulting in the supply risk of AO and AOX also fluctuating. The import sources of PSA in the downstream stage are relatively concentrated, and SRI is also constantly fluctuating due to the changing import share. In the downstream stage, the share of FR imported from China continues to rise, with about 65% of FR imported from China, resulting in SRI rising from 0.27 in 2011 to 0.48 in 2019. The import structure of LAB and MC has gradually changed from centralized to decentralized, and the supply risk has gradually decreased. The import source and structure of SO remain relatively stable, and the SRI remains around 0.09.

Figure 5 shows the import structure and risks of Japan, India, and Thailand from 2011 to 2019. For Japan, India, and Thailand, the domestic antimony industry chain is weak in the upstream and midstream stages, and the supply risk of FR is high.

As far as Japan is concerned, in all stages of the antimony industry chain, there are supply risks for commodities in the upstream and midstream stages, LAB and FR in the downstream stage. In the upstream and midstream stages, from 2011 to 2019, the import structure of AO and AOX has changed from relatively centralized to decentralized. Although the supply risk is still relatively high, SRI has decreased significantly. The SRI of LAB decreased slightly, from 0.39 in 2011 to 0.32 in 2019. The import sources of the FR are relatively concentrated, mainly from China, and the import quota gradually increased from 2011 to 2019, resulting in a doubling of SRI. In the downstream stage, the supply risk of PSA and MC also fluctuated due to the change in import share. The supply risk of SO increased slightly, from 0.14 in 2011 to 0.19 in 2019.

In India, from 2011 to 2019, supply risks mainly lie in commodities in the upstream and midstream stages, as well as PSA and SO in the downstream stage. In the upstream stage, the import structure of AO is relatively concentrated and the import source is single. Due to the change in import share, SRI rises in fluctuation, from 0.45 in 2011 to 0.65 in 2019. In the midstream stage, the main import source of AOX is China. Due to the fluctuation of import share, SRI first increased and then

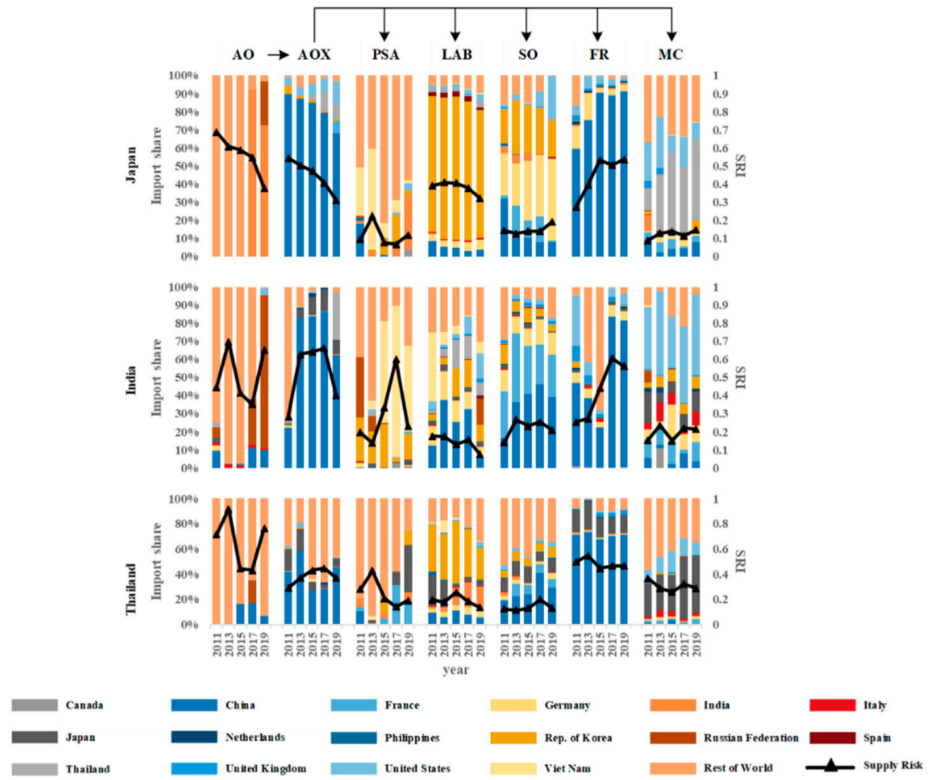

FIGURE 5
Import structures and risks of key commodities in the antimony industry chain for Japan, India, and Thailand.

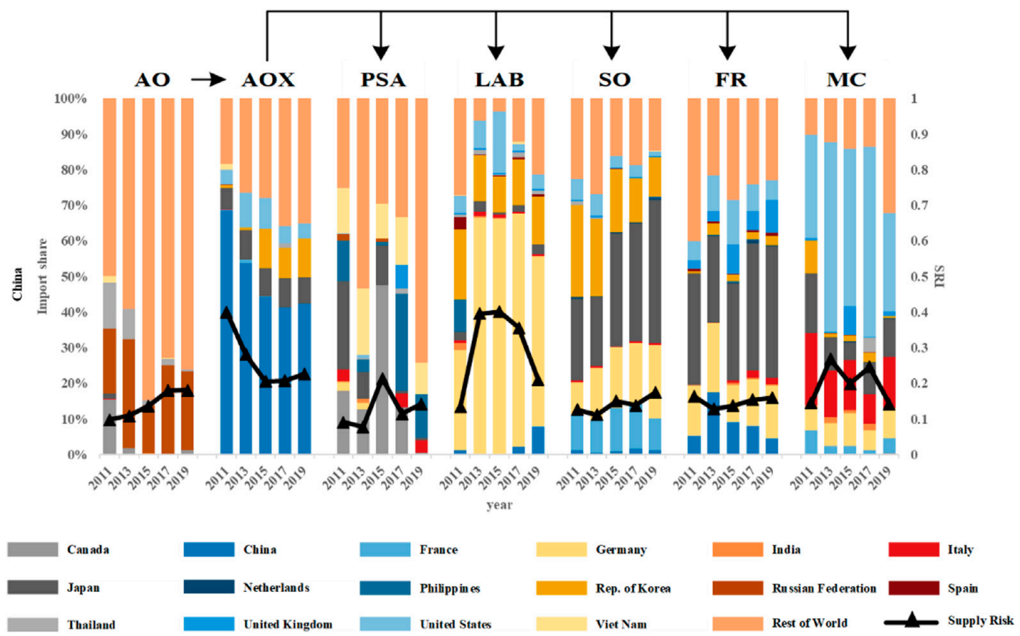

FIGURE 6
Import structures and risks of key commodities in the antimony industry chain in Vietnam.

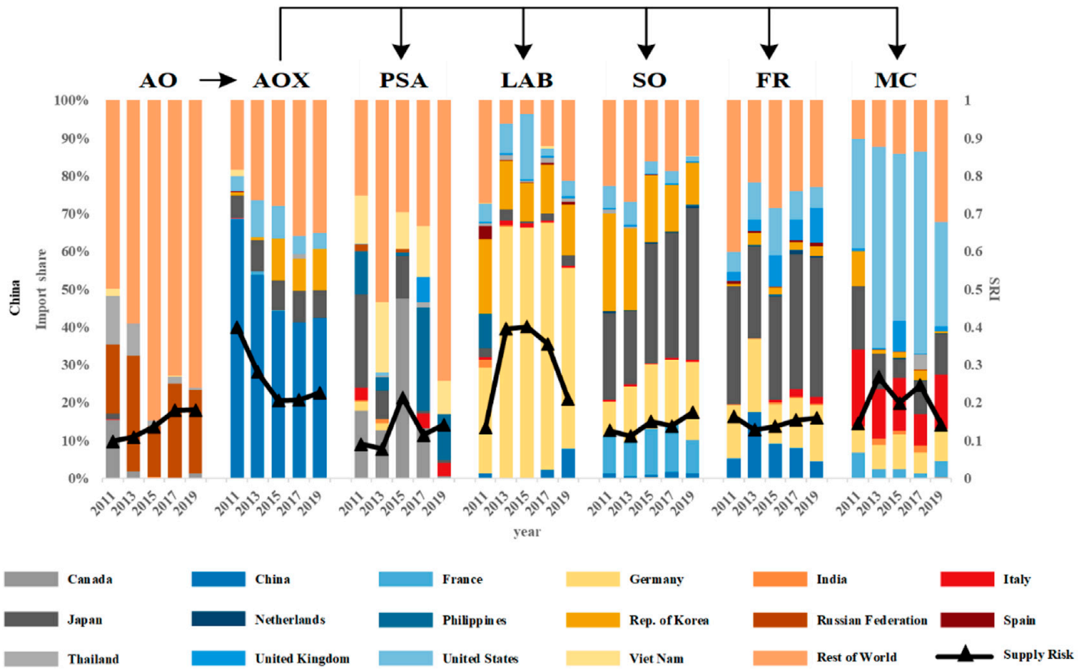

FIGURE 7
Import structures and risks of key commodities in the antimony industry chain in China.

decreased, rising from 0.28 in 2011 to 0.4 in 2019. The supply risk of PSA and SO in the downstream stage changes similarly. Due to the change in import share, SRI first increases and then decreases. In the downstream stage, the supply risk of LAB, SO and MC is relatively stable. The SRI of LAB decreased by 10% from 2011 to 2019, while the SO and MC increased by about 6%.

In terms of Thailand, from 2011 to 2019, supply risks mainly lie in commodities in the upstream and midstream stages, as well as FRs in the downstream stage. In the upstream stage, the import structure of AO is relatively concentrated, and more than 75% of AO is imported from a single country, resulting in a high SRI. Due to the change of import share in the midstream stage, the supply risk of AOX first increased and then decreased from 2011 to 2019, and the SRI increased from 0.29 in 2011 to 0.37 in 2019. In the downstream stage, from 2011 to 2019, about 65% of FR were imported from China, resulting in higher supply risks. In the downstream stage, the SRI of LAB and MC fluctuated slightly due to the change in import share. The import structure of PSA has changed since 2013, with the increase of import sources and the gradual decline of supply risk. The supply risk of SO is relatively stable, and the SRI remains around 0.13.

Figure 6 shows the import structure and risks of Vietnam from 2011 to 2019. In Vietnam, from 2011 to 2019, supply risks mainly focused on PSA and MC in the upstream, midstream, and downstream stages. In the upstream stage, the import structure of AO in 2011 was single, and the supply risk was high. Since 2013, Thailand and Russia have become the main import sources, and the supply risk has decreased. In the midstream stage, the SRI of AOX first increased and then decreased due to the change in import structure. In the downstream stage, the import structure and source of PSA are constantly changing, resulting in the continuous fluctuation of supply risk. In the downstream stage, the import structure of LAB has become relatively concentrated from 2011 to 2019, with SRI rising from 0.19 in 2011 to 0.25 in 2019. The import structure of SO and FR has gradually become decentralized, resulting in a gradual decline in supply risk. From 2011 to 2019, the import sources of MC gradually increased, and the import structure gradually dispersed. Although the supply risk is still relatively high, SRI decreased by about 40%.

Figure 7 shows the import structure and risks of China from 2011 to 2019. In China, from 2011 to 2019, supply risks were mainly identified in LAB in the antimony industry chain. Most labs are imported from Germany. During this period, the SRI of LAB experienced a small fluctuation, gradually rising from 0.13 to 0.21. In the upstream stage, the SRI of AO increased slightly to about 0.18. The decline of AO production in China has reduced the SRI of AOX by about half, from 0.4 in 2011 to 0.22 in 2019. In the downstream stage, the supply risk of PSA, SO, FR and MC are relatively low.

4 Discussion

Country-specific recommendations can be made based on the actual supply conditions of representative countries shown in

Figure 3. In Germany, France, Italy, and United Kingdom, although the antimony industry chain is relatively complete and mature, the supply risk of AO urgently needs to be reduced. According to the EU 2020 list of key mineral resources, antimony is regarded as a key mineral. The defense industry and decarbonization strategies of the European Union and the United Kingdom describe the national objectives of promoting the development of the antimony industry. Under the guidance of these strategies, a large number of technology development and demonstration projects have been launched, providing strong support for the commercialization of antimony products. The long-term and clear development strategy has promoted the formation of a complete antimony industry chain in Germany, France, Italy, and the United Kingdom, making the four countries become the world leaders in antimony-related technologies. However, the lack of critical metal resources has seriously affected the safety of the antimony industry chain. The global antimony supply structure is difficult to change. The geographical distribution of antimony is too concentrated. For economic reasons, there is little international trade in antimony. The effective way to reduce risks in Germany, France, and the UK is to establish domestic inventories of refined antimony and increase the investment of overseas antimony mining companies. Italy can increase the mining volume of domestic antimony mines.

For Australia, Canada, and the United States, the whole antimony industry chain is relatively complete, but the supply risk of AO, AOX, and FR is relatively high. Australia, Canada, and the United States have successively listed antimony as a key mineral. As a well-established developed country, the long-term development strategy has promoted the formation of the antimony industry chain. As a powerful country in science and technology, high value-added industries gradually dominate, while low value-added industries are gradually eliminated, and even transferred abroad, resulting in the imbalance in the development of the domestic antimony industry chain. Antimony mining is closely related to the production of AOX and FR. Usually, antimony mining companies can take into account the mining of AO and the production of AOX and FR. Although Australia, Canada, and the United States are rich in antimony resources as large resource countries, the development of this industry has been stagnant due to the high cost of antimony mining, resulting in relatively high supply risks of AO, AOX, and FR. The effective way to reduce risks in Australia, Canada, and the United States is to improve policy and financial support for antimony mining companies and strengthen the research and development of antimony mining and beneficiation technology.

For Japan, India, and Thailand, the domestic antimony industry chain is weak in the upstream and midstream stages, and the supply risk of FR is high. Japan, India, and Thailand do not have sufficient antimony resources, resulting in the uneven development of the antimony industry chain, and the supply risk of AO, AOX, and FR is relatively high. The effective way to Japan, India, and Thailand to reduce risks is to increase investment in overseas antimony mining companies and establish a solid trade partnership with major antimony mining countries.

For Vietnam, the whole antimony industry chain is relatively complete, and there are supply risks in terms of MC. Vietnam has attracted a large number of foreign-funded enterprises to invest and build factories in its country because of cheap labor and preferential policies for foreign investment. Many foreign-funded enterprises have not only promoted the development of local antimony-related technology in Vietnam, but also established a complete antimony industry chain in Vietnam. Due to the high technical content involved in MC, the relevant technologies are firmly in the hands of a few countries. Moreover, due to the vigorous development of Vietnam's industry and manufacturing industry, Vietnam has an increasing demand for MC, resulting in higher supply risks. At the national level, the government needs to strengthen the introduction of foreign investors and increase the R&D and application of new technologies to reduce supply risks. At the enterprise level, increase R&D investment and establish joint ventures to reduce supply risks.

For China, it is necessary to optimize and stabilize the whole antimony industry chain. At present, the domestic antimony industry chain is still in the stage of rapid development and maintains its development momentum with the strong support of the Chinese government. However, the production process of some antimony products in developed countries still lags far behind that in China. It is necessary to fully understand and evaluate the supply risks of commodities at all stages. At the national level, China must further establish a safe and reliable domestic production system. The government needs to improve the localization rate of key commodities in the antimony industry chain, such as LAB and MC. Specific measures can be taken, including strengthening policy support for the industry, increasing financial support for new technology research and development, demonstration, and application, and strengthening infrastructure construction. At the enterprise level, relevant manufacturers can digest, absorb, and rebuild the introduced technology, establish joint ventures, and speed up independent innovation to strengthen the weak nodes in the antimony industry chain.

5 Conclusion

Antimony will be widely used in new energy vehicles and energy storage devices and will play an important role in the energy transition. The risk of antimony supply will have a great impact on the energy transition. In this paper, we assess the antimony supply risk through the industry chain. This study has an in-depth understanding of the supply risk of commodities in the antimony industry chain from 2011 to 2019. The results show that there are significant supply risks in the current antimony industry chain. First, countries with high upstream supply risks in the industry chain include Canada, France, Germany, India, Japan, Thailand, and the United Kingdom. And, countries with high supply risks in the midstream include Australia, India, Japan, Thailand, and Vietnam. Meanwhile, countries with high downstream supply risks include Canada, India, Japan, and Thailand.

Some countries, like China, the United States, and Germany, play a key core role in different sectors of the industry chain. As different countries have advantages in different sectors of the industry chain, it is difficult for a single country to get rid of supply risks. The competitive advantage of the major developed countries lies in the terminal sector, while China's competitive advantage lies in the upstream and middle industrial sectors. So, countries must strengthen industrial division and cooperation to maximize benefits. The supply risk of the industry chain will eventually be passed on to various countries and sectors. The governance of the antimony industry chain needs the active participation and open cooperation of governments all over the world. Establishing an open and cooperative trade environment is the best way to reduce the supply risk of antimony industry chain.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: https://comtrade.un.org/.

Author contributions

YZ proposed the idea of this research; JL conducted research, analyzed data and wrote a paper; All authors discussed the results and revised the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

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Carbon emission reduction calculation for the green transformation of traditional hotel design

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The green transformation design of traditional hotels aims to reduce the consumption of materials and energy and reduce the emission of harmful substances. Carbon emission, usually used to measure energy consumption, is a representative indicator to evaluate the effect of the green transformation process. This paper adopts the emission factor method to measure the carbon emission reduction in the process of hotels' green transformation from the whole life cycle of hotels, and the results show that: 1) From the perspective of the hotel life cycle, the construction process is the stage with the most carbon emissions. 2) From the perspective of a single hotel, high-star hotels have larger emissions than low-star hotels; 3) As the number of three and four-star hotels far exceeds the five-star hotels, overall, four-star hotels ranked first in total emission reduction. 4) From the perspective of provinces, the hotel industry emission reduction potential of different provinces varies greatly, among which Guangdong, Zhejiang, and Jiangsu provinces are at the top of the list. The future carbon reduction potential of the Chinese hotel industry is very considerable. The content of this paper enriches the research in the field of carbon emission measurement and also provides a reference for the management agency to designate the carbon peaking and carbon neutrality goals of the hotel industry.

KEYWORDS

traditional hotel, green transformation, carbon reduction measurement, carbon peaking and carbon neutrality, the hotel industry

Introduction

In recent years, issues such as greenhouse gas emissions and addressing climate change cannot be ignored in global sustainable development. Energy Information Administration, (2021) released by the U.S. Energy Information Administration predicts that from 2020 to 2050, total carbon emissions from OECD countries are expected to increase by 5% (600 million tons), and non-OECD countries will increase by 35% (8 billion tons). As the world's largest carbon emitter, China's carbon reduction policy has attracted worldwide attention. In September 2020, China proposed "We strive to peak carbon dioxide emissions by 2030 and achieve carbon dioxide emissions neutrality by 2060." At the 75th United

Nations General Assembly, In September 2021, the State Council unveiled a guiding document on the country's work to achieve carbon peaking and carbon neutrality goals under the new development philosophy, which provided practical guidance for realizing the "Carbon peaking and carbon neutrality." With feasible theoretical guidance, introducing a series of "dual carbon" policies has demonstrated China's image as a major responsible country.

As a strategic industry that promotes global cultural exchanges and economic development, tourism accounts for 8% of the world's carbon emissions and is growing at an annual rate of 3% (Wang et al., 2022), and the hotel industry is one of the three major industries in tourism industry. As one of the pillar industries of energy conservation, emission reduction and low-carbon transformation, the hotel industry is the key link for China to achieve the goal of "carbon peak and carbon neutrality." How to guide hotel design to take environmental performance as the starting point, reduce material and energy consumption and emission of harmful substances is the key point of the current green transformation of traditional hotels. Research on these contents needs to be based on the measurement of carbon emissions in the hotel industry. However, there are few empirical papers on energy-saving and emission reduction in the hotel industry. Relevant studies are mainly based on field research in individual regions, and very few pieces of literature measure carbon emissions from the national hotel industry; most literature (Fu et al., 2019) remains on the qualitative discussion and theoretical analysis of the green hotel industry, and the quantitative research of green hotel industry is minimal.

Based on the previous research results, this paper uses the data published in the "Ministry of Culture and Tourism of the People's Republic of China, 2020" to calculate the carbon emission reduction of the green transformation of various star-rated hotels in China, enriching the existing research in the field of carbon emission measurement. Discussing the primary sources of carbon emissions and promoting the concept of low carbon, is conducive to the implementation of the energy-saving and green design of hotels. It provides theoretical reference and empirical support for the management department to formulate "dual carbon" policies for the hotel industry and tourism.

The rest of the paper is organized as follows: the second part reviews the previously available literature, the third part is the calculation of carbon reduction, and the last part is the conclusion and policy implication.

Literature review

Green hotel-related standardization documents in China

As early as 2007, China issued the "*National Standard for Green Hotels*" (hereafter referred to as the "*Standard*"), which made qualitative regulations for the green operation and management of hotels. From green design, safety management, energy conservation management, consumption reduction management, environmental protection, health management, and green publicity, the "*Standard*" comprehensively divides green hotels into five-leaf levels to one-leaf levels according to their green performance from excellent to bad. Every 2 years, the green hotel enterprises that have been evaluated are reviewed, and the "*Standard*" preliminarily establishes the green hotel evaluation system. In 2011, the National Tourism Administration issued the "*Guidelines for Energy Conservation and Emission Reduction in Tourist Hotels*" (hereinafter referred to as the "*Guidelines*"), stating that tourist hotel enterprises should establish a management mechanism for energy conservation and emission reduction, including organization, implementation, and assessment; establish an independent measurement system for various types of energy, and conduct statistics and audits on energy consumption. The "*Guidelines*" makes detailed requirements for all aspects of the design and operation process in terms of hotel design, energy-using equipment, operation stages, and emission reduction transformation It also requires green hotels to conduct publicity and emission reduction guidance to consumers and actively purchase items with environmental protection certification; quantitative recommendation standards are set for the comprehensive energy consumption and water consumption of the hotel.

In 2016, the industry standard "*Green Tourism Hotel*" was issued to define the green tourism hotel—green tourism hotel refers to a hotel that adheres to the concept of sustainable development, adheres to clean production, maintains hotel quality, advocates green consumption, uses resources reasonably, protects the ecological environment, and undertakes community and environmental responsibilities. "*Green Tourist Hotel*" has formulated more detailed evaluation rules: the evaluation standards cover eight aspects: environmental management, green design, energy management, resource management, pollution prevention and control, product and service provision, safety and employee health management, and social responsibility; The evaluation is divided into two categories of 16 essential inspection items and seven categories of 150 evaluation items. The open detailed evaluation guidelines make the tourist hotel have the rule to follow and can carry out the green transformation more targeted. It also makes the rating agency scoring criteria more objective and persuasive, which will be beneficial to the green transformation of the hotel industry in the long run.

Most of the current standards and regulations on green hotels in China are still based on qualitative evaluation. Although some documents provide quantitative data, they are only recommended standards, and the data lack more theoretical and empirical data support. There is no detailed and specific quantification method for the emission measurement of the hotel industry in China. The green transformation process of hotels still needs to establish a sound and complete institutional system to make further specifications (Geng et al., 2020).

Overview of domestic and foreign research

In recent years, with the worsening of climate warming, how to control carbon dioxide emissions, the main greenhouse gas, has attracted attention from all walks of life, and the measurement of carbon emissions is the basis of quantitative emission reduction. The tourism industry represented by the hotel industry, as one of the long-term strategic pillar industries in the industrial structure, has also become a research hotspot in academia.

However, there are few pieces of literature about carbon emissions in the hotel industry. This paper also refers to the measurement methods of building carbon emissions that are strongly related to the hotel industry and finds that the existing literature mainly use life cycle assessment method and input-output method for carbon emission measurement. Filimonau et al. (2011) pointed out that the life cycle assessment (LCA) is suitable for the calculation of carbon emissions in the tourism hotel industry. Some scholars calculated the carbon emissions by dividing the hotel operation activities. Hu et al. (2015) took "One night's hotel stay in a standard room" as an operations cycle and calculated a five-star hotel by constructing a complete consumption life cycle of service preparation, service provision and service completion. Similarly, Michailidou et al. (2016) measured the operation stage of Greek hotel industry by taking a 7-day journey operation as a life cycle. Other scholars construct the life cycle based on the stage of the hotel. Schwartz et al. (2018) divided the sources of CO_2 emission during the whole life cycle of the hotel industry into five stages: embodied CO_2; operations-related CO_2; demolition stage; renewables and recycle stages. Peng et al. (2021) constructed a 50-years full life cycle from the physicochemical stage, usage stage and exhaust gas stage. This paper makes a comprehensive reference to these two piece of literature when establishing the life cycle.

Besides, LCEA (life cycle energy assessment) is a method for a more detailed classification of energy consumption. At present, many scholars in China also use this method to measure the carbon emissions of the hotel industry (Huang et al., 2015; Chen, 2019; He and Yang, 2019). Scholars in other countries have also applied this method, Oluseyi et al. (2016) calculated the hotel CO_2 emission of electricity powered by diesel generation in Nigeria; Salehia et al. (2021) found that six luxury hotels in Iran produced 3–4 times more carbon emissions from energy consumption than other countries. Huang et al. (2014) further considered indirect emissions and used the emission factor method to calculate the carbon emissions of 21 hotels in Eastern China. Shen et al. (2017) also considered carbon dioxide emissions generated by solid waste treatment in addition to energy consumption emissions.Zhang and Wu (2019) further calculated the carbon emissions of various buildings from the embodied carbon emissions of building materials and the operation stage according to their uses.

Some scholars also used the input-output method to measure the carbon emissions of the hotel industry, mainly at the level of provinces and industries. For example, Li et al. (2021) used the input-output method and the emission factor method to measure the carbon emissions generated by the energy consumption of the hotel industry in various provinces and made an in-depth analysis of the energy efficiency of the hotel industry.

There are few existing studies on green hotels, and most of them focus on qualitative analysis. Fu et al. (2019) put forward suggestions on the operation and development of green hotels from the aspects of planning and design, construction and construction, opening preparation, daily operation, transformation, and expansion. Ke and Leng (2020) sorted out the life cycle of buildings and proposed a green rating system based on carbon dioxide emission data, providing some guidance for future green hotel evaluation standards.

At present, there are many studies conducted on the measurement of carbon emissions in the hotel industry, but the field of green hotel carbon emissions is still in theoretical analysis and qualitative discussion. The "carbon" quantification policy formulation still needs more empirical support. This paper uses the data published in the "Ministry of Culture and Tourism of the People's Republic of China, 2020" to measure and calculate the carbon emission reduction of the green transformation of star-rated hotels in China, which enriches the existing research related to the green hotel industry.

Calculation of carbon reduction

Data sources

The relevant data of the hotel industry in this article comes from the "Ministry of Culture and Tourism of the People's Republic of China, 2020" published by the National Tourism Administration, and the emission factor data comes from the "IPCC (2019)," "Department of Climate Change, National Development and Reform Commission, (2014)" and "Department of Climate Change, National Development and Reform Commission (2011)".

Descriptive statistics

Tables 1, 2 summarize the basic information of star-rated hotels in China and star-rated hotels in major provinces and cities in China.

TABLE 1 Basic information on star-rated hotels in China.

Hotel class	Number of restaurants	Number of rooms (thousands/set)	Average occupancy rate (%)
Five-star hotel	820	264	40.38
Four-star hotel	2399	437.5	39.09
Three-star and below	5,204	322.56	38.02

TABLE 2 Basic situation of star-rated hotels in major provinces and cities in China.

Province	Total amount	Amount of five-star hotel	Amount of four-star hotel	Amount of three-star and below
Guangdong	551	101	129	321
Zhejiang	500	82	168	250
Shandong	454	34	137	283
Yunnan	389	17	72	300
Guangxi	381	12	106	263
Jiangsu	376	78	129	169
Sichuan	366	34	115	217
Beijing	362	53	102	207
Xinjiang	346	14	51	281
Henan	344	21	80	243
Hubei	312	22	80	210
Gansu	304	2	80	222
Jiangxi	293	17	122	154
Liaoning	293	25	67	201
Hebei	285	24	113	148
Fujian	279	51	124	104
Hunan	272	17	60	195
Shaanxi	269	16	48	205
Anhui	245	23	110	112
Guizhou	217	6	68	143
Inner Mongolia	191	12	31	148
Shanghai	188	71	59	58
Shanxi	179	12	50	117
Qinghai	178	2	37	139
Tibet	161	3	44	114
Chongqing	151	27	45	79
Heilongjiang	149	6	36	107
Hainan	98	21	35	42
Jilin	91	4	32	55
Ningxia	82	0	31	51
Tianjin	69	13	28	28

Calculation process

Drawing on Schwartz et al. (2018) and Peng et al. (2021), this paper constructs a full life cycle (in 50 years) from the two dimensions of building demolition and hotel operation stage. This paper uses the emission factor method to measure the carbon emissions of each process. Among them, the carbon emission measurement of traditional hotels draws on the research results of Huang et al. (2014), the emission factors of traditional hotels in various star-rated are reported

TABLE 3 The carbon emission factors of traditional hotels.

Carbon emission sources		Five-star hotel	Four-star hotel	Three-star and below
Construction stage (kgCO2·m^{-2})	Construction stage	544.5	615.9	611.7
	Retrofit stage	127.2	143.9	142.9
	Demolition phase	67.3	76.1	75.6
	Waste disposal	1,068.9	1,209.1	1,200.9
Operation stage (kgCO2·m^{-2})	Electricity consumption	59.6	86.2	94.5
	Gas consumption	25.6	10.4	0.7
	Water consumption	0.0	0.1	0.1
	Solid waste	0.5	1.5	2.5
	Wastewater	4.8	4.4	4.0
The average area of hotels (m^2)		43,199.6	17,815.8	3,643.8

TABLE 4 The carbon emission factors of green hotels.

Carbon emission sources		Qualified			Standard			Advanced		
		Five-star hotel	Four-star hotel	Three-star and below	Five-star hotel	Four-star hotel	Three-star and below	Five-star hotel	Four-star hotel	Three-star and below
Construction stage	Construction stage (kgCO2·m^{-2})	450.02	400.93	309.89	368.20	343.65	268.98	319.11	286.38	195.86
	Retrofit stage (kgCO2·m^{-2})	14.84	13.22	10.22	12.14	11.33	8.87	10.52	9.44	6.46
	Demolition phase (kgCO2·m^{-2})	5.69	5.07	3.92	4.66	4.35	3.40	4.04	3.62	2.48
	Waste disposal (kgCO2·m^{-2})	2.21	1.97	1.52	1.81	1.69	1.32	1.57	1.41	0.96
Operation stage	Comprehensive energy consumption (kgCO_2·m^{-2}·year^{-1})	137.12	122.16	94.42	112.19	104.71	81.95	97.23	87.26	59.67
	Water consumption (kgCO_2·room^{-1}·day^{-1})	0.58	0.43	0.33	0.43	0.29	0.19	0.33	0.18	0.12

TABLE 5 Carbon emissions in each link of a single traditional hotel.

Carbon emission sources		Five-star hotel	Four-star hotel	Three-star and below
Construction stage (tCO_2)	Construction stage	23,522.16	10,973.45	2,229.03
	Retrofit stage	5,494.98	2,563.49	520.72
	Demolition phase	2,907.33	1,356.31	275.51
	Waste disposal	46,176.01	21,541.81	4,375.77
Operation stage (tCO_2)	Electricity consumption	2,574.26	1,535.44	344.20
	Gas consumption	1,104.93	184.62	2.60
	Water consumption	0.00	1.83	0.37
	Solid waste	23.51	27.42	9.28
	Wastewater	207.66	78.60	14.48
Total (tCO_2)		82,010.85	38,262.97	7,771.96

in Table 3. As shown in Eq. 1, the carbon emissions E_{k1} of a single traditional hotel are calculated by accumulating the product terms of the various activity emission factors $R_{i,k}$ and the average area of each star hotel S_i, in which i represents different activities, and k represents different star hotel.

TABLE 6 Carbon emissions of a single star-rated green hotel under different scenarios.

Carbon emission sources		Qualified			Standard			Advanced		
		Five-star hotel	Four-star hotel	Three-star and below	Five-star hotel	Four-star hotel	Three-star and below	Five-star hotel	Four-star hotel	Three-star and below
Construction stage (tCO_2)	Construction stage	19,440.8	7,142.9	1,129.2	15,906.1	6,122.5	980.1	13,785.3	5,102.1	713.7
	Retrofit stage	640.9	235.5	37.2	524.4	201.8	32.3	454.5	168.2	23.5
	Demolition phase	245.9	90.4	14.3	201.2	77.4	12.4	174.4	64.5	9.0
	Waste disposal	95.6	35.1	5.6	78.2	30.1	4.8	67.8	25.1	3.5
Operation stage (tCO_2)	Comprehensive energy consumption	5,923.3	2,176.3	344.0	4,846.3	1865.4	298.6	4,200.2	1,554.5	217.4
	Water consumption	67.9	145.7	246.3	49.8	99.3	137.5	38.5	62.9	89.9
Total (tCO_2)		26,414.5	9,825.9	1776.6	21,606.1	8,396.6	1,465.8	18,720.6	6,977.3	1,057.0

TABLE 7 Emission reductions of single hotel greening under different scenarios.

Scenarios	Qualified			Standard			Advanced		
Hotel class	Five-star hotel	Four-star hotel	Three-star and below	Five-star hotel	Four-star hotel	Three-star and below	Five-star hotel	Four-star hotel	Three-star and below
Carbon reduction (tCO_2)	55,596.34	28,437.10	5,995.33	60,404.74	29,866.34	6,306.16	63,290.23	31,285.64	6,714.93

TABLE 8 Emission reductions potential of national hotels under different scenarios.

Degree of greening	Qualified			Standard			Advanced		
Hotel class	Five-star hotel	Four-star hotel	Three-star and below	Five-star hotel	Four-star hotel	Three-star and below	Five-star hotel	Four-star hotel	Three-star and below
Carbon reduction potential (million tons of CO_2)	45.589	67.936	30.972	49.532	71.351	32.578	51.898	74.741	34.689
Total (million tons of CO_2)	144.497	153.460	161.329						

$$E_{k1} = \sum S_i \times R_{i,k} \tag{1}$$

Similarly, the emission factors of green hotels in various star-rated is reported in Table 4. And the carbon emissions E_{k2} of a single green hotel are calculated by Eq. 2, j represents different scenarios.

$$E_{k2} = \sum S_{i,j} \times R_{i,j,k} \tag{2}$$

The carbon emissions reduction ER_k of a single hotel is calculated by Eq. 3. The emission reduction potential $TER_p$of hotels in each province is multiplied by the emission reduction of each star hotels and the number of hotels N_p as shown in Eq. 4.

$$ER_k = E_{k1} - E_{k2} \tag{3}$$

$$TER_p = \sum ER_{k,p} \times N_p \tag{4}$$

Calculation results

Table 5 shows the carbon emissions of a single traditional hotel, and it is obvious that the construction stage is the big head

TABLE 9 Emission reduction of hotels in major provinces under different scenarios.

Province	Qualified (million tons of CO_2)				Standard (million tons of CO_2)				Advanced			
	Five-star hotel	Four-star hotel	Three-star and below	Total	Five-star hotel	Four-star hotel	Three-star and below	Total	Five-star hotel	Four-star hotel	Three-star and below	Total
Guangdong	5.6152	3.6684	1.9245	11.2081	6.1009	3.8528	2.0243	11.9779	6.3923	4.0358	2.1555	12.5837
Zhejiang	4.5589	4.7774	1.4988	10.8352	4.9532	5.0175	1.5765	11.5473	5.1898	5.2560	1.6787	12.1245
Jiangsu	4.3365	3.6684	1.0132	9.0181	4.7116	3.8528	1.0657	9.6301	4.9366	4.0358	1.1348	10.1073
Shandong	1.8903	3.8959	1.6967	7.4828	2.0538	4.0917	1.7846	7.9301	2.1519	4.2861	1.9003	8.3383
Beijing	2.9466	2.9006	1.2410	7.0882	3.2015	3.0464	1.3054	7.5532	3.3544	3.1911	1.3900	7.9355
Fujian	2.8354	3.5262	0.6235	6.9851	3.0806	3.7034	0.6558	7.4399	3.2278	3.8794	0.6984	7.8056
Sichuan	1.8903	3.2703	1.3010	6.4615	2.0538	3.4346	1.3684	6.8568	2.1519	3.5978	1.4571	7.2069
Shanghai	3.9473	1.6778	0.3477	5.9729	4.2887	1.7621	0.3658	6.4166	4.4936	1.8459	0.3895	6.7289
Hebei	1.3343	3.2134	0.8873	5.4350	1.4497	3.3749	0.9333	5.7579	1.5190	3.5353	0.9938	6.0481
Jiangxi	0.9451	3.4693	0.9233	5.3377	1.0269	3.6437	0.9711	5.6417	1.0759	3.8168	1.0341	5.9269
Guangxi	0.6672	3.0143	1.5768	5.2583	0.7249	3.1658	1.6585	5.5492	0.7595	3.3163	1.7660	5.8418
Anhui	1.2787	3.1281	0.6715	5.0783	1.3893	3.2853	0.7063	5.3809	1.4557	3.4414	0.7521	5.6492
Henan	1.1675	2.2750	1.4569	4.8994	1.2685	2.3893	1.5324	5.1902	1.3291	2.5029	1.6317	5.4637
Yunnan	0.9451	2.0475	1.7986	4.7912	1.0269	2.1504	1.8918	5.0691	1.0759	2.2526	2.0145	5.3430
Hubei	1.2231	2.2750	1.2590	4.7571	1.3289	2.3893	1.3243	5.0425	1.3924	2.5029	1.4101	5.3054
Liaoning	1.3899	1.9053	1.2051	4.5003	1.5101	2.0010	1.2675	4.7787	1.5823	2.0961	1.3497	5.0281
Xinjiang	0.7783	1.4503	1.6847	3.9133	0.8457	1.5232	1.7720	4.1409	0.8861	1.5956	1.8869	4.3685
Hunan	0.9451	1.7062	1.1691	3.8205	1.0269	1.7920	1.2297	4.0486	1.0759	1.8771	1.3094	4.2625
Gansu	0.1112	2.2750	1.3310	3.7171	0.1208	2.3893	1.4000	3.9101	0.1266	2.5029	1.4907	4.1201
Shaanxi	0.8895	1.3650	1.2290	3.4836	0.9665	1.4336	1.2928	3.6928	1.0126	1.5017	1.3766	3.8909
Chongqing	1.5011	1.2797	0.4736	3.2544	1.6309	1.3440	0.4982	3.4731	1.7088	1.4079	0.5305	3.6472
Guizhou	0.3336	1.9337	0.8573	3.1246	0.3624	2.0309	0.9018	3.2951	0.3797	2.1274	0.9602	3.4674
Shanxi	0.6672	1.4219	0.7015	2.7905	0.7249	1.4933	0.7378	2.9560	0.7595	1.5643	0.7856	3.1094
Inner Mongolia	0.6672	0.8816	0.8873	2.4360	0.7249	0.9259	0.9333	2.5840	0.7595	0.9699	0.9938	2.7231
Hainan	1.1675	0.9953	0.2518	2.4146	1.2685	1.0453	0.2649	2.5787	1.3291	1.0950	0.2820	2.7061
Tibet	0.1668	1.2512	0.6835	2.1015	0.1812	1.3141	0.7189	2.2142	0.1899	1.3766	0.7655	2.3319
Heilongjiang	0.3336	1.0237	0.6415	1.9988	0.3624	1.0752	0.6748	2.1124	0.3797	1.1263	0.7185	2.2245
Qinghai	0.1112	1.0522	0.8334	1.9967	0.1208	1.1051	0.8766	2.1024	0.1266	1.1576	0.9334	2.2175
Tianjin	0.7228	0.7962	0.1679	1.6869	0.7853	0.8363	0.1766	1.7981	0.8228	0.8760	0.1880	1.8868
Jilin	0.2224	0.9100	0.3297	1.4621	0.2416	0.9557	0.3468	1.5442	0.2532	1.0011	0.3693	1.6236
Ningxia		0.8816	0.3058	1.1873		0.9259	0.3216	1.2475		0.9699	0.3425	1.3123

of the whole emission in a hotel's life circle. From the perspective of the operation stage, electricity consumption is the main carbon emission source of the single hotel in all the star levels.

Table 6 shows the calculation results of carbon emissions under three different conditions: qualified, standard and advanced for a single green hotel of each star class.

Finally, the carbon emission of the green hotel is subtracted from those of the traditional hotel and obtain the carbon emission reduction potential of the traditional hotel in different scenarios as shown in Table 7. Compared between different hotel types, the emissions of five-star hotels are generally higher than that of four-star hotels, and the emissions of four-star hotels are higher than those of hotels below three stars. Among them, the emission reductions of a single five-star hotel are 55,596.34tCO_2, 60,404.74tCO_2, and 63,290.23tCO_2 under green qualified, standard, and advanced levels respectively. While the emission reduction potential of a single three-star hotel and below is the smallest, with an emission reduction ranging from 5,995.33 to 6,714.93 tons. This is in line with common sense. Traditional five-star hotels have luxurious decoration, large scale and complete supporting facilities, and their carbon emissions are large in the construction process. In the operation process, five-star hotels often pay attention to the quality of service obtained by customers, and the amount of carbon dioxide produced by energy

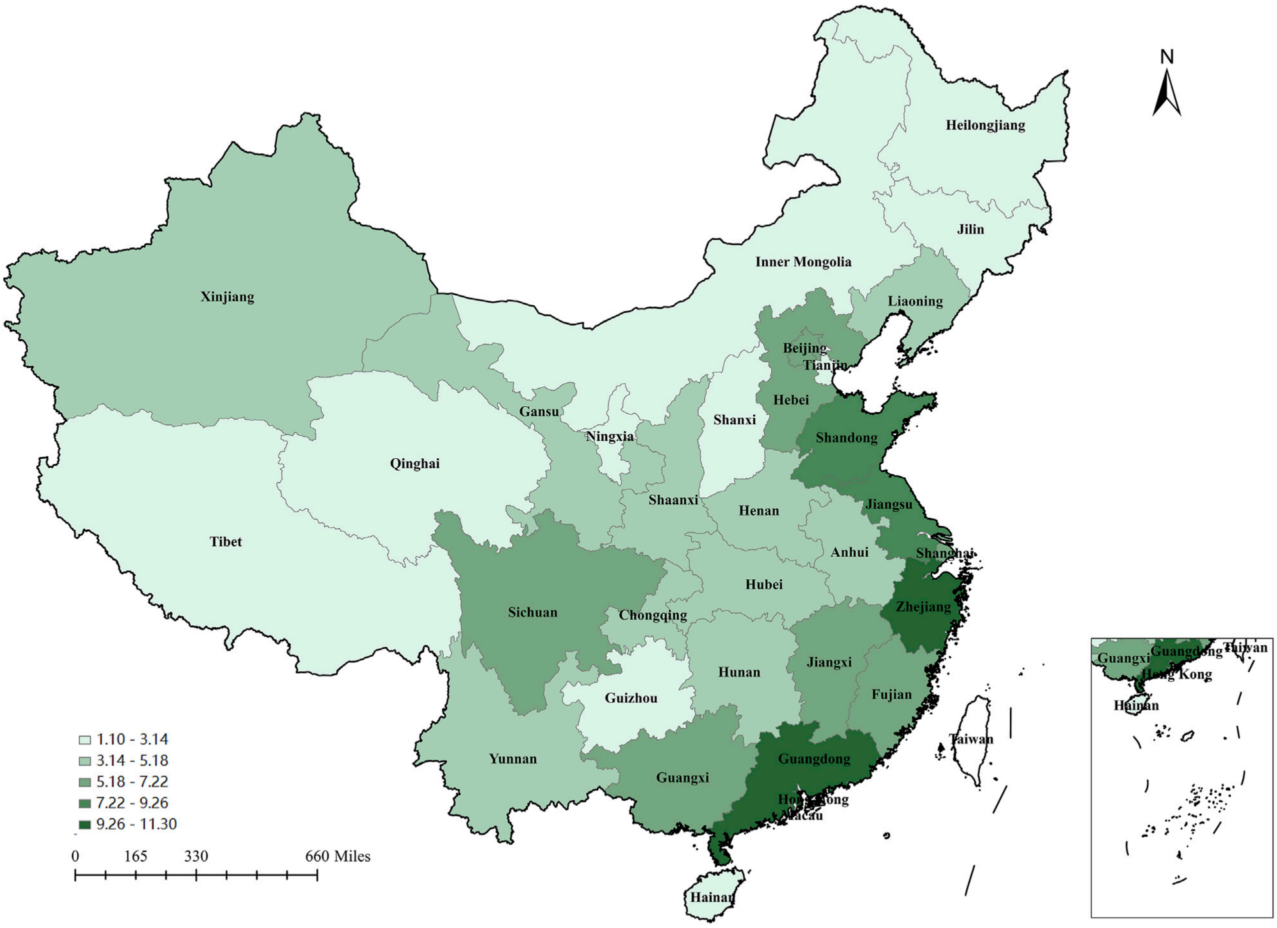

FIGURE 1
Carbon reduction potential of hotel industry in major provinces (based on green qualification level).

consumption is also more than others. However, for low-star traditional hotels, the scale of the hotel is limited, and the carbon emission in the construction and operation process is comparatively low. In terms of carbon reduction, the five-star hotel may conduct more thorough green operation due to goodwill consideration. The first zero-carbon hotel in China, Songzanrinka Hotel, is also a five-star hotel. While three-star hotels may be slightly weaker in terms of transformation power and financial ability. But the difference between the standards followed by five-star hotels and three-star hotels is relatively small, so the carbon reduction potential of five-star hotels is much higher than that of other star hotels.

This paper also calculates the carbon emission reduction of the national hotel green transition based on the "Ministry of Culture and Tourism of the People's Republic of China, 2020" data, and the results are shown in Table 8. It is obvious that the emission reductions at the greening qualified level of the national five-star, four-star, and three-star and below hotels are 45.589 million tons, 67.936 million tons, and 30.972 million tons respectively; when reaching the standard green level, the estimated emission reductions of three kinds of hotels are 49.532 million tons, 71.351 million tons and 32.578 million tons; when reaching the advanced green level, the national five-star, four-star, and three-star and below hotels are expected to reduce emissions by 51.898 million tons, 74.741 million tons and 34.689 million respectively. According to the previous research results, a single traditional hotel of five-star has the greatest emission reduction potential. But the amount of four-star, three-star and below hotels in China far exceeds that of five-star hotels, which makes the national four-star hotels have the largest emission reduction potential in the overall green transformation process, followed by five-star hotels, and three-star hotels and below, no matter the level of greening is.

Finally, this paper calculates the total carbon reduction through the green transformation of star-rated hotels in major provinces and cities across China. The results are shown in Table 9. It can be seen that Guangdong, Zhejiang, and Jiangsu provinces rank in the top three in terms of emissions reduction potential during the green transformation of the hotel industry in Chinese major provinces. The number of hotels in these three provinces is higher than that in other regions due to the influence of the regional economy and tourism (Chen et al., 2017), and the corresponding carbon reduction potential also ranks high. When reaching the green qualified level, the total emission reductions numbers of the five-star, four-star, and three-star and below hotels in the three provinces are 11.2081, 10.8352, and 9.0181 million tons of CO_2; when the green standard level is reached, the total emission reductions of those provinces are 11.9779, 11.5473, and 9.6301 million tons of CO_2; 10.1073 million tons of CO_2. The five-star hotels in Guangdong province have the greatest emission reduction potential for the green transformation process. When reaching the green qualified, green standard, and green advanced level, the carbon reduction amounts are 5.6152 million tons of CO_2, 6.1009 million tons of CO_2, and 6.3923 million tons of CO_2, correspondingly. Since the number of four-star hotels is more than that of five-star hotels in the two provinces, four-star hotels' overall carbon reduction potential ranks first among all the star-rated hotels. In order to make the data better presented, we draw a GIS map (Figure 1) of the carbon reduction potential of hotels in major provinces by taking reaching the green qualification level as an example since under other situations the maps are very similar to this one.

Conclusion and policy implication

(1) The research results show that the hotel's construction stage and energy consumption are the major focus on emission reduction in a single hotel's life cycle. Construction emission reduction is mainly for establishing new hotels, and the management agencies should put forward stricter requirements, such as developing more environmentally friendly standards so as to motivate hotel owners to select energy-saving and green design schemes, use recyclable building materials, and introduce new low-carbon technical equipment to complete the construction process. In terms of reducing energy consumption, also requires the joint efforts of the hotel itself and the management department. On the one hand, it is necessary to purchase environmental protection and energy-saving equipment, and to cultivate the energy-saving and environmental protection awareness of hotel service personnel; on the other hand, relevant departments need to reduce the supply of fuel for power generation in a reasonable way, to establish and improve the clean energy supply system, promote the scope of clean energy application, and speed up the realization of the green operation in the hotel industry.

(2) According to the overall carbon reduction calculation results of all the star-rated hotels, four-star hotels and five-star hotels have high carbon emissions. When formulating the carbon reduction policy of the hotel industry, these high-star hotels should also focus on carbon reduction, and then gradually implemented it in three-star and below hotels. In addition, the emission reduction potential of hotels in different provinces also varies greatly, and the management departments should adopt measures to local conditions, and promote the carbon reduction work of hotels orderly. Such as setting up some pilot areas in Guangdong, Zhejiang, and Jiangsu, the three major provinces of the hotel industry emissions, establishing a complete carbon emissions measurement mechanism, organizing professional teams to assess the management facilities and management of low carbon performance of local hotels regularly, and building a trading platform for the hotels to purchase quotas for unavoidable carbon emissions. In the future, this series of carbon reduction action plans will be further extended to the whole country.

Research limitations and discussion

The limitations of this study are concentrated in two aspects, one is the lack of time trend dynamic research, and the other is the lack of considering the difference in emission reduction potential of the same star hotels. This paper only calculates the carbon emission reduction potential of the hotel industry statically based on the statistical data of 2020 and does not analyze the emission reduction trend of the hotel industry from the time dimension. Scholars can continue to study the dynamic changes in carbon emission reduction in the hotel industry. In addition, due to the difficulty in obtaining data, this paper only calculates carbon emission reduction based on the average level of star-rated hotels. However, in reality, there may be great differences in the carbon emissions of the same-star hotels, and the carbon emission reduction potential of each-star hotel should also be a reasonable interval. The future calculation can do more in-depth subdivision research in this aspect.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JQ conceived and designed the study. CS provided the data. ZG and JQ wrote the paper. ZG analyzed the results. All authors read and approved the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Designing the profile of industrial consumers of renewable energy in Romania under the impact of the overlapping crisis

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Prior to the outbreak of the conflict in Ukraine, the European energy markets had already been in a profound state of crisis with prices reaching top levels and with minimum supplies. The cost of the energy has had a significant impact on the performance and the sustainability of the majority of the economic operators, most of them considering the overgrowth of the price of the energy and the raw materials as the main risks in terms of the short - term development of the operational activity. Given the current situation, the aim of the study is to identify new solutions to reduce the negative effects of the present day crisis on the Romanian economic operators. In this context, the study focuses on the following objectives: O1—estimating the social and economic effects on the economic operators as a result of the energy crisis; O2—identifying the key factors which make the economic operators switch from the traditonal resources consumption to the renewable energy consumption and O3 - analyzing the influence factors in stimulating the investments in the renewable energy. The research methods that have been used are based on the quantitative analysis with the help of a questionnaire applied to 264 Romanian production companies. The final results of the present study refer to designing an overall profile of the industrial consumers given the escalation of the energy crisis worldwide. The findings of the study can be useful both for the final energy consumers and for the producers and distributors alike and ultimately for the European and national legislators whose decisions are closely related to the very future of these economic entities.

KEYWORDS
renewable energy, investments, green certificate, energy crisis, sustaianability

Introduction

As a result of the difficulties and the turmoils on the global energy market generated by the invasion of Ukraine by Russia, the European Commission submitted the REPower EU plan which is meant to ensure Europe's independence in terms of the Russian fossil fuels long before 2030 taking into account the invasion of Ukraine by Russia. The design of this plan represents an answer to the request of 85% of the Europeans who believe that the European Union should reduce its reliance on the Russian petrol and gas as soon as possible in order to support Ukraine. The main objectives of this plan are as follows: energy saving; the production of clean energy; the diversification of their own sources of energy. No doubt that this particular plan is backed up by certain financial and legal measures and decisions which are meant to facilitate the rapid building of a new infrastructure and of a new energy system for Europe.

Consequently, it is of an utmost importance the analysis of the issues with which the Romanian economic operators have to deal with as a result of the impact of the overlapping crises during the last 2 years and especially of the increase in the energy and raw materials prices. Thus, the amount of energy that already comes from renewable sources in Romania should be quantified. The term *renewable source* stands for that particular type of energy which is produced from using the natural resources. Given this fact, it is important to analyze if these particular resources have the capacity to regenerate - at least at the same speed they are used–or if they are not depleted on the timescale of geological eras. This means that their present use would not have a significant impact on the future generations' possibility to benefit from them too.

According to the data provided by the Initiative for Competitivity, Romania registered in 2015 a degree of coverage of the energy needs from imports of only 17.1%, thus occupying a third place in terms of energy independence within the European Union where there was a 54% average. Romania is the thrid state within the European Union in terms of its energy independence following Estonia (7.4%) and Denmark (13.1%).

The Romanian economic operators have suffered from a strong negative impact of the sanitary crisis, yet the conflict in Ukraine has increased the negative effects on the performance and the sustainability of their activity even more, especially due to the expensive energy and the lack of the raw materials whose value has gone up tremendously in the last few months. However, it is very important that the investments and the innovation regarding the transition processes to a green energy becomes a new opportunity and not a danger for these companies.

The reason for undergoing the present study lies in the fact that the industrial energy consumers from Romania have found themselves unprepared for the effects of the energy crisis, as very many of them have been forced to stop their manufacturing process. The shocks of the pandemic crisis as well as of the war in Ukraine have basically managed to rewrite the entire future of the energy sector in the whole Europe. In Romania, there has been a series of bankruptcies of many companies. Since so far, the environmental objectives have been a top priority, but now the focus point refers to the energetic security. For all these consumers, energy supply used to be perceived as an ordinary activity, but today this security is completely threatened, which is why it is very important that even the industrial consumers to ask themselves questions whether Romania is able to satisfy the energy needs and from what sources, while limiting the increase in emissions. Nowadays, it is vital for all the economic operators to actively get involved into solving all these issues generated by the energy crisis, which means that there is a general need for more flexibility and a mix of techologies based on more or less exploited existing resources. Consequently, the present research has been determined by the need of identifying the demands and by the difficulties faced by the industrial consumers who have been lured to be part of an unstoppable race in terms of the prices for the raw materials and for the energy itself, given the fact that the inflation reached a 10% value according to the National Bank of Romania, whereas the value of the products and/or the services offered by these operators have become unsustainable themselves. In other words, it can be appreciated that nowadays there is an emergency situation that compresses the operating margins which have already been reduced by several economic operators and which risks to lead to the slowing down or even to the foreclosure of many business activities. The main objectives of the study are as it follows: O1—evaluating the economic and social effects on the economic operators as a result of the energy crisis; O2—identifying the key factors in making the economic operators switch from the consumption of the traditional resources to the renewable energy and O3—analyzing the influence factors in stimulating the investments in the renewable energy.

The final results of the present study refer to designing an overall profile of the industrial consumers given the worldwide escalation of the energy crisis, as well as testing the opinions of the managers, the investors and of the specialized personnel in some manufacturing entities in terms of the production and the renewable energy consumption. Given the fact that the costs will not be the same as they were before the crisis due to the existing political priority to continue towards a green transition - considered to be essential in order to reduce the dependency on the Russian fossil fuels - it can be considered as necessary to design a profile of the energy consumers, in order to identify their major issues and to be able to consolidate their resilience step by step.

Regarding the *limitations of the study*, it is important to highlight the fact that they are the result of a lack of a realistic strategy to reduce the carbon emissions in all the sectors of activity which can be put into place in a short period of time by the national governement, by the political decison-makers, as well as by the industries' representatives, considering the significant direct impact of this matter on the industrial consumers. This is the reason why their theoretical background, as well as their answers may contain certain amount of subjectivity. Another setback of the research itself refers to the fact that the national energy system is not properly equipped for outside shocks and other unusual combinations of

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events, especially in the energy production sector which is a key part of the energy system itself and which has generated a chain reaction for the industrial consumers, especially the ones in the manufacturing sector. It is unlikely and prematurely for this type of consumers to be able to identify the possible opportunities which are presented by this crisis, as this thing can only be possible when Romania will have a real chance of rethinking its whole energy system in order to adjust it to the transition process and to the climate change measures, by maintaining the supply security as its top priority. In this particular situation, the industrial consumers have faced an unexpected crisis which has led to a fair amount of unwillingness to respond to the questionnaire. They have been extremely concerned with the future of their business, they constantly felt threatened and without any protection against the consumption government policies and energy prices.

The novelty of this topic resides in designing the profile of the Romanian industrial consumer in the times when the energy crisis has significantly influenced the profitability and the sustainability of their businesses, whereas their concern for identifying and use of alternative green energy resources seems to become less important in comparison with the energetic security. The need for outlining a new profile of the energy consumer is of a significant importance for the economic and social environment, due to the fact that it provides the means to counterbalance all these effects and to avoid the risk of the companies' bankruptcy, based on a whole range of solutions and suggestions which the government needs to be well aware of, take into account and implement as soon as possible because they would facilitate further focus on renewables and capping gas prices. The final results indicate the fact that the confidence of the industrial consumers is influenced by the acquired knowledge in terms of the renewable energy sources, by the level of social awareness and by their willingness to acquire and extend their knowledge in this particualr field according to their position within the company (i.e. manager, investor or specialized personnel).

Regarding the structure of this paper, the first section comprises the literature review on the evaluation of the effects of the energy crisis on the industrial consumers and of the interest for the green investments in the sustainable energy, in order to overcome the dependancy on the fossil fuels. This section it is followed by the research methodology which presents a descriptive and an analytical approach, aiming at developing a model for counteracting the latest profile of the industrial energy consumers given the uncontrolled crisis. In this particular section the selected dependent and the independent variables are described, too. There is also the results section that presents the empirical results, the objectives and the validation of the results. The study concludes with a conclusion section where a number of recommendations for the government are substantiated and policy implications are highlighted in the context of a severely affected economic cycle.

Literature review

The present-day energy crisis has relaunched the chance for a certain number of European companies in the sense that, on the one hand, they need to observe the European and the national polictied and on the other hand, to become more proactive, to protect their competitiveness better and to consolidate their resilience. Regarding the vision of the European Union in terms of the energy sector, it is based on the energy efficiency and the renewable energy, while the Green European Agreement also makes reference to specific aspects such as the energy affordability, the market integration, the market connectivity and digitalization. The use of the green energy techologies (GET) represents an essential step towards a sustainable future from the European point of view, fact that calls for a close study of the factors influencing the wish of the final consumers to make use of a renewable energy (Jabeen et al., 2021). During the last decades, the energy demand has been continuously increasing worldwide which, given the current dependence of power generation on fossil fuels, has resulted in a continuous increase of the carbon emissions (Pradhan et al., 2021). This is the reason why the main trajectory of the energy sector in Europe relies on the transition to an economy based on low carbon emissions and on increased energy efficiency, even stressing the need for fiscal and financial incentives for research and development of renewable technologies (Bersalli et al., 2020). Last but not the least, the development of the resilience in terms of the energy constraints may give way to an increase of the effectiveness and the improvement of the results of the research-development activity, whereas by encouraging the investments in the energy production may be a solution for diminishing the negative effects of the present energy crisis (Löffler et al., 2022; Saadaoui, 2022).

In the face of the vulnerabilities, threats and risks faced by Romania as an EU country, in the new turbulent and unpredictable geopolitical context of global security, amplified by the global energy crisis, the Romanian state should have a strategy to strengthen the resilience of critical energy infrastructures, based on predictability, flexibility, continuity, adaptability and resilience. (Fîţă et al., 2022). The energy markets have obviously gone through significant turmoils since the COVID-19 outbreak. For example, at the end of 2021, the increase of the cost of the natural gases has caused a new type of crisis which has led to certain risks in terms of the lack of energy supply worldwide and gave way to the issue of the energy security as a key factor (Berahab, 2022). As far as Romania is concerned, as in all the rest of the European Union countries, the monetary policy has changed by becoming more restrictive, whereas the emergence of the limitations imposed by the national debt will call for more "cautious" fiscal policies according to the recommendations of the European Commission. The unprecedented growth of the energy costs in the European Union shows that no matter what the energy supply sources there are, the majority of the state members face an energy crisis, leading to a decrease in their capacity for economic development, fact that highlights that there exists a close relationship between the energy crisis and the development outcomes. Energy constraints could therefore negatively influence development outcomes (Adom et al., 2021). At the same time, the volatility of the costs of the natural resources has become more and more important due to the fact that their costs plays a key role in the economic growth. Thus, their volatility, as well as their influence on the economic performance has established new research tendencies and streamlines (Thanh and Linh, 2022; Wen et al., 2022). Most of the costs for the energy resources have an impact on both the producers and the consumers. Consequently, the understanding of the energy transition is crucial for predicting the future business, societal and ecological trends. The future economic, environment and social changes depend on the means that the energy policy will shape the energy transition and will adjust to the connected changes (Gatto, 2022). Based on the empirical findings, the studies that are mentioned in this section of the study suggest the capping of the costs and the promotion of the ecological innovation. There could be corrective actions in order to continuously improve the economic and financial performance, as well as to reduce the volatility of the cost for the natural resources. Unlike the present study which focuses on the profile of the renewable energy industrial consumer, other studies (Żywiołek et al., 2022) have focussed on measuring the confidence level of the household consumers in terms of the renewable energy sources. The findings have shown that the confidence of the people in charge with the household energy is influenced by the knowledge of renewable energy, the level of social awareness and their willingness of acquiring and expanding their knowledge in this field. The importance of identifying the profile of the renewable energy consumer is supported by other studies too, they analyzing some factors that are more or less similar to the ones that are discussed in this study. For example, in a group of 28 research articles on the topic of the renewable energy, there are three factors that have been identified as supporting - in a near future - the changes in terms of the renewable energy industrial consumers such as: sustainable techologies for the local energy systems, energy storage and the breakthroughs in terms of flexibility, as well as the use of the solar energy in several sectors of activity (Kılkış et al., 2019). In spite of the fact that the findings of the above-mentioned study are more than agreed by the law-makers, they do not take into account the uncertain conditions generated by a series of crises in which industrial consumers no longer have predictable policies and are unable to ensure the sustainability of their activity. On the other hand, there are also studies according to which during an economic crisis, the investements in a clean energy are highly likely to take place as a result of the need to protect the environment and to preserve a clean air (Shaikh et al., 2022), therefore the industrial consumers should have a stronger voice in terms of the importance hierarchy of using the renewable energy sources and ensuring the energy security.

The review of the above mentioned literature has shown that many studies have already looked into the environment crisis which is generated by the consumption of the traditional energy resources and by identifying ways to reduce the carbon footprint and stimulate renewable energy production without taking into account the negative effects of an unforseen energy crisis. There are no specific studies which can provide predictable policies regarding the present and future effects of the energy crisis on the sustainability and profitability of the industrial energy consumers' businesses by outlining a proper economic development framework. Consequently, the present study fills in the existing gaps by shaping up a profile of the industrial consumers during an overlapping crisis. This provides an opportunity to test the industrial consumers' perceptions of uncertain and unpredictable conditions in a context of multiple crises and to determine their level of confidence in renewable energy sources.

Materials and methods

The research methodology has initially relied on the review of the specialty literature and on its content analysis. The second stage refers to the questioning of the Romanian industrial energy consumers. The questions have been thus formulated so that they could evaluate the opinion of the managers, the investors and of the specialized personnel regarding the effects of the present energy crisis and of the consumption of greeen energy, too.

Based on both the descriptive analyses and on the use of the thinking energy system, the cognitive model of the industrial renewable energy consumption and the evaluation of the effects of the present crisis and the stakeholders'interests (such as, for example, the managers, the investors and the specialized personnel) have been described and analyzed. The comparative analyses of the three mentioned above categories of stakeholders have been used in order to study the existing general and specific knowledge on the analyzed matter that significantly has been influenced by the recent changes in the consumption patterns of the industrial consumers.

Discriptive statistics

The study is based on the quantitative research (see Figure 1), namely on the questionnaire method. The survey comprises 19 questions out of which 17 are open questions and two are matrix type questions and it was applied only to production companies from Romania, registering 264 responses of which 104 were managers, 96 were investors and 64 were specialised employees.

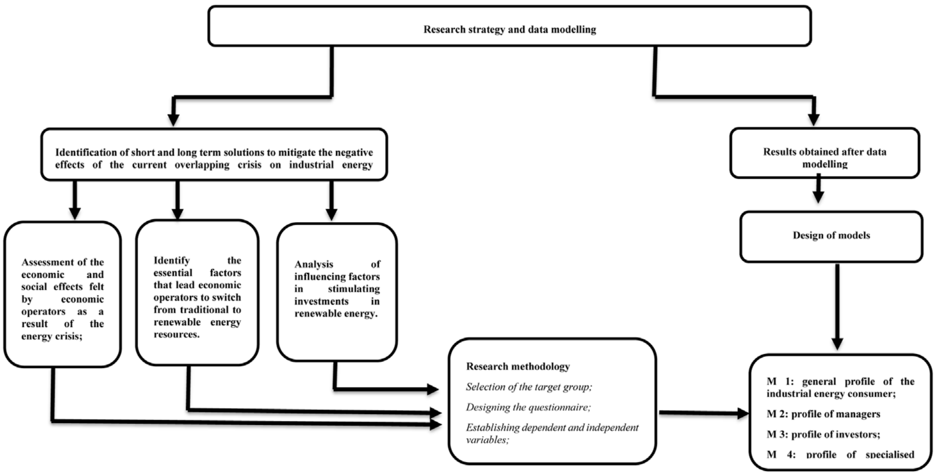

FIGURE 1
Research strategy and data modelling.

TABLE 1 The structure of the sample and of the type of the respondents.

Types of companies	Large	44	16.67 (%)	Management	12	27.27 (%)
				Investors	12	27.27%
				Specialised Employers	20	45.46
	Medium	36	13.63	Management	8	22.22
				Investors	24	66.67
				Specialised Employers	4	11.11
	Small	184	69.70	Management	84	45.65
				Investors	60	32.61
				Specialised Employers	40	21.74

The inclusion criteria regarding the selection of the companies are the following: production companies, companies which have an ongoing activity or which have registered a downsize during the last 5 years, companies whose financial reporting can be checked and which have responded to all the questions of the questionnaire. Moreover, only the answers of the managers, stakeholders or the specialized personnel have been taken into account. *The exclusion criteria* are as follows: the companies carrying out another type of activity apart from manufacturing; the companies which failed to answer all the questions as well as the companies which have gone bankrupt or have registered a decrease of their activity during the last 5 years.

According to Table 1, there are large companies which answered the questions (16.67%), the medium ones (13.63%) and the small ones (69.70%), the ones which have the employees who are concerned with the threats of the present multiple crises and which are, ate the same time, willing to focus mainly on the green energy. These are the companies which activate in Romania, with a Romanian capital and which do not rely on a foreign support. Most of the companies belong to the manufacturing and processing sectors and have a small revenue and assets below 700.000 euros.

In order to design the general profile of the companies which are renewable energy consumers, there were six independent variables which were set in place displaying the specific and general knowledge about the green certificates and the renewable energy, the key factors for the onset of the global energy crisis and the solutions for overcoming the crisis as well as the level of the corruption and the profiteering in the energy sector. The dependent variable identified with the *general profile of the industrial consumer* (*Pic*) which has been designed based on the previous data comprises economic, financial and social data regarding the respondents (see Table 2). As far as the other three

TABLE 2 Description and definition of the researched independent variables.

Variables	Description
Kwg	General nowledge generale regarding the production and consumption of the renewable energy and the role of the green certificates
Kws	Specific knowledge regarding the renewable energy production and consumption and the role of the green certificates
St_k	The stakeholders who are interested in the renewable energy production and consumption
Cr	Corruption in the industry of renewable energy
If	Key factors in the onset of the global energy crisis
Sol	Solutions in overcoming the energy crisis
Pic	The general profile of the industrial consumer
Pm	Managers'perception
Pi	Investors'perception
Pse	The perception of the specialised employees

TABLE 3 Dependent variables and regression model equations.

Dependent Variables	Type of model
General model	$Pic = \alpha_1 + \beta_{11} \cdot \mathrm{Kwg} + \beta_{12} \cdot Kws + \beta_{13} \cdot Stk + \beta_{14} \cdot Cr + \beta_{15} \cdot If + \beta_{16} \cdot Sol + \varepsilon_1$
Managers	$Pm = \alpha_2 + \beta_{21} \cdot \mathrm{Kwg} + \beta_{22} \cdot Kws + \beta_{23} \cdot Stk + \beta_{24} \cdot Cr + \beta_{25} \cdot If + \beta_{26} \cdot Sol + \varepsilon_2$
Investors	$Pi = \alpha_3 + \beta_{31} \cdot \mathrm{Kwg} + \beta_{32} \cdot Kws + \beta_{33} \cdot Stk + \beta_{34} \cdot Cr + \beta_{35} \cdot If + \beta_{36} \cdot Sol + \varepsilon_3$
Specialised employees	$Pse = \alpha_4 + \beta_{41} \cdot \mathrm{Kwg} + \beta_{42} \cdot Kws + \beta_{43} \cdot Stk + \beta_{44} \cdot Cr + \beta_{45} \cdot If + \beta_{46} \cdot Sol + \varepsilon_4$

secondary models are concerned, they have been developed in relationship with the position or the status of the respondents within the company (i.e. managers, investors or specialized personnel).

In order to design the particular models referring to the profile of the managers of these companies, of the investors or of the specialized personnel, the study has resorted to the use of the same independent variables as in the case of the general profile of the small, medium and large industrial consumers (see Table 2).

The linear regression model was defined based on the function:

$$Y_i = \alpha + \sum_{j=1}^{6} \beta_{ij} X_{ij} + \varepsilon_i \mathrm{i} = 1 \ldots \mathrm{n} \qquad (1)$$

where n stands for the size of the sample which was tailored for each and every model.

In designing the profiles of the renewable energy industrial consumer and the three secondary models which have been described above, the reasearch relied on the multiple linear regression model (see Table 3).

One of the most important advantages in estimating a multiple linear regression model refers to the fact that it allows the forecast on the changes of the independent variables in relationship with the dependent variable. The regression model facilitates getting the parameters corresponding to the formulated set of variables when the data series are recorded in the statistical units for a period of time or for just a moment as well as to highlight the reliance among the variables during a specific timeframe. The other factors influencing the resulting variable have been grouped in the residual variable.

The reason for using the multiple regression analysis relies on the fact that it deals with the relationships among a dependent variable and one or several independent variables implying, at the same time, the causality relationship. This means that the independent variables are the cause and the dependent variable represents the effect of the cause. In the event that there is a causality relationship between an independent and a dependent variable, it needs to be justified by some economic theory.

The limitations of the study and comparative analysis with other similar studies

One of the most significant downsize of the empiric research refers to the fact that in designing the model on the estimation of the behavior of the renewable energy industrial consumer the law of demand implying that there is a relationship between the requested/consumed energy quantity and its price, provided the rest of the variables influencing the request are constant, there is not enough data to support the causality relationship (between the price which can be the very reason for it and the demended quantity/consumption which could be considered as the effect itself). This the reason why the causality needs to be reinforced in its turn by the economic theory referring to the phonomenon which has been tested empirically.

As it was mentioned above, one of the most common forecast method that is used in order to design the profile of the energy consumer is the use of the multiple linear regression model. Hence, according to the present study, the perception of the managers, the investors and of the specialised personnel as part of the group of the Romanian economic operators, the who are renewable energy consumers and who have been suffering as a result of the present energy crisis, have been estimated based on a regression model including as follows: the general knowledge on the production and the consumption of renewable energy and the role of the green certificates; the stakeholders who interested in the production and the consumption of renewable energy; the corruption in the renewable energy industry; the key factors in the onset of the global energy crisis; the solutions in overcoming the energy crisis. According to these models, the forecast of a variable, for example the Y variable, has to do not only with its previous values, but also with the present and previous values of the variables influencing this particular variable.

In order to support the functionality of the studied model, there will be mentioned certain studies which have shown significant results based on a similar research logic. For example, by using an analysis of the price tendency (Bianchini et al., 2022) certain market options with the highest chance of reducing the costs or profit making have been researched. The final results have shown that on the German market the consumers have the highest chances of reducing their energy supply costs based on the market options related to the network tariffs and the energy market. Bianchini et al. (2022) have shown that the flexible use of the energy itself allows the reduction of the energy costs as well as some extra cost benefits. The findings of Sun and Nie (2014) have indicated that the standard renewable portfolio policy is more efficient for cutting down the carbon emissions as well as for improving the extra consumers. They have demosntrated that there is an inversely proportional relationship between the investment in the research and development and the cost reduction. The Sadorsky (2009) model has demonstrated that the capital gains bought per unit in the renewable energy sector are higher than the labor gains, thus indicating the capital-intensive characteristics of the renewable energy sector which is a very important aspect for the management, the specialised personnel and for other categories of stakeholders alike. The empirical results of Abeliotis et al. (2010) based on the linear regression method as part of a survey which took part in Greece has launched the hypothesis that income is the strongest predictor variable of 3R (reduce–reuse–recycle) activities and affects the eco-friendly behaviour negatively.

Unlike the nature of the independent variables which have been used in the above-mentioned studies, in the model suggested in the present study the variables comprise the following:

$$\text{Pic} = f\,(\text{Kwg},\ \text{Kws Stk Cr If},\ \text{Sol}) \tag{2}$$

The interaction among the model's variables also takes place within the evaluation models of the perceptions of the managers, the investors and of the specialised personnel regarding the renewable energy consumption and the effects of the energy crisis. The variables of the model have been established in such a way so as the oversight of the direct, indirect and of the global effects on the renewable energy industrial consumers should be possible.

Results and discussion

The economic situation of many countries shows that there are small or medium energy producers who are not fully aware of the importance of the production and the consumption of renewable energy. It is the energy which is mentioned on their bill in the form of green certificates. A proper training of the management of such companies, of the stakeholders and of the specialised personnel in terms of the renewable energy production and consumption could have a significant impact on the escalation of certain negative effects that are generated by the present energy and geopolitical crisis. In this context, the profile of the industrial renewable energy consumer can provide a series of key data both to the legislator and to the renewable energy producers and suppliers.

Designing the general profile of the small, medium and large industrial consumers

The present study shows the findings as a result of processing the responses of the small, medium and large industrial consumers. In designing the general profile of the small, medium and large industrial consumers a series of the most relevant influential variables for the present energy crisis have been establishes such as: general and specific knowledge regarding the production and consumption of renewable energy and the role of the green certificates; identifying the key stakeholders who are directly involved in the production and the renewable energy consumption; identifying the corruption level in the renewable energy industry from the perspective of the small and medium industrial consumers; ranking the key factors in the onset of the global energy crisis as well as the solutions regarding the means of overcoming the energy crisis.

According to Table 4, it can be noticed that there is a relationship among the dependent varible Pic and the Kwg, Kws, Stk, Cr, If and Sol independent variables with a 0.281 value. By analyzing the ratio of determinacy, it can be

TABLE 4 Summary model corresponding to the dependent variable for Pic.

Model	R	R Square	Adjusted R Square	Std. Error of the estimate	Durbin-watson
1	0.281[a]	0.079	0.058	0.69850	1.966

a. Predictors: (Constant), Sol, If, Kwg, Kws, Cr, Stk

b. Dependent Variable: Pic

TABLE 5 ANOVA corresponding to the dependent variable for Pic.

Model		Sum of Squares	Df	Mean Square	F	Sig. (b)
1	Regression	10.769	6	1.795	3.679	0.002
	Residual	125.392	257	0.488		
	Total	136.162	263			

a. Dependent Variable: Pic

b. Predictors: (Constant), Sol, If, Kwg, Kws, Cr, Stk

TABLE 6 The coefficient of the independent variables for the Pic model.

Model		Unstandardized Coefficients		Standardized coefficients	t	Sig
		B	Std. Error	Beta		
1	(Constant)	3.374	0.472		7.153	0.000
	Kwg	-0.089	0.147	-0.037	-0.603	0.547
	Kws	-0.359	0.097	-0.316	-3.701	0.000
	Stk	0.197	0.067	0.254	2.965	0.003
	Cr	-0.108	0.076	-0.087	-1.411	0.159
	If	-0.021	0.029	-0.044	-0.713	0.476
	Sol	0.094	0.040	0.147	2.364	0.019

a. Dependent Variable: Pic

observed that the variables' change influences by 7.9% the Pic variable. The findings resulting from the analysis of the answers provided by the 264 representatives of the small, medium and large industrial consumers highlight the fact the lack of the educated industrial consumers from the point of view of the opportunities that are offered by the renewable energy consumption.

As a result of taking into account the value of the Sig. = 0.002 significance threshold under, hence, the resulted model is validated (see Table 5).

As a result of testing out the model, the following regression equation is as follows:

$$Pic = 3.374 - 0.089 \cdot \text{Kwg} - 0.359 \cdot Kws + 0,177 \cdot Stk - 0.108 \cdot Cr - 0.021 \cdot If + 0.094 \cdot Sol \quad (3)$$

Consequently, according to the regression quotients, the order of influence on the general profile of the (Pic) renewable energy industrial consumer is as follows: Kws, Stk, Sol, Cr, If și Kwg (see Table 6). Hence, according to the above mentioned model, it can be noticed that the general profile of the small, medium and large industrial consumers is most significantly influenced by the specific knowledge regarding the renewable energy production and consumption and by the

TABLE 7 Residual statistics corresponding to the dependent variable for Pic.

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.2396	3.2099	2.6534	0.19697	264
Residual	-1.58724	0.93255	0.00000	0.69205	264
Std. Predicted Value	-2.101	2.825	0.000	1.000	264
Std. Residual	-2.267	1.332	0.000	0.989	264

a. Dependent Variable: Pic

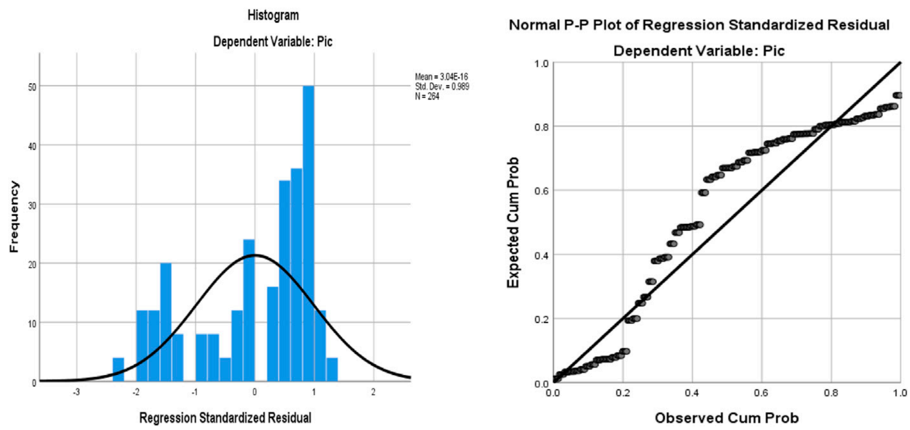

FIGURE 2
The histogram and the digrama Q−Plot flowchart corresponding to the Pic dependent variable.

role of the green certificates, too, which means that the gathering of such information may persuade the renewable energy consumers to give up the traditonal energy. However, both the costs and the time for achieving this target fail to convince them. From this point of view, the study done by Gambardella & Pahle (2018) has reached the conclusion that the purchase of an increased amount of renewable energy will not necessarily lead to a decrease of the amount paid by them.

Another key factor refers to the stakeholders who are interested in the renewable energy production and the consumption such as: the renewable energy producers and suppliers, the civil society, the investors or other private entities.

Out of the personal respondent categories, the most interested in the renewable energy are the managers and the investors of the companies from the urban environment who have a total assets of 350.000–1.999.999 euros, a turnover of approximate 700.000–999.999 euros and a number of employees ranging between 10—29 and a gearing ration of under 60% (see Table 7).

The histogram distribution of the Pic dependent variable (see Figure 2) is weak towards the left which means that the profile of the industrial consumers is more uncertain given the manifestation of the energy crisis. However, once the negative effects on the activity of these economic entities escalate, it will be possible to outline a more stable and consistent profile which is situated on the maximum point of the Gaussian curve which means within the median range on the ascending path.

The distribution of the trend line on the *Q-Q Plot* chart of the dependent varible is inhomogeneous which means that the deviations in terms of the predicted right are significant and inherent for the energy crisis timeframe (the fact that this observational study focuses on the activity of the economic entities from the beginning of the energy crisis up to the present, needs to be highlighted).

On the same theme line as the present study, the study of Singh et al. (2019) highlights the fact that the respond to the demand programs and those of energy saving have been adjusted based on the electirc energy consumption models of the consumers, yet they disregard in an exhaustive manner the data ralted to the social and demographic as well as the social and economic chracteristics, the specific features of the demand

TABLE 8 Summary model corresponding to the dependent variable for Pm.

Model	R	R Square	Adjusted R Square	Std. Error of the estimate	Durbin-watson
1	0.435[a]	0.190	0.139	0.59040	2.088

a. Predictors: (Constant), Sol, Kwg, If, Kws, Cr, Stk

b. Dependent Variable: Pm

TABLE 9 ANOVA corresponding to the dependent variable for Pm.

Model		Sum of Squares	Df	Mean Square	F	Sig. (b)
1	Regression	7.907	6	1.318	3.781	0.002
	Residual	33.812	97	0.349		
	Total	41.719	103			

a. Dependent Variable: Pm

b. Predictors: (Constant), Sol, Kwg, If, Kws, Cr, Stk

facility and the behavior of its dweller in terms of the energy consumption. The very same factors can have a significant influence on the energy consumption and can facilitate a better understanding of the consumer's behavior.

Testing the managers perception

This section of the study analyzes the perception of the managers from the economic entities on which the reasearch was focused.

Managers have a key role in setting the organizational objectives and in using the resources effeciently. The latest energy crisis has had managers identify the solutions to improve their production activity and to reach the level of performance in order to meet their goals. According to Belous et al. (2022), as a result of price increase lately, the managers of the large energy consumer companies have designed alternative energy supply plans such as the transition towards the renewable enrgy, for example. Consequently, it ca be stated that the managers are demanded to develop and implement a new organizational goal such as the energy management of production activities in order to optimize the expenses. In this respect, in order to analyze the Romanian managers' perception regarding the energy consumption based on the above mentioned variables, the following econometric model has been designed:

$$Pm = 2.242 + 0.018 \cdot Kwg - 0.278 \cdot Kws + 0.130 \cdot Stk + 0.239 \cdot Cr - 0.074 \cdot If + 0.158 \cdot Sol \tag{4}$$

where Pm stands for the managers'perception, the rest of the variables have been previously described.

By analyzing the data in Table 8, it can be noticed that when comparing the Pm dependent variable and the independent variables, the value of the ratio of correlation is 0.435, whereas the analysis of the determinacy report shows that the variation of the independent varibles has a 19.0% on the variance of the Pm variable. The analysis of the responses of the managers shows their particular interest in the general profile of the industrial consumer from the point of view of the opportunities provided by the renewable energy production and consumption.

As for the general profile of the industrial consumer, the model as a result of the answers of the managers will be validated. The value of the Sig. = 0.002 significance threshold is situated under the value of 0.05 (see Table 9).

Unlike the general profile of the industrial consumers, it can be observed that the managers of these companies are more interested in acquiring general knowledge regarding the production and the consumption of renewable energy and less interested in the specific knowledge, yet they have no interest at all on the issue of the corruption in this field (see Table 10). The study of Herbes et al. (2017) which has been done on a sample of German managers from renewable energy groups identified the

TABLE 10 Coefficients of the independent variables corresponding to the variable for Pm.

Model		Unstandardized Coefficients		Standardized coefficients	t	Sig
		B	Std. Error	Beta		
1	(Constant)	2.242	1.087		2.062	0.042
	Kwg	0.018	0.350	0.006	0.051	0.960
	Kws	-0.278	0.167	-0.312	-1.666	0.099
	Stk	0.130	0.118	0.210	1.098	0.275
	Cr	0.239	0.113	0.247	2.117	0.037
	If	-0.074	0.039	-0.189	-1.899	0.061
	Sol	0.158	0.056	0.300	2.832	0.006

a. Dependent Variable: Pm

obstacles in terms of the implementation that these entities faced. They mainly refer to the unwillingness to take risks of both the managers and the other members, the concerns related to the impact on the environment or to the ethics of certain models which, in spite of the fact that they are legal, they fail to correspond to the requirements of the lawmaker. At the same time, they lack the specifications of the competences and of the time devoted by the managers which is mostly not paid for at all. Thus, their study, in the same manner as the present study alike, highlights the fact that it is important for the managerial competences and knowledge to be present in this relatively new field of renewable energy. The authors Żywiołek et al. (2022) have shown that confidence is a key factor itself and that it has an impact on the perception of the energy sources whereas the acquired knowledge allow the proper management of the waste energy by thus reducing the costs. The authors have also emphasized the fact that the confidence of the people managing the household energy is influenced by the reliability of the renewable energy sources which refer to knowledge, i.e. the level of social awareness and their willingness of acquiring and extending their knowledge in this field. Thus, it was spotted the need to highly promote the benefits of using the renewable energy sources which have significant effects in terms of cost reduction and the protection of the. It also can be considered that the renewable energy sources are a legit option to the global energy crisis that manifests in almost every country.

The managers'interest in the requirements and the policies promoted by the stakeholders that are involved in the renewable energy production and consumption as well as finding reliable solutions for the implementation of the renewable energy sources exert a considerable amount of influence upon the managers as they are less concerned with the external factors that are responsible for the outbreak of the energy crisis. Consequently, managers are interested in implementing these renewable energy sources due to their impact on the decrease of the energy cost which has direct implications on the performance of their organizations. The same conclusion has also been drawn by Drosos et al. (2021) as a result of questioning 510 Greek managers, 97.6% of them stating that it is mandatory for these measures to be taken and which will lead to energy savings according to the legal requirements on the environment protection.

The influence ranking on the managers'perception regarding the renewable energy production and consumption in relationship with the general profile (Pm) is the following: Sol, Cr, If, Kws, Stk şi Kwg.

It can also be noticed that managers that are the most interested in the renewable energy consumption are those of the companies from urban areas with a total assets ranging between 350.000 and 1,999.999 euros and a turnover ranging between 700.000 and 999.999 euros, with a number of employees ranging between 10 and 29 and a gearing ratio of over 60%. The less interested managers are those managing the small companies that have a turnover under 700.000 euros, with few employees and a high gearing ratio as well as the managers of the large companies with lots of employees and large debts (see Table 11).

In the case of the Pm analysis, the histogram is asymmetrical and does not follow the Gaussian curve, yet it has a shift to the left which means that there is a residual variation of the managers'perception in relationship with the regression variable on the downward slope (i.e. the 1.5–2.5 range) as shown in Figure 3. By analyzing the managers'responses, it can be stated that they are interested in the energy consumption and in the identifying the solutions for switching to renewable energy in order to cut down on their production costs.

TABLE 11 Residual statistics corresponding to the dependent variable for Pm.

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.3455	3.3000	2.8125	0.27707	104
Residual	−1.38797	0.83750	0.00000	0.57295	104
Std. Predicted Value	−1.686	1.759	0.000	1.000	104
Std. Residual	−2.351	1.419	0.000	0.970	104

a. Dependent Variable: Pm

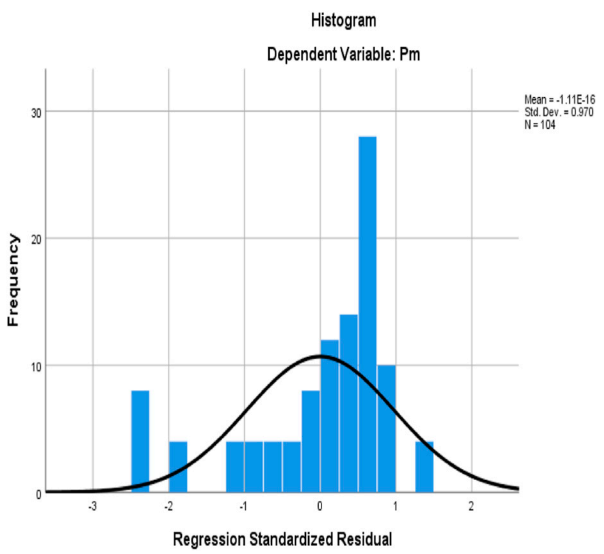

FIGURE 3
Histogram corresponding to the dependent variable for Pm.

Investors perception

As a rule, investors are considered the most important category of stakeholders for a company due to the fact that they invest their own assets in that particular business. No doubt that, in their turn, they will pursue their interests, namely the chance of making big profits and of investing in sustainable businesses.

No doubt that investors will be highly interested in the renewable energy costs and in the way they will affect their profits, yet, at the same time, the concern for ensuring the sustainability of their investments will become a top priority when it comes to the protection of the environment and to setting in place of the organisational policies which will show the community their best intentions (Socoliuc et al., 2018; Socoliuc et al., 2020; Ciubotariu et al., 2021). Consequently, the findings of this paper reinforce the ideea that the investments in the renewable energy depend on the stability and the dependability of the regulatory framework characterizing the renewable energy investments.

The work as a result of the processing and interpretation of the data has shown that the investors, unlike the managers, are not interested in acquiring general and specific knowledge about the renewable energy and the green certificates even if they are well aware of the fact that it is the only way of ensuring them the sustainability of their businesses. It is worth mentioning the fact that they more concerned with the external factors which are responsible for the outbreak of the energy crisis and with the existence of the soultions which can diminish their effects as they are concerned with the fact that their invested capital may undergo inherent, uncontrollable management risks.

As a result of the analysis of the answers of the investors and based on the correlation factors among the Pi dependent variable and the independent variables, the equation for the model can be expressed as follows:

$$Pi = 5.423 - 1.559 \cdot Kwg - 0.022 \cdot Kws + 0,268 \cdot Stk - 0.423 \cdot Cr + 0.101 \cdot If + 0.127 \cdot Sol \quad (5)$$

where Pi which stands for the dependent variablevariabila expresses the investors'perception.

As the investors represent the most important category of stakeholders for any company and the ones investing their own capital in that particular business, it is no doubt that, in their turn, they will pursue their own interests. One can notice that there is a 0.683 correlation among the Pi variable and the Kwg, Kws, Stk, Cr, If și Sol independent variables which are very close to the threshold of a significant correlation. The same tendency has been observed in terms of the determinacy ratio which leads to the conclusion that the change of the independent variables will influnce with 46.6% the change of the Pi variable. The investors'answers and the intepretation of the data show that the investors, unlike the managers, are much more interested in the opportunities related to the renewable energy production and consumption (see Table 12).

Given the fact that for the general profiles of the industrial consumer and the managers the models which have been generated as a result of the respondents'answers have been validated with a significance 0.002 threshold, in the case of

TABLE 12 Summary model corresponding to the dependent variable for Pi.

Model	R	R Square	Adjusted R Square	Std. Error of the estimate	Durbin-watson
1	0.683[a]	0.466	0.430	0.52210	1.999

a. Predictors: (Constant), Sol, Kws, If, Cr, Kwg, Stk

b. Dependent Variable:Pi

TABLE 13 ANOVA corresponding to the dependent variable for Pi.

Model		Sum of Squares	Df	Mean Square	F	Sig. (b)
1	Regression	21.198	6	3.533	12.961	0.000
	Residual	24.260	89	0.273		
	Total	45.458	95			

a. Dependent Variable: Pi

b. Predictors: (Constant), Sol, Kws, If, Cr, Kwg, Stk

TABLE 14 Coefficients of the independent variables for Pi.

Model		Unstandardized coefficients		Standardized coefficients		
		B	Std. Error	Beta	t	Sig
1	(Constant)	5.423	0.711		7.630	0.000
	Kwg	-1.559	0.244	-0.580	-6.397	0.000
	Kws	-0.022	0.119	-0.020	-0.183	0.855
	Stk	0.268	0.086	0.319	3.136	0.002
	Cr	-0.423	0.143	-0.246	-2.959	0.004
	If	0.101	0.038	0.215	2.622	0.010
	Sol	0.127	0.056	0.199	2.270	0.026

a. Dependent Variable: Pi

TABLE 15 Residuals statistics corresponding to the dependent variable for Pi.

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	1.7598	3.5000	2.6042	0.47238	96
Residual	−0.68019	0.99077	0.00000	0.50534	96
Std. Predicted Value	−1.788	1.896	0.000	1.000	96
Std. Residual	−1.303	1.898	0.000	0.968	96

a. Dependent Variable: Pi

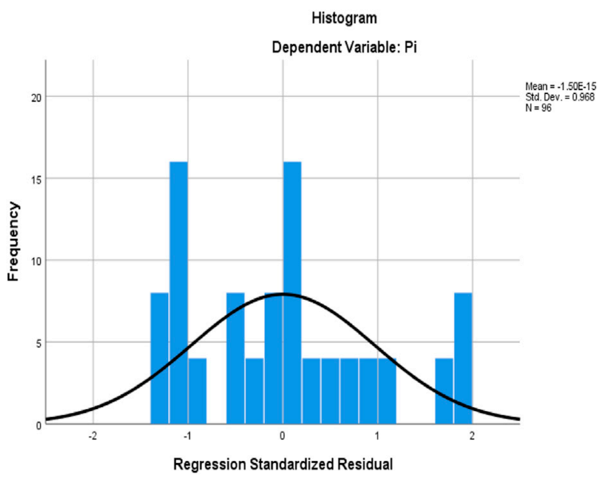

FIGURE 4
Histogram corresponding to the dependent variable for Pi.

the investors the significance threshold Sig. = 0.000. This fact is a clear indication of the fact that it is the best validation of the model itself and that the investors are the most interested in the renewable energy production and consumption (see Table 13).

The influence order in terms of the investors'perception for the Pi dependent variable is as follows: Kwg, Stk, Cr, If, Sol and Kws (see Table 14).

According to the model 5) and to the residual statistics (see Table 15), it is observed that the investors in large companies which have a turnover of over 8.000.000 euros and over 50 employees and which have the gearing ratio of under 60%, are much more interested in the general and specific information regarding the renewable energy production and consumption, the social, economic, political and environmental factors that are responsible for the outbreak of the energy crisis and the solutions to eradicate it. In contrast, the investors in the smalll companies with a turnover between 700.000 and 999.999 euros, with a numebr of employees ranging between 30 and 50 and with a high gearing ratio as well as the investors in large companies with lots of employees and a huge debts are less interested in acquiring the knowledge on the renewable energy production and consumption or on the causes of the energy crisis and the means to address it.

The case of the Pi analysis, the histrogram does not follow the Gaussian curve which means that there is a resudual variation of the investors'perception in relationship with the regression variable on a descendant slope in the 1–2.5 range as shown in Figure 4. Basically, apart from the fact that the investors are interested in investing in the development of the renewable energy projects, they are also concerned with both a short-term and a long-term investment gains.

The perception of the specialized personnel

In spite of the fact that nowadays the concept of digitalization is a very popular one, there are still many industry branches which have been affected by the lack of a high demand of specialized personnel. This has taken the toll on the any business turnover in general (Chew & Entrekin, 2011). Their value and uniqueness rely on the "silent expertise" which could be valuable for the competition whereas these abilities and knowledge have to do with the core internal developed processes which have been shaped throughout time (Entrekin & Court 2001). For example, one can establish a direct relationship between the perceived organizational support and the organizational results, especially in terms of the organizational citizenship behavior and the work performance (Shen et al., 2014). A dependable employee who is specialized in his activity represents the human resource whose knowledge and performances contribute significantly to the organizational performance and sustainability and to a consistent creation of a competitive advantage for that particular company. In the field of the renewable energy, studies have shown that the employees'high level of knowledge may have a significant impact on the entities'sustainable development. Thus, the study of Nasirov et al. (2021) has shown the impact of the renewable enrgy technologies on the creation of new jobs at a more sustained pace than in the traditional energy sector. This is the reason why the opinion of this particular group of employees regarding the renewable energy production and consumption is tested, considering also the fact that it may be a key factor in designing the profile of the industrial consumers. The equation of the model as a result of testing the perception of the specialised employees is as follows:

$$Pse = 2.498 + 0.785 \cdot Kwg - 0.200 \cdot Kws + 0,325 \cdot Stk - 0.473 \cdot Cr - 0.026 \cdot If - 0.142 \cdot Sol \quad (6)$$

where Pse, as the dependent variable, stands for the perception of the specialised personnel.

Consequently, it can be noticed a growing interest for the general knowledge regarding the renewable energy production and consumption, matter that can be explained by the fact that this is a relatively new and dynamic field of activity. This means updating the general knowledge as the specialised personnel believes that they are not responsible for the accumulation of specific knowledge.

Studies have shown that in 2025, the employees of the hydropower industry would represent the biggest proportion of the average total number of the employees in the renewable energy production sector in Romania (74.68%), whereas the employees in the solar energy production sector will represent 14.31%, the ones in the energy production from biomass sector

TABLE 16 Summary model corresponding to the dependent variable for Pse.

Model	R	R Square	Adjusted R Square	Std. Error of the estimate	Durbin-watson
1	0.439[a]	0.193	0.108	0.78870	2.611

a. Predictors: (Constant), Sol, Kwg, Kws, Cr, If, Stk

b. Dependent Variable: Pse

TABLE 17 ANOVA corresponding to the dependent variable for Pse.

Model		Sum of Squares	Df	Mean Square	F	Sig. (b)
1	Regression	8.481	6	1.414	2.272	0.049
	Residual	35.456	57	0.622		
	Total	43.938	63			

a. Dependent Variable: Pse

b. Predictors: (Constant), Sol, Kwg, Kws, Cr, If, Stk

TABLE 18 Coefficients corresponding to the independent variables for Pse.

Model	Unstandardized coefficients		Standardized coefficients		t	Sig
	B	Std. Error	Beta			
1	(Constant)	2.498	1.252		1.995	0.051
	Kwg	0.785	0.389	0.270	2.018	0.048
	Kws	-0.200	0.266	-0.105	-0.752	0.455
	Stk	0.325	0.148	0.333	2.191	0.033
	Cr	-0.473	0.166	-0.378	-2.851	0.006
	If	-0.026	0.076	-0.047	-0.344	0.732
	Sol	-0.142	0.119	-0.170	-1.186	0.240

a. Dependent Variable: Pse

will represent 5.8% and the ones in the wind energy production sector will represent 5.2% (Tănasie et al., 2022).

Given this context, the renwable energy is essential factor which can lead to the decrease of Europe's dependency on the imported energy. Moreover, the stimulation of the use of renewable energy sources in Europe needs to have in place a "New Energy Pact" which is based on a coordinated effort in the entire Europe in order to build a larger capacity of renewable energy (Tănasie et al., 2022).

As in the case of the management and of the investors, the specialised personnel is also reluctant to the manifestation of corruption in the energy field and less concerned with the direct causes of the present energy crisis.

As a result of the increasing demand of specialised personnel in many industry branches, it can ne noticed that there is a 0.439 correlation between the PSE dependent variable and the analysed independent variables. The value is below a significant correlation. A similar perception with the one of the managers has also been highlighted by the ratio of determinacy which refers to the fact that the variation of the independent varibles exert a 19.3% influence on the Pse variable. The responses of the specialised personnel indicate the fact that the employees'high

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TABLE 19 Residuals statistics corresponding to the Pse dependent variable.

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	1.6909	3.1348	2.4688	0.36691	64
Residual	−1.45290	0.87520	0.00000	0.75020	64
Std. Predicted Value	−2.120	1.815	0.000	1.000	64
Std. Residual	−1.842	1.110	0.000	0.951	64

a. Dependent Variable: Pse

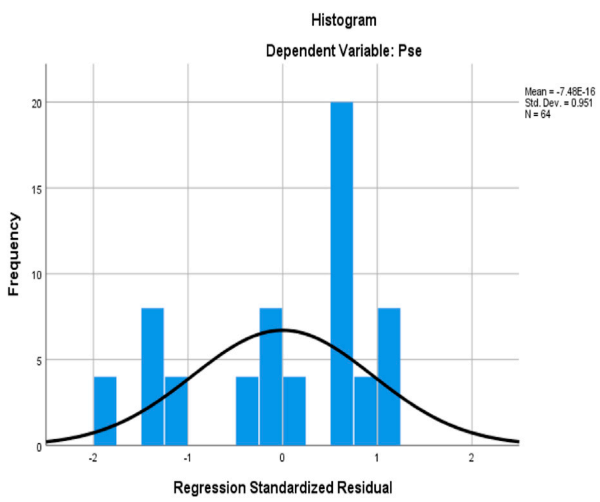

FIGURE 5
Histogram corresponding to the Pse dependent variable.

level of knowledge may significantly influence the entities'sustainable development, whereas the interpretation of the data suggests the fact that the specialised personnel, unlike the investors, are less interested in the opportunities offered by the renewable energy producrion and consumption which is the same with the managers'perception and above the general profile (see Table 16).

If in the case of the investors the significance threshold (Sig.) had the value of 0,00 - showing therefore the best validation of the model–in the case of the specialised personnel the Sig. value is 0.049, fact that places it at the validation limit. This situation indicates that the specialised personnel is the least interested in the renewable energy production and consumption (see Table 17).

The influence order in terms of the specialsed personnel's perception (Pse) is as follows: Cr, Stk, Kwg, Sol, Kws and If (see Table 18).

Moreover, it has been noticed that the specialsed personnel in the companies with a turnover ranging from 700.000 to 999.999 euros, with over 50 employees and with a gearing ration of over 60% are interested in the renewable energy production and consumption, while the specialised personnel in the small companies are not interested in these information at all (see Table 19).

As far as the Pse analysis is concerned, the histogram does not follow the Gaussian curve. This means that there is a residual variation of the specialised personnel's perception in terms of the regression variable on the descending slope in the 1.25–2.5 range as shown in Figure 5. Thus, it can be stated that the specialised personnel is not interested in the renewable energy as it is more focussed on the duties listed in the job description. Consequently, in spite the fact that at present there is a continuous growth of the energy prices in all the European countries, the industrial gas and energy consumers will inevitably experience significant loses which will force them to reduce their production. As a result of this situation, testing the opinions of the management, of the investors and of the specialised personnel from these production entities can be an information resource for the lawmaker and for those that are involved in the production and consumption of renewable energy which shows that there are practical and long-lasting solutions to their problems. The significant carelessness of the national and European policies in terms of the other energy sources have made the energy system even more vulnerable with paradoxical consequences from the point of view of the environment, too (Fanelli and Ortis, 2022). However, according to a study by Deloitte România (2021), Romania has invested one billion euros in wind parks which are expected to generate 2,17 billion euros in the country's economy with an additional direct impact of 2,95 billion euros between 2021 and 2030. The possible benefits are not limited to the energy production. According to the same study, the energy transition can have positive effects in construction, transportation, energy services, in the industrial production and in the automotive industry alike, a total investments of 82,5 billion euros in these sectors could have an impact of 364,6 billion euros in Romania's GDP in the period of 2021–2030. All these accomplishments could bring about benefits especially for the industrial consumers.

Limitations of the study

It is important to highlight the fact that one of the obstacles of this research has been the low number of respondents as the energy industrail consumers from Romania are reluctant to the possibility of being questioned as such. The economic, financial and social issues have had serious consequences on the operational activity of these operators who mostly reduced their activity or went bankrupt. The lack of a coherent legislation and of certain predictable government policies is another downsize of the present study due to the fact that the industrial consumers are not protected and become vulnerable. This is the reason why most of them have been biased in answering the questions which could influence the cause-effect relationship that has been estimated based on the regression model. Another downsize of the present study reffers to the fact that the area where these consumers operate has been overlooked as there is an informational asymmetry in the interpretation of the answers which characterizes especially the consumers from the monoindustrial areas that rely on carbon consumption. They are more interested in perceiving the impact of the current crisis in relation to green energy consumption policy, thus being able to assess the resilience of these operators and mitigate the social impact which will be difficult to ignore.

Conclusion

In a market economy, any kind of crisis is bound to have an impact on the final consumer. This situation manifests itself nowadays as a result of the energy crisis, the electricity and gas bills which have gone up and it seems that the situation tends to escalate from month to month. It seems that the most affected of all are, as always, the producers of goods and services due to the fact that the supply of raw materials, materials, fuels, salaries etc. that are necessary for the ongoing functioning of the manufacturing processes are closely connected with the increase of the energy costs. The energy crisis refers not only to the costs increases for all the consumers, but also to a specualtive reaction of the market, the final consumer becoming the only victim of this process. No doubt that apart from the undisputed economic effects, there are also certain *social and political consequences* which cannot be overlooked such as: the geopolitical imbalance created by the war in Ukraine (Romania's neighbour) that has determined obvious effects on the national economy, hindering both the creation of a strategy and the effective production of green energy from renewable resources, or the government took the wrong approach by not regulating the energy market, which led to an energy price formation that determined a series of negative knock-on effects, materialized by extremely high prices for both household and industrial consumers.

On the other hand, the economic measures that are urgently needed to deal with the current energy crisis must be implemented, but both companies and governments must take into account and distinguish between short-term and long-term measures. It is essential to emphasise this aspect, as the effects of these measures are interdependent, in the sense that short-term measures will have an immediate effect on prices and quantities of consumed energy (managers and specialised staff being directly involved and responsible for the decisions and actions taken), while long-term measures, which mainly concern investments, will have a direct impact on investors' interests, even contributing to their total or partial discouragement. In conclusion, the general model of optimising measures and decisions affecting industrial energy consumers should help the legislator to understand the real problems faced by producers in his country and to direct his governmental decisions and policies to support them.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the (patients/ participants OR patients/participants legal guardian/ next of kin) was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

Conceptualization, VG and MS; methodology, MC, MT, and EH; data curation, AM, MS, and AGM; writing—original draft preparation, EH, MT, and AM; formal analysis, investigation, visualization, VG and MC supervision, validation, MS, MC, and AGM. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Assessing the supply risk of geopolitics on critical minerals for energy storage technology in China

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Energy storage technology as a key support technology for China's new energy development, the demand for critical metal minerals such as lithium, cobalt, and nickel is growing rapidly. However, these minerals have high external dependence and concentrated import sources, increasing the supply risk caused by geopolitics. It is necessary to evaluate the supply risks of critical metal minerals caused by geopolitics to provide a basis for the high-quality development of energy storage technology in China. Based on geopolitical data of eight countries from 2012 to 2020, the evaluation indicators such as geopolitical stability, supply concentration, bilateral institutional relationship, and country risk index were selected to analyze the supply risk of three critical metal minerals, and TOPSIS was applied to construct an evaluation model for the supply risk of critical metal minerals of lithium, cobalt, and nickel in China. The results show that from 2012 to 2017, the security index of cobalt and lithium resources is between .6 and .8, which is in a relatively safe state, while the security index of nickel resources is .2–.4, which is in an unsafe state. From 2017 to 2020, lithium resources remain relatively safe, and the security index of nickel has also risen to between .6 and .7, which is generally in a relatively safe state. However, the security index of cobalt has dropped to .2, which is in an unsafe or extremely unsafe state. Therefore, China needs to pay attention to the safe supply of cobalt resources and formulate relevant strategies to support the large-scale development of energy storage technology.

KEYWORDS

critical metal minerals, geopolitics, storage energy technology, institutional distance, supply risk

Introduction

With the advancement of the global low-carbon energy transition, many countries have increasingly realized that there is an important relationship between "critical metals" and "low-carbon energy" (Wang et al., 2021). Critical metal minerals are mostly in the form of symbiotic or associated minerals (Peiró et al., 2013), with the slow expansion of production capacity (Ali et al., 2017), unbalanced geographical distribution, and high concentration, which are easy to cause competition, conflict, or even war, and have great geopolitical risks. Suppliers of critical metal minerals could gain geopolitical leverage by cutting supplies (Habib et al., 2016). In particular, climate change has caused a new global energy governance pattern, and the supply chain security of minerals needed for the low-carbon energy transition has become a strategic issue (Wang et al., 2012; Wang et al., 2014; Chao et al., 2016; Wang et al., 2016). Under this circumstance, the secure supply of critical metals will become a decisive factor affecting the future development of new energy technologies (Wu et al., 2020).

The efficient energy storage technology, which requires several kinds of critical metals, is expected to well solve the problem caused by photovoltaic power generation and wind power generation characterized by strong intermittency and high volatility. Lithium-ion batteries with low cost, high efficiency, and fast response time are ahead of other energy storage technologies (Li et al., 2022). Future energy storage technologies will focus on the development of lithium-ion batteries. The upstream raw materials of the lithium battery supply chain mainly include the mining, production, and refining of lithium, cobalt, and nickel resources. With the expansion of the lithium battery development scale, the demand for lithium, cobalt, and nickel also increases (Eggert, 2011; Zhai et al., 2019).

The future development of energy storage technology will continue to be limited by critical metal minerals. Previous studies concerning the geopolitical supply risk of critical metal minerals still need to be improved to cover energy storage technologies. The geopolitical competition for these critical mineral resources is fierce, and the supply risks caused by the geopolitical risks will also increase (Wang, 2019). However, the existing geopolitical supply risk assessment methods lack a full range of indicators, such as political, economic, financial, trade, and others. For instance, Graedel et al. (2012) proposed the geopolitical supply risk of critical minerals with the worldwide governance indicator and the global supply concentration indicator. Habib et al. (2016) selected the HHI indicator to estimate the geopolitical supply risk of metals. There are also some studies that summarize the strategic planning of critical metal minerals in typical countries to provide reference for formulating relevant policies (Mao et al., 2019; Zhang et al., 2019; Yu and Yang, 2020). In addition, it is predicted that China's demand for lithium, cobalt, nickel, and other minerals will grow rapidly, which is highly dependent on foreign countries. In 2020, China's external dependence on cobalt, nickel, and lithium resources was 97%, 92%, and 72%, respectively (Cheng et al., 2022). Precisely, 80% of China's cobalt resources are from the Democratic Republic of the Congo, and lithium is mainly from Australia. 82% and 9% of imported nickel resources are from the Philippines and Indonesia as well (Wang, 2022). It is urgent need to create a comprehensive and multi-perspective assessment of the geological risks of critical metal minerals supplied to energy storage technology in China, considering the increasingly complex international political and economic situation.

The study aims to assess the geopolitical supply risk of three critical metal minerals (lithium, cobalt, and nickel) used in energy storage technologies, and a full spectrum with multiple indicator perspectives is taken into account. Indeed, this paper will: 1) establish a risk assessment method for the geopolitical supply risks of critical minerals, including single factor analysis and comprehensive assessment; 2) analyze the political, economic, and financial risks in critical mineral source countries through the national governance index and country risk index based on the single factor perspective; 3) evaluate China's trade risk with mineral source countries by the supply concentration index and the institutional distance index also based on the single factor perspective; 4) integrate the geopolitical assessment model to comprehensively assess the supply risk of lithium, cobalt, and nickel resources in China based on the comprehensive perspective; 5) put forward several policy suggestions based on the geopolitical supply risk of China's imported critical minerals, considering the tendency of electrochemical energy storage technology in the future.

Impact of geopolitical supply risk of critical minerals on energy storage technology

In recent years, countries worldwide have been paying more and more attention to energy transformation and the deployment of new energy industries. This process consumes a lot of metal resources and is very dependent on critical metal minerals (Vidal et al., 2013). The World Bank report shows that the production of minerals such as lithium, cobalt, nickel, and graphite will increase by nearly 500% by 2050 to meet the growing demand for clean energy technologies (World Bank, 2020). The International Energy Agency also points out that the global energy system's demand for critical minerals could increase sixfold by 2040 (International Energy Agency, 2022). By 2050, most of the growth in global energy demand will come from renewable energy and clean energy technologies, which in turn will drive exponential growth in global demand for critical minerals such as lithium, cobalt, nickel and rare Earth elements.

The rapid growth in demand for critical mineral resources has strengthened the deep-rooted concept of resource scarcity in the oil and gas era, prompting countries to pay more attention to the security of the cross-border supply of mineral resources. The geopolitical disputes related to critical metal minerals have already emerged, and their geopolitical impact will increase daily. Therefore, it is necessary to pay attention to the geopolitical risk characteristics and development trends of critical metal minerals and identify geopolitical risk factors that may affect critical minerals.

Geographical distribution and geopolitical risk characteristics of critical metal minerals

Critical mineral resources are geographically concentrated in a few specific countries and regions. In 2022, global cobalt reserves are about 7.6 million tons, mainly concentrated in the Democratic Republic of the Congo, Australia, and Cuba, which account for 71% of global cobalt reserves. Global proven lithium reserves are about 22 million tons, mainly concentrated in Chile, Australia, and Argentina, and 2/3 of the lithium reserves are located in the "lithium triangle" of Latin America; global proven nickel reserves are more than 95 million tons, mainly concentrated in Indonesia, Australia and Brazil, which together account for 61% of the total global reserves (USGS, 2022).

According to the "Global Risk Report" released by the World Economic Forum, geopolitical risk has always been one of the five significant risks affecting global development (World Economic Forum, 2019). In addition, non-geographic factors have also caused geopolitical changes, especially the rapid development of renewable energy has led to new changes to the geopolitical pattern (Daniel and Rick, 2016).

Influenced by the global resource supply and demand pattern, and the evolution of the competition pattern, the global governance system of strategic resources is in the process of continuous evolution. Extreme geopolitical events led by states are constantly affecting the supply chains of the global resource system. Geopolitics is an important factor affecting the sustainable supply of critical minerals at present (Hayes and Mccullough, 2018). Developed countries and economies such as the United States, the European Union, and Japan have promulgated lists of critical materials or critical minerals (National Research Council, 2008; European Commission, 2014; Wang et al., 2017), and the field has become an arena for the world's gaming.

The impacts of geopolitical risk of critical minerals on energy storage

For China, the critical mineral geopolitical risks are characterized as follows.

1) Some critical mineral resources are geographically concentrated in several specific countries and regions, and are easily controlled by a few countries (Henckens et al., 2016). Critical minerals markets are vulnerable to geopolitical influence and might be at risk of supply chain disruption. Taking lithium batteries as an example, if lithium, cobalt, nickel, and other industries cannot extend downstream, they will always face the problem of being too large but not strong, and the added value of products is too low (Xu, 2020), which increases the limitations of the development of battery energy storage technology.
2) The rapid growth of critical minerals will accelerate the reshaping of the geopolitical pattern of the world's strategic mineral resources. The International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA) pointed out that suppliers of some critical mineral resources such as lithium, cobalt, nickel, and rare Earth metals could gain new geopolitical leverage by cutting off the supply of critical metals (Internatioanl Energy Agency, 2018; IRENA, 2022). With the advent of the era of electric vehicles and the smart grid, the large-scale development of battery energy storage technology is restricted by the shortage of critical mineral resources.
3) The competition between China and the United States in critical minerals will be more intense in the future. The United States Geological Survey analyzed the dependence of China and the United States on non-energy minerals, and found that both China and the United States rely heavily on imported minerals as many as 11 kinds. In the future, the two countries will likely to face fierce battles for resources in South America, Africa, and elsewhere (Gulley et al., 2018).
4) The geopolitical risk of China's critical mineral resources is still relatively high, and its market stability is vulnerable to global populism, trade protectionism, and resource nationalism.

Through the analysis of the global distribution and geopolitical pattern of critical metal minerals, it is found that the stable supply of exporting countries and the geopolitical strategy of each country will become an important prerequisite for the supply of critical minerals. Critical metal minerals will be a limiting factor for China's renewable energy development.

Methods and data

Indicator system

The degree of political and social stability in the world's major resource countries has a significant impact on resource supply security, particularly in countries where resources are over-concentrated in unstable political security situations. These countries could affect the supply security of critical metal resources by controlling the supply of resources in the resource market or changing the rules of international trade in metal resources, thereby causing supply constraints and price volatility.

For the lithium, cobalt, and nickel imported by China, geopolitical factors have a particularly prominent impact on their safe supply, so it is necessary to conduct a risk assessment under geopolitical conditions. The supply risk evaluation indicators caused by geopolitical factors are the global governance indicators of mineral resource countries, the country risk indicators of mineral resource countries, supply concentration, and bilateral government institutional distance. The index system of geopolitics' influence on the supply of critical minerals is shown in Table 1.

Research methods

Bilateral government institutional distance

Institutional distance is the degree of similarity or difference between two countries regarding rules, norms, and perceptions. There are a variety of indicators to measure institutional distance, such as the Global Governance Indicators (WGI), the International Country Risk Guide (ICR), the Fragile States Index (FSI), etc. WGI has been widely used in some criticality assessments because of its rigor, high comprehensiveness, and wide coverage (Liu and Zhou, 2018). For example, the WGI index was used as a basis to estimate the country risk in the research of assessing the long-term supply risks for mineral raw materials (Rosenau-Tornow et al., 2009). The Yale team proposed a supply risk assessment system for the raw material that uses the WGI index as a geopolitical factor (Graedel et al., 2012). Based on previous research (Wang et al. 2018), considered the WGI index and HHI index to evaluate the global supply risk of critical minerals for new energy vehicles. The results showed that graphite has the greatest supply risk and selenium has the lowest supply risk in terms of WGI-PV (Political Stability, and Absence of Violence/Terrorism).

China's import of critical metal minerals faces an increasingly complex international environment. The influence of political and social systems in exporting countries is prominent. There are African countries with low levels of government governance and political instability, and developed economies with high government effectiveness and stable domestic political situation. The institutional distance varies, and the risk of critical minerals supply is also different.

According to previous research (Xu et al., 2017; Li et al., 2020), Eq. 1 is used to measure the institutional distance between China and resource-importing countries from the six dimensions of the World Bank's global governance index WGI.

$$\mathbf{INSD_{jt}} = \frac{\mathbf{1}}{\mathbf{6}}\frac{\sum_{\mathbf{K=1}}^{\mathbf{6}}\left(\mathbf{I_{kt}} - \mathbf{I_{jkt}}\right)^{\mathbf{2}}}{\mathbf{V_{IK}}} \tag{1}$$

where I_{kt} and I_{jkt} are the scores of China and country j on the *k*th institutional dimension in year t, respectively. V_{IK} is the variance of the scores of all sample countries on the *k*th institutional dimension.

Global supply concentration (HHI)

The HHI, calculated as the sum of the squares of the production shares of each producing country, is a widely used indicator of market concentration. It ranges from a theoretical minimum of zero when production is evenly distributed among an infinite number of

TABLE 1 Indicator system for evaluating the impact of geopolitics on the supply risk of critical metal minerals.

Components	Impact	Indicator
Geopolitical stability	positive	National Political Stability WGI
Supply concentration	negative	Resource concentration HHI
Bilateral Institutional Relations	negative	Bilateral Government Institutional Distance DI
Country Risk Index	positive	Country risk level ICR

TABLE 2 HHI classification.

Grade	Low concentration	Moderate concentration	High concentration
HHI value	<1,500	1,500 to 2500	>2500
Base score	0	100/3	200/3

countries, to a maximum of 10,000 when all production is concentrated in one country. Combined with this market concentration indicator, it is possible to analyze whether China has multiple supplier countries to choose from or is limited to one or two major suppliers (Gulley et al., 2018). The supply of mineral resources concentrated in one or a few countries could greatly impact the supply of mineral resources once the political situation or mining policies in these countries change. The higher the concentration of critical minerals, the greater the supply risk. In this study, The Herfindahl-Hirschman Index (HHI) could be used to measure the global supply concentration of lithium, cobalt, and nickel (see Eq. 2), and then assess their geopolitical supply risks. For instance, Habib used the HHI index to measure the geopolitical supply risk of 52 metals in the world, and the results showed that the distribution of geological reserves led to the geopolitical risk of critical metal resources (Habib et al., 2016).

$$\mathbf{HHI} = \sum_{\mathbf{i=1}}^{\mathbf{N}} (\mathbf{S_i}) \tag{2}$$

where HHI is the Herfindahl Hirschman index; S_i is the squared number of shares of country i in the market; N represents the number of countries.

Table 2 shows the three levels of market concentration HHI. The higher the score, the higher the risk implied by the concentration of mineral material supply.

TOPSIS method

The supply risk evaluation indicators caused by geopolitics involve a wide range of fields, and the units and weights are not uniform. To avoid the influence of subjective factors, the entropy weight method is used for data processing. The TOPSIS method proposed by Hwang and Yoon (1981) is used to measure the distance between different data and the optimal value to evaluate the security degree of supply at different times.

The weighting matrix was firstly constructed by the entropy weighting method. Then the TOSIS model was used to evaluate the supply risk of lithium, cobalt, and nickel resources at different times.

1) Construction of evaluation index system matrix

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{3}$$

where x_{11}, ... x_{1n} represent the geopolitical data of the source countries of critical metal mineral imports for a given year respectively; x_{m1}, ... x_{mn} represent the geopolitical data of critical metal mineral import source countries in year m respectively.

2) The indicators are uniformly normalized according to the physical-social nature of the geopolitical data indicators.

$$x_{ij} = \frac{K_{ij} - min\ (K_{ij})}{max(K_{ij}) - min\ (K_{ij})}\ \text{(applies to positive indicators)} \tag{4}$$

$$x_{ij} = \frac{max(K_{ij}) - K_{ij}}{max(K_{ij}) - min\ (K_{ij})}\ \text{(applies to negative indicators)} \tag{5}$$

where i is the evaluation index (i = 1,2,3,...m). j is the index year (j = 1,2,3,...n); k_{ij} is the initial value of the evaluation index system; $\max(k_{ij})$ is the maximum value of index k_{ij}; $\min(k_{ij})$ is the minimum value of indicator k_{ij}; x_{ij} is the standardized value, and the matrix Z is obtained by standardization.

3) The data are normalized (eliminating the magnitude), and transformed into matrix Z.

$$Z_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}} \tag{6}$$

$$Z = \begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{m1} & \cdots & z_{mn} \end{bmatrix} \tag{7}$$

4) Entropy weighting method to calculate weights

The information entropy e_i is calculated, see equation (Eq. 8).

$$e_i = -\frac{1}{ln\,n}\sum_{j=1}^{n} z_{ij} \times ln\,z_{ij}$$
$$\textbf{If } \mathbf{z_{ij} = 0}, \textbf{ then } \lim_{f_{ij}\to 0} \mathbf{z_{ij} \times ln\,z_{ij} = 0} \tag{8}$$

The indicator weights w_i is calculated, see equation (Eq. 9)

$$w_i = \frac{1 - e_i}{m - \sum_{i=0}^{m} e_i} \tag{9}$$

5) The construction of the TOPSIS model

For the objectivity of the evaluation results, a normalized analysis matrix Q is created according to the index weights w_i.

$$Q = \lfloor y_{ij} \rfloor m \times n = \lfloor w_i \times z_{ij} \rfloor m \times n \tag{10}$$

6) Calculation of Euclidean distance between indicators

$$D = \frac{Z - Z_{min}}{(Z_{max} - Z) + (Z - Z_{min})} \tag{11}$$

7) Comprehensive evaluation index calculation

$$C_j = \frac{D_i^-}{D_i + D_i^-} \tag{12}$$

where D is the Euclidean distance; C_j is the composite evaluation index, the $C_j \in [0, 1]$.

8) Evaluation level

Referring to previous studies (Liu et al., 2018; Long and Yang, 2018; Sun et al., 2018; Qu et al., 2022)), the evaluation results were divided into five safety levels: extremely unsafe, unsafe, basically safe, relatively safe and safe. Since the supply risk comprehensive evaluation index ranges from 0 to 1, the larger the index, the higher the degree of security. The extremely unsafe state takes the value of 0–.2, the unsafe takes the value of .2–.4, the basic safe takes the value of .4–.6, the relative safe takes the value of .6–.8, and the safe state is .8-1.

Data

Production and storage of critical metal minerals

The data on production and storage of three critical minerals, including lithium, cobalt, and nickel from 2012 to 2020 are provided by the United States Geological Survey (USGS). According to the report "MINERAL COMMODITY SUMMARIES 2022″published by USGS (USGS, 2022), mineral lithium resources are in various stages of development in Australia, Austria, Brazil, Canada, China, Democratic Republic of the Congo (DRC), Czech Republic, Finland, Germany, Mali, Namibia, Peru, Portugal, Serbia, Spain, the United States, and Zimbabwe. The DRC remains the world's main source of mined cobalt, supplying more than 70% of the world's cobalt minerals. The global proven nickel reserves are about 94 million tons, mainly concentrated in Indonesia, Australia, the Philippines, and Brazil, with Indonesia and the Philippines currently accounting for 45% of global nickel production.

The worldwide governance indicator

If the political situation of a country or region is unstable, it will affect the stability of the mining production of the country. The Worldwide Governance Indicators (WGI) produced by Kaufmann and Kraay (Kaufmann et al., 2010) could be used to measure the degree of political stability. Its well-designed planning and robust continuity have attracted more and more attention from researchers and practitioners (Zang, 2012). The Worldwide Governance Indicators (WGI) project reports aggregate and individual governance indicators for over 200 countries and territories over the period 1996–2020 for six dimensions of governance: Voice and Accountability (VA), Political Stability, and Absence of Violence/Terrorism (PV), Government Effectiveness (GE), Regulatory Quality (BQ), Rule of Law (RL), Control of Corruption (CC). Each indicator adopts a percentile scale (ranked from 0 to 100) to indicate the ranking level of the country's governance items. The higher the value, the higher the ranking of the governance level (Wang et al., 2018). The weights of the above six dimensions are .16, .25, .13, .14, .17, and .15, respectively (Cao et al., 2022). The World Governance Index calculates a score based on the weight of these six indicators, with a higher score indicating a more politically stable country. As a result, the WGI index enables cross-country and cross-time comparisons of governance levels. In the following, VA, PV, GE, BQ, RL, and CC are used to represent the six indicators.

International country risk ratings

The International Country Risk ratings (ICR) published by PRS Group over 140 countries and regions, including political risk, economic risk, and financial risk (PRS Group, 2017; Zhang, 2017). Political risk is assessed by assessing government stability, socioeconomic conditions, investment status, internal conflict, external conflict, corruption, political-military, religious tensions, law and order, ethnic tensions, and democratic accountability. Economic risk is assessed by assessing GDP *per capita*, real annual GDP growth, annual inflation rate, budget balance as a percentage of GDP, and current account balance as a percentage of GDP. Financial risk is assessed by assessing external debt as a percentage of GDP, external debt service as a percentage of exports of goods and services, current account as a percentage of exports of goods and services, net liquidity and exchange rate stability, and other factors. The ICR database is not only the most widely used source of risk data by universities around the world, but also used by the world's largest institutional investors, multilateral organizations, central banks, and other institutions. All data could be found in the Supplementary Table S1.

Risk assessment of cobalt, lithium, and nickel supply in China based on geopolitics

Single-factor analysis of supply risk of cobalt, lithium, and nickel

National governance index of critical mineral suppliers

According to the Global Governance Indicator (WGI), the national governance index of the three main source countries of cobalt, lithium, and nickel is calculated (Figure 1).

As can be seen from Table 3 and Figure 2, the source country of cobalt, the Democratic Republic of the Congo (DRC), has the lowest national governance index and the highest supply risk. In the process of importing cobalt resources in the future, China needs to pay close attention to the degree of social stability in DRC and pay comprehensive attention to the changes in six dimensions, such as VA, PV, GE, RQ, RL, and CC, to formulate targeted countermeasures. Lithium is mainly from Chile, Australia, and Argentina. 80% of its production is in Chile. The governance index in Australia and Chile is very high. Moreover, China also has a

TABLE 3 National governance index of importing countries of lithium, cobalt, and nickel imports.

Supplier country	2012	2013	2014	2015	2016	2017	2018	2019	2020
Congo (DRC)	18.19	25.88	22.79	21.38	20.79	18.60	16.66	18.66	18.68
Indonesia	47.19	48.73	52.08	48.83	53.92	53.13	53.95	53.55	54.28
the Philippines	45.13	48.02	51.69	50.06	45.89	45.62	45.61	46.94	48.45
Brazil	62.05	58.35	60.17	56.05	55.27	52.41	51.25	50.83	51.99
Chile	87.09	86.77	86.51	85.05	84.83	84.77	84.23	81.16	81.29
Australia	98.44	98.53	98.29	97.36	98.26	97.09	97.85	96.96	97.03
Argentina	51.64	50.86	48.67	50.36	59.95	61.06	60.10	57.05	56.25

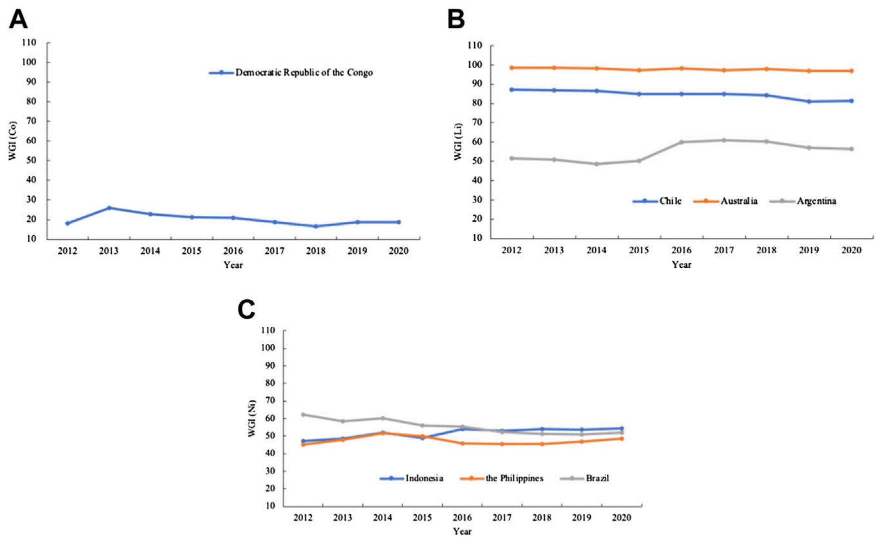

FIGURE 1
Change trend of cobalt **(A)**, lithium **(B)**, and nickel **(C)** resource supply risk index based on WGI.

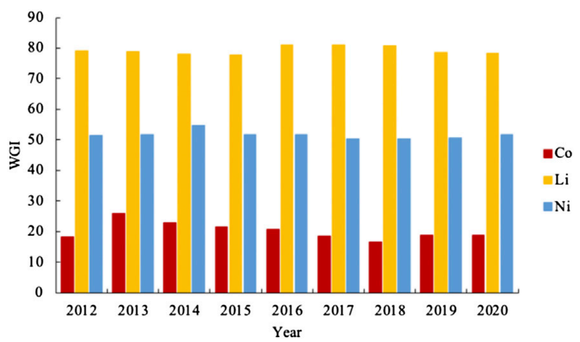

FIGURE 2
Comprehensive trend of lithium, cobalt, and nickel resource supply risk index based on WGI.

certain amount of lithium mineral reserves, so the supply risk of lithium is relatively low. The majority of nickel comes from Indonesia, the Philippines, and Brazil, and the governance index indicates that the society is more stable. Because of the abundance of nickel, the supply risk of nickel is also low.

Country risk index of critical mineral suppliers

Country risk indicator includes political risk, economic risk, and financial risk. It combines specific country factors such as currency risk, political leadership, military and religion in politics, and corruption (Wang and Wu, 2008). It is a comprehensive reflection of a country's degree of political, social, and economic stability. The country risk indices of critical metal mineral source countries were calculated based on the national risk index database, and the results are shown in Table 4 and Figure 3. Risk ratings range from a high of 100 (least risk) to a low of 0 (highest risk).

It is shown that the degree of risk is similar to that of the World Governance Index. Compared to the World Governance Index, these country risk indices have a small gap, ranging from 35-60 (Figure 4); while the World Governance Index has a minimum of 10 and a maximum of 96, with a large value gap. Since the country risk index includes political risk, economic risk, and financial risk, its value can more closely reflect the risk of these countries in the critical mineral trade.

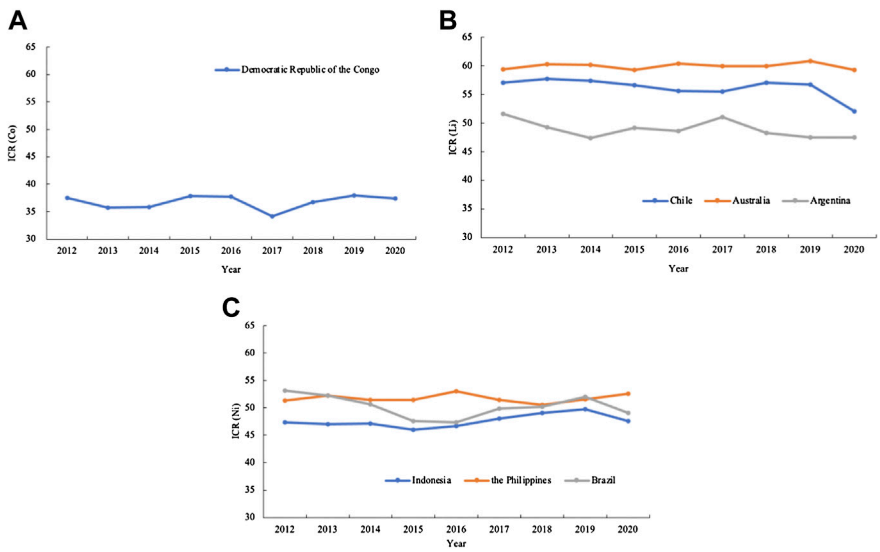

FIGURE 3
Change trend of cobalt **(A)**, lithium **(B)**, and nickel **(C)** resource supply risk index based on ICR.

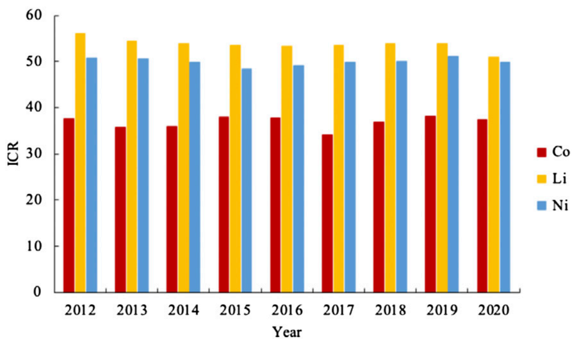

FIGURE 4
Comprehensive trend of lithium, cobalt, and nickel resource supply risk index based on ICR.

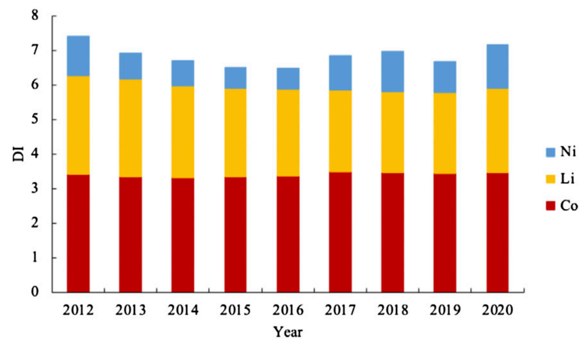

FIGURE 6
Bilateral institutional distance between China and critical mineral source countries.

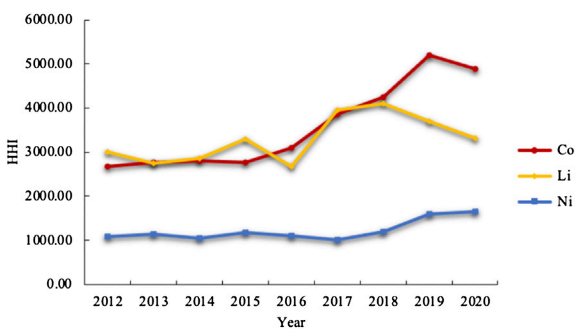

FIGURE 5
Concentration index for critical metal minerals.

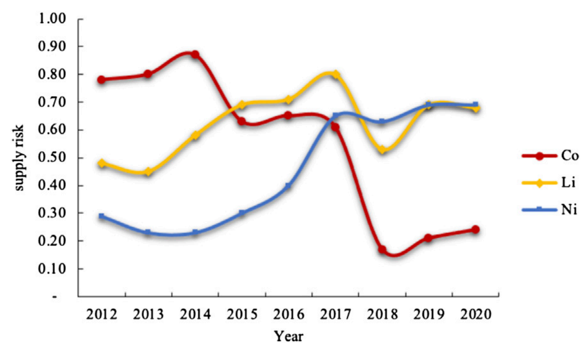

FIGURE 7
China's imported lithium, cobalt, and nickel minerals supply risk assessment.

10.3389/fenrg.2022.1032000

TABLE 4 Country Risk Index (ICR) for critical mineral supply countries.

Supplier country	2012	2013	2014	2015	2016	2017	2018	2019	2020
Congo (DRC)	37.48	35.67	35.80	37.83	37.70	34.10	36.75	38.01	37.39
Chile	57.08	57.70	57.41	56.58	55.55	55.45	57.02	56.68	52.09
Australia	59.39	60.33	60.16	59.26	60.34	59.91	59.91	60.84	59.29
Argentina	51.55	49.25	47.35	49.11	48.63	51.08	48.22	47.48	47.48
Indonesia	47.36	47.05	47.10	46.04	46.69	48.06	49.08	49.80	47.61
the Philippines	51.28	52.25	51.41	51.42	53.09	51.47	50.55	51.55	52.54
Brazil	53.15	52.27	50.61	47.57	47.36	49.81	50.15	52.05	49.10

TABLE 5 Concentration index (HHI) for critical minerals.

Critical mineral	2012	2013	2014	2015	2016	2017	2018	2019	2020
Co	2679.53	2770.89	2806.69	2758.79	3096.19	3855.64	4238.77	5191.63	4882.19
Li	2996.57	2744.91	2857.29	3294.63	2672.23	3952.30	4101.38	3692.60	3309.24
Ni	1,082.34	1,132.62	1,041.78	1,169.10	1,101.30	1,016.91	1,201.88	1,589.56	1,654.40

TABLE 6 Bilateral institutional distance between China and the source countries of lithium, cobalt, and nickel imports.

Supplier country	2012	2013	2014	2015	2016	2017	2018	2019	2020
Congo (DRC)	3.43	3.34	3.31	3.35	3.36	3.48	3.46	3.45	3.47
Indonesia	.39	.51	.36	.72	.37	.43	.27	.32	.45
the Philippines	.52	.43	.14	.30	.67	1.19	.98	.98	.96
Brazil	2.49	1.23	1.63	.78	.74	1.26	2.19	1.32	2.30
Chile	3.04	3.00	2.85	2.80	2.84	2.99	2.83	2.50	2.10
Australia	3.49	3.50	3.37	3.30	3.36	3.41	3.38	3.36	3.23
Argentina	1.95	2.00	1.76	1.50	1.33	.74	.83	1.14	1.99

The concentration ratio of critical metal minerals (HHI)

HHI describes the dynamic nature of metal geopolitical supply risk based on mineral production data, and the results can provide a basis for metal mineral supply risk assessment.

As can be seen from Table 5 and Figure 5, the global demand for cobalt resources in 2012–2015 was relatively small, and its concentrated supply index is within 2800.06. With the development of low-carbon energy technology, there is an increasing demand for cobalt resources, and the concentration index of cobalt also reached 4882.19 in 2020, indicating that the supply risk of cobalt resources increased. The HHI value of lithium is as low as 2672.23 and as high as 4101.38, and the market concentration remains at the level I. From 2012 to 2020, the HHI value of nickel resources is mostly around 1,000, the market concentration is low (level III), and its supply risk is also low.

Bilateral government institutional distance

Bilateral institutional differences increase the supply risk of China's imports of critical mineral resources. If the regime environment between China and the mineral resource importing country is similar or the difference is small, it is easier to integrate into the regime environment of the host country, and it is easier to adapt to each other's transaction rules, and the transaction risk is also lower. If the difference (distance) between the bilateral government systems is significant, the supply risk of critical minerals imported by China will also increase.

From the average bilateral government regime distance, China and DRC have the most significant institutional distance, and are the largest in terms of PV, GE, BQ, RL, and CC, and their supply risks are also the largest; China has the smallest distance from the Indonesian regime system. It is the smallest in PV, GE, BQ, and RL, but larger in CC. Overall, the supply risk is the smallest. China and Argentina have slight differences in BQ, RL, and CC aspects, but large differences in PV and GE. In general, the regime distance is in the middle, and the supply risk is also medium. The difference between China and Australia and Chile in each dimension is positive, and the bilateral institutional distance is the largest. The regime distance between China and the other two countries, the Philippines and Brazil, is in the middle, and the risk is also medium (Table 6 and Figure 6).

TABLE 7 Weights of indicators for lithium, cobalt, and nickel resources in China.

Indicator system	Indicator meaning	Weights
Geopolitical stability	Political stability of resource importing countries (WGI)	.23
Supply concentration	Concentration of mineral resources (HHI)	.26
Bilateral institutional relations	Bilateral government institutional distance (DI)	.21
Country risk index	The degree of country risk in resource-importing countries (ICR)	.30

TABLE 8 The results of the comprehensive evaluation of the supply risk of cobalt, lithium, and nickel resources in China.

Critical metal	Indicator	2012	2013	2014	2015	2016	2017	2018	2019	2020
cobalt	WGI	.17	.18	.20	.14	.14	.14	.04	.05	.05
	HHI	.20	.21	.23	.16	.17	.16	.04	.05	.06
	DI	.16	.17	.18	.13	.14	.13	.04	.04	.05
	ICR	.23	.24	.26	.19	.19	.18	.05	.06	.07
	Comprehensive evaluation index	.78	.80	.87	.63	.65	.61	.17	.21	.24
lithium	WGI	.11	.10	.13	.16	.16	.18	.12	.16	.16
	HHI	.12	.12	.15	.18	.18	.21	.14	.18	.18
	DI	.10	.09	.12	.14	.15	.17	.11	.14	.14
	ICR	.14	.14	.17	.21	.21	.24	.16	.21	.20
	Comprehensive evaluation index	.48	.45	.58	.69	.71	.80	.53	.69	.68
nickel	WGI	.07	.05	.05	.07	.09	.15	.14	.16	.16
	HHI	.08	.06	.06	.08	.10	.17	.16	.18	.18
	DI	.06	.05	.05	.06	.08	.14	.13	.14	.14
	ICR	.09	.07	.07	.09	.12	.20	.19	.21	.21
	Comprehensive evaluation index	.29	.23	.23	.30	.40	.65	.63	.69	.69

In conclusion, the regime distance between China and the source countries of critical minerals imports in each dimension of the Global Country Governance Index shows that political stability, government efficiency, regulatory quality, legal rules, and corruption control, etc. directly affect the degree of supply risk of critical minerals. The more unstable the host country's politics, the higher the supply risk.

To reduce supply risks, China needs to carefully study the characteristics and differences of importing source countries in terms of PV, GE, BQ, RL, and CC, and take timely countermeasures to integrate into the host country's regime environment at minimal cost and minimize the trading risks.

Comprehensive assessment of lithium, cobalt, and nickel supply risks based on the TOPSIS model

Evaluation index weight

The index weight is measured according to the entropy weight method, and the results are shown in Table 7. To further prove the rationality of the index, this study compared and analyzed the evaluation index systems of other experts. Ma et al. (2019) constructed an evaluation index system for China's nickel resource supply security in five dimensions: resource stock, resource supply and demand, resource development, international production and sales, and international market prices. The results show that the share of nickel reserves in the world's total reserves has a weight of 16.5% in the security index system, and the concentration of producing countries has a weight of 5.6%. Considering the share of reserves in the total world reserves and the production concentration have a similar meaning, the weight of supply concentration is 22.1%. The critical mineral concentration weight is 26% in this study, which is basically reasonable. Taking the supply risk of critical metals in clean energy technology as the research object, Huang et al., 2020 established a supply risk assessment system from four aspects: supply reduction risk, demand increase risk, geopolitical risk, and social supervision risk. The results show that the geopolitical supply risk of lithium is medium, and the geopolitical supply risk of cobalt is high, which is consistent with the evaluation results of our study. Chen (2021) established a multi-level comprehensive evaluation model of supply chain risk including natural risk, geopolitical risk and investment environment risk, and concluded that geopolitical risk has an important impact on both

TABLE 9 The results of the comprehensive evaluation of the supply risk of cobalt, lithium, and nickel resources in China with a reduced time window.

Critical mineral	2012	2013	2014	2015	2016
Co	.83	.79	.85	.60	.62
Li	.51	.49	.57	.66	.70
Ni	.28	.25	.31	.30	.46

critical mineral supply base and supply channel risk, which is consistent with the result that geopolitical risk has the highest weight in the evaluation index system of our study.

Comprehensive assessment of supply risk of critical metal minerals of lithium, cobalt, and nickel

The results of the comprehensive assessment of the supply risk of China's imported lithium, cobalt, and nickel resources are shown in Table 8 and Figure 7.

From 2012 to 2017, the safety index of lithium was between .6 and .8, which was a relatively safe state. In 2018, it dropped to .53, which was basically safe. After then, it rose to .68, showing a relatively safe situation. Among the many influencing factors, high supply concentration, unstable bilateral institutional relations, and strong market monopoly power play a negative role in the security of China's lithium resources. From 2012 to 2016, the safety index of nickel was between .2 and .4, which was in an unsafe state. From 2017 to 2020, the safety index of nickel was between .6 and .7, which was generally in a relatively safe state.

As for cobalt resources, the safety index of cobalt was between .6 and .8 from 2012 to 2017, which is a relatively safe state. However, from 2018 to 2020, the safety index of cobalt dropped to .2, which is an unsafe and extremely unsafe state. This might be due to the rapid growth in demand for cobalt in the battery sector after 2018, leading to a consequent increase in cobalt supply risk. Global refined cobalt production in 2018 was 128,000 tons, a year-on-year increase of 10%. China's refined cobalt output was 83,000 tons, a year-on-year increase of 15%. Since 2018, the demand for cobalt has been growing at a rate of more than 10%. It also can be seen from the national governance index of the DRC, which was between 20 and 25 before 2018 and dropped to below 16 after 2018, with an increase in social instability. The cobalt production concentration index has also increased from less than 35% to more than 50%. With the decrease in the national governance index and the increase in the concentration of cobalt production in DRC, the geopolitical risk of DRC has sharply increased, and the supply risk of cobalt has increased accordingly. Moreover, since 2018, the DRC government has regarded cobalt as a strategic mineral resource, and the tariff has increased from 2% to 10%, which has increased the supply cost of cobalt and increased the supply risk of cobalt resources. Therefore, China urgently needs to pay attention to the safe supply of cobalt. It can ensure the safe supply of cobalt resources by actively expanding the allocation of overseas cobalt resources other than Congo (DRC) and increasing investment in deep-sea cobalt mining to provide resource guarantee for China's sustainable economic and social development.

Robustness test

Shorten time window length

In November 2016, the State Council of the People's Republic of China approved the "National Mineral Resources Planning (2016-2020)", which listed 24 kinds of minerals such as oil, natural gas, coal, and rare Earth into the strategic mineral catalog as the key objects for macro-regulation and supervision management. To avoid policy interference, this paper excludes data after 2017 for robustness testing. Table 9 shows that the degree of geopolitical supply risk for the three critical minerals are consistent with the original results, indicating that the study results remain robust after excluding policy factors.

Assumptions of the weights given by AHP methods

Indicator weight coefficients are determined using the Analytic Hierarchy Process (AHP). In the AHP, the main steps are as follows: 1)

TABLE 10 Indicator weights results.

Indicator	Feature vector	Weight (%)	Maximum eigenvalue	CI value
WGI	.909	22.727	4.000	.000
HHI	1.091	27.273		
DI	.727	18.182		
ICR	1.273	31.818		

The eigenvectors are (.909,1.091,0.727,1.273), and the weights of four indicators are 23% (WGI), 27% (HHI), 18% (DI), 32% (ICR), respectively. In addition, the maximum eigenvector (4.000) is derived by combining the eigenvectors. The CI, value (.000 < .1) is calculated by using the maximum eigenroot value [CI = (maximum eigenroot-n)/(n-1)], which means that the judgment matrix satisfies the consistency test and the calculated weights are consistent.

TABLE 11 The results of the comprehensive evaluation of the supply risk of cobalt, lithium, and nickel resources in China with the AHP weights.

Critical mineral	2012	2013	2014	2015	2016	2017	2018	2019	2020
Co	.78	.77	.70	.68	.64	.63	.29	.28	.34
Li	.58	.52	.47	.60	.70	.77	.56	.57	.65
Ni	.37	.35	.27	.43	.48	.68	.62	.60	.60

Construction of the judgment matrix A. 2) Using the square root method to find the eigenvectors. 3) Consistency verification. 4) AHP weight determination.

The geopolitical supply risk results of cobalt, lithium, and nickel evaluated based on the entropy weight method and the AHP, method are consistent, indicating that the results with different weights are robust and reliable (Tables 10, 11).

Discussion and conclusion

With the acceleration of global renewable energy development, some radicalization and politicization tendencies have emerged, driving the adjustment of the world energy political pattern, and accelerating the evolution of energy security concepts, strategies, and international energy security framework (Zhao, 2022). Under this circumstance, the geopolitical risks of the safe supply of lithium, cobalt, and nickel resources required by China's energy storage technology have also increased, and there is an urgent need to evaluate the geopolitical risks of their supply. Based on the relevant geopolitical data of 8 major source countries of critical metal minerals from 2012 to 2020, the study selects the degree of geopolitical stability, supply concentration, bilateral institutional relationship, and country risk index through supply risk analysis and geopolitical risk factor identification, and constructs a supply risk evaluation model for lithium, cobalt, and nickel using the TOPSIS model. The conclusions and suggestions are as follows.

1) To achieve the goal of "carbon neutralization and carbon peak", China is vigorously developing renewable energy. With the increase of wind and solar power generation projects, the importance and urgency of energy storage are becoming more and more obvious, and battery energy storage technology will usher in a huge development opportunity. However, battery energy storage is limited by the supply of critical metal minerals. In addition, critical minerals are more susceptible to geopolitical influence and have a higher risk of supply chain disruption. The future rapid growth of the demand for critical minerals will accelerate the reshaping of the world's strategic mineral resources geopolitics
2) The country governance index and country risk index of import source countries of lithium, cobalt, and nickel were calculated, and the supply risk of three critical metal mineral resources was estimated. The major producing countries of cobalt resources have high geopolitical index changes and social unrest, and the supply risk is the greatest. Chile and Argentina, suppliers of lithium resources, have increased social instability and supply risks in recent years. Indonesia, the Philippines, and Brazil, suppliers of nickel resources, showed an increasing trend of governance index and low supply risk. The degree of political stability, government efficiency and regulatory quality, the rule of law, and corruption control in the importing country directly affect the degree of risk of critical mineral supply. The institutional distance between China and DRC is the largest, so the supply risk of cobalt resources is also the largest.
3) Based on the TOPSIS model, the supply security index of critical minerals such as lithium, cobalt, and nickel in 2012–2020 was calculated. The main factors that cause fluctuations include the degree of political stability and non-violence, political leadership, military and religion in politics, the level of the rule of law, government effectiveness, corruption control, etc. Followed by economic risk and financial risk. Starting in 2018, the index of cobalt dropped to .2, which is an unsafe and extremely unsafe state. China's demand for cobalt is more than 90% dependent on foreign countries, and the main importing country is the Democratic Republic of the Congo. The Democratic Republic of the Congo. is one of the world's least developed countries as determined by the United Nations. The term of the new President of the Democratic Republic of Congo is from 2019 to 2023, and the political risks are high, including the dissatisfaction of long-term loyalists caused by the imbalance of political rewards, the dissatisfaction of veteran politicians caused by the imbalance of the old and the new, the dissatisfaction of some provinces caused by the imbalance of geographical distribution, and the social dissatisfaction caused by the uneven distribution of economic resources. In addition, the new mining law implemented by the Democratic Republic of the Congo will further push up the cost of mining taxes and fees that are already too high and have a negative impact on the investment of foreign companies (Lu et al., 2018). Therefore, China's import of cobalt resources faces great geopolitical supply risks.

We have several policy suggestions by combined results as follows: For the government, China could strengthen resource diplomacy and build a community with a shared future for global critical mineral resources security. Additionally, China could also pay attention to the substitution and recycling of critical mineral resources (Zhai et al., 2021), that is, to reduce dependence by exploring alternative materials, improving processing efficiency, and increasing recycling (Gulley et al., 2018). For domestic enterprises, they could not only respond to the "Belt and Road Initiative (BRI)" and acquire critical mineral resources for new energy from abroad through international capacity cooperation (Mao, 2022), but also cooperate with critical mineral resource countries in exploration and development by providing technologies, funds, and markets. For the three different critical minerals, it is necessary to stabilize the cooperation in the DRC in many aspects to ensure the supply of cobalt resources upstream. China would promote the large-scale, intensive, and green development of lithium resources, and orderly promote the construction of national lithium resource bases. It is also urgent for China to increase the prospecting of nickel resources and establish overseas nickel resource development bases.

This study just analyzed the geopolitical risk of critical metal mineral supplying countries, other risks such as the geopolitical risks of transport channels should also be identified. In the future, based on this study, the whole supply chain database including critical metal mineral bases and transportation channels could be constructed to dynamically identify supply chain risk factors, and a supply chain risk prediction model could be established to minimize supply risks to further develop and promote battery storage energy technology to ensure the large-scale development of renewable energy in China.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

Conceptualization, BW, LW, and SZ.; methodology, BW, LW, and S.Z.; validation, B.W.; formal analysis, BW; investigation, BW; resources, BW, NX, and QQ; data curation, BW, NX, and QQ; writing—original draft preparation, BW; writing—review and editing, BW, LW, and SZ; supervision, LW; project administration, LW; funding acquisition, LW and SZ. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.1032000/full#supplementary-material

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Research on key cobalt technologies based on patent analysis

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Based on global cobalt technology patents, this paper uses patent data mining and co-occurrence methods to identify technology application trends, key technology areas, key technology layouts, and technology roadmap. According to the development trend, the development of co-cobalt technology is divided into slow and rapid development stages. The conclusion are: 1) In terms of key technologies, E35-V (Cobalt compound) is the long-term R&D focus in the field of cobalt, and X16-B01F1 (Lithium-based) is the most important key technology area at present. 2) China, Japan, the United States, and South Korea are the main contributors to key cobalt technologies, mainly focusing on the R&D layout of L03-E01B5B (Lithium electrode) technology in the field of X16-B01F1 (Lithium-based). 3) Regarding the cooperation relationship between patent applicants, cooperation between groups is relatively close, cooperation between different countries is less, and transnational cooperation is mainly concentrated in developed countries, among which the United States has the most transnational partners. 4) In the field of cobalt's most important electrode material technology LG Chemical Co., Ltd. (Korea) and Sumitomo Metal Mining Corporation (Japan) are the two companies with clear technology lines, while Univ Cent South (China) has a late technology development. Finally, we make suggestions for the development of cobalt technology: focus on core technology for R&D and innovation, actively study the technology status and innovation mode of leading companies, and strengthen the cooperation among different R&D institutions.

KEYWORDS

cobalt, patent layout, key technologies, patent analysis, co-occurrence

1 Introduction

Cobalt is an important emerging key mineral resource. Several countries such as the United States, China, and Japan have now included cobalt in their national strategic mineral inventories, making it a key mineral for global strategic mineral research and assessment (McCullough and Nassar, 2017). The Democratic Republic of Congo is the world's largest producer of cobalt ore reserves and production. Cobalt production in the DRC has been a major global supply for decades. At the same time, China is the largest producer of refined cobalt globally, followed by Finland and Canada (Dehaine et al., 2021). Cobalt is widely used in high-tech fields such as aerospace, chemical, electronics, medical and high-temperature magnetic alloys (Hayes and McCullough, 2018). In addition to these applications, cobalt is used to manufacture catalysts, desiccants, dyes, pigments, and pharmaceuticals (Sun et al., 2019). At the same time, cobalt is also an important raw material. Due to the rapid development of new energy electric vehicles, the battery industry has become cobalt's most important consumption field (Liu et al., 2020). With the rapid development of strategic emerging industries and the transformation of some clean energy sources, fuel vehicles have gradually shifted to electric vehicles, and the economic value, as well as the demand for cobalt, has multiplied (Campbell, 2019). As a frontier material for future development, cobalt has made breakthroughs in related patent technologies, and the number of global patent applications has increased exponentially. Many enterprises worldwide have started early in the patent development of cobalt-related technologies, but most still lack patent layouts of critical technologies. Enterprises involved in cobalt technology R&D in each country must grasp related technologies' global patent application trends and actively lay out key patent technologies to improve their competitive advantages. Therefore, it is crucial to understand the current global critical technologies of the cobalt industry and their development rules and analyze the technology planning and innovation models of critical technologies in each country to promote the high-quality development and strategic layout of cobalt technology.

Scholars' research on cobalt mainly revolves around two aspects: one is the analysis of cobalt ore resources in terms of reserves, supply, and trade, and the other is the development and application of cobalt-related technologies. Horn et al. (2021) studied three deposit types of cobalt and identified 104 deposits in Europe currently being explored for cobalt, 79 of which are located in Finland, Norway, and Sweden. Fu et al. (2020) found by quantifying the material market of cobalt that with the increase in demand for lithium batteries, the demand for cobalt resources is expected to grow by more than 300% in the next decade, and the future faces a significant risk of supply concentration and mining restrictions of cobalt resources. In addition, some scholars have also studied the flow of cobalt using a trade-related material flow model and found that the supply and demand of cobalt have seen rapid growth, with the Democratic Republic of Congo, the United States, China, and Japan being the major powers in the cobalt trade network (Cullen and Allwood, 2013; Sun et al., 2019). Other studies have used a link predictive analysis model, combined with trade networks, to forecast the international trade relationship of cobalt (Liu et al., 2020). The results show reduced trade stability of cobalt and forecast the next three and 5 years for the countries most likely to trade cobalt ore.

Cobalt is currently being studied in various technological fields of technology and applications, such as catalysts, alloy materials, magnetic materials, medicine, and battery materials. Cobalt can be used as a catalyst to improve energy utilization, and Kim et al. (2020) synthesized cobalt-based catalysts with enhancement by inserting traces of palladium. Kim et al. (2018)also prepared cobalt-based catalysts with different base strengths by controlling the amount of yttrium oxide. Metallic cobalt can also be used with other metals to make alloys to generate high-temperature alloys, magnetic alloys, and anticorrosive alloys (Talapatra et al., 2009; Garcia et al., 2016; Yu et al., 2018; Wang et al., 2022). In medical research, cobalt was found to be a trace element in the human body, and its metabolic level was associated with thyroid hormones (Alkjaer et al., 2005). Lin et al. (2020) found that cobalt compounds can act as antimicrobial agents, promote bone cell growth, and reduce inflammatory responses. Cobalt also has many cutting-edge studies in the field of battery materials. Luo et al. (2022) summarized recent nickel-rich and cobalt-as-cathode materials. He et al. (2015) found that cobalt sulfide can be used not only as a lithium-ion battery electrode material but also as a cathode active material in rechargeable magnesium batteries.

Patent data is the world's largest and most reliable source of technical information and one of the most effective indicators of the current state of technological intellectual property development (Safin and Manteuffel, 2016). Patent analysis methods can be used to identify the state of technological development and current research hotspots and predict future development and competitor innovation trends (Zou et al., 2018). At present, few scholars have conducted an overall overview and analysis of the technology field of cobalt from the perspective of patent technology. Most of the existing patent technology research focuses on the downstream of cobalt, such as lithium-ion battery technology. Lee and Su (2020) used patent analysis methods to analyze lithium-ion battery patent trends using patent metrics and analyzed the technological innovation and similarity of the top six patent assignees. Aaldering and Song (2019) used a data-driven approach combining patent co-classification analysis, link prediction algorithm application, and text mining techniques to highlight the post-lithium-ion battery technology research advances. Malhotra et al. (2021) analyzes the evolution of lithium-ion battery knowledge trajectories over the past 50 years.

From the studies mentioned above, it can be found that previous studies lacked research on the cobalt industry from the perspective of patent analysis, while cobalt belongs to the critical raw materials of the future, and researching key technologies of cobalt is of great significance for countries to carry out technological R&D and strategic layout. As global competition becomes increasingly fierce, science and technology innovation has also become a core indicator of national competitiveness. Improving the level of critical technologies and innovation

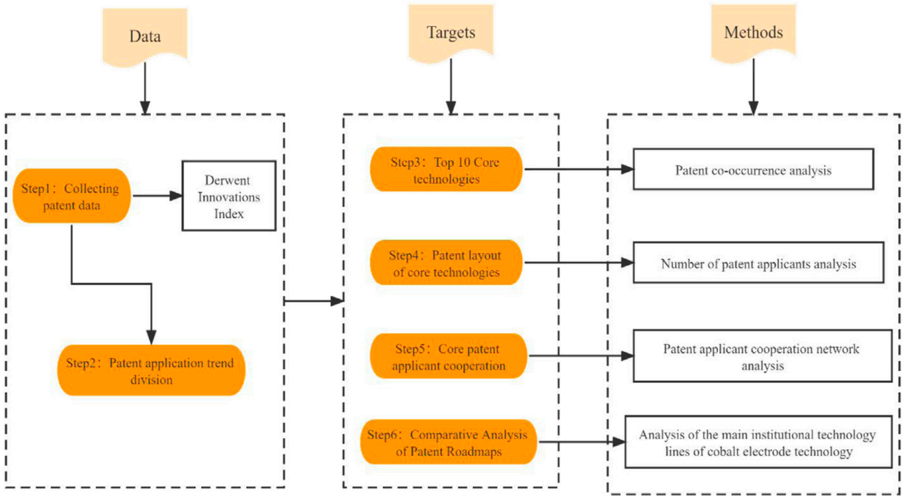

FIGURE 1
Research framework.

capability has become a significant task at present. Therefore, assessing the R&D trends and the current situation in the field of cobalt key technologies, determining the national competitive posture of key technologies, and clarifying the future key technology R&D directions are of great practical significance for countries to carry out the layout of cobalt key technology R&D and improve their scientific and technological innovation capabilities. Therefore, in order to effectively evaluate the critical technologies of cobalt, this paper takes the patent data of cobalt as the basis, firstly divides the technological development of cobalt into the slow development stage and rapid development stage according to the development trend, then uses patent analysis and co-occurrence analysis to determine the critical technologies of cobalt in each stage, followed by the analysis of the technology layout and cooperation of patent applicants. Finally, patent applicants in cobalt's most important electrode material technology field are selected to analyze the patent technology routes. The rest of this report is organized as follows. Section 2 introduces the research framework and methodology, Section 3 presents the research content, and Section 4 concludes and presents the policy comments of this paper.

2 Research framework and methods

Based on patent data mining methods such as patent analysis and co-occurrence analysis, this paper first delineates the development trend of cobalt patent technology. The key technologies at different development stages are identified, and on this basis, the patent technology layout and the cooperation relationship between patent applicants and patent application countries are analyzed. Finally, the patent applicants in the most important electrode material technology field of cobalt are selected for the analysis of patent technology routes. The overall analysis framework of this paper is shown in Figure 1, and the whole analysis process is refined into the following six steps.

Step 1: Data acquisition and processing. Patents are an important carrier of technological research and development results and contain 90%–95% of the world's technical information, so technology research based on patent analysis is more scientific and comprehensive (Altuntas and Gök, 2020; Bai et al., 2021). In this study, patent information related to the vital mineral cobalt industry was extracted using the Derwent Innovations Index (DII). The Derwent Patent Database is one of the most authoritative patent databases in the world, containing patent information from over 50 patent-granting institutions worldwide, with a unique classification system and high value-added patent information (Yuan and Li, 2020). The search topics are as follows: (Cobalt metal* OR cobalt ore* OR cobalt salt* OR cobalt compound* OR cobalt mining* OR cobalt oxide* OR cobalt hydroxide* OR cobalt chloride* OR cobalt sulfate* OR cobalt oxalate* OR cobalt carbonate* OR cobalt sulfide* OR lithium cobaltate* OR cobalt smelting and processing* OR cobalt recovery), the data collected span from 1 January 1967, to 1 June 2022, and the number of patent applications searched was 218,267.

Step 2: Classify the development stages according to the patent application trends. The major economies of cobalt patent applications: Japan, the United States, Germany, the United Kingdom, China, and South Korea, are extracted based on patent data, their historical patent application trends, and the

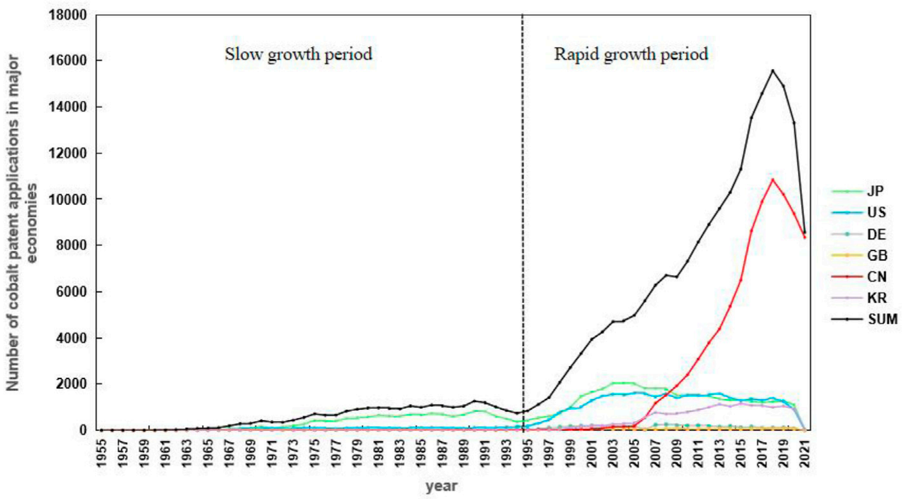

FIGURE 2
Global trends in cobalt technology patent applications by major countries.

global trend of total cobalt patent applications are analyzed. By analyzing the overall trend of patent applications, the development of cobalt technology patents is divided into two stages.

Step 3: Key Technology Identification. The Derwent Innovation Index (DII) database provides information such as the year of patent filing, the country of filing, and the Derwent Manual Code of the patent, which can help us identify key technologies. Based on the Derwent classification codes, experts form Derwent manual codes by hand to refine patent data in technology areas. In this paper, we analyze the co-occurrence of Derwent manual codes in the patent data of the cobalt industry, form a patent co-occurrence network diagram, and make a qualitative judgment on the key technologies of the cobalt industry based on the visualized information. Among them, the key technologies in the cobalt field were identified by combining the number of patent occurrences and the centrality index of social network analysis. On this basis, the number of occurrences of key technologies and the intermediary centrality index was used as horizontal and vertical coordinates, and the mean of the two was used as the origin to establish a right-angle coordinate system to analyze the differences in importance and attention according to the quadrants of key technology distribution. Among them, more occurrences of a patent node indicate that the patent is a current research hotspot (Robinson et al., 2013), while the higher the intermediary intra-centrality index indicates that the node plays a greater role as a bridge in the network.

The formula proposed by Freeman (1978) for the betweenness centrality index is as follows:

$$BC_i = \sum_{s \neq i \neq t} \frac{n_{st}^{i}}{g_{st}}$$

where:g_{St} = the number of shortest paths from technology field s to technology field t.n_{st} = the number of shortest paths passing through technology field i among the g_{St} shortest paths from technology field s to technology field t.

Betweenness centrality index refers to the number of times a node acts as the shortest bridge between two other nodes. When a node acts as a bridge more often, its betweenness centrality is higher. In patent co-occurrence networks, nodes with high betweenness centrality represent key nodes connecting existing and emerging technologies, and these nodes represent the key technology areas in the network (Freeman, 1978).

Step 4: Technology layout of core patent applicants. Based on the identification of cobalt key technologies, statistics containing information on the application fields of key technologies at different stages, the principal applicants and applicant countries of key technologies are identified based on the number of patent applicants and patent applicant countries in the technology fields. China, Japan, the United States, and South Korea, the major economies of global cobalt patent applications, are selected to compare the number of applications in different key technologies in significant countries. Analyze the gap in the layout of key technologies and R&D strength between countries at different stages. Secondly, a bimodal network is constructed based on the relationship between key technologies and patentees to form a cobalt key technology distribution map of patentees. The important applicants of key technologies are judged by judging the size and color of nodes and the thickness of edges in the network.

Step 5: Cooperation analysis of core patent applicants. Key technology patent applicants are extracted, and an undirected

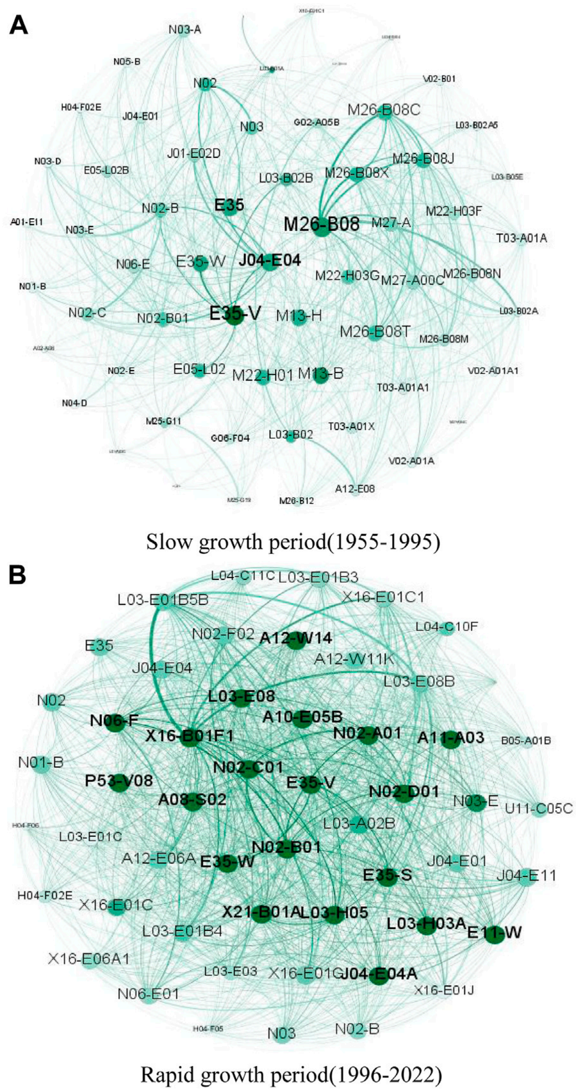

FIGURE 3
Identification of key cobalt technologies at different stages.

weighted cooperation network of patent applicants with patent applicants as nodes, cooperation relationship as edges, and cooperation time as weights are constructed according to the cooperation relationship between patent applicants. Next, this cooperative network is analyzed by combining the number of nodes, the number of edges, the average clustering coefficient, and the average path length in the social network analysis. The number of nodes and edges represent the size of the network, the average clustering coefficient indicates the closeness of cooperative relationships in the network, and the average path length indicates the average number of steps to form cooperative relationships among patent applicants. Secondly, the cross-country cooperation relationships at different stages are extracted. An undirected weighted cobalt key technology cross-country cooperation network is constructed, with nodes representing different institutions, node colors representing the countries to which the institutions belong, and edges representing the number of cooperation between different institutions.

The average clustering coefficient formula is as follows (Saramäki et al., 2005):

$$C_i = \frac{2n_i}{k_i(k_i - 1)}$$

$$\bar{C} = \frac{1}{N}\sum_{i=1}^{N} C_i$$

where:k_i = the number of patent applicant partnershipsn_i = total number of partnerships

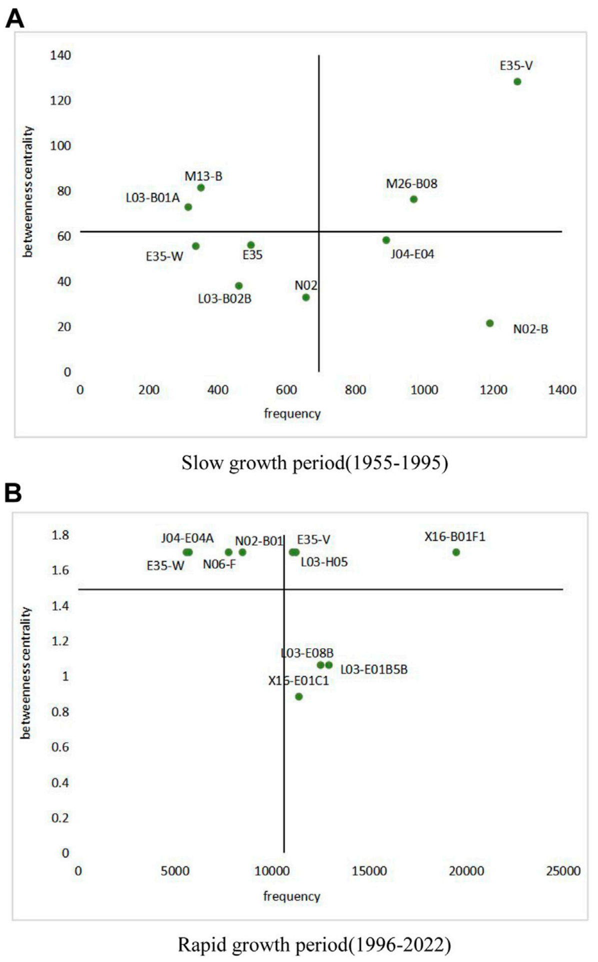

FIGURE 4
Number of occurrences and betweenness centrality cross-coordinates.

The average clustering coefficient is a coefficient that measures the degree of clustering of nodes in a graph. In a cooperative network of patent applicants when the clustering coefficient is closer to 1, then the closer the cooperative relationship between patent owners is.

The average path length equation is as follows (Watts and Strogatz, 1998):

$$L = \frac{1}{n(n-1)}^{*} \sum_{ij} d_{ij}$$

where:L = average shortest path length between nodes in the network .n = number of technical fields.d_{ij} = the shortest distance between the technical field i and j.

The average path length is the shortest path length between any two nodes, that is, the average number of steps of cooperation between nodes in the patent applicant's cooperation network. The smaller the average path, the easier it is for patent applicants in the cooperative network to generate cooperative relationships.

Step 6: Based on the results of the identified cobalt key technology areas, the most important electrode technology areas were selected at present, and then the top three different country patent owners, LG Chem Ltd. (Korea), Sumitomo Metal Mining Co. (Japan), and Univ Cent South (China), were selected. A patent roadmap was created based on patent citation relationships, as well as the number of patent citations and the number of family patents. By analyzing the technology patent roadmaps of different organizations, the technological development paths of the patentees were compared.

3 Results and discussion

3.1 Trend analysis of cobalt patent applications

The global trend of technology applications for cobalt materials is shown in Figure 2. Patent applications for cobalt-related technologies first began around the 1960s, and the number of applications began to show a rapid growth trend after the 21st century. Currently, the countries with a large number of cobalt-related patent applications worldwide are China, the United States, and Japan. The earliest cobalt technology patent was applied for by the United States in 1955, while the earliest patent in China was applied for in 1986, compared with the late start of cobalt industry technology research and development in China. Specifically, the development of global patents related to cobalt technology is divided into two main stages.

The first stage was from 1955 to 1995, a period of slow technological development with few patent applications. In the 1940s, the United States first paid attention to and developed cobalt-based alloys, and at the end of the 1950s, cobalt-based alloys were widely cast and used in the United States. Global patents on cobalt technology were mainly in the hands of Japan and the United States. The second phase, from 1996 to the present, is a period of rapid technological growth, with the total number of patent applications increasing rapidly. Japan and the U.S. still hold many technology patents, but the number of patent applications in China and Korea is also growing rapidly. Due to the global financial crisis in 2008, the growth rate of cobalt industry consumption in many countries was restrained and slowed down. Refined cobalt production and sales in China have surged due to the stagnation of many overseas projects. The rapid growth of cobalt technology patents filed in China has made it the most important country and the main driver of technology development in the cobalt industry. There is an 18-month lag in current patent

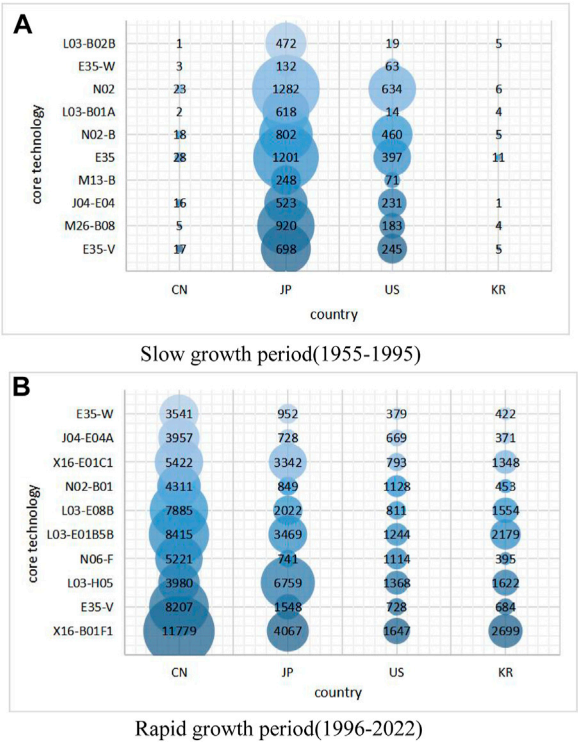

FIGURE 5
Patent applications in key technologies in major countries.

applications, so the data for the latter period is for reference only.

3.2 Global cobalt key technology identification analysis

According to the slow and rapid development stages divided in 3.1, the hot patent technology fields with frequencies greater than 200 times and greater than 3,000 times are extracted for co-occurrence analysis, as shown in Figure 3. The nodes in the graph represent the technical field of cobalt, the node size represents the frequency of occurrence of that technical field, and the node color represents the betweenness centrality of the technical field. The edges between the nodes represent the two technical fields that appear in the patent at the same time, and the weights of the edges represent the number of times the two technical fields appear at the same time. The figure shows that the technology nodes of M26-B08, J04-E04, E35, and E35-V in the slow development stage are darker and larger in color. According to the patent codes, we can find that Nickel or cobalt alloys, Catalysts, Compounds of other metals, and Cobalt compounds are the important and hot technology areas of cobalt. There are more important and hot technology areas in the second stage, and the technology nodes of A10-E05B, X16-B01F1, L03-E01B5B, and E35-W are larger and darker, indicating that Chemical modification by carbonisation, Lithium-based, Lithium electrodes, Nickel compound, etc. are the hot technology industries of cobalt.

In order to better identify the key technology areas, this paper uses the top 10 Derwent Manual Code ranked by the product of frequency and betweenness centrality in the technology areas to represent the top 10 key technology areas (as Table 1 shows). Based on the identification results and the meaning of the entries of the Derwent manual codes, it can be concluded that the first ranking of cobalt key technology patents in the slow development stage is E35-V (Cobalt compound), M26-B08 (Nickel or cobalt alloy), J04-E04 (Catalysts), M13-B (Coating from solution or suspension of metal compounds), etc. also belong to the key technology area of cobalt in this stage. In the rapid development stage, X16-B01F1 (Lithium-based) replaced E35-V (Cobalt compound) as the top-ranked key technology, and L03-H05(Vehicles), L03-E01B5B (Lithium electrodes), and L03-E08B (Production of electrodes) also became important key technology areas for cobalt in this stage. In 1990, Sony invented the lithium-ion battery, and the demand for lithium cobaltate as one of the anode materials began to increase rapidly, and its related technology patents also became the key technology of the cobalt industry. Cobalt-containing batteries are widely used because of their high energy density, en-vironmental safety, and stable performance.

From the trend of cobalt key technologies over time, it can be found that E35-V (Cobalt compound) ranks first and second in the slow development phase and the rapid development phase, respectively, indicating that Cobalt compound has been the focus of technology research and going in the cobalt industry. x16-B01F1 (Lithium-based) has been ranked first in the rapid growth phase. It has been the top-ranked key technology area so far. From the rapid growth stage, the most important use of cobalt is for lithium-ion batteries as the electrode material for ternary batteries. From the vital technology changes in each phase, catalysts such as J04-E04 (Catalysts) and N06-F (Catalyst support) have been necessary critical technologies for the cobalt industry. E08B (Production of electrodes) has become the new key technology for the cobalt industry.

In order to further analyze the characteristics of critical technologies, we created a matrix for each phase of technology topics with the number of patent occurrences as the horizontal axis and the betweenness centrality as the vertical axis. We took the average of the two as the intersection point of the analysis (as Figure 4 shows).

In the slow development stage, the first quadrant is the quadrant with the high occurrence and high intermediate centrality. E35-V (Cobalt compound) and M26-B08 (Nickel or cobalt alloy) are located in the first quadrant, where E35-V (Cobalt compound) has the highest occurrence and highest

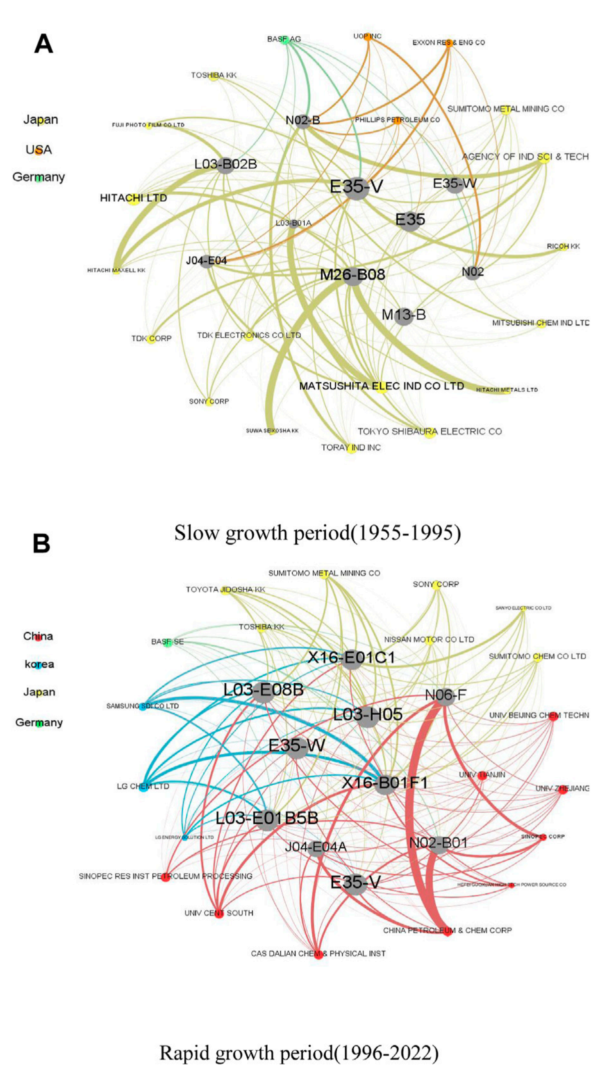

FIGURE 6
Technology distribution of major patent owners.

intermediate centrality, indicating that it is the focus of R&D in the slow development phase. M13-B (Coating from solution or suspension of metal compounds) and L03-B01A (Variable resistors) are located in the second quadrant, where key technologies play a mediating role in the technology field but are less studied. The third quadrant is the low incidence and low intermediate centrality quadrant, where the key technologies are less important and less studied than the other key technologies, E35-W (Nickel compound), E35 (Compounds of other metals), N02 [Fe, Co, Ni, Cu, noble metal—element, (hydr)oxide, inorganic salt, carboxylate] and L03-B02B (Magnetic non-metals) are located in this quadrant. The fourth quadrant is the high occurrence and low intermediate centrality quadrant, where J04-E04 (Catalysts) and N02-B [Cobalt—element, (hydr) oxide, inorganic salt, carboxylate catalyst] are located, and the key technology for this phenomenon is a popular research area, but the relationship with other key technologies is weak.

Similarly, the three technology areas in the first quadrant of the rapid development phase are X16-B01F1 (Lithium-based), E35-V (Cobalt compound), and L03-H05 (Vehicles), indicating that these three technologies are the focus of research in the rapid development phase and are in a critical position. Among them, X16-B01F1 (Lithium-based) is the first in the number of occurrences and intermediary centrality, which is the most important key technology in the rapid development stage. There are four technology areas in the second quadrant, namely N02-B01 (Cobalt element or oxide catalyst), N06-F (Catalyst support), J04-E04A (Redox catalysts), and E35-W (Nickel compound), and this quadrant's key technologies are more closely linked to other technologies but are relatively less studied. In the fourth quadrant, L03-E01B5B (Lithium electrodes), L03-E08B (Production of electrodes), and X16-E01C1 (Oxides, complex oxides) are a hot research area but have less connection with other technologies. Among them, the lithium-ion and electrode field is a hot R&D area for cobalt but relatively less connected with other technology fields.

3.3 Patent layout of key technologies

According to the statistics of patent applications for cobalt key technologies, China, Japan, the United States, and South Korea account for 40%, 23%, 16%, and 7% of the global total patent applications for cobalt key technologies, respectively. Therefore, this paper focuses on the technological layout of cobalt critical technologies in China, Japan, the United States, and South Korea at different stages of development. As shown in Figure 5, the size of the bubbles indicates the number of patents filed by each country on crucial technologies. The horizontal coordinates represent countries, and the vertical coordinates represent different key technologies.

As can be seen from the Figure 5, during the slow growth period, Japan has an absolute advantage in the number of patent applications for crucial technologies of cobalt, especially in the fields of E34 (Compounds of other metals) and N02 [Fe, Co, Ni, Cu, noble metal—element, (hydr)oxide, inorganic salt, carboxylate] in two technical fields. The U.S. technology areas of N02 [Fe, Co, Ni, Cu, noble metal—element, (hydr)oxide, inorganic salt, carboxylate] and N02-B Cobalt—element, (hydr)oxide, inorganic salt, The number of patent applications in N02-B [Cobalt—element, (hydr)oxide, inorganic salt, carboxylate catalyst] is high, while China and Korea are less competitive and have fewer patent applications at this stage. During the rapid growth period, China has an absolute advantage in the number of patent applications for critical technologies and is the most competitive country overall; it is mainly in the patent fields of X16-B01F1 (Lithium-based), L03-E01B5B (Lithium electrodes) and L03-E08B (Production of electrodes). Japan is

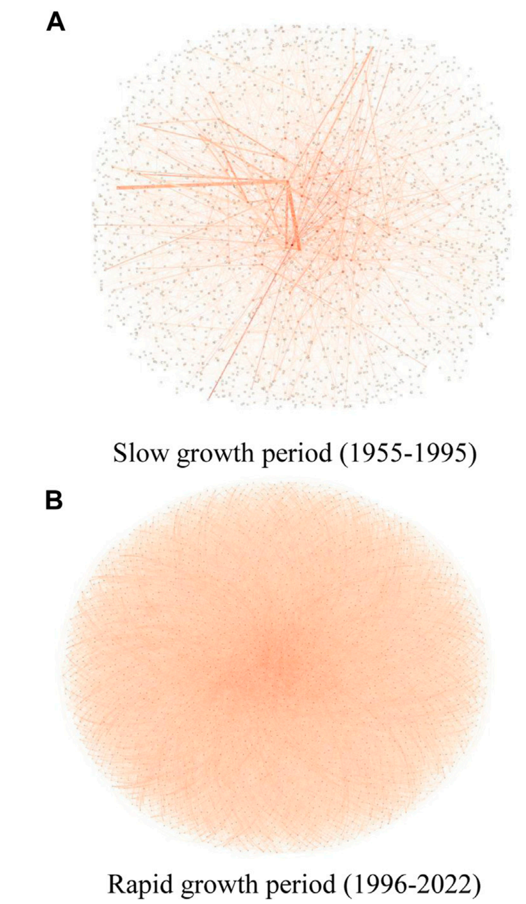

FIGURE 7
Patent roadmap of the main patent owner in the field of electrode technology for cobalt.

second only to China in the number of applications for crucial cobalt technologies, but it overtook China as the world's top filing country in L03-H05 (Vehicles). However, Japan has relatively few applications in catalyst technologies such as N06-F (Catalyst support) and J04-E04A (Redox catalysts). The critical technology applications in the U.S. at this stage are mainly in the fields of X16-B01F1 (Lithium-based) and N02-B01 (Cobalt element or oxide catalyst), and the number of patent applications for N02-B01 (Cobalt element or oxide catalyst) has exceeded that of Japan The number of patent applications for N02-B01 (Cobalt element or oxide catalyst) has surpassed that of Japan and is only surpassed by China. Korea is mainly in X16-B01F1 (Lithium-based) and L03-E01B5B (Lithium electrodes) technologies.

Compared with the slow development stage, the number of applications in China and Korea has increased significantly. Both China and Korea mainly focus on the R&D of X16-B01F1 (Lithium-based) and L03-E01B5B (Lithium electrodes) technology areas. China's total number of patent applications for key cobalt technologies surpasses Japan's, making it the most competitive country. However, Japan has the highest number of applications in the world in L03-H05 (Vehicles).

In order to analyze the layout of different companies in the field of cobalt key technologies, this paper selects the major patent owners whose total patent applications in key technologies in the slow development stage and the rapid development stage exceed 50 and 200, respectively, for comparison, and their patent technology layout is shown in Figure 6. Among them, gray nodes represent key technologies, yellow, orange, green, blue, and red nodes indicate Japanese, American, German, Korean and Chinese patentees, respectively, and the thickness of connecting lines between nodes represent the number of patent applications for key technologies. As seen from Figure 6A, the key technology companies applying for cobalt in the slow development stage mainly originate from Japan, such as HITACHI LTD., MATSUSHITA ELEC IND CO. LTD., TDK ELECTRONICS CO. LTD., etc. The main layout is E35-V (Cobalt compound) and M26-B08 (Nickel or cobalt alloy). PHILLIPS PETROLEUM CO and TDK CORP in the United States are also an essential part of cobalt key technology. Secondly, BASF AG in Germany also has more patents in N02-B [Cobalt-element, (hydr)oxide, inorganic salt, carboxylate catalyst] and E35-V (Cobalt compound).

It can be seen in the rapid development stage that the main origins of companies applying for cobalt key technology are starting to become diversified, mainly China, Korea, Japan, and Germany. Chinese CAS DALIAN CHEM & PHYSICAL INST, CHINA PETROLEUM & CHEM CORP, and UNIV ZHEJIANG are the main contributors to the vital cobalt technology in China, mainly in N02-B01 (Cobalt element or oxide catalyst) and N06-F (Catalyst support). Chinese universities and research institutes are an important part of the global cobalt key technology patentees and have strongly promoted cobalt key technology innovation. In addition, Japan's SANYO ELECTRIC CO. LTD., TOYOTA JIDOSHA KK, and SONY CORP have strong R&D strength in key cobalt technologies, mainly in the field of X16-B01F1 (lithium-based) technology. LG CHEM LTD. and SAMSUNG SDI CO. LTD. of Korea have focused on X16-B01F1 (Lithium-based) and X16-E01C1 (Oxides, complex oxides), and these two companies have the largest number of patents in X16-B01F1 (Lithium-based) technology, so Korea has a certain technological advantage in Lithium-based. BASF SE of Germany has more patents in X16-B01F1 (Lithium-based) and N02-B01 (Cobalt element or oxide catalyst).

3.4 Key technology patent applicant cooperation network

In order to study the cooperative relationship of key technology patent applicants of cobalt, this paper uses Gephi software for the co-occurrence diagram of patent applicants, as shown in Figure 7. In order to understand

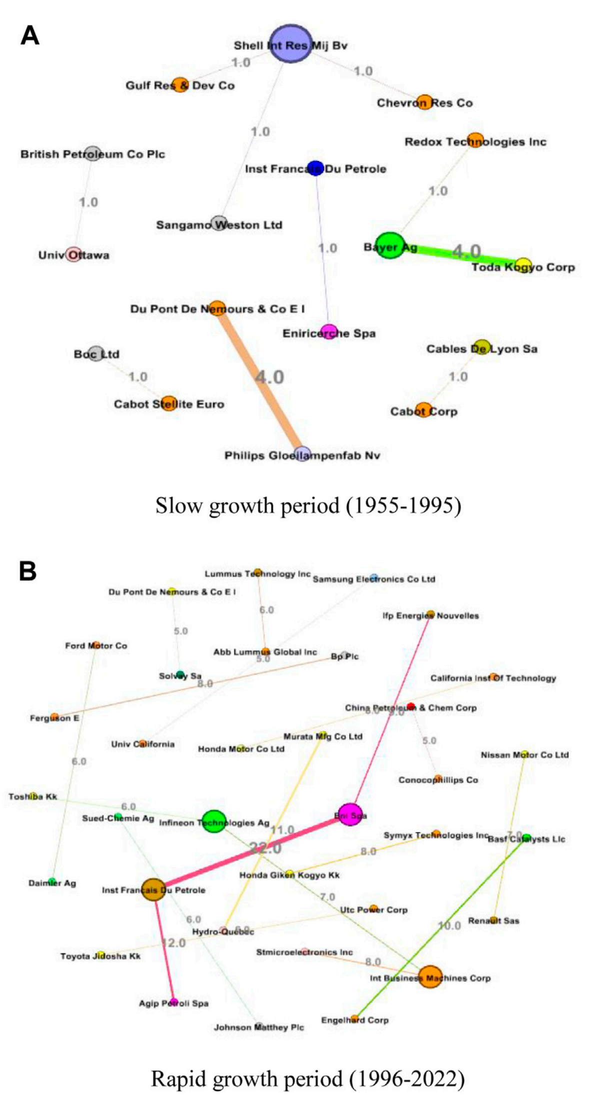

FIGURE 8
Cross-border cooperation network for key cobalt technologies.

the evolutionary characteristics of the overall cooperative network, the parameters of the overall network characteristics of the cooperative network at different stages are compiled in Table 2 in this paper. It can be seen from the figure that from the slow growth stage to the rapid development stage, the network size expands, and the number of cooperative relationships increases rapidly. The average clustering coefficient and the average shortest path length in Table 2 represent the degree of close cooperation among patent applicants. It can be found that the average clustering coefficient becomes larger and the average path value becomes smaller, indicating that the cooperative relationships among patent applicants are getting closer and closer. The cooperation network shows the characteristics of large dispersion and small aggregation, with close cooperation among institutions in the same country but less cooperation among institutions in different countries.

In order to deeply analyze the cross-border cooperation relationship of patent applicants, the patent applicants with a high number of cross-border cooperation in both phases are visualized in Figure 8. Different colors in the figure represent the countries from which the organizations come, with yellow representing Japan, orange representing the US, purple representing the Netherlands, green representing Germany, red representing China, blue representing Korea, gray representing the UK, pink representing Canada, rose pink representing Italy, and brown representing France. As seen from the figure, in the slow development stage, US firms engage in more cross-border cooperation, with more frequent cooperation between institutions in the US and the Netherlands. The number of cross-border collaborations by global institutions in the slow development stage is relatively small. In the rapid development stage, cross-border cooperation among patent applicants increased, with the most frequent cooperation between Italy and France. Italy's Eni, Germany's Infineon, and France's Inst Francais collaborate more frequently with other countries. Overall, cross-border cooperation in key cobalt technologies is mainly concentrated in developed countries such as the US, Italy, and the UK, with the US having the most cross-border partners.

3.5 Comparative analysis of major patentees based on patent roadmap

The technology roadmap is an important tool for strategic planning and decision-making, as it can clearly show the pulse and frontier of technology development to relevant organizations through visualization. In this paper, we have selected the critical technology area of cobalt in electrodes and created a patent roadmap based on the patent citation relationship based on the three organizations from different countries with the largest number of related patents, LG Chem Ltd. (Korea), Sumitomo Metal Mining Co. (Japan) and Univ Cent South (China). The critical patents in the patent roadmap are determined based on the frequency of patent citations, key technology areas, and the number of family patents. According to the statistical analysis, in the field of cobalt electrode technology, LG Chem Ltd. (Korea) has 993 patent records, Sumitomo Metal Mining Co. (Japan) has 419 records, and Univ Cent South (China) has 424 records. The patent technology roadmap of the three organizations in the field of electrodes is shown in Figure 9, with the gray part of the figure

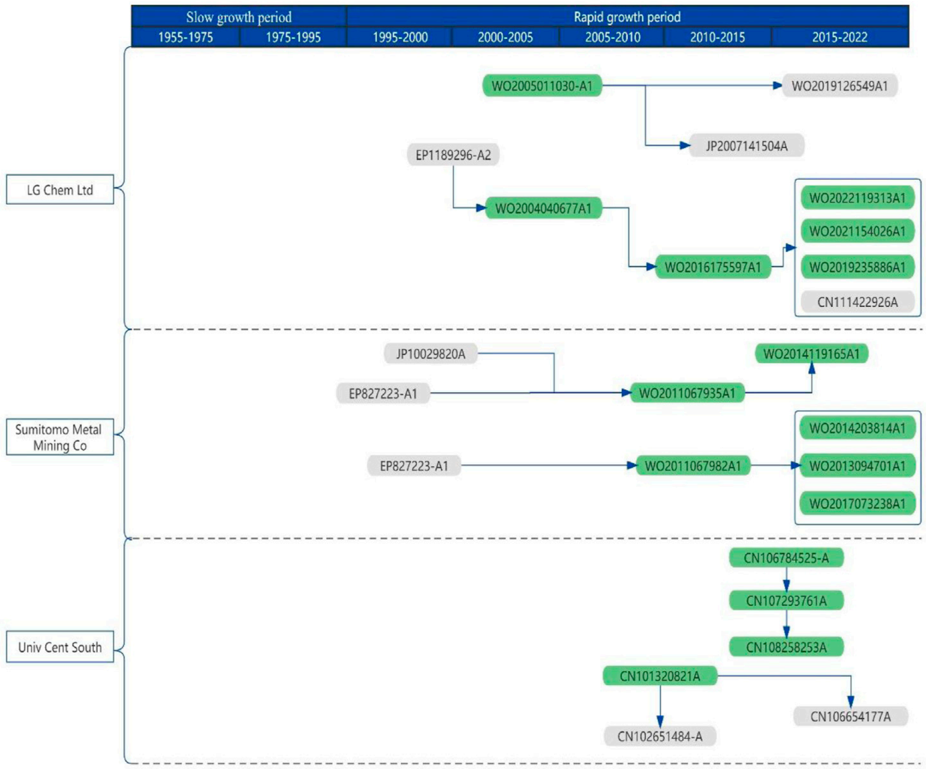

FIGURE 9
Collaborative network of patent applicants for key technologies.

showing the patents of other organizations and the green part showing the patents of their organizations.

LG Chem Ltd. filed a patent WO2004040677A1 on optimized cathode materials for cobalt-containing lithium batteries in 2004, which was cited 71 times. As a result of this technology, the patent WO2016175597-A1 on cathode active material for cobalt-containing lithium-ion secondary batteries was filed in 2016 and was cited 21 times, with 12 family patents. 2005 LG Chem Ltd. filed a patent WO2005011030A1 on anode active material for cobalt-containing lithium-ion secondary batteries, with 22 family patents, and was cited 66 times. On this basis, LG Chem Ltd. and other organizations applied for several patents related to cobalt-containing electrode materials and became the country with the largest number of patents for cobalt electrode materials in the world.

In 2011, Sumitomo Metal Mining Co. applied for WO2011067935A1, "Manufacture of nickel-cobalt-manganese composite hydroxide particles for manufacturing cathode active materials," which has 16 patents in the family and has been cited 76 times. In addition, WO2014119165A1, "Manufacture of nickel-cobalt composite hydroxide for active cathode materials," was filed in 2014 with 29 citations and 16 family patents. Sumitomo Metal Mining Co. Based on this, more related patents have been filed.

In 2008, Univ Cent South applied for patent CN101320821A on the technology of integrated energy storage components for capacitors and lithium-ion batteries, which was cited 32 times, and two family patents. 2017, Univ Cent South applied for CN106784525A on the technology of lithium-sulfur battery diaphragm and graphene preparation, which was cited 47 times.

In general, the core technology of the most popular electrode material for cobalt is receiving attention from various companies. Among them, LG Chem Ltd. (Korea) and Sumitomo Metal Mining Co. (Japan) are two companies with clear technology lines, while Univ Cent South (China) is late in developing its technology. Univ Cent South (China) has more patents for critical technologies, but the quality of core technologies is poorer than the other two organizations.

4 Conclusion and policy implications

4.1 Conclusion

The current research lacks research on cobalt key technologies from the perspective of patent analysis, while cobalt belongs to the key raw materials of the future. There are

TABLE 1 Top 10 key technologies for cobalt.

Rank	Derwent manual code	Category meaning	Frequency	Betweenness centrality
(A) Slow growth period (1955–1995)				
1	E35-V	Cobalt (Co) compound	1270	128.27305
2	M26-B08	Nickel or cobalt alloy	969	76.24981
3	J04-E04	Catalysts	889	58.208617
4	M13-B	Coating from solution or suspension of metal compounds [general]	351	81.39311
5	E35	Compounds of other metals [general]	496	56.00599
6	N02-B	Cobalt—element, (hydr)oxide, inorganic salt, carboxylate catalyst [general]	1190	21.424194
7	L03-B01A	Variable resistors	314	72.818273
8	N02	Fe, Co, Ni, Cu, noble metal—element, (hydr)oxide, inorganic salt, carboxylate [general]	656	32.892766
9	E35-W	Nickel (Ni) compound	336	55.550736
10	L03-B02B	Magnetic non-metals [general]	461	38.007232
(B) Rapid growth period (1996–2022)				
1	X16-B01F1	Lithium-based	19480	1.699919
2	E35-V	Cobalt (Co) compound	11214	1.699919
3	L03-H05	Vehicles	11049	1.699919
4	N06-F	Catalyst support	8466	1.699919
5	L03-E01B5B	Lithium electrodes	12917	1.062272
6	L03-E08B	Production of electrodes	12491	1.062272
7	N02-B01	Cobalt element or oxide catalyst	7749	1.699919
8	X16-E01C1	Oxides, complex oxides	11372	0.884227
9	J04-E04A	Redox catalysts	5707	1.699919
10	E35-W	Nickel (Ni) compound	5578	1.699919

gaps in the research on the development trend, patent owners, key technology layout, and technology development route of cobalt key technology, etc. Assessing the R&D trend and current situation in the field of cobalt key technology is of great practical significance for countries to carry out the R&D layout of cobalt key technology and improve their scientific and technological innovation capability. Therefore, this paper divides the development trend into slow development stages and rapid development stages and uses patent analysis and symbiosis analysis to identify key technologies according to the current status of technology development in the global cobalt industry. On this basis, the layout of key technologies in the cobalt industry is analyzed from the perspective of the key technology patent applicants and the countries to which the applicants belong, and the cooperative relationship among the patent applicants is analyzed. Finally, by analyzing the technical routes of the main patent owners in the most critical core technology field of cobalt-electrode material technology, the main conclusions drawn are as follows:

(1) Patent co-occurrence analysis is used to identify critical technologies and important cobalt features at different stages. E35-V (Cobalt compound) belongs to the key technologies that have been the focus of R&D in the cobalt industry, while X16-B01F1 (Lithium-based) is the most important key technology area at present.
(2) The patent layout of cobalt key technologies is analyzed according to the patent applicants and the countries to which they belong. China, Japan, the United States, and South Korea are the main contributors to cobalt key technologies. Each country concentrates on the layout of R&D in the X16-B01F1 (lithium-based) fields L03-E01B5B (lithium electrode) technologies.
(3) Based on the cooperation network of cobalt key technology patent applicants, the cooperation relationship is analyzed. Collaboration networks have become closer over time between patent applicants. Most collaborative relationships are domestic, with fewer patent applicants cooperating across borders. Transnational cooperation in

TABLE 2 Basic parameters of cooperative networks in different stages of cobalt key technologies.

Stage	Number of network node	Number of sides	Average clustering coefficient	Average path length
1955–1995	2141	2497	0.617	6.957
1996–2022	20160	133218	0.637	3.711

cobalt key technologies is mainly concentrated in developed countries such as the United States, Canada, and the United Kingdom, among which the United States has the most transnational partners.

(4) The three organizations with the highest number of relevant patents in different countries were identified according to the key technology areas of electrode materials for cobalt, and a patent roadmap was established based on the patent citation relationship. LG Chem Ltd. (Korea) and Sumitomo Metal Mining Co. (Japan) are the two companies with clear technology lines, while Univ Cent South (China) has a later technology development.

4.2 Policy implications

Identify the key technology areas of cobalt, and analyze the critical technology layout of applicants and applicant countries as well as the cooperation relationship to provide certain reference values for the R&D, innovation, and strategic layout of relevant technologies in this field. Combining the above research findings, the following recommendations are made.

(1) We should strengthen the R&D and innovation of core technologies such as X16-B01F1 (lithium-based) and L03-E01B5B (lithium electrode) around the cobalt industry chain and pay close attention to the new developments in the field of cobalt in recent years. In recent years, cobalt, an important raw material for new energy power batteries, has had a broad market prospect. In the future, we should increase our technological research and development efforts and innovation to expand our technological fields.

(2) Countries should increase support for critical enterprises to promote their research and development of key technologies to gain advantages for international competition. For enterprises with strong international competitiveness, other enterprises can actively learn from the technology status and innovation models of leading enterprises, such as Sony Corporation of Japan and Lg Chemical Co. of Korea. Actively promoting the cooperation of different R&D institutions and building industrial R&D technology innovation alliances, not only limited to the cooperation within the country but also strengthening the transnational partnership, is conducive to accelerating the R&D process to improve the efficiency of technology achievement transformation.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Materials, further inquiries can be directed to the corresponding author.

Author contributions

ZH contributed to the study conception, data collection, methodological application, and paper writing. TD was involved in the improvement, revision and refinement of the study.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Mapping global platinum supply chain and assessing potential supply risks

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Platinum is widely considered as a critical mineral. According to the most optimistic scenario, the demand for platinum could increase 240-fold globally by 2050 due to the enormous demand potential for green hydrogen and fuel cell vehicles. By integrating network analysis and evaluation indicators, this study develops a framework to visualize the global platinum upstream supply chain, pinpoint supply-related risk areas, and assess the position of various nations in the supply chain. We conclude that there is a significant risk of disruption to the global platinum upstream supply chain. Following is a summary of the main conclusions: First, the global platinum supply network and primary platinum product trade network are both relatively sparse, with poor network connectivity, and the overall network's risk-resistance is weak. Second, at the non-geographical production country level, the global platinum mining countries, the countries of the producing companies, and the countries of the shareholders of the producing companies are all highly concentrated. Third, the global platinum supply and demand markets are significantly divided, and South Africa holds a significantly stronger national position in the platinum supply network than any other nation, except for the national level of producing companies' shareholders. However, the national role of South Africa in the trade network is not as strong as that of consuming countries and transit countries. The study proposes that global platinum consuming countries can reduce supply risks by increasing domestic platinum mine production, building international large-scale integrated mining corporations, and raising global supply share by investing in overseas mines.

KEYWORDS

platinum, supply chain, supply risk, network analysis, platinum trade

1 Introduction

Platinum is widely considered as a critical mineral (European Commission, 2020; U.S.Geological Survey, 2022; Natural Resources Canada, 2021; Australian Government Department of Industry, 2022), and is used in a variety of sectors, ranging from automotive, jewelry, petroleum, chemical, glass, electronics, and medicine (Johnson Matthey, 2020). The low-carbon transition has become a global consensus. As a critical raw material for fuel cells and green hydrogen generation, platinum is crucial to the global development of low-carbon clean energy, and is known as a "green energy metal" along with lithium, cobalt, and copper (Johnson Matthey, 2021). Due to the huge demand potential of fuel cell vehicles and green hydrogen, the demand for platinum will grow significantly in the future. According to Rasmussen et al. (2019), worldwide platinum demand might climb 240-fold by 2050 to a high of 51,400 tons. In contrast to the rapidly growing demand, PGMs (Platinum Group Metals) are among the rarest metals, with only around 0.0005 part per million (ppm) platinum in the earth's upper crust. (U.S.Geological Survey, 2018). Additionally, the distribution and production of platinum resources are highly unequal (U.S.Geological Survey, 2020), with 30% of global PGMs deposits holding more than 97% of known PGMs resources. It is primarily found in the Bushveld Complex in South Africa, the Noril 'SK-Talnakh Area in Russia, and the Great Dyke in Zimbabwe. The hydrogen economy is driving a sharp increase in platinum demand, but the scarcity and highly concentrated distribution of PGMs in the world raises the question: Will the significant growth in global platinum demand lead to increased supply risk? Therefore, identifying and evaluating global platinum supply chain risk can assist relevant nations in developing effective policies to mitigate supply concerns.

Currently, the tendency of reverse globalization is highlighted, and supply chain security come to the fore as a major concern for all nations (White House, 2021; Trump, 2017; HM Government, 2017). Mineral resources risk evaluation from a supply chain perspective is more capable of systematically portraying the risk level of each link, which has received wide attention from scholars and policymakers. Supply chains may be understood, designed, and managed using network analysis (Bellamy and Basole, 2012). In recent years, the quantitative and visual analysis of mineral resources supply risk based on complex networks has gradually become a research hotspot (Sun, 2022). By constructing a multi-layer complex network consisting of manufacturers, traders, shareholders, and countries to which they belong, the risk is systematically evaluated and the position of different participants in the network is presented through visualization techniques, and each indicator affecting the supply risk is dissected and visualized. Nuss et al. (2016a) mapped supply chains for five product platforms, then proposed a set of network indicators (product complexity, producer diversity, supply chain length, and potential bottlenecks) to assess the situation for each platform in the overall supply chain networks. van den Brink et al. (2020) evaluated cobalt supply chain risks by geographically explicitly mapping the cobalt supply chain and companies, and applying supply risk indicators and company linkages. Xun et al. (2021) mapped the global fuel cell vehicles industrial chain during the period of 2017–2019, using the combined indicator of HHI (Herfindahl-Hirschman Index) and HHI-WGI (World Governance Index), as well as network analysis, to assess the supply risks of relevant key commodities. Wen et al. (2021) constructed a complex network with copper mines, copper refineries, shareholders, and countries as nodes to study the supply risk from a network structure standpoint. The effectiveness of supply chain network analysis in revealing supply restrictions and bottlenecks in the supply chain has been demonstrated; however, no such study has been carried out for the PGMs.

Raw materials supply can be disrupted as a result of trade conflicts (Schmid, 2019) and pandemics (Ahmed, 2020). For example, restrictions on the export of rare earth metals and minerals from China and the COVID-19 pandemic closed some or all of several mines, smelters, and refineries, destabilizing the supply of copper, gold, silver (MacDonald et al., 2020), and technology metals such as cobalt, lithium, and nickel (Akcil et al., 2020).

Complex network is also a popular method for analyzing international trade issues nowadays (Geng et al., 2014; Vidmer et al., 2015; Zhong et al., 2017; Chen et al., 2020). The overall structural characteristics of the network were assessed by network density, average clustering coefficient and other metrics (Wang et al., 2020; Peng et al., 2021; Wang et al., 2022). The analysis of selected indicators such as degree centrality, strength centrality, closeness centrality, and betweenness centrality enables for the investigation of nations' trade roles and trading position (Fan et al., 2014; Nuss et al., 2016b). There has been little research conducted on the trading network of PGMs. Tokito et al. (2016) focused solely on the risk characteristics of trade clusters when analyzing the complexity of the international trade network of platinum primary goods. In contrast, the focus of this study is on the relevance and control of nations in the platinum mining trade network.

The evaluation of mineral resources supply risk based on the index system is more one of the hot research topics in this field. In the evaluation of important minerals, the United States, the European Union, and others have developed evaluation models that use supply concentration, foreign dependency, and governance risk of supplying countries as indicators. (National Research Council, 2008; U.S. Department of Energy,2011; European Commission, 2011; European Commission, 2014; European Commission, 2017; European Commission, 2020). Based on such models, a large number of scholars have systematically evaluated the supply risk of critical minerals (Yang et al., 2013; Grandell and Thorenz, 2014; Wang et al., 2018). The most popular evaluation indicators are country risk, market concentration, reserve-production ratio, and by-product dependence (Achzet and Helbig, 2013). Regarding the supply risk evaluation of platinum, Yuan et al. (2020) introduced a criticality assessment approach to quantitatively examine platinum supply risk drivers, end-user vulnerability, market dynamics indicators, and their interrelationships in a time-dependent way. However, prior research mostly examined the supply risk of a specific link in the supply chain, and the evaluation structure was vulnerable to the influence of indicator selection.

Previous studies on global PGMs supply risks have shown that the greatest risk comes from upstream platinum mine supply (Xun et al., 2021), and the biggest supply risk is the political risk posed by South Africa due to its dominance in the world's platinum resources and supply (Mudd et al., 2018; Yuan et al., 2020). Based on this, this study focuses on upstream platinum supply and proposes combining network analysis with risk evaluation indicators to build a global platinum supply chain risk assessment framework to evaluate the risk of the upstream supply chain of platinum and analyze the position of countries in the upstream supply chain network.

The main innovation of this study is to provide a new perspective on upstream platinum supply chain risks and to visualize the various relationships in the global upstream platinum supply chain. This study can be used by policymakers and businesses to identify supply bottlenecks and the risk of supply disruptions. This is accomplished by addressing two research gaps.

(1) A global platinum supply chain risk assessment framework combining network analysis and evaluation indicators was constructed. A complete upstream platinum supply chain network was created by mapping the world's platinum supply, examining the connections between platinum mines, producing countries, mining companies, and company-owned shareholders, combining with the world's primary platinum product trade network, and combining with evaluation indicators to assess the supply risk of upstream platinum.
(2) The status of main participants involved in the global platinum upstream supply chain are identified. The effect of the key suppliers in the supply chain is evaluated through the

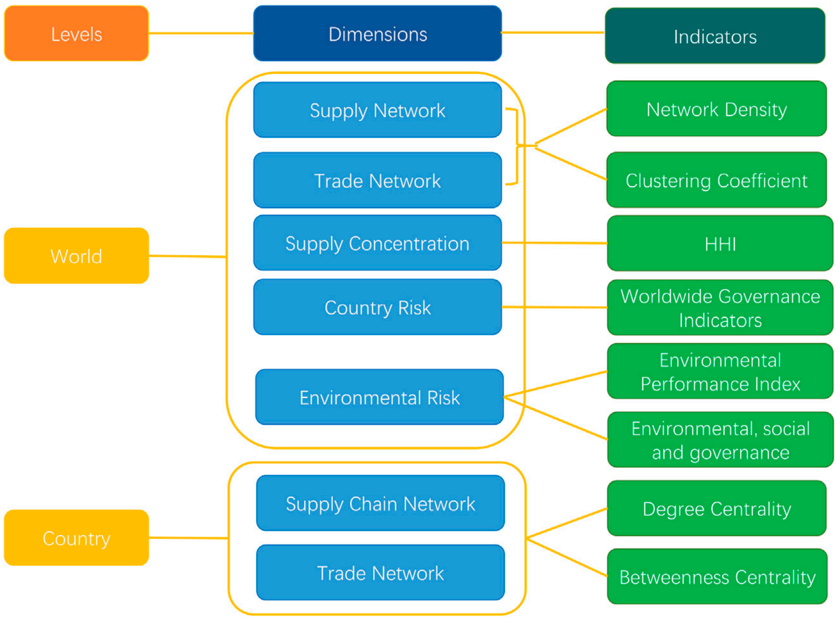

FIGURE 1
The global platinum supply chain risk assessment framework.

development of the countries' status index, which assesses the status of suppliers and merchants in the global supply networks for platinum mines and primary products.

2 Methods and data

2.1 System boundary

This section describes the system boundaries of this study. This study focuses on the risk assessment of the upstream supply chain of platinum, including the mining and refining stages. Platinum trade products are selected as global platinum primary products with trade codes HS-711011 and HS-711019. Unless otherwise specified, the data time selected for this study is 2019. This is due to the fact that the global platinum mine supply in 2020 is affected by the shutdown of Anglo American Platinum's converter plant and COVID-19 pandemic, and the data is significantly lower than the level in recent years.

2.2 Methods

This study proposes a global platinum supply chain risk assessment framework based on network analysis and index evaluation, and conducts risk assessment at two levels: global overall supply risk and participants' status (Figure 1). At the global overall supply risk level, five evaluation dimensions of global platinum supply network, international platinum primary product trade network, supply concentration, country risk, and environmental risk are constructed, and five evaluation indicators of network density, clustering coefficient, HHI, WGI, and EPI (Environmental Performance Index) are selected. The global platinum supply network and international platinum primary product trade network together constitute the upstream supply chain network of platinum. At the level of global platinum suppliers' status, two dimensions of the global platinum supply network and the international platinum primary product trade network are constructed, and the calculation formula of the subject's status is designed based on the two evaluation indicators of degree centrality and betweenness centrality.

2.2.1 Supply chain network

2.2.1.1 Supply network construction

Based on complex network theory, this research constructs a global platinum supply network (GPSN). The supply network model consists of node set (V) and edge set (E), namely GPSN=(V, E), where node $V = \{V_{Mj}, V_{Fj}, V_{Sj}, V_{Cj}: j = 1,2,3 \ldots n\}$represents mines, companies, shareholders of companies, countries; $E = \{ek: k = 1,2, \ldots ,m\}$represents the relationship between the suppliers. The matrix expression of the global platinum supply network is:

$$GPSN = (V, E) = \begin{bmatrix} 0 & \omega_{MF} & \omega_{MS} & \omega_{MC} \\ \omega_{FM} & 0 & \omega_{FS} & \omega_{FC} \\ \omega_{SM} & \omega_{SF} & 0 & \omega_{SC} \\ \omega_{CM} & \omega_{CF} & \omega_{CS} & 0 \end{bmatrix} \quad (1)$$

In the formula, ω_{MF} and ω_{FM} represent the connection between the mines and the companies, respectively; ω_{MS} and ω_{SM} represent the connection between the mines and the shareholders of the company, respectively; ω_{MC} and ω_{CM} represent the connection between the mines and the countries, respectively; ω_{FC} and ω_{CF} represent the connection between the companies and the countries, respectively.

GPSN uses platinum mines (M), platinum production companies (F), shareholders of platinum production company (S), and countries (C) as

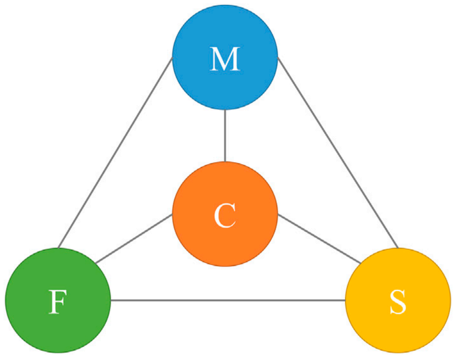

FIGURE 2
Schematic diagram of global platinum supply network (GPSN).

network nodes. Platinum mines (M) and mines' countries (CM), platinum mines (M) and affiliated platinum production companies (F), platinum mines (M) and shareholder of platinum production companies (S), platinum production companies (F) and company's countries (CF), platinum production companies (F) and the shareholders of the platinum production companies (S), the shareholder of the platinum production companies (S) and the shareholder's countries (CS) are established as edges (Figure 2), with the platinum production as the weight of the edges. The size of the node reflects the production of a supplier, that is, the bigger node represents the greater production of the corresponding supplier. The width of the edge represents the scale of mine production, that is, the thicker edge indicates the greater production between the two suppliers.

2.2.1.2 Overall characteristic analysis index

In the study, network density and average clustering coefficient were selected as overall network indicators to assess the risk propagation in the global platinum supply network.

(1) Network Density. The indicator measures the closeness of the connection between the subjects in the network. Calculated by dividing "the number of edges actually present in the network" by the "theoretical maximum number of edges in the network". The network density ranges from 0 to 1, and the larger the value, the closer the connection between the subjects. The formula for the network density (Geng et al., 2014):

$$\triangle = \frac{2m}{n(n-1)} \tag{2}$$

In the formula, m is the actual number of edges in the network, and n is the number of nodes in the network.

(2) Average Clustering Coefficient. Clustering coefficient describes the degree of clustering between nodes in a network, ranging from 0 to 1. The larger the value, the closer the connectivity between the neighbors of node i. The clustering coefficient mainly reflects the tightness of a network. The formula for the clustering coefficient (Watts and Strogatz, 1998):

$$CC_i = \frac{n_i}{k_i(k_i-1)} \tag{3}$$

In the formula, n_i is the number of connected edges between adjacent nodes of node i, and k_i is the degree value of node i.

The Average Clustering Coefficient (–CC) can reflect the tightness of all nodes in a network. The calculation formula is as follows (Watts and Strogatz, 1998):

$$\overline{CC} = \frac{1}{n}\sum_{i=1}^{n} cc_i \tag{4}$$

2.2.1.3 The roles of major participants

In the study of complex network, degree centrality and betweenness centrality are commonly used indicators to measure the importance of nodes. Node importance can quantitatively reflect the control and influence of a node in the network. Based on the above-mentioned indicators, this study designs the calculation and publicity of participant' status to measure the position and influence of each supplier in the platinum supply chain network.

(1) Degree Centrality. Degree centrality is the most direct indicator to measure the importance of nodes. The more edges a node has, the greater its direct influence in the network, and the more important the node is in the network. The calculation formula of the degree centrality of node i is (Freeman, 1977):

$$C_i = \frac{k_i}{2(N-1)} \tag{5}$$

In the formula, C_i is the degree centrality of node i, k_i is the degree value of the node, and N is the total number of nodes in the network.

(2) Betweenness Centrality. The index reflects the node's ability to control the flow of resources in the network by indicating the probability that a node resides on the shortest path between two other nodes. The larger the value, the stronger the betweenness of the node, that is, the stronger the control ability of the node. The betweenness centrality formula of node i is (LiHuangZhang et al., 2022):

$$C_{(b)i} = \frac{2}{(n-1)(n-2)}\sum_{p=1}^{n}\sum_{q=1}^{n} g_{pg(i)} \Big/ g_{pq} \tag{6}$$

where g_{pq} is the shortest path between nodes p and q.

(3) Status indicators in the network. Based on the two indicators of degree centrality and betweenness centrality, the formula for calculating a participant's status defined in this study is:

$$NS_i = \sqrt{NC_i{}^{*}NC_{(b)i}} \tag{7}$$

where NS_i is the status of node i in the network; NC_i and $NC_{(b)i}$ are the normalized degree centrality and normalized betweenness centrality of node i, respectively, and their calculation formulas are:

$$NC_i = \frac{C_i - \min(C)}{\max(C) - \min(C)} \tag{8}$$

$$NC_{(b)i} = \frac{C_{(b)i} - \min(C_{(b)})}{\max(C_{(b)}) - \min(C_{(b)})} \tag{9}$$

where C and $C_{(b)}$ represent the degree centrality and betweenness centrality of all nodes in the network, respectively.

2.2.2 Trade network

Supply disruptions or trade reductions are important factors in supply risk. As in the global flow of platinum material, the largest flows are platinum primary products, i.e. unwrought platinum or in powder form and platinum in semi manufactured forms (Nansai et al., 2014). If there is trade risk in platinum primary products, it will seriously affect the global supply of platinum resources. Therefore, this study mainly discusses the international platinum primary product trade network.

Based on complex network theory, this study constructs an international platinum primary product trade network (IPCN). The trade network model consists of node set (V) and edge set (E), namely IPCN=(V, E), where node V = {v_j:j = 1,2,3 . . . n} represents trading countries; E = {e_k:k = 1,2, . . . ,m} represents trade relations between countries. The adjacency matrix expression of the trade network model is:

$$\mathrm{IPCN} = (V, E) = \begin{bmatrix} 0 & \omega_{1,2} & \cdots & \omega_{1,n} \\ \omega_{2,1} & 0 & \cdots & \omega_{2,n} \\ \vdots & \vdots & 0 & \vdots \\ \omega_{n,1} & \omega_{n,2} & \cdots & 0 \end{bmatrix} \quad (10)$$

where $\omega_{i,j}$ is the weight of the link from node i to node j, measured by the trade volume of platinum primary products from one country to another.

The IPCN takes countries (areas) as nodes, the trade relations between countries (areas) as the edges, the direction of trade flow as the direction of the edges, and the trade volume of platinum primary products as the weights of the edges. The size of the node reflects the total trade volume of a country (area), that is, the larger the node, the greater the trade volume of the corresponding country (area). The width of the side represents the scale of the trade volume, which means the thicker the side, the greater the trade volume between the two countries (areas). Overall characteristic analysis indicators and countries' status index are the same as GPSN.

Both GPSN and IPCN are visualized by Gephi, which uses network metrics to visualize and analyze networks of various scales.

2.2.3 Supply concentration

This study mainly selects HHI, WGI, EPI and the ESG (Environmental, Social and Governance) score of platinum companies to quantitatively evaluate the global platinum supply risk.

"HHI" refers to the Herfindahl-Hirschman Index, a generally accepted measure of market concentration. HHI is calculated by squaring the market share of each competing firm in the market and summing the results. In this study, we use the HHI index to assess countries concentration, companies concentration and mines concentration. According to the standards of the U.S. Department of Justice and Federal Trade Commission (U.S. Department of Justice & FTC, 2018), the HHI index between 1500 and 2500 is moderately concentrated, and the HHI index greater than 2500 is highly concentrated.

$$HHI = \sum\nolimits_i Si^2 \quad (11)$$

where Si is the market share of country i (in percentage unit).

2.2.4 Country risk

The World Governance Index (WGI) is used to evaluate a country's governance level, aggregating comprehensive indicators of six dimensions of governance in more than 200 countries and regions from 1996 to 2020, including voice and accountability (VA), political stability and absence of violence/terrorism (PV), government effectiveness (GE), regulatory quality (RQ), rule of law (RL) (World Bank, 2020). All indicators are scored from −2.5 (weak governance) to 2.5 (strong governance). Poor governance is a key factor in determining supply risk, as supply in poorly governed countries can be disrupted, for example by generating political unrest (European Commission, 2014). The WGI is obtained by averaging the six dimensions. WGI is normalized to 0–1 by Eq. (12) (Xun et al., 2022).

$$WGI_{scaled} = -0.2 \times WGI + 0.5 \quad (12)$$

The aggregate indicator of country political risk is defined as HHI-WGI, which takes into account both the diversity and stability of supplying countries. The calculation formula of HHI-WGI is:

$$HHI - WGI = \sum\nolimits_i Si^2 \times WGI_{i,scaled} \quad (13)$$

where $WGI_{i,\ scaled}$ is the WGI standardized by country i.

2.2.5 Environmental risk

The Environmental Performance Index (EPI) summarizes the state of sustainability around the world and measures how closely countries are aligned with established environmental policy goals (Wendling, et al., 2018). The EPI ranks 180 countries on environmental health and ecosystem vitality based on 32 performance indicators across 11 question categories. The EPI scores range from 0 to 100, with 0 representing the lowest environmental performance score and 100 representing the highest environmental performance score. EPI is normalized to 0–1 by Eq. (14).

$$EPI_{scaled} = \frac{100 - EPI}{100} \quad (14)$$

The aggregate indicator of national environmental risk is defined as HHI-EPI, which takes into account the diversity of supplying countries and the environmental risks in the supply process. HHI-EPI is calculated by Eq. (15).

$$\mathrm{HHI - EPI} = \sum\nolimits_i Si^2 \times EPI_{i,scaled} \quad (15)$$

where $EPI_{i,\ scaled}$ is the EPI standardized by country i.

ESG is a measure of the health and stability of a business. S&P Global publishes ESG scores and individual index scores for environmental factors (E), social factors (S), governance and economic factors (G) for the world's major mining companies. Each item is scored on a scale from 0 to 100. The higher the score, the lower the ESG risk. A company's ESG score is weighted by Eq. (16).

$$ESG_p = \frac{\sum_i ESG_i \times p_i}{\sum_i pi} \quad (16)$$

where ESG_i is ESG score of company i and P_i is platinum production of company i.

TABLE 1 Indicator description and supply chain risk explanation.

Indicators	Description	Supply chain risk explanation
Network density	The tightness of the connection between the subjects in the network	The greater the network density of a network, the closer the nodes are connected, and the stronger anti-risk ability in the network
Clustering coefficient	The degree to which the neighbors of a node in the network are connected to each other	The higher the clustering coefficient of a network, the better the connectivity of the network and the stronger the anti-risk ability of the network
Degree centrality	The number of connections per node in the network	The larger the value, the less likely the node is to suffer supply chain disruptions
Betweenness centrality	The probability that a node is on the shortest path between two other nodes in the network	The larger the value, the stronger the betweenness. A node with high betweenness centrality can act as a bridge between other nodes, and removing a node with high betweenness centrality is more likely to cause interruption of material flow or information flow
HHI	Supply concentration of global platinum mining countries, companies and mines	The higher the supply concentration, the greater the risk of interruption of a supply subject in the supply chain
Worldwide Governance Indicators	WGI is used to evaluate a country's governance level	If a country has poor governance, there is a risk of supply interruption
Environmental Performance Index	EPI measures how closely countries are aligned with established environmental policy goals	The lower a country's environmental performance score, the greater the environmental risk arising from platinum production
Environmental, social and governance	ESG measures the health and stability of a business	The lower a company's ESG score, the greater the potential supply risk

TABLE 2 Risk assessment of the global platinum supply chain.

Evaluative dimension	Evaluation indicator	Risk level		
		Low risk 1 2 3	Medium risk 4 5 6	High risk 7 8 9
Supply Network	Network Density	>0.6	0.4–0.6	<0.4
	Average Clustering Coefficient	>0.6	0.4–0.6	<0.4
Trade Network	Network Density	>0.6	0.4–0.6	<0.4
	Average Clustering Coefficient	>0.6	0.4–0.6	<0.4
Supply Concentration-Market	HHI-Countries	<1500	1500–2500	>2500
	HHI-Companies			
	HHI-Mines			
Supply Concentration-Geographic position	HHI-Countries (mine)	<1500	1500–2500	>2500
	HHI-Countries (company)			
	HHI-Countries (shareholder)			
Country Risk	HHI-WGI	<1500	1500–2500	>2500
Environmental Risk	HHI-EPI	<1500	1500–2500	>2500
	ESG	<40	40–60	>60

The indicator descriptions in global platinum supply chain risk assessment framework and supply chain risk explanations corresponding to each indicator are shown in Table 1.

2.2.6 Supply risk rating

Based on the global platinum supply chain risk assessment framework constructed in this paper, each indicator is measured. The determination of the risk level of each indicator mainly draws on previous research results (Zhu, 2016; Wang et al., 2021) and industry standards (U.S. Department of Justice & FTC, 2018). Since there are few studies on the network density and average clustering coefficient of the supply network, the reference is to the index rating of the mineral trade network. After calculation, the score of each indicator is divided into three risk levels: low risk (1–3 points), medium risk (4–6 points), and high risk (7–9 points). According to the risk level corresponding to the evaluation results of each index, each evaluation index is scored (Table 2). In the study, equal weight was assigned to each index, and the score of each index was weighted and averaged to obtain the score of platinum mine supply chain risk, and the evaluation results of each dimension were presented on the radar chart.

2.3 Data

This section provides an overview of global platinum mine supply chain data. In the global platinum supply chain network, the national-level platinum mine production and refined platinum production come from USGS; the production data of platinum mines, platinum production companies and shareholders of platinum production companies are from S&P Global. In addition, data for the companies, shareholders and countries to which platinum mines belong, the shareholders and countries to which platinum mines belong, and the countries of the platinum company's shareholder are also from S&P Global. According to S&P Global, there are 43 platinum mines worldwide for which production is available in 2019, with a combined production of 226.98t. This is approximately 22% higher than the global platinum production according to the USGS, but S&P Global is the only source for which company- and mine-level data are currently available. In the study, the production of selected platinum mines, platinum mining companies, shareholders of platinum mining companies and corresponding producing countries are all greater than 1t, and suppliers with smaller production are excluded. The resulting global platinum mine supply chain network involves 11 countries, 15 platinum production companies, 28 platinum mines, and 22 shareholders of platinum mine companies.

In the trade network of global platinum primary products, the international trade data of global platinum primary products were downloaded from the UN Comtrade Database the UN Comtrade Database (UN Comtrade, 2021). The HS code are HS-711011 and HS-711019. Since data reported by importing countries often differ from those reported by exporting countries, this paper uses import data, which is generally considered more reliable because imports generate tariff revenue and exports do not (van den Brink et al., 2020). The trade data in the paper is the physical weight of imports in 2019, measured by the kilogram. In addition, this study excluded trading countries with an import volume of less than 10 kg, leaving the top 99.8% of the total trade flow. The exclusion of these trade relations and trading countries does not affect the research on major trading countries and trade relations. The research includes a total of 65 countries.

In order to estimate the country risk and environmental risk of the global platinum mine supply, the WGI and EPI of the platinum mine producing country or region need to be obtained. WGI is from the World Bank (World Bank, 2020), and EPI is from a report jointly issued by the Yale Center for Environmental Law and Policy and the Center for International earth Science Information Network in Columbia University (Wendling, et al., 2020). The ESG scores for platinum mines also come from S&P Global. Due to the limitation of data availability, the ESG score of 2021 is selected.

3 Results and discussion

3.1 Overall evaluation of supply risk

3.1.1 Supply network

The global platinum supply network includes 11 countries, 15 companies, 28 mines, and 22 shareholders of companies, as shown in Figure 3. Different colors represent different communities in the network. The global platinum supply network can be divided into 12 communities. Results showed that the network density of the global platinum supply network was calculated to be 0.05. As there is no comparable supply network for other minerals, the global platinum supply network has a very low network density and a very sparse network compared to the trade network for minerals, with a "high risk" rating (Hou et al., 2018). The reason for this may be related to the fact that the global platinum supply network is made up of several participants: mines, companies, countries, and shareholders. If the platinum supply is interrupted, all suppliers will face great risks. The network density can only reflect the number of associations in the network, and the clustering coefficient of the network is also measured to gain insight into the network's association status (Zhu, 2016). After calculation, the average clustering coefficient of the global platinum supply network is 0.5, indicating that the relationship between the neighbors of the supplying subjects is relatively close and at "medium risk". For each participant, the more associated partners, the lower the clustering coefficient, and the looser the connection between the participant and the supplier partner. To comprehensively assess the risk resistance of the global platinum supply network, the two indicators of network density and average clustering coefficient are used. It is concluded that the global platinum supply network is very sparse and poorly connected, and the overall risk resistance of the network is weak.

3.1.2 Trade network

The international platinum primary product trade network is shown in Figure 4, the trade network can be divided into four communities. This study calculated the network density of the international platinum primary product trade network, and the result is 0.17, which is lower than that of oil, coal, lithium and other minerals (Zhong, 2016; Zhu, 2016), with a "high risk" rating. Because of the limited number of nations active in the global platinum primary products trade network, the number of trade ties created is equally minimal, resulting in a sparse network (Zhong, 2016). If there is a trade disruption, the importing countries will face a greater risk. The average clustering coefficient of the global platinum primary products trade network is 0.49, which means that the trading countries are more interconnected and at "medium risk". If a country's trading partners are closely related, then the country has a higher clustering coefficient; conversely, if a country's trading partners are loosely related, then the country has a lower clustering coefficient (Zhong, 2016). Based on the network density and average clustering coefficient evaluations, it is concluded that the global trade network of primary platinum products is relatively low and has a weak anti-risk ability (Figure 5).

3.1.3 Supply concentration

In the study of supply concentration, we analyze it at two levels: the market concentration and the country concentration.

3.1.3.1 Supply concentration-market

At the level of market concentration, we examined not only the production concentration of platinum producing countries, but also the production concentration of platinum production companies and production mines, which is more microscopic than previous studies. The HHI index of 11 platinum mining producing nations, 35 platinum mining corporations, and 43 platinum mines were calculated to be

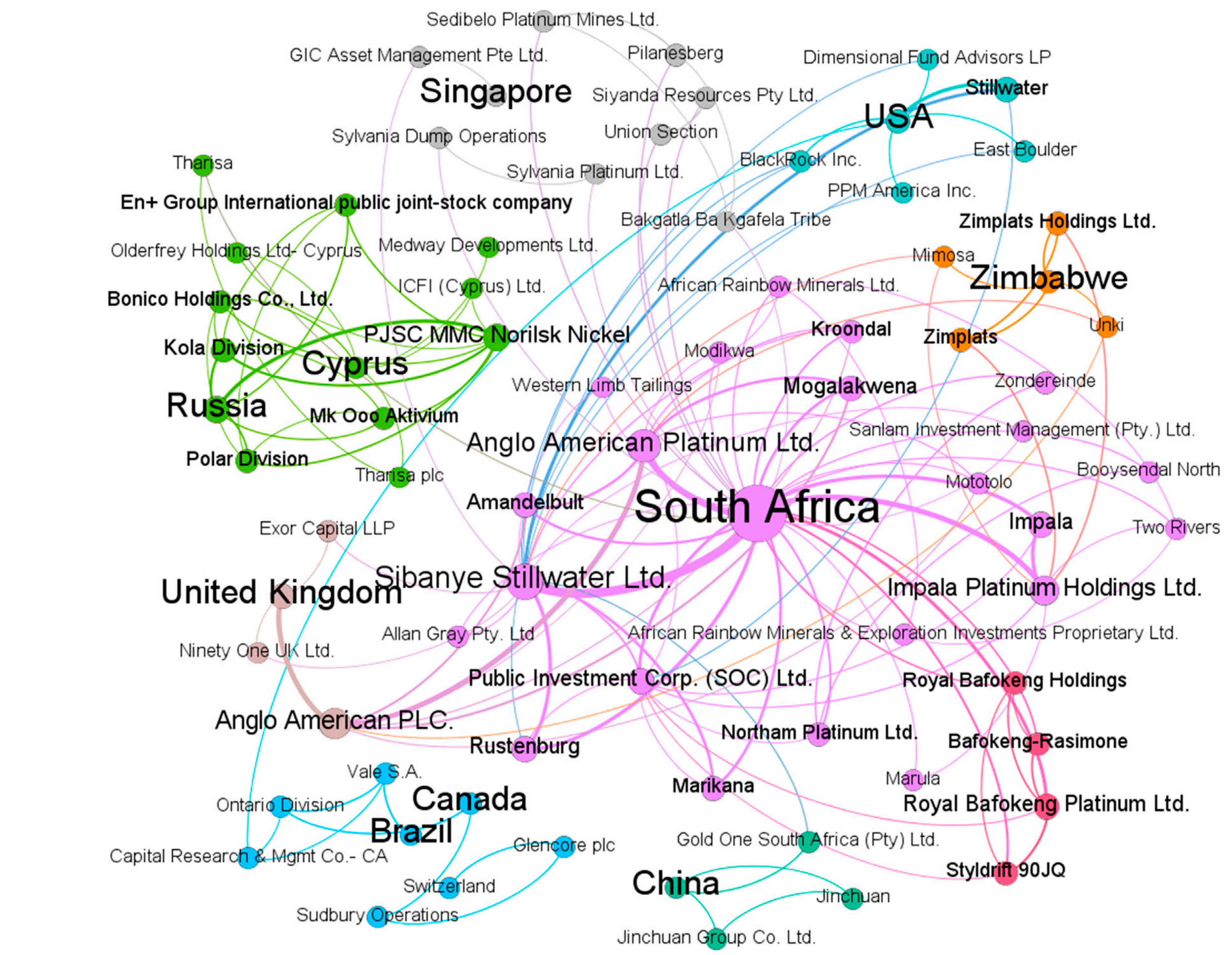

FIGURE 3
The global platinum supply network (GPSN).

5355, 1542, and 550, respectively, which are placed in "high risk," "medium risk," and "low risk." The production of South Africa accounts for 72% of the global production, and the production of the top five platinum production companies accounts for 78%; the production of the top five platinum production mines accounts for 43%. Although the concentration of companies and mines is relatively scattered, it does not mean that a decrease in the production of a platinum producer or a platinum mine has little impact on the global platinum supply. In 2020, the shutdown of Anglo American Platinum's converter plant and the disruption of South Africa mining industry production due to the impact of COV-19 epidemic reduced global platinum supply by about 16% (Johnson Matthey, 2021). Studies have shown that the average ore grade of most platinum producers or projects has shown a long-term and gradual downward trend (e.g. Impala, Northam), although the downward trend appears to have slowed for some platinum producing enterprises in recent years (eg Anglo Platinum. Lonmin, Noril'sk-Taimyr) (Mudd et al., 2018), the decline in platinum ore grade will affect platinum production.

Most of the global platinum smelters are built in areas close to major mines, such as Norilsk in Russia and Bushveld in South Africa, and PGMs mined in Zimbabwe are currently refined in South Africa (Johnson Matthey, 2020). The platinum smelters and refiners can use both primary concentrates and recycled materials to produce PGM powders or bars (Xun et al., 2022). In 2018, South Africa produced about 140 tons of refined platinum (U.S.Geological Survey, 2021a), the US produced about 25 tons of refined platinum (U.S.Geological Survey, 2021b), and Russia produced about 20 tons of refined platinum. It can be seen that the global platinum mine production and refined products are dominated by South Africa.

3.1.3.2 Supply concentration- countries

At the geographical concentration level, we examined the supply concentration of countries where platinum mines, platinum mining firms, and owners of platinum mining companies are located in the global platinum mining supply network. The HHI for countries of the platinum mines, the countries of platinum companies and the countries of shareholders of platinum companies are 6737 (Figure 6A), 5252 (Figure 6B) and 2736 (Figure 6C), respectively, all of which are at "high risk". In particular, the countries of producing mines and the countries of platinum companies are oligopolistic. From the perspective of non-geographical producing countries, about 71% of the platinum mine production is produced in South Africa, and about 82% of platinum companies production is also located in South

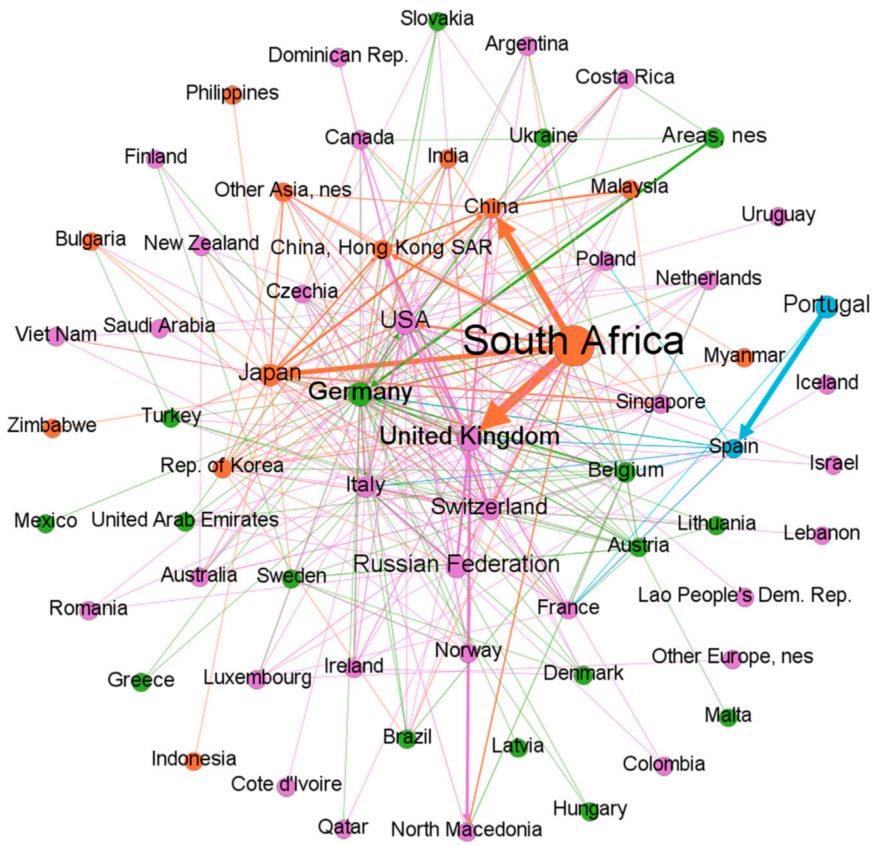

FIGURE 4
International platinum primary product trade network (IPTN).

Africa, but 39% of platinum mine company shareholders in South Africa, 35% in the United Kingdom and 6% in the United States. In other words, although South Africa has a monopoly in the global platinum supply chain, the United Kingdom and the United States also hold platinum resources that are comparable to South Africa's production from the standpoint of the shareholders of platinum mining companies.

3.1.4 Country risk

ESG has emerged as one of the most central issues in today's global mining sector. For the first time in 12 consecutive years, KPMG has ranked ESG as the top industry risk (Deloitte, 2022; KPMG, 2022). The possibility of supply disruptions can be reflected by the supplier's ESG performance which can be quantified by WGI and EPI (Xun et al., 2022).

South Africa is the world's largest producer of platinum and an exporter of primary platinum products, accounting for 71.5% and 27% of the world's production and exports, respectively. South Africa has an average WGI score of 0.15 and is in the weaker governance scale on the WGI Index on a scale of −2.5 (weak governance performance) to 2.5 (strong governance performance). Among the six evaluation indicators of WGI, Political Stability and Absence of Violence/Terrorism scored the lowest. South Africa has strict labor laws, strong labor unions, tense labor relations and frequent strikes. The Marikana riots in 2012, which murdered 34 miners, had a significant influence on South African platinum mine productivity. (Harvey, 2016; Mudd et al., 2018). 70,000 South African platinum mine employees went on strike in 2014–2015, which resulted in a 40% decrease in global platinum production. (Rasmussen et al., 2019). Russia, the second largest producer of platinum mine, has an average WGI score of −0.58, with the lowest score in Voice and Accountability among the six indicators, and is in a weaker governance level. Zimbabwe, the third largest platinum producer, has an average WGI score of −1.21, with low scores in all six indicators and a weak governance rating. Canada and the United States have relatively strong governance with WGI scores of 1.57 and 1.09, respectively, but these two countries have a relatively low share of platinum production, accounting for 3.9% and 2.2% of global production, respectively. By normalizing the political risk for the six platinum producing countries with production greater than 1 ton (99% of global production), the HHI-WGI for platinum producing countries is 2552 (Table 2), which indicates a high political risk and is "high risk".

3.1.5 Environmental risk

The EPI, published by Yale University, rates and grades countries based on how well they perform on sustainability challenges. The world's leading platinum producers, South Africa, Russia and

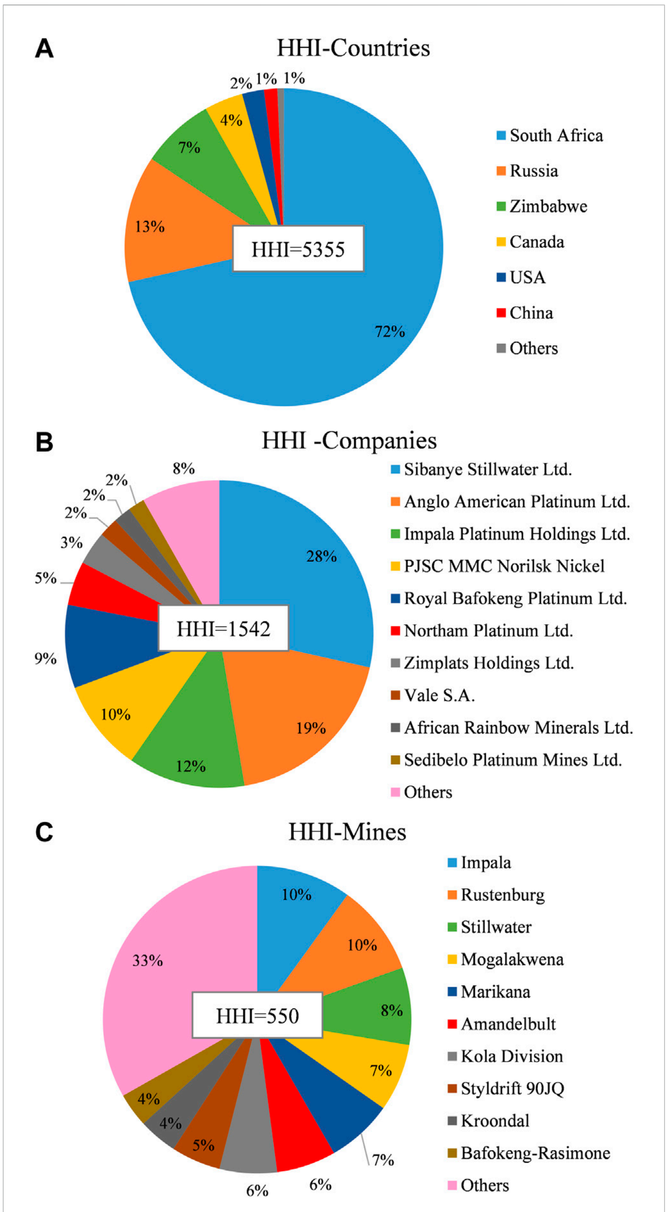

FIGURE 5
Global platinum market concentration: **(A)** HHI index of platinum producing countries, **(B)** HHI index of platinum producing companies, **(C)** HHI index of platinum mines.

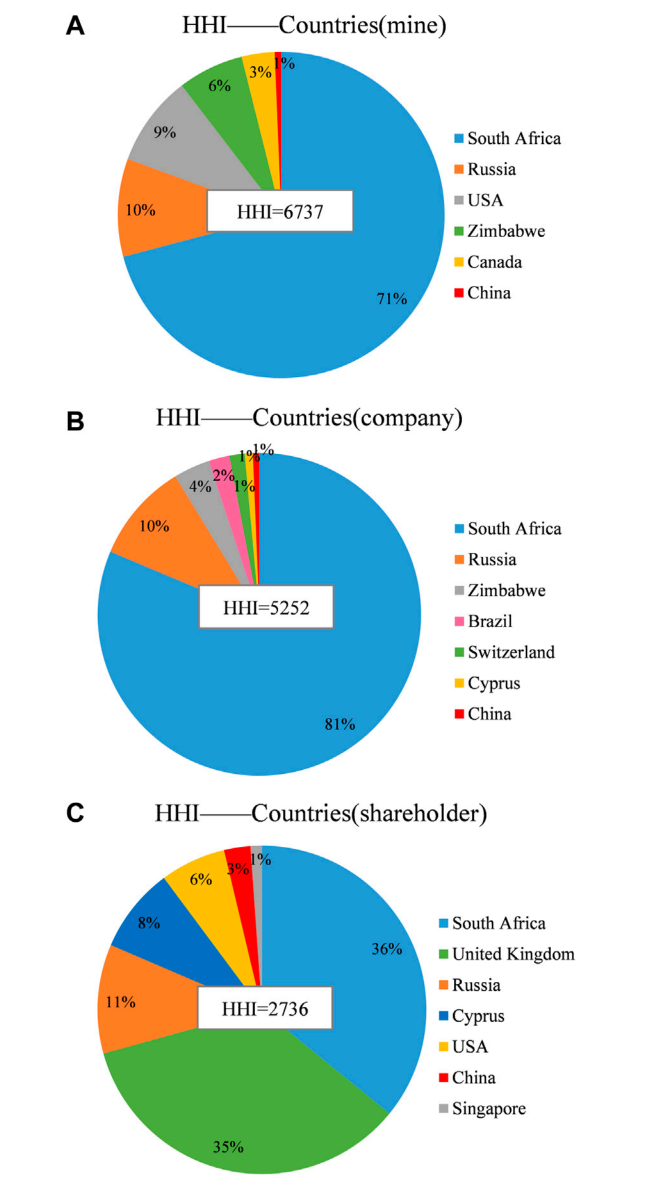

FIGURE 6
Global platinum producing countries concentration: **(A)** HHI index of the countries of platinum mines, **(B)** HHI index of the countries of platinum companies, **(C)** HHI index of the countries of shareholders of platinum companies.

TABLE 3 Political and environmental risks of major platinum mine producing countries in the world.

	South Africa	Russia	Zimbabwe	Canada	United States of America	China	Result
WGI	0.15	−0.58	−1.21	1.57	1.09	−0.36	
WGI_{scaled}	0.47	0.62	0.74	0.19	0.28	0.57	
HHI-WGI	2403	103	41	3	1	1	2552
EPI	43.1	50.5	37	71	69.3	37.3	
EPI_{scaled}	0.57	0.50	0.63	0.29	0.31	0.63	
HHI-EPI	2909	82	35	4	2	1	3033

TABLE 4 ESG scores of the top 10 platinum companies in the world.

Rank	Company	Production(t)	ESG	E	S	G
1	Sibanye Stillwater Ltd	64.7	42	44	43	38
2	Anglo American Platinum Ltd	42.9	68	67	70	66
3	Impala Platinum Holdings Ltd	27.9	61	70	52	61
4	PJSC MMC Norilsk Nickel	21.9	43	—	—	—
5	Royal Bafokeng Platinum Ltd	19.9	30	34	23	33
6	Northam Platinum Ltd	10.5	38	44	38	32
7	Zimplats Holdings Ltd	8.0	—			
8	Vale S.A.	4.6	67	80	61	61
9	African Rainbow Minerals Ltd	4.2	28	24	29	31
10	Sedibelo Platinum Mines Ltd	4.0	—			
	Average		49.3			

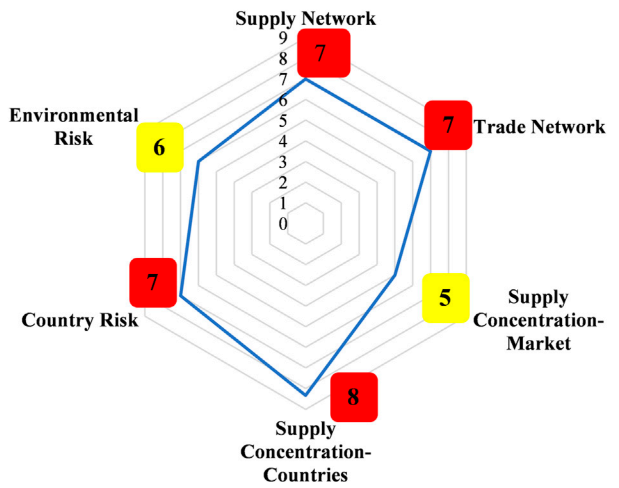

FIGURE 7
Radar chart of overall assessment of global platinum supply risk.

Zimbabwe, with EPI scores of 43.1, 50.5 and 37, ranked 95th, 58th and 123rd, respectively, out of 180 countries evaluated. With high EPI rankings but low platinum production, Canada and the United States were placed 20th and 24th, respectively, while China was ranked 120th (Table 3). By normalizing the environmental risk for the six platinum producing countries with production greater than 1 ton (99% of global production), the HHI-EPI for platinum producing countries is 3033, which is "high risk". The higher the HHI-EPI, the higher the concentration of supply in the supplying countries, and the higher the environmental risk, which implies a higher probability of negative environmental impacts in the supply process (Xun et al., 2022).

This study also assesses ESG at the platinum mining company level to determine the likelihood of supply disruptions at the company level. The overall ESG scores of the world's leading platinum producing companies are low, and they face a relatively high risk of supply disruption. By weighting the ESG scores of eight of the top 10 global platinum companies available by production, the average ESG score is 49.3 (Table 4). Individual enterprises, however, have less than 50 ESG scores and are vulnerable to supply, including Sibanye Stillwater Ltd, PJSC MMC Norilsk Nickel, Royal Bafokeng Platinum Ltd, Northam Platinum Ltd, and African Rainbow Minerals Ltd. Although Zimplats Holdings Ltd.'s ESG score is not currently available, Zimbabwe's WGI and EPI are both low in the global rankings, therefore it is speculated that Zimplats Holdings Ltd.'s ESG score is lower than the global average.

3.1.6 Supply risk rating

The aforementioned study led to the calculation and scoring of 13 indicators across 5 dimensions of the global platinum mine upstream supply chain risk. Among them, Supply network score is 7 ("high risk"), Trade network score is 7 ("high risk"), Supply concentration-Market score is 5 ("medium risk"), Supply concentration-Countries score is 8 ("high risk"), Country Risk score is 7 ("high risk"), and Environmental Risk score is 6 ("medium risk"), resulting in a global upstream platinum mining supply chain risk composite score of 7, rated as "High risk". In order to assess the possible supply risks of each dimension more clearly, we present Supply concentration-Market and Supply concentration-Countries and the scores of the other four dimensions on the radar chart (Figure 7). By comparing with the trade network of nickel ore, lithium ore, rare earth and other minerals (Zhu, 2016; Hou et al., 2018; Wang et al., 2022), this study evaluates the overall supply risk of the global platinum supply network and platinum primary product trade network. It is considered that the average clustering coefficient of the global platinum supply network and platinum primary product trade network is moderate, but the network is sparse, the connectivity is poor, and the overall anti-risk ability of the network is poor. The three indicators of Supply Concentration, Country Risk, and Environmental Risk are all closely related to the concentration of global platinum mine production.

Regarding the supply risk of global platinum mine, we first discuss the global platinum resource endowment and whether there is a problem of exhaustion. According to research, the worldwide supply of PGMs resources will not be depleted in the coming decades (Jowitt et al., 2020), and it is unlikely to be a development restriction for future platinum applications.

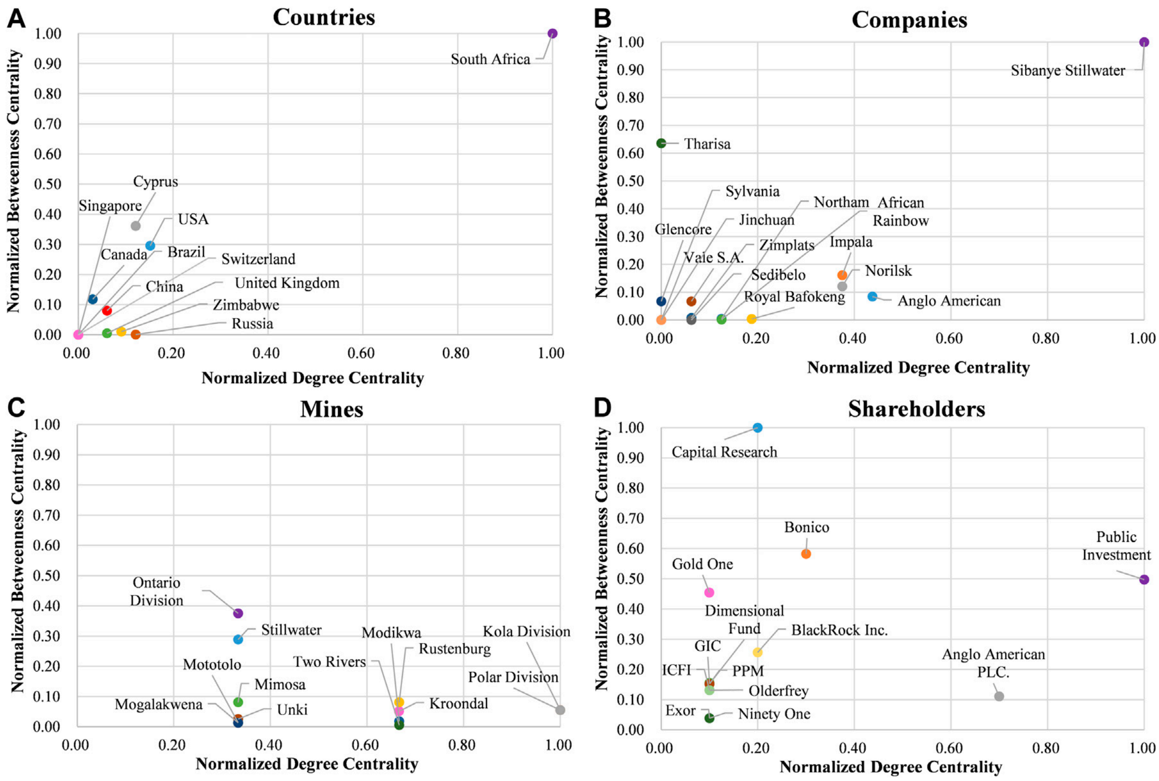

FIGURE 8
The betweenness centrality of various supply subjects in the global platinum supply network: **(A)** The betweenness centrality of countries, **(B)** The betweenness centrality of companies, **(C)** The betweenness centrality of mines, **(D)** The betweenness centrality of shareholders.

However, the distribution of PGMs reserves and demand is extremely mismatched due to the distribution of global resources (Hao et al., 2019), and there may be greater supply risks.

The distribution of global platinum mine resources is highly concentrated. Exploration for platinum mine and research on the genesis of deposits have grown significantly in recent years in an effort to disrupt South Africa's and Russia's supply monopolies on the world's platinum ore resources (Maier, 2005). Potential prospects in the United States, Canada, Finland, Australia, and parts of Africa have been the focus of large-scale geophysical and geochemical exploration campaigns (Hoatson, 1998; Fiorentini et al., 2010; Lapworth et al., 2012), but the high concentration of global platinum resources has not yet been broken. It is expected that changing this situation will be tough.

In 2019, South Africa's platinum mine production accounted for 72% of global production, and South Africa's platinum mine production came from almost a single mining area–the Bushveld Igneous Complex (Mudd et al., 2018). Platinum mine production in South Africa is affected by underlying technological (e.g. mining depth), infrastructure (e.g. secure supply of energy to mining areas) and social (e.g. recent mine strikes and related violence) issues (Mudd et al., 2018), and appears to be directly influenced by the level of social progress in the region (Yuan et al., 2020). The WGI of South Africa is close to the global average level, and the environmental risk rating is lower than the global average level. If the supply is disrupted, it will have a serious impact on the global platinum mine supply.

Platinum mine production in Russia accounts for 13% of global production. Russia's WGI is lower than the global average, and its environmental risk is comparable to the global average. Affected by the Russia-Ukraine conflict, Russian refiners were removed from the London Platinum and Palladium Market (LPPM) delivery list by on 8 April 2022, and Russia's platinum mine production and exports have also increased uncertainty. Platinum supply in Russia is also at risk.

One of the most essential approaches to mitigate the risk of the platinum supply chain is to develop secondary supply of platinum. Despite the fact that the global supply structure of PGMs refining is comparable to that of mining, the supply risk of PGMs refining is reduced by more than 30% if secondary supply is taken into account (Xun et al., 2022). A sector-by-sector examination reveals that the majority of the world's secondary supply of platinum is recovered from autocatalytic and jewelry scrap. In terms of recycling regions, the United States, the European Union, and Japan account for the majority of the world's secondary supply of platinum (Yuan et al., 2020). As early as 1998, 76% of end-of-life products containing platinum were recycled in the United States (Alonso et al., 2012). Several nations in the European Union have recycling goals for used vehicles since 2006. With the global secondary supply of platinum accounting for 26% of total platinum supply in 2019, which can fulfill 16% of global platinum consumption, the global in-use stocks of PGMs provide good potential for recycling (Johnson Matthey, 2021).

Having sufficient PGMs reserves is a crucial assurance approach to reduce risk in the upstream supply chain of platinum and seize the lead

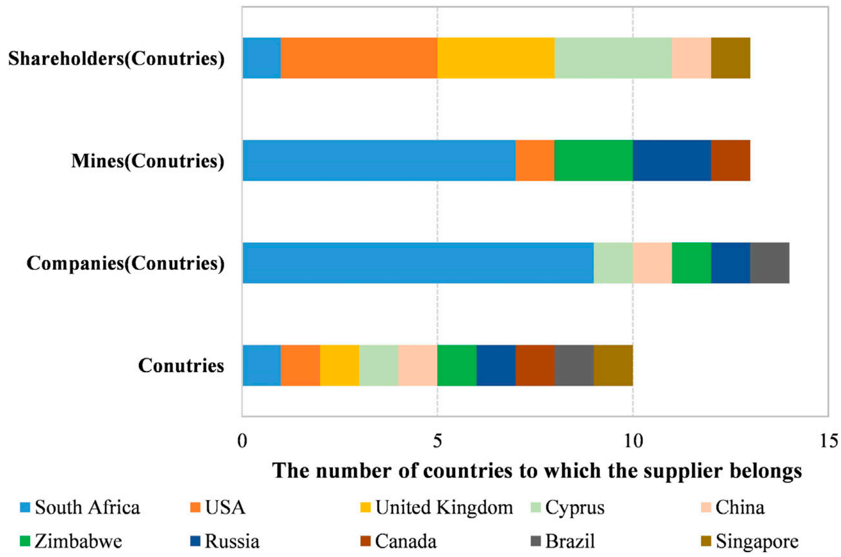

FIGURE 9
The countries of the top 10 suppliers of betweenness centrality in the global platinum supply network.

in the global hydrogen energy industry in the future, in addition to securing a steady supply source. The major industrialized nations of the world have put in place a thorough strategic reserve management system for rare metals. The United States, Russia, the European Union, and Japan, for example, have all designated PGMs as strategic reserve metals (Ji and Tian, 2022). A nation's emergency response capacity can be increased by having national strategic reserves, which can handle emergencies.

3.2 Supply risk analysis of main participants

Network analysis can be used to find out the most important participants in relation to their network placement, which is also known as centrality, i.e. the location in the network (Lee and Sohn, 2015). The overall network indicators are selected above to evaluate the overall anti-risk capability of the network. Both the Supply network and the Trade network have relatively weak anti-risk capabilities and are classified as "high risk", but the position and risk exposure of different participants within the network are worth further exploration.

3.2.1 The position of the major participants in the supply network

Based on Eq. 7, this study calculates the status of platinum producing countries, platinum ore companies, platinum mines, and shareholders of platinum mine companies in the global platinum supply network (Figure 8). The stronger the betweenness centrality of a country (company/mine/shareholder), the more it acts as a "bridge" in the supply network. It is important to highlight these nodes, since their removal may cause supply disruption (Nuss et al., 2016a).

In terms of global platinum producing countries (Figure 8A), South Africa is undoubtedly the country with the highest degree centrality and betweenness centrality, that is, the strongest control. The control of other countries in the network is far from that of South Africa, which produces several times more platinum than Russia, Zimbabwe, the United States, Canada, etc. (Johnson Matthey, 2020). South Africa has a large number of platinum mines, production companies and refineries, and countries with diverse production locations are less prone to supply chain disruptions than countries with fewer production locations (Nuss et al., 2016a). The United States came in second while Cyprus came in third. This is because, in addition to owning the Stillwater mine locally, the United States also has investment holdings in some South African platinum mining producing companies. In addition to being the registered place of Tharisa plc, Cyprus is also the registered place of part of the shareholders of the Russian Norilsk company. Cyprus' position in the network is more a reflection of Russia's platinum supply.

For the global platinum producing companies (Figure 8B), Sibanye Stillwater Ltd. has the highest betweenness centrality, which is also the world's largest platinum producer. It is followed by South Africa's Impala Platinum Holdings Ltd, Russia's PJSC MMC Norilsk Nickel and South Africa's Anglo American Platinum Ltd, which are ranked third and fourth among global platinum producers, respectively. It can be seen that the control power of global platinum production companies is strongly proportional to the amount of platinum production.

In terms of platinum mines (Figure 8C), Canada's Ontario division is the mine with the highest betweenness centrality, followed by Stillwater in the United States, and Russia's Kola division and Polar division in third place. The control of global platinum mines has little to do with mine output and much to do with the comprehensiveness of the company to which it belongs. The control of global platinum mines has little to do with mine output and more to do with the comprehensiveness of the company it belongs to. The Ontario division mine belongs to Vale S.A, the third largest mining company in the world (ranked by market capitalization). The Stillwater mine, a subsidiary of Sibanye Stillwater Ltd, is the world's largest platinum producer and ranks 24th among the top 40 global mining

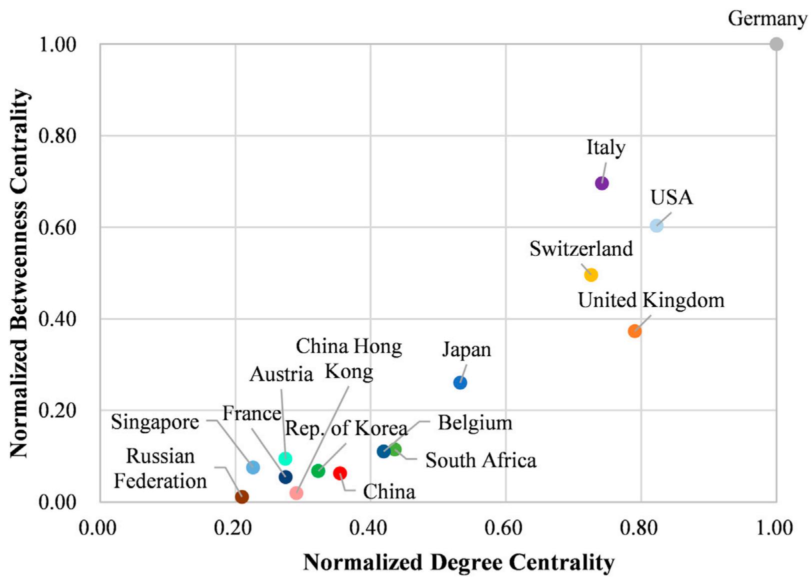

FIGURE 10
Country (area) position of the international platinum primary product trade network.

companies by market value. The Kola division mine and the Polar division mine are owned by PJSC MMC Norilsk Nickel, the sixth largest mining company in the world. In other words, mines owned by large integrated mining companies act as a "bridge" role in the supply network.

In terms of shareholders of global platinum mining companies (Figure 8D), the highest betweenness centrality is Public Investment Corp. (SOC) Ltd. in South Africa. Rounding out the top five are Capital Research and Mgmt Co. in the United States, Bonico Holdings Co. Ltd. in Cyprus, Anglo American PLC. in the United Kingdom, and BlackRock Inc. in the United States. In terms of shareholders of global platinum mining companies (Figure 8D), the most betweenness centrality is Public Investment Corp. (SOC) Ltd. in South Africa. Capital Research and Mgmt Co. of the United States, Bonico Holdings Co. Ltd. of Cyprus, Anglo American PLC. of the United Kingdom, and BlackRock Inc. of the United States round out the top five. Among the top five shareholder status, only one company is affiliated with South Africa, while companies in the United States and the United Kingdom have an important position. Cyprus' Bonico Holdings Co. Ltd. is a stakeholder of Norilsk Nickel, which has its registered office in Cyprus, while Bonico is a Russian corporation.

Following that, we examine the countries that are home to the top ten participants of betweenness centrality (Figure 9). At the country level of each supplier, 10 countries are involved, of which South Africa is the largest producer; at the company's country level, 14 countries are involved, of which 9 are in South Africa; at the country level of the mine, 13 countries are involved, of which 7 are in South Africa; at the country level of the company's shareholders, 13 countries are involved, including one in South Africa, four in the United States, three in the United Kingdom, three in Cyprus (where the Russian company is registered). Therefore, in the global platinum supply network, South Africa has strong control at the level of platinum producing countries, companies and mines. However, the United States, the United Kingdom, and Russia have greater power over than South Africa at the company's shareholder level (Figure 9).

3.2.2 The position of the major participants in trade network

In 2019, the global trade in platinum primary products was 502 tonnes (physical). The main exporter of platinum primary products is South Africa (1.78 million tons), followed by the United Kingdom (470 kilotons), Germany (450 kilotons), the United States (350 kilotons), and Japan (320 kilotons); while the main importer is The United Kingdom (950 kilotons), China (710 kilotons), Germany (410 kilotons), the United States (410 kilotons), Japan (380 kilotons), etc. South Africa is the world's largest supplier and exporter of platinum, with the majority of primary platinum products going to the United Kingdom (33%), China (22%), Japan (16%), China Hong Kong (7%), and the United States (7%). The United Kingdom, Germany, the United States and Japan are both major exporters and major importers, and can be regarded as transit points for international trade in primary platinum products. Because platinum is widely employed in industrial domains such as catalysts, electronics, and glass, primary platinum product importers are primarily concentrated in advanced industrial countries. (Tokito et al., 2016).

The position of each trading country in the international platinum primary product network is then assessed (Figure 10). At the top of the list is Germany, the most extensively connected country in the platinum primary products trade network, with the strongest control. Germany is a global leader in the import and export of platinum primary products. It is also an important producer of automobile exhaust catalysts and automobiles (Xun et al., 2022). The following countries on the list are Italy, the United States, Switzerland, the United Kingdom, and Japan, in which the United States and Japan are the two most important global producers in the automotive industry. Zurich in Switzerland is the center of platinum spot trading, and the United Kingdom has a globally important platinum transaction market (Harvey, 2016). As the world's second largest platinum consumer market and the second largest importer of primary products, China only ranks 12th, with weak control and a relatively high probability of supply disruption. South Africa, the world's largest producer and exporter of platinum, is only seventh. That is, although South Africa is an oligarch in the global supply of platinum mine, its position and control in the trade network is not as powerful as that of transit and consumer countries represented by Germany, Italy, the United States, Switzerland and the United Kingdom. In general, countries that play a pivotal role are often thought to have excellent anti-risk capabilities.

3.2.3 Comprehensive analysis of participants status

China, the United States, Europe, and Japan are now the world's top platinum consumers (Johnson Matthey, 2020). The consumer countries involved in the global platinum supply network are China, the United States, the United Kingdom, etc., but their platinum mine production and national status are far inferior to that of the supplier country, South Africa. The platinum supply and demand markets are highly separated. The key importing countries in the platinum primary product trade network are China, the United States, Europe, and Japan. With the exception of China, the majority of other consuming countries have a higher national position in the trade network than South Africa. In general, South Africa has the strongest control in the global platinum supply market; the United States has the most sway over the consumer market; and China is the weakest and most vulnerable. By focusing on overseas investment, regional supply risks can be effectively reduced (Sun et al., 2019).

Currently, the largest consumer of platinum in the world is automotive exhaust catalysts. The major producers of ICEV-related PGM catalysts are the United States, China, Japan, and Germany, all of which are also major producers of automobiles (Xun et al., 2022). Platinum is a critical raw material for fuel cells, and the future development of global fuel cell vehicles may bring about significant changes in platinum consumption. The global producers of PGM catalysts for fuel cell vehicles are mainly South Korea and the United States, which are also major producers of fuel cell vehicles; other producers include China, Japan, and Germany (Xun et al., 2022). Considering the manufacturing technical barriers, global production of PGM catalysts is concentrated in specific countries and regions, and capacity transfer is difficult (Islam et al., 2018). Therefore, it is challenging to change the global platinum supply and demand pattern and national position in the short term.

4 Conclusion

This study constructs a global platinum mine supply chain risk assessment framework that integrates network analysis and evaluation indicators, and analyzes the global platinum mine upstream supply chain risk in detail. By mapping the supply network of global platinum producing countries, mines, companies, and company-owned shareholders, as well as the international platinum primary product trade network, the visualization of various relationships in the global platinum mine upstream supply chain is realized. The global supply structure of refined platinum products is similar to the supply structure of platinum mines. The analysis of the supply network of platinum mines in this paper also provides a reference for the supply structure of refined platinum products. The main conclusions are as follows:

First, the global platinum mine upstream supply chain risk comprehensive score is 7 points, and the rating is "high risk". Among them, Supply network, Trade network, Supply concentration-Countries and Country Risk all have supply risks, and with the risk of supply chain interruption being very high.

Second, although the global platinum supply network and platinum primary product network are closely related to their neighbors, they are both sparse networks, with poor overall network connectivity and weak anti-risk capabilities.

Third, at the non-geographic level of producing countries, global supply concentration is high in the producing countries of platinum mines, in the countries of the producing companies and in the countries of the shareholders of the producing companies. Global concentration, however, is moderate in platinum producing companies and low in platinum mines.

Fourth, South Africa has an absolute monopoly on the resources and supply of global platinum mine, but at the level of shareholders of companies in the global platinum supply network, it has less control than the United States, the United Kingdom and Russia. In the international platinum primary product trade network, the control is not as good as that of the transit and consumer countries represented by Germany, Italy, the United States, Switzerland, and the United Kingdom.

Restricted by the global platinum resource endowment, platinum resources and production are dominated by South Africa. This high geographical concentration is unchangeable. Platinum consuming countries can reduce supply risks by doing the following:

First, optimize the supply structure of platinum upstream supply chain. Improve the supply capacity of domestic platinum mines and allied platinum mines; if domestic platinum resources are scarce, the domestic supply capacity can be increased by increasing secondary resource recovery.

Second, build an international large-scale comprehensive mining company. International large-scale integrated mining companies and their subordinate mines can act as a "bridge" role in the supply network while maintaining strong control.

Third, increase the global supply share by investing and holding overseas mines. The global platinum supply and demand market are severely separated. Platinum consuming countries can learn from how the United States and the United Kingdom engage in platinum mining companies in South Africa to raise the production of overseas equity mines and strengthen their influence and voice in the platinum supply market.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

PL: Conceptualization, Methodology, Software, Writing-original draft, review and editing; QL: Data curation, Methodology; PZ: Writing-review and editing; YL: Formal analysis.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Carbon footprint and emission reduction potential of the artwork auction market

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Greenhouse gas emissions from human activities have become the leading cause of climate problems. Reducing greenhouse gas emissions from human economic activities and realizing carbon neutralization are the main means of sustainable economic development. Among them, carbon emission reduction of large-scale activities including auctions bears the brunt. Through the emission factor method, this paper estimates the carbon footprint of a typical artwork auction and divides the auction market into different sizes, according to the average round-trip distance of the number of participants. The results show that a typical 3-day medium-sized artwork auction with 500 people's carbon footprint is about 270 tons of carbon dioxide. The traffic carbon emission of participants accounts for a large proportion of the total carbon footprint, particularly composed of the traffic carbon emissions of a small proportion of long-distance participants. Therefore, the transition from offline to virtual artwork auctions can significantly reduce the carbon footprint by 90%–95%. We put forward suggestions on improving the auction carbon footprint accounting process and industry carbon neutralization system, and promoting the development of relevant technologies for the virtual artwork auction market.

KEYWORDS

carbon footprint, artwork auction market, network virtualization, emission factor method, IPCC

1 Introduction

In November 2021, the World Meteorological Organization released a report on the "global climate situation in 2021" at the 26th United Nations Climate Change Conference. The report data show that the global greenhouse gas concentration reached a new high in 2020, and this growth continued in 2021. Moreover, the global average temperature in 2021 (from January to September) was about 1.09°C, higher than that from 1850 to 1900. At present, it is listed by the World Meteorological Organization as the sixth or seventh warmest year. There will be several climate changes that human beings cannot adapt to (Dillender, 2019). Energy activities are usually the main source of carbon emissions (Levine and Aden, 2008; Kang and Kang, 2022). About 90% of carbon emissions come from energy production and consumption activities in developed countries in 2021 (IPCC, 2021). Sports events (Huang et al., 2012), cultural exchanges (Yates et al., 2022), and other activities are significant sources of energy consumption terminals (Borggren et al., 2013). A lot of energy is consumed from preparation to the holding of large-scale activities. The energy conservation and emission reduction of these large-scale activities are gradually receiving attention.

Since 2006, major events and activities worldwide have taken measures to achieve carbon neutrality. In 2006, the football World Cup in Germany launched an environmental protection plan called "green goal." The plan was advocated using renewable energy and materials, taking pollution-free public transport, and investing in the treatment of unavoidable pollution. The World Cup finally became the first green international sports event (Dolles and Söderman, 2010). The 2006 Turin Winter Olympics was the first Olympic event that achieved "carbon neutrality." Carbon dioxide during the Olympics was offset by forestry, energy conservation, and emission reduction and renewable energy plans (Auruskeviciene et al., 2010). By building 5,000 mu of carbon sink forest, the 2010 UN Climate Change Tianjin Conference can achieve "carbon neutralization" because all 12,000 tons of carbon dioxide emitted by the conference can be absorbed by the carbon sink forest in the next 10 years. Since then, the 2014 APEC meeting in China (Tong et al., 2020) and the 2016 G20 summit in Hangzhou, China (Colin, 2016), have achieved "carbon neutrality" through afforestation. In 2022, the Winter Olympic Games held in Beijing minimized carbon emissions through low-carbon venues, low-carbon energy, low-carbon transportation, low-carbon office, and other measures. At the same time, a carbon offset will be realized by utilizing the forestry carbon sink and enterprise donation to ensure the realization of the carbon neutralization goal (Zhao et al., 2021). The estimation of carbon dioxide emissions and the comparison between online and offline forms are helpful in understanding the potential of carbon reduction. We further put forward suggestions on improving the auction carbon footprint accounting process and industry carbon neutralization system, and promoting the development of relevant technologies for the virtual artwork auction market.

Calculating carbon dioxide emissions during major events and conferences is relatively mature, and there are many ways to achieve carbon neutralization. However, in artistic activities, carbon neutralization has not been paid attention to. There is limited research on measuring the carbon footprint of artwork auctions, and few auctions have achieved net-zero emission. China's art auction market ranks first in the world, according to the China Association of Auctioneers, and by 2020, China had 8,565 artwork auction enterprises and 99,981 auction transactions, with a year-on-year increase of 11.1%. The total business volume of the artwork auction market was 838.705 billion yuan with a year-on-year increase of 15.39%, exceeding the growth rate of the GDP. With the rapid expansion of the auction industry, its accompanying environmental problems should be paid attention to. The general artwork auction needs four stages, namely, auction commission, display, auction, and settlement and delivery, and the duration is longer than that of the general meeting. Like other large-scale activities (Hischier and Hilty, 2002; Dolf and Teehan, 2015; Ewijk and Hoekman, 2021), there will be a lot of energy consumption and carbon dioxide emissions during the artwork auction. The auction has a great potential for emission reduction. The realization of zero net carbon dioxide emissions will significantly promote carbon neutralization. The accounting of the carbon footprint of the artwork auction is helpful in understanding the environmental pressure brought by the auction market and the significance of transforming offline auctions into online carbon neutralization and boosting the realization of carbon neutralization. The research objectives of this paper are as follows. First, identify the carbon emission link of the auction and calculate the carbon emission of the auction. Furthermore, predict the carbon emission trend of the auction in the future based on the accounting results and put forward suggestions on emission reduction measures of the auction industry. This paper expounds the accounting method, scope, and process.

The remainder of the article is organized as follows: in Section 2, a literature review on carbon footprint accounting is presented; in Section 3, the methodology and the empirical result utilized in this study are explained; in Section 4, the future trend is forecasted; and in Section 5, the conclusions and related policy implications are provided.

2 Literature review

2.1 Measurement methodology

A carbon footprint refers to the amount of greenhouse gases produced by a specific activity or entity (Druckman and Jackson, 2009). There are three common carbon footprint measurement methodologies, namely, the input–output method, carbon emission factor, and life cycle methods. The input–output method is mainly based on the input–output table. The direct and indirect carbon dioxide emissions can be estimated according to the direct consumption coefficient and complete consumption coefficient of products (Li et al., 2021). The input–output method takes the whole economic system as the boundary and is suitable for the carbon emission accounting of a macrosystem (Zhu et al., 2012). The IPCC Guidelines described the carbon emission factor method in detail. The overall calculation is that greenhouse gas emissions are equal to the level of activity data multiplied by the carbon emission factor (Sproles, 2009). Determining carbon emission factors is the key to accounting carbon emissions. At present, many scholars calculated the carbon emission factors of different emission subjects, such as energy (Fott, 1999; Spalding-Fecher, 2011), products (Shen et al., 2016), and industry (Huo et al., 2013). There are also many standards and documents that provide reference values of carbon emission factors in various dimensions. The life cycle method refers to analyzing the environmental impacts caused by a product in various stages of production, use, waste, recycling, and reuse (Zobel et al., 2002). The process analysis method which finally quantifies the carbon emission of each process in the life cycle is the carbon footprint calculation method based on a life cycle theory.

The existing carbon footprint research includes macro research and micro research (Table 1). Macro research mainly considers the impact of the international trade and industrial structure (Wang and Zhang, 2021). From a micro perspective, there are many relatively complete carbon emission accounting standards and guidelines in the world and are mainly divided into two categories. One is to calculate the carbon emissions consumed by enterprises or projects, and the other is to calculate the carbon emissions based on the whole life cycle of products or services (Ma et al., 2013). GHG protocol is an enterprise greenhouse gas accounting standard formulated by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), which reduces the repeated calculation of enterprises and projects and reduces the accounting cost (Garcia and Freire, 2014). The Intergovernmental Panel on Climate Change provides the IPCC guidelines on climate change to guide economic sectors in accounting for carbon emissions (Wigley and Raper, 1992). At present, most of the greenhouse gas accounting systems are globally based on IPCC guidelines that have wide applicability. The ISO series standards formulate the specific calculation method of a carbon footprint, oriented to the greenhouse gas emissions and emission reductions in the whole life cycle of goods or services (Garcia and Freire, 2014).

TABLE 1 Relevant guidelines and standards of carbon footprint accounting.

Name	Formulating organization	Sphere of application	Characteristic
GHG protocol	World Resources Institute/World Business Council for Sustainable Development	Enterprises and projects	GHG protocol stipulates the accounting issues related to the measurement and reporting of greenhouse gas emissions, which reflects the inventory of greenhouse gases
ISO series standards	International Organization for Standardization	Enterprises and projects	It aims to improve the reliability and consistency of greenhouse gas quantification and reporting through a neutral standard to improve the comparability of reporting results
IPCC guidelines	Intergovernmental Panel on Climate Change	Enterprises and projects	Greenhouse gas emissions are fully considered in the calculation process. It is a method to calculate carbon emissions through the consumption of energy and fossil fuels
GB/T 24,040 national standard	National Standardization Management Committee	Enterprises and projects	It provides basis for LCA practitioners in China and specifies the requirements for developing LCA.
PAS 2050	British Standards Institute	Products and services	It is a carbon footprint assessment method based on a product level, which provides a basic process for calculating GHG emissions in the whole life cycle of products

TABLE 2 Carbon content, carbon oxidation rate, and carbon dioxide emission of different fossil fuels.

Fuel variety	Carbon content per unit calorific value (tC/GJ)	Carbon oxidation rate (%)	Carbon dioxide emissions (ton)
Anthracite	27.49×10^{-3}	85	4.18
General bituminous coal	26.18×10^{-3}	85	3.98
Fuel oil	21.10×10^{-3}	98	3.70
Gasoline	18.90×10^{-3}	98	3.31
Diesel oil	20.20×10^{-3}	98	3.54
Kerosene	19.60×10^{-3}	98	3.43
Other oil products	20.00×10^{-3}	98	3.50
Liquefied petroleum gas	17.20×10^{-3}	98	3.01
Natural gas	15.30×10^{-3}	99	2.71

TABLE 3 Traffic carbon emissions from artwork auctions of different sizes.

Size	Average round-trip distance	Traffic carbon emissions
Small-sized auction	About 2000 km	About 80 tons
Medium-sized auction	About 5,500 km	About 250 tons
Large-size auction	About 8,000 km	About 400 tons

2.2 Activity of carbon footprint accounting

Many scholars use different methods to calculate the carbon footprint of human economic activities. The macro research mainly includes countries, regions, and industries. Hertwish and Peters (2009) analyzed the carbon footprint of countries in the context of globalization and international trade. Herrmann and Hauschild (2009) used the input–output analysis to examine the carbon footprint of trade in developed countries. (Stepchenkova, 2013) used the life cycle assessment method to assess the Norwegian system's carbon emissions of power transmission. Uvarova et al. (2014) used the IPCC method to analyze the activities related to the oil industry in Russia from 1990 to 2009 and found that the amount of carbon dioxide increased sharply with the increase in energy consumption. Micro research mainly includes products, enterprises, families, and services. The difficulty of research lies in the definition of the scope of carbon footprint accounting. The household carbon footprint is a mature content in carbon footprint research. Lenzen (2001) used the multi-region input–output hybrid LAC approach to construct the German household carbon footprint calculator, accounting for the impact of incomes and scales. Zen et al. (2021) calculated the carbon emissions of Malaysian households in their daily life through investigation and statistics. The results showed that the carbon emissions of households reached 11.76 tons, which was different between urban and rural areas.

For large-scale activities and events, there is also much research dedicated to accurately determining the responsibility subject and accounting scope and accurately calculating the carbon dioxide generated in the process. Hischier and Hilty (2002) calculated the carbon footprint of transportation, conference supplies, and other processes in the 15th international environmental information seminar held in Zurich in 2001 but not considering the energy consumption of accommodation, catering, and conference room. Dolf and Teehan (2015) calculated the carbon footprint of a basketball game at Columbia University in 2011 and systematically considered five categories of items, namely, transportation, accommodation, catering, solid waste, and on-site power consumption into the accounting system. Neugenauer et al. (2020) applied the carbon footprint accounting method of sports events to academic conferences. The accounting scope included conference procurement, power consumption of the conference working group, and other items according to the characteristics of the conference. Achten et al. (2013), Desiere (2015), and Collins and Cooper (2017) all emphasized the carbon footprint accounting of conference activities and transportation. The purpose of carbon footprint accounting is to assess the environment of the activity itself and implement emission reduction measures in the process of an activity and offset the emission of the parts that cannot be reduced. Jckle (2021) compared the carbon footprint of the joint European political research conference held by online meetings and traditional offline meetings and concluded that the carbon footprint of online meetings was reduced by 90% compared with conventional offline meetings and put forward many suggestions on energy conservation and emission reduction in future meetings. Tugcu et al. (2012) assessed the environmental problems of the 2014 FIFA World Cup in Brazil and the 2016 Summer Olympic Games in Rio de Janeiro and believed that the sports institutions and the Brazilian government paid too much attention to the infrastructure of events while ignoring economic, social, and environmental problems. Diederichs and Robers (2016) analyzed the carbon emissions of the 2010 South Africa World Cup and the 17th United Nations Climate Change Conference and discussed how to offset the carbon footprint generated by the two events, as well as the impact of carbon offset methods and carbon neutralization plan on the economy of Durban, South Africa.

Most of the research subjects of the relevant literature are large-scale sports events or academic conferences, and there is hardly any literature studying the carbon emission of artwork auctions. The artwork auction is an important trading channel for artwork. The auction company is entrusted by the client to auction related items and collect parts of the commission. The auctions are a way for auction companies to sell art. Similar to other large-scale events, the preparation and implementation of the auction need to consume a lot of energy and consumables. We analyze the whole process of a typical auction, calculate each segment's carbon emissions, and understand the carbon emissions of the artwork auction industry. Based on the digital trend of the artwork auction industry, we predicted the changes in the carbon footprint of the artwork auction market in the future.

3 Carbon footprint measurements for auction

3.1 Calculation model

This paper uses the carbon emission factor method to calculate the carbon footprint of the auction, which is a method to calculate the carbon emission through the consumption of energy and fossil fuels. Greenhouse gas emission is the product of activity data and emission factors, as shown in Formula 1

$$E_{GHG} = AD \times EF. \tag{1}$$

E_{GHG} refers to greenhouse gas emissions whose unit is tons of carbon dioxide. AD refers to the greenhouse gas activity data. EF is the carbon emission factor.

The carbon emission factors related to the auction process in this paper come from various standard documents. The low calorific value of natural gas comes from the *China Energy Statistics Yearbook 2011*; the low calorific value of other fossil fuels comes from the research on the Chinese greenhouse gas inventory. The carbon content per unit calorific value and carbon oxidation rate comes from the *provincial greenhouse gas inventory guidelines (pilot)*. The power grid emission factor adopts the average national power grid emission factor of 583.9 kg CO_2/MWh in the *guidelines for accounting methods and reporting of greenhouse gas emissions of enterprises (revised version in 2021)* issued by the general office of the Ministry of Ecological Environment. The emission factors of transportation, accommodation, catering, and other related activities refer to *2012 Guidelines to Defra/DECC's GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors* issued by the UK Department of environment, food, and rural affairs. The emissions factor of waste disposal refers to the provincial greenhouse gas inventory guidelines (pilot).

3.2 Calculation process

Through the company's official website, the auction held by Beijing Poly International Auction Co., Ltd. was studied. We found that the auctions generally require a 3-day preview and 1-day auction and that there are about 500 people in the auction (including participants and organizers). So, this paper takes a typical 4-day three-night artwork auction with 500 people as the accounting object.

The *implementation guidelines for carbon neutralization of large-scale activities (for Trial Implementation)* issued by the Ministry of Ecology and Environment of the people's Republic of China have strict carbon emission accounting boundaries for the whole process of various large-scale activities. Therefore, based on the document, the emission activities of the artworks auction are divided into fossil fuel combustion, purchased power emission, traffic emission, and waste disposal, as shown in Figure 1. The specific calculation formula is as follows:

$$E_{GHG} = AD_{Gi} \times EF_{Gi} + AD_E \times EF_E + AD_{Tj} \times EF_{Tj} + E_W. \tag{2}$$

E_{GHG} refers to greenhouse gas emissions whose unit is ton. AD_{Gi} is the activity data on the ith fossil fuel combustion whose unit is GJ. EF_{Gi} is the carbon emission factor of ith fossil fuel whose unit is ton/GJ. AD_E refers to the activity data on purchased electricity whose unit is Kwh. EF_E

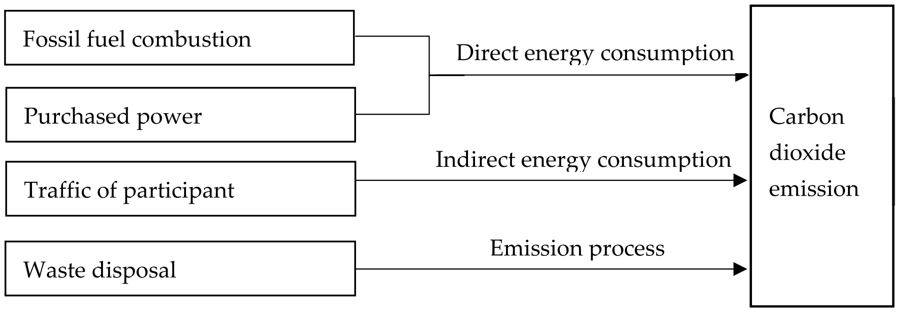

FIGURE 1
Decomposition of emission activities of auctions.

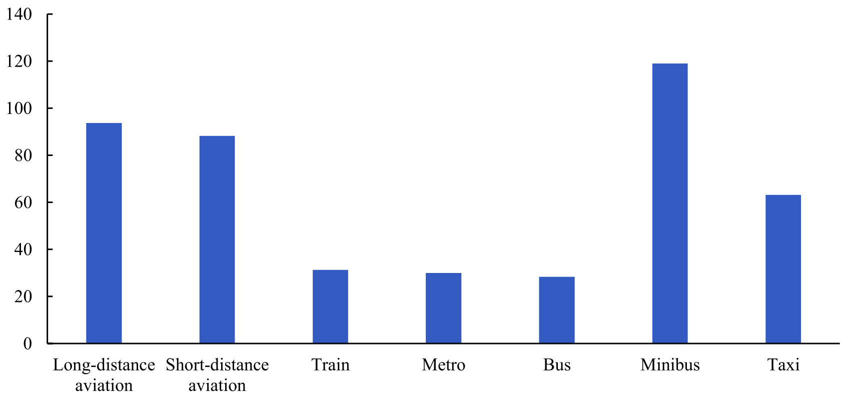

FIGURE 2
Carbon dioxide emissions of different vehicles driving 1,000 km (unit: kg).

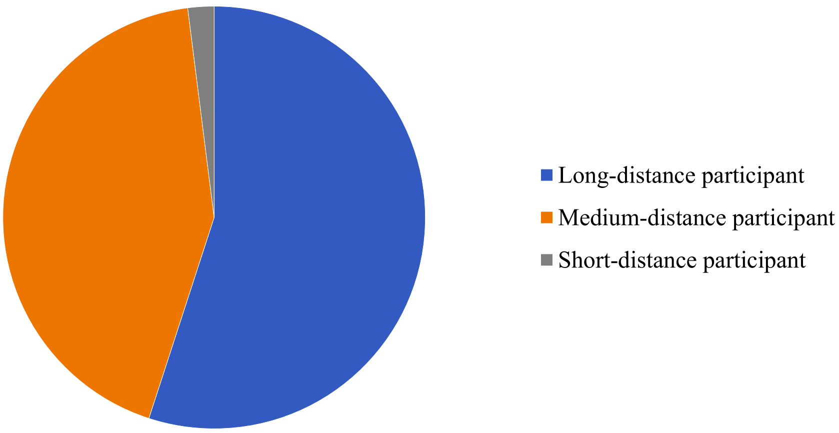

FIGURE 3
Proportion of carbon dioxide emissions of different round-trip distances in a medium-sized artwork auction.

refers to the average power emission factor whose unit is ton/Kwh. AD_{Tj} is the activity data on the *j*th vehicle, which is equal to the average round-trip distance of a person multiplied by the number of people. EF_{Tj} is the default value of the emission coefficient of the *j*th vehicle, and the unit is ton/km. AD_{Wn} is the activity data on the *n*th waste treatment method whose unit is kg. E_W refers to greenhouse gas emissions of waste disposed.

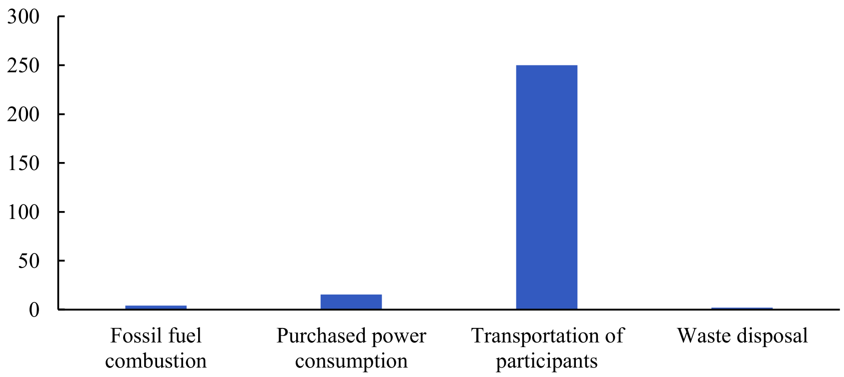

FIGURE 4
Carbon dioxide emissions from different departments of a medium-sized artwork auction (unit: ton).

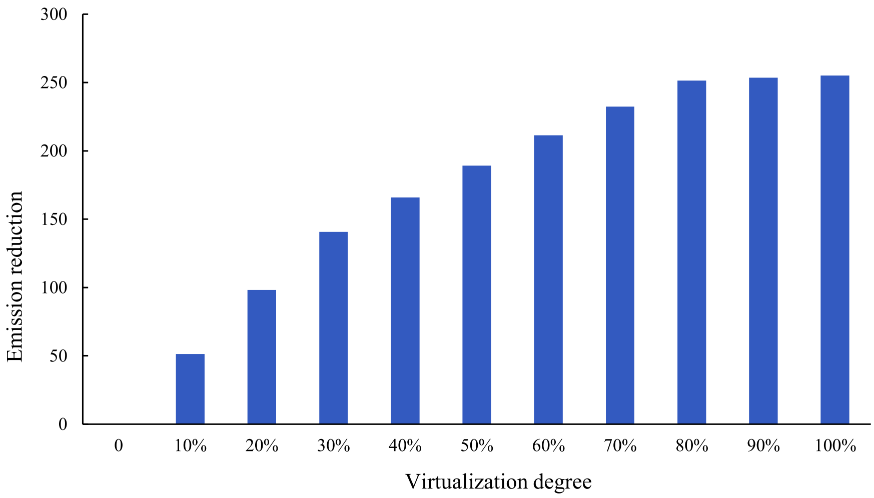

FIGURE 5
Traffic emission reduction under different degrees of virtualization (unit: ton).

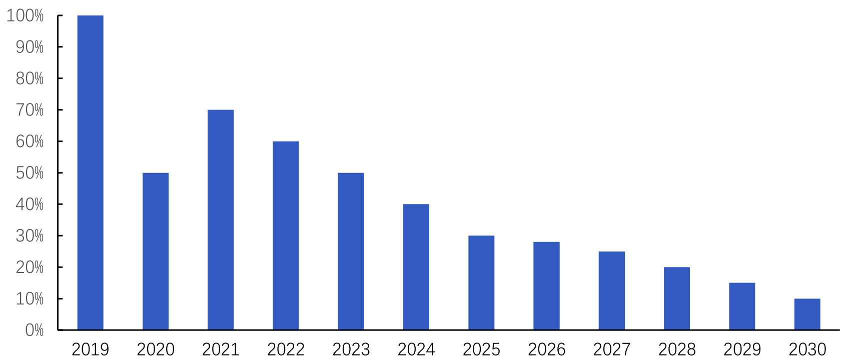

FIGURE 6
Emission trend from 2019 to 2030 (based on the 2019 carbon emissions).

Fossil fuel combustion emission refers to the emission of facilities for fossil fuel burning in large-scale event venues and staff offices. A typical 3-day conference will consume 178800 MJ of energy (Hischier and Hilty, 2002). According to China's greenhouse gas research inventory, the amount of carbon dioxide emitted by using different types of energy will be different (Table 2). The carbon emission factor equals to the carbon content per unit calorific value multiplied by carbon oxidation and 44/12. The carbon content per unit calorific value of anthracite is 27.49×10^{-3}tC/GJ, and the carbon oxidation rate of fuel is 85%. If anthracite is used throughout the meeting, the energy consumption of an artwork auction will produce 4.18 tons of carbon dioxide. If other fossil fuels are used, the total amount of carbon dioxide emitted is as shown in the following paragraphs. Under the condition of providing the same energy, the carbon dioxide emission of anthracite is the highest, and the use of natural gas emits the least carbon dioxide.

For the accounting of carbon dioxide generated by net power consumption purchased at the artwork auction, it is necessary to understand the accommodation of power consumption and power emission factors caused by auctions. The power consumption of accommodation is 18.1 Kwh for one person per night (Filimonau et al., 2011). The power consumption of accommodation of a 500-person artwork auction will be 9,050 kW h per day and 27,150 Kwh in the whole process. According to *the guidelines for accounting methods and reporting greenhouse gas emissions of enterprises' power generation facilities (revised in 2021)*, the national average power emission factor was adjusted from 0.6101 tCO_2/MWh in 2015 to the latest 0.5839 tCO_2/MWh with a decrease of about 4.3%. According to the latest average emission factor of electricity, the net consumption of electricity purchased at the artwork auction will produce 15.85 tons of carbon dioxide.

Traffic emissions refer to the emission of traffic activities generated by the meeting organizers, participants, and other appropriate personnel who participated in the meeting, such as aircraft, high-speed rail, subway, taxi, and private car. According to the *2012 Guidelines to Defra/DECC's GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors*, the default data on CO_2 emission parameters of vehicles are as follows. Under the condition of the same distance, the carbon dioxide emitted by a bus travel is the least (Figure 2).

Ewijk and Hoekman (2021) examined several international conferences and found that the average round-trip distance of participants ranged from 1980 km to 9,564 km. Suppose that the average round-trip distance is about 2000 km for a small artwork auction and that 60% of the participants travel by train with an average round-trip distance of 1,000 km and 40% of the participants travel by short-haul air, with an average round-trip distance of 4,000 km. Under the aforementioned assumptions, the traffic emissions of a small artwork auction will reach 80 tons. The average round-trip distance of a medium-sized artwork auction is about 5500 km. Participants mainly take long-distance, short-distance air, and train transportation to the meeting. Moreover, 20%, 50%, and 30% of participants travel by train, short-distance air, and long-distance air with average round-trip distances of 1,200 km, 5,000 km, and 10,000 km, respectively. The carbon dioxide emission generated by transportation is 254.38 tons. For an international large-sized artwork auction with an average round-trip distance of more than 7,000 km, the traffic carbon emission is expected to be 300–450 tons. Notably, the carbon emissions caused by the round-trip transportation of participants accounts for more than 80% of the total carbon emissions of the artwork auction. Also, with the increase in the average round-trip distance of participants, the average carbon emissions per kilometer are also increasing (Table 3).

Through the hypothesis of the medium-sized artwork auction, it is found that 30% of long-distance participants account for more than half of the total traffic emissions, while 30% of short-distance participants account for only about 5% (Figure 3). A small number of long-distance participants account for a large part of the total traffic emissions. Therefore, the traffic carbon emission of long-distance participants is the key to emission reduction. The online artwork auction can enable these long-distance participants to join an auction at home, while short-distance participants' on-site participation can improve the auction atmosphere, and the artwork auction organizers can offset emissions of short-distance participants at a lower cost.

The output of waste is highly related to the number of people. According to the data on domestic waste in major cities in China's statistical yearbook, the weight of waste treated by landfill is 0.15 kg for one person per day, and the weight of waste treated by incineration is 0.28 kg for one person per day. In the 1-day artwork auction, about 75 kg and 140 kg of domestic waste will be produced and treated by landfill and incineration, respectively. The 4-day three-night artwork auction will have about 645 kg of total wastes, including domestic waste and other types of waste, such as documents and display boards. The weight of waste treated in the landfill, where the greenhouse gas is mainly methane, is about 0.7 tons. The weight of waste treated by incineration is about 1.3 tons, of which the greenhouse gas is primarily carbon dioxide.

$$E_W = (MSW_L \times L_0) \times (1 - OX) \times GWP + IW \times CCW \times FCF \times EF \times 44/12. \quad (3)$$

MSW_L refers to the amount of waste disposed of by a landfill whose unit is a ton. L_0 refers to the methane generation potential of the landfill site, whose value is about 0.1, and the unit is a ton of methane/ton of waste. OX refers to the oxidation factor whose value is 0.1. GWP is the global warming potential of methane, whose value is 25. IW refers to the amount of waste disposed by incineration. CCW refers to the proportion of carbon content in waste, which experts judge to be 20%. FCF refers to the proportion of mineral carbon in the total carbon of waste, with an average value of 39%. EF refers to the combustion efficiency, whose value is 95%. 44/12 refers to the conversion coefficient from carbon to carbon dioxide.

The carbon emission factor of landfill treatment is 2.25 and that of incineration treatment is 0.2717. The huge difference is that methane has a high global warming potential. The emission of landfill treatment is about 1.6 tons of carbon dioxide equivalents, and the emission of incineration treatment is about 0.36 tons of carbon dioxide equivalents. In a typical artwork auction lasting 4 days and three nights, the emission from waste treatment is about 2 tons of carbon dioxide equivalents. If the proportion of landfill treatment is reduced and incineration treatment is increased, the carbon dioxide emission will be lower.

To sum up, a typical artwork auction will range from 70 tons to 520 tons. The emission of fossil fuel combustion will range from 2.7 tons to 4.4 tons due to fuels used, of which the emission caused by natural gas is the least and that caused by anthracite is the highest (Figure 4). The emission of net electricity consumption by artwork auction is about 15.85 tons of carbon dioxide equivalents, and the specific emissions are affected by local electricity emission factors. The carbon dioxide emissions caused by the traffic of participants are the central part of the carbon footprint of the artwork auction. The range of participants attracted varies due to the size of the artwork auction. The carbon dioxide emissions vary significantly, ranging from 50 tons to 500 tons. The disposal method affects the carbon dioxide emission from waste treatment, and the emission is about 2 tons. The lowest carbon emission department is waste treatment, and the highest department is the transportation of participants.

4 Discussion

Technology is seen as a sustainable way to achieve a low-carbon or carbon-free environment (Sun et al., 2019). Combining virtual reality technology and artwork auction is a new form of application, which is the performance of technological development applied in the market economy. Science and technology enables the auction to break through the limitations to space and time and display the three-dimensional effect of the traditional physical exhibition through virtual and accurate technologies. It emphasizes the novelty and impact of the theme, pays attention to the combination of pictures and substance, and fully stimulates the audience's visual, auditory, and other sensory organs. It has the characteristics of multi-sensibility, interactivity, independent selectivity, and on-the-spot feeling, which enhances the user experience and promotes the digital transformation of auctions. Then, works can be displayed more comprehensively, vividly, and realistically, which effectively improves the display effect of the works. Christie's, a famous artwork auction house, launched a new version of its application that uses virtual reality technology to allow participants to view private art collections remotely.

According to *the statistical annual report of 2020 China's cultural relics and artworks auction market*, 94% of the auctions were held online in 2020 under the background of the epidemic, and it was 2.5 times higher than that in 2019, with a turnover of 1.353 billion yuan. The scale of the pure online auction has been further improved, and online bidding is enthusiastic. The flow of participants caused a large part of the total carbon footprint of the artwork auction. In addition, the carbon dioxide emitted by the long-distance transportation of participants, whose proportion is low, accounts for the main part of the total traffic emissions of the artwork auction (Neugebauer et al., 2020). Allowing long-distance participants to switch from face-to-face participation to online video and even completely virtual artwork auctions can significantly reduce carbon emissions (Neugebauer et al., 2020; Ewijk and Hoekman, 2021; Jckle, 2021).

In order to explore the emission reduction potential of the virtual auction, this paper supposes a medium-sized artwork auction where 20%, 50%, and 30% of the participants travel by train, short-haul air, and long-distance air with the average round-trip distance of 1,200 km, 5,000 km, and 10,000 km, respectively. The whole process of the auction emits about 400 tons of carbon dioxide equivalents. The degree of virtualization is expressed by the proportion of online participants in the total number. This paper assumes that the degree of virtualization of the artworks auction will gradually increase until it is completely virtualized to calculate the emission reduction of the auction (long-distance participants will be given priority to virtualization). As shown in the Figure 5, the marginal amount of emission reduction decreases with the improvement of virtualization. When the degree of virtualization of the auction is 30%, the carbon dioxide emission of transportation is reduced by 55%. As long as the degree of virtualization of the artworks auction is 80%, the carbon dioxide emissions from transportation can almost be ignored. When all auction participants participate online, the carbon dioxide emission will only be 5%–10% of the offline artwork auction.

Since 2020, the time and space constraints and high costs caused by COVID-19 have had a significant impact on the artwork auction market, which forced the auction industry to accelerate the pace of digitalization. By creating a digital space for artwork auction to achieve interaction between products, services, and humans, the physical and time constraints of the auction industry have been broken. Christie's annual artworks auction revenue online increased by 262%, and Phillips', increased by 134%. However, the crown of digital transformation belongs to Sotheby's, whose online artwork auction revenue has increased by 25% in 2019 and 440% in 2020. More than 70% of Sotheby's artwork auctions were held online in 2020, only 30% in 2019, and new online bidders increased by more than 40%. Based on the carbon emissions in 2019, the cancellation of offline auctions and the online holding of artwork auctions in 2020 made the expectation of carbon emissions in 2020 to be only half of that in 2019. After the normalization of the epidemic, carbon emissions are expected to rebound, but it is still the mainstream trend of the auction industry that digital transformation causes emission reduction (Figure 6). Before 2025, with the rapid transformation of artwork auctions, carbon emissions will decline rapidly. However, after 2025, due to the urgent need to break through critical technologies to achieve further digital transformation, the speed of emission reduction will slow down. By 2030, the artwork auction's carbon emissions are expected to only be 10% of those in 2019.

5 Conclusion and policy implications

Since the outbreak of the COVID-19 epidemic in 2020, most artwork auctions have been transferred online. Virtual auctions and hybrid-virtual auctions are more environmentally friendly alternatives to offline auctions. We estimated the carbon footprint and found that the traffic emission of participants, particularly composed of the traffic emission of a few long-distance participants, accounts for a large proportion of the total emission and that the transition from a face-to-face artwork auction to virtual auction can significantly reduce the carbon footprint by 90%–95%. Based on the aforementioned analysis results, we put forward the following suggestions. In a typical auction, the emission of fossil fuel combustion varies from 2.7 tons to 4.4 tons due to different fuels used. The consumption of electricity purchased in the auction will produce about 15.85 tons of carbon dioxide, and the specific emission is affected by the local power emission factors. Based on the different average round-trip distance, the carbon dioxide emissions vary significantly, ranging from 50 tons to 500 tons. The carbon dioxide emission from waste treatment is affected by the treatment method, and the emission is about 2 tons. Finally, it further predicts the carbon emissions of the auction in the rapid development of a virtual reality technology. We find that, by 2030, the artwork auction's carbon emissions are expected to be only 10% of those in 2019. The institutional quality matters in carbon emission reduction (Sun, et al., 2022). Therefore, we proposed the following policy recommendations based on the research results.

First, the relevant departments should improve the accounting methodology of artwork auction carbon footprint, simplify the accounting process of the auction's carbon emission, and build a carbon footprint calculator for the artwork auction market. A clear understanding of the carbon emissions in the auction's organization process can help organizers evaluate the emission reduction potential of different links. The regulatory authorities should propose a plan to reduce the greenhouse gas emission of the activity to the greatest extent and require that all behaviors in each link, including the start-up stage, preparation stage, development stage, and ending stage, meet the emission control policy.

Second, the relevant departments build a carbon neutralization system for the artwork auction industry improving the transparency and the regulatory process of emissions. The organizers should invite third-party institutions to monitor on-site emissions and collect data. Different quantities of carbon quotas will be allocated to auctions of various sizes. The government should allocate different amounts of carbon quotas to artwork auctions of different sizes and require auctions to take the initiative to implement actions to regulate greenhouse gas emissions voluntarily and need the organizers to neutralize the actual greenhouse gas emissions through carbon offsets.

Finally, the development of the "meta-universe" and other virtual technologies should be promoted. The efficiency and experience of the auction process should be improved. Also, carbon neutralization of the artwork auction industry should be realized. So, the digital transformation should be encouraged to avoid the transportation and accommodation of participants and reduce the carbon dioxide emission of high-emission links.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

JC conceived and designed the study. CQ provided the data. JC and CQ wrote the manuscript. CS analyzed the results. All authors read and approved the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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A review of China's resources of lithium in coal seams

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Lithium gains an increasing importance in new energy vehicles and stationary energy storage, and development and utilization of lithium mines has attracted great attention around the world. In addition to the traditional lithium resources, lithium resources in coal seams have great potential in industrial application. Therefore, how to develop and utilize them is strategically significant for guaranteeing supply of lithium resources in China and promoting clean energy transformation. This paper summarizes the metallogenic ages, occurrence, enrichment factors, availability of lithium resources in coal seams in China. Conclusion are obtained as follows. i. coal-hosted lithium deposits discovered in China so far mainly occur in the Carboniferous-Permian strata of North China. They are less concentrated in smaller range in the Permian strata of Qilian-Qinling. ii. In China, coal-hosted lithium is mainly enriched in aluminum-bearing minerals. Lithium in coal seams mainly occurs in the inorganic matter, and some occurs in the organic matter. iii. Lithium enrichment in coal seams is caused by stable supply of aluminum and lithium-bearing minerals and special structural and geological factors. iv. According to China's national standards on grades of lithium content in coal seams, the metallogenic belts of lithium in coal seams at the southern foothill of Yin Shan and in Qilian-Qinling have the potential of lithium development and extraction, covering Junger mining area in Inner Mongolia, and Pingshuo and Ningwu mining areas in Shanxi.

KEYWORDS

lithium in coal seams, clean energy, China, lithium ore, development potential

1 Introduction

The soaring demand of lithium-ion batteries for new energy vehicles and stationary energy storages (Ma and Li, 2018; Zhong et al., 2018) needs to be supported by more supply of global lithium resources, the development of high-purity lithium products and low-cost lithium extraction methods (Wang and Chao, 2017; Yang et al., 2019). In 2007, the U.S. Congress listed lithium as strategic resources for U.S. economic development (Zhou et al., 2014). In 2009, the European Commission listed lithium as critical material for the economic development of Europe (Wang et al., 2014). The strategic importance of lithium resources has gradually become prominent. How to reasonably develop and utilize lithium resources may become the focus of global new energy competition in the 21st century (Zheng et al., 2007; Seredin et al., 2013; Su et al., 2019; Lunde Seefeldt, 2020). The coal resources in China are abundant and widely distributed. In recent years, lithium, germanium, gallium, rare earth and other strategic mineral resources have been found in coal seams. The comprehensive utilization of these associated

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resources is of great significance to guarantee the availability of emerging strategic mineral resources for China.

In a very long time, the lithium has not been developed from coal, which has not attracted much attention until 2008. Afterwards, many scholars in China (Liu Gangjun, Zhuang Xinguo, Sun Beilei, Yi Shu, Ning Shuzheng et al.) have analyzed the lithium content in coal with their focus on individual mining areas in China and have found an extraordinary enrichment of associated lithium in No. 4 and No. 9 coal seams of the Pingshuo Mining Area of Ningwu Coalfield, No. 2 and No. 8 coal seams in the Malan Mining Area of Xishan Coalfield, as well as No. 15 coal seam in the southern part of Jincheng Mine in Shanxi Province and No. 9, 10, and 11 coal seams of the Shenghui Mine of the Huoxi Coalfield, etc. By contrast, few scholars (Dai Shifeng et al.) have studied and analyzed the occurrence and distribution of lithium in coal seams in China from a broader perspective, and their studies are far from systematic and comprehensive. There are many deficiencies in basic research and application study, since research in this regard is still at the primary stage and the research issues are complex and difficult.

On the basis of systematic analysis of literature about lithium resources in coal seams, this paper discusses the occurrence, enrichment factors, availability of lithium resources in coal seams in China. It supplement basic research on lithium resources in coal seams in China. According to national standard *Guidance for Utilization and Classification of Content of Valuable Elements in Coal,* the metallogenic belts with highest development potential are determined, which is conducive to the forecast, exploration and development of lithium deposits in coal. This provides a reference to explore, develop and utilize lithium resources in coal seams in China and points out one pathway for circular economy of coal resources, which is of great significance to ensure China's resource security.

2 Distribution of lithium resources in China

China is rich in lithium resources. According to China Mineral Resources released by the Ministry of Natural Resources, P.R.C., China's lithium reserves in 2022 is 4,046,800 tons (lithium oxide) and is mainly concentrated in Qinghai Province, Sichuan Province and Tibet Autonomous Region, accounting for about 90% of lithium reserves in China. In addition, there are also lithium resources identified in Jiangxi Province, Henan Province, and Xinjiang Uygur Autonomous Region. The salt-lake lithium resources account for more than 80% of the industrial reserves of lithium in China and are mainly distributed in Qinghai and Tibet (Li H et al., 2014). Lithium ore mainly include spodumene and lepidolite, of which spodumene type is mainly distributed in Sichuan Province and Xinjiang Uygur Autonomous Region, and lepidolite type is mainly in Jiangxi Province (Li J et al., 2014; Qi et al., 2014).

Although China is rich in lithium resources, its resource endowment is poor and the industrial development cost is high. Therefore, the development of lithium resources in China stays in a very low level. According to USGS, although China's lithium output ranks third around the world in 2022, it only accounts for about 15% of the total global production (USGS, 2023). The largest granitic pegmatite-type lithium deposit is located in Aba Prefecture and Ganzi Prefecture of Sichuan Province (Liu et al., 2017), but bad transportation along with other constraints of this area hinder the development of lithium resources. In Jiangxi Province, the lepidolite content is quite low and lithium extraction cost is high. In Qinghai Province, there are many associated elements such as boron, potassium, magnesium and sodium in Qinghai Salt Lake, with high magnesium content and low lithium content. Bad weather makes the development of the lithium production in this region discontinuous. The salt lakes in Tibet have high lithium content (Sun et al., 2010), but the climate there is quite harsh.

The biggest problem in the development of lithium resources in salt lakes in China is the high Mg/Li ratio and high lithium extraction cost (Sun et al., 2012), for which technological breakthroughs need to be made. Therefore, the domestic lithium production cannot meet the demand in the short term, and import from overseas market is still needed for a certain period of time in the future.

In recent years, high content of associated lithium have been found in coal seams in China, especially in Junger Coalfield in Inner Mongolia and Ningwu Coalfield in Shanxi Province (Sun et al., 2010; Dai et al., 2012a), which makes associated lithium deposits in coal seams or coal strata an ideal alternative for the exploration of lithium resources. This is of great practical significance for further improving the availability of lithium resources in China.

3 Metallogenic age of lithium resources in coal seams

From the 1950s–1970s, some researchers from coal industry and mineral resources departments of China surveyed elements in coal during geological survey. In the recent 2 decades, people have conducted in-depth research on the enrichment mechanism and environmental impact of trace elements in coal. The metallogenic theories and practical utilization of germanium is the most in-depth studied and best used element among all valuable trace elements in coal. Large or super large coal germanium deposits including those in Lincang, Yunnan Province and Wulantuga, Inner Mongolia have been discovered (Sun et al., 2010; Pu et al., 2012). Many geologists have also analyzed the concentration of lithium in coal. For example, in Junger Coalfield, the average content of lithium in coal seams in the Harwusu Coal Mine is 116 mg/kg (Li H et al., 2014; Ning et al., 2017) and that in Heidaigou Coal Mine is 143 mg/kg. In Guanbanwusu Coal Mine, the average content of lithium in coal seams is 264 mg/kg, and even up to 1320 mg/kg (equivalent to 0.28% Li_2O) in coal ash (Sun et al., 2010; Jin, 2014; Sun et al., 2014). In Jungar No. 6 primary mineable coal bed, there is a super large lithium deposit (Qin et al., 2015; Zhu et al., 2016). Extraordinary enrichment of lithium has also been found in Ningwu Coalfield (Li H et al., 2014; Liu and Ming-yue, 2014; Shu and Wang, 2014), of which the average content of lithium in coal seams No. 4 and No. 9 in Pingshuo Mining Area is 128.27 mg/kg and 152 mg/kg respectively (Liu, 2007; Liu et al., 2019). However, significant progress has not been made in terms of metallogenic theories.

Many Chinese scholars have studied the distribution characteristics of lithium resources. In the first, Sun Shenglin et al. (2014) reviewed the distribution of lithium resources in coal seams in China. Zhu et al. (2016) studied the types and distribution of coal-hosted metal deposits in North China. Ning et al. (2017) made statistics on the lithium content in 25 coal mines along with studies on its metallogenic age and characteristics in Inner Mongolia, Shanxi, Henan, Chongqing and Guangxi Province. The

TABLE 1 Lithium content in coal seams in China (10^{-6}) (Sun et al., 2013a; Li H et al., 2014; Sun et al., 2016; Zhu et al., 2016; Ning et al., 2017).

Province	Coal field/mining area/mine field	Era	Minimum	Maximum	Average
Inner Mongolia	Jungar Mining Area	C_2	1.1	601	114
	Heidaigou Coal Mine in Junger mining Area	C_2	12	657	143
	Guanbanwusu Coal Mine in Junger mining Area	C_2	80	566	264
	Harerwusu Coal Mine in Junger mining Area	C_2	0.1	470	116
	Zhuozi Mountain Mining Field	C_2	38	203	105
Shanxi Province	Pingshuo Mining Area	P_1	13	211	128
		C_2			152
		C_2	94	506	238
	Anjialing Coal Mine Pingshuo Mining Area	P_1	42	196	117
		C_2	60	840	230
	Antaibao Coal Mine Pingshuo Mining Area	P_1	66	141	116
		C_2			144
		C_3	50	141	121
	JingGong No.1 Underground Coal Mine Pingshuo Mining Area	P_1	86	199	141
		C_2			139
	JingGong No.2 Underground Coal Mine Pingshuo Mining Area	P_1	83	211	113
		C_2			176
	JingGong No.3 Underground Coal Mine Pingshuo Mining Area	C_2			96
	Jincheng Mining Area	C_2	183	199	188
	HuoXi Coal Field Shenghui Coal Mine	C_2	65	154	94
	Xishan Coal Field	C_2	259	302	286
Henan Province	ShaanMian-Jiyuan Xin'an Mine	P_1	57	101	83
	Guhanshan Coal Mine in Jiaozuo	P_1	30	97	48
Chongqing	Nanwu Mining Area	P_3	17	257	96
	Nantong Mining Area	P_3	103	171	131
Guangxi Province	Fusui Coalfield	P_3	13	355	188
Gui Zhou Province	Liuzhi-Shuicheng Mining Field	P_3	9	105	28

content of lithium in coal seams in China are shown in Table 1. It is not difficult to know from Table 1 that coal-hosted lithium deposits discovered so far in China mainly occur in the Carboniferous-Permian strata of North China and Permian strata of South China. They are less concentrated in smaller range in the Permian strata of Qilian-Qinling.

4 Occurrence characteristics of lithium resources in coal seams

Some scholars have studied the occurrence and enrichment of lithium resources in coal seams. Zhuang Xinguo et al. (2001) conducted a study on trace element characteristics of Late Permian coal seams of Liuzhi Coalfield and Shucheng Coalfield in Guizhou Province and concluded that lithium in coal seams may have affinity for aluminosilicate; Sun et al. (2012) suggested that high concentration of lithium in coal seams has a close relationship with inorganic matter; Dai et al. (2012b) found that the occurrence of lithium in Guanbanwusu Coal Mine is mainly closely associated with aluminosilicate minerals in coal seams; Liu and Ming-yue. (2014) and Wang, (2018) studied on the enrichment mechanism of lithium in No. 9 stable minable coal of Pingshou Mining Area of Ningwu Coalfield and concluded that lithium is overwhelmingly enriched in inorganic matter and rarely enriched in organic matter. In a study conducted by Lewinska Preis et al. (2009) on trace

TABLE 2 Occurrence of lithium in some coal seams in China.

Scholars	Coal mines	Mechanism of occurrence and enrichment	Relationship with inorganic matter	Relationship with organic matter	Related minerals
Wang and Zhang. (2019)	Guanbanwusu Coal Mine of Junger Coalfield, Ordos Basin	Enrichment of lithium in high-grade coal is related to silicates	Related with silicates	—	Silicate
Dai et al. (2012a)	Guanbanwusu Coal Mine of Junger Coalfield, Ordos Basin	Lithium occurrence is closely related to aluminum silicate	Closely related with aluminum silicate	—	Aluminum silicate
Dai et al. (2012b)	Pingshuo Mining Area in Ningwu Basin	Lithium enrichment is closely related to aluminum containing minerals such as kaolinite	Related with aluminum containing minerals	—	Aluminum containing minerals such as kaolinite
Liu and Ming-Yue. (2014), Wang. (2018)	Pingshuo Mining Area in Ningwu Basin	The vast majority of lithium enrichment is closely related to inorganic matter	Related with inorganic substances and clay minerals	Weak relationship with organic matter	Kaolinite, quartz, calcite, pyriteetc.
Sun et al. (2010), Liu et al. (2017), Shu and Wang. (2014), Zhuang et al. (1998)	Pingshuo Mining Area in Ningwu Basin	Lithium is mainly presented in aluminosilicates, with fewer organically bound lithium elements	Related with iorganic matter, especially silicates; weak relationship with organic matter		Silicoaluminate, organic matter
Sun et al. (2012)	—	High concentration lithium is closely related to inorganic matter	Related with inorganic matter	—	Inorganic matter
Zhuang Xinguo et al. (2001)	Guizhou Liuzhi and Shuicheng Coalfields	Lithium has an affinity for aluminosilicates	Having an affinity for aluminosilicate	—	Inorganic silicoaluminate
Lewinska-Preis et al. (2009)	Spitsbergen District, Norway	Related with minerals	Related with minerals	Having an affinity for organic matter	—
Lucyna et al. (2009), Lei et al. (2015b)	Longyearbyen Mine Norway	72% of lithium combined with organic matter	—	Combining with organic matter	—
Swaine, (1990)	—	Lithium may be absorbed by clay minerals	Related with clay minerals such as kaolinite	—	Clay minerals such as kaolinite

elements in coal from the Kaffioyra and Longyearbyen coal mines in the Spitz Bergen, Norway, it is shown that lithium in coal from the former is 100% associated with minerals, whereas lithium in coal from the latter shows a high affinity for organic matter (concentration value of 72%). Swaine (1990) held that lithium can be absorbed by clay minerals such as kaolinite.

The research on lithium resources in coal seams at home and abroad is still at the primary stage. According to the existing data, lithium in coal is mainly related to inorganic components in coal, but it is also related to organic matter (Pougnet et al., 1985; PEI et al., 2018). Liu and Ming-yue. (2014) believed that the lithium in No. 9 coal mine in Pingshuo mining area of Wu Coalfield is mainly enriched in inorganic substances while only about 5.5% of lithium has an affinity for organic substances. These inorganic minerals are kaolinite, boehmite, chlorite group minerals, quartz, calcite, pyrite and amorphous clay minerals. In lithium bearing coal seams, lithium may be adsorbed by clay minerals; Dai et al. (2012a) and Wang and Zhang. (2019) also reached a similar conclusion on the enrichment of lithium in Guanbanwusu Coal Mine in Jungar Coalfield and believed that 80% of lithium in high-grade coal is related to silicate, while 60% of lithium in low-grade coal is related to silicate. However, in Longyearbyen Coal Mine in Norway, 72% of lithium is combined with organic matter (Lucyna et al., 2009; Lei et al., 2015a).

According to the existing research findings, among all the lithium bearing coalfields, the Ningwu Coalfield in Shanxi Province is the one that has been thoroughly studied. Particularly, the occurrence of lithium in stable minable coal seams No.4 and No.9 of Pingshuo mining area have been deeply studied by many scholars (Zhuang et al., 1998; Sun et al., 2010; Shu and Wang, 2014; Liu et al., 2017). In Pingshuo mining area, coal seam No.4 is the main minable coal seam (He, 2006; Sun et al., 2013b), of which the maximum value of lithium content is 211.28 mg/kg (Sun et al., 2012); The maximum value of lithium content in coal seam No.9 in Pingshuo mining area is 840 mg/kg, with an average value of lithium content of 152 mg/kg (Sun et al., 2010; Dai et al., 2012b). The results of SCEP analysis of coal samples show that the lithium in coal samples mainly exists in silicate, with a content value up to 482 mg/kg, while the value of lithium bonded in organic matter is only 32 mg/kg. The data show that lithium in coal seam No.9 is closely associated with inorganic matter, especially silicate, but is less closely associated with organic matter (Shu and Wang, 2014) (Table 2).

In a word, coal-hosted lithium often occurs in aluminosilicate minerals. In addition, it may be adsorbed by clay minerals such as kaolinite, boehmite, chlorite group minerals, quartz, calcite, pyrite and clay-like amorphous minerals. In summary, China's lithium in coal seams is mainly enriched in inorganic matter, especially the aluminosilicate minerals, but not likely in organic matter. This study provides the insight into distribution and enrichment of lithium in coal seams and the reference for relevant study.

5 Geological factors for lithium enrichment in coal seams

According to the existing research findings, coal-hosted lithium mainly occurs in aluminum containing minerals and has similar metallogenic conditions with gallium. The geological factors for lithium enrichment in coal seams are: stable supply of aluminum and lithium sources, special tectonic and geological background, continuously and stable weathering and denudation and continuous movement of surface water. The coal-hosted lithium mainly occurs in aluminosilicate minerals and is greatly affected by weathering crust. It is difficult for lithium element to concentrated in nature and there is a series of long geological process before high concentration of Li occurs. For example, according to research on coal-hosted lithium in Pingshuo mining area by Liu and Ming-yue. (2014), Li H et al. (2014) and Shu and Wang, (2014), Ningwu basin is in an blocked bay where the coal seams have been developed for a long time without or with little interference, and it is a favorable place for peat accumulation and formation of lithium-rich coalfields. (Fan et al., 2018).

Sun Y Z et al. (2010) believe that there are three enrichment modes of lithium in coal seams: i. lithium is only enriched in seam roof, seam floor and vein rock, but not enriched in coal seams, such as in the case of the Tongxing Coal Mine in Henan Province; ii. lithium is not only enriched in seam roof, seam floor and vein rock, but also enriched in coal seams, such as in the case of Antaibao Coal Mine in Shanxi Province; iii. the lithium content in both coal samples and gangue samples is rather low, such as in the case of the Adohai Coal Mine.

In sum, lithium enrichment in coal seams is caused by stable supply of aluminum and lithium-bearing minerals and special structural and geological factors such as continuous weathering-denudation. The enrichment patterns vary in different metallogenic belts. Some lithium only occurs in the rock or is enriched both in rock and coal. Understanding these geological factors and enrichment pattern is of great significance for lithium exploration and development.

6 Evaluation of availability of lithium in coal seams

To evaluate the availability of lithium resources in coal seams, the following factors need to be considered: i. Whether lithium is abnormally enriched and whether there is mineralization on a scale; ii. How lithium exists in coal directly affects its availability and thus the difficulty of extraction. It may exist in ionic state, compound form or be adsorbed by certain minerals. Different forms of existence correspond to different levels of likelihood and efficiency of lithium extraction; iii. the behavior of lithium in the combustion process and its degree of enrichment in products of coal combustion. Since lithium is extracted from coal combustion products, the coal ash yield is an important parameter to evaluate lithium grade in coal (Dai and Robert, 2008); iv. Whether it is technically and economically feasible to develop and utilize lithium in coal. The extraction cost and technical feasibility are important factors in availability evaluation. In short, the availability of lithium in coal is affected by many factors, which should be considered for comprehensive evaluation.

Besides, environmental and economic sustainability should be considered in the extraction of lithium from coal. For the environmental aspect, the extraction process has a far-reaching impact on water resources, soil and air, especially when dealing with waste and tailings. In particular, the release of heavy metals may pollute water and affect aquatic ecosystems. A waste management system should be established to effectively separate, categorize and treat waste and tailings. Efficient waste treatment technologies should be adopted, such as solidification and resource recycling, to reduce the negative impacts on water resources, soil and air. In addition, since harmful elements are oftentimes enriched in coal-hosted lithium deposits, their distribution, forms of existence and formation mechanism should be studied to reduce environmental pollution and harm to human health in the process of lithium extraction, development and utilization (Dai et al., 2014). As for the economic aspect, the cost of extraction, technical feasibility, market demand and price fluctuations have a direct impact on economic sustainability. Besides lithium, other beneficial metal elements such as rare earth elements, gallium and silicon should be extracted together with lithium to improve the utilization efficiency of resources, reduce costs and realize industrial production (Xu et al., 2021). In addition, the study on their migration from coal to coal ash, existing forms and availability matters for the comprehensive development and utilization of coal ash and circular economy of coal industry. The advanced technology and experience of lithium extraction at home and abroad should be learned and introduced. In line with the concept of reduction, reuse and zero emission advocated by circular economy, technologies suitable for lithium extraction from coal ash should be effectively applied, which can reduce the cost, increase profit margin, and better serve the national economy.

In summary, a comprehensive evaluation is tremendously required to make extraction of lithium from coal environmentally and economically sustainable in order to gain utmost economic benefits and to protect environment at the same time. This involves scientific and effective waste treatment methods, clear environmental policies, efficient extraction technologies and market surveys. Such a comprehensive evaluation not only helps the sustainability of the extraction process, but also strategically guide the development of related industries.

According to China's *Guidance for Utilization and Classification of Content of Valuable Elements in Coal (GB/T 41042-2021)* published in 2021, basic technological property, major uses, occurrence states of coal, and symbiosis with other elements, and occurrence and distribution of harmful elements hindering extraction of valuable elements should be considered in utilization of coal with extremely high content of valuable elements. The conditions such as seam thickness, occurrence, scale and structure, and effects of production and processing methods on the coal quality should be considered.

The delineation of metallogenic belts of coal-hosted lithium provides a basis to evaluate the feasibility in tapping the potential of lithium resources in coal seams. According to study on China's coal-hosted metal metallogenic belts by Ning et al. (2019), the lithium resources in coal seams are divided into three metallogenic belts: i. the metallogenic belt at the southern foothill of Yin Shan. This metallogenic belt contains the southern Inner Mongolia Autonomous Region, the northern Shanxi Province, as well as a

TABLE 3 Grades of lithium content in coal seams.

Grades	No.	Lithium content in coal seams ω(Lid)/(μg/g)
Low lithium-content coal	Li-1	ω(Lid)≤10
Medium lithium-content coal	Li-2	10<ω(Lid)≤50
High lithium-content coal	Li-3	50<ω(Lid)≤120
Extra high lithium-content coal	Li-4	ω(Lid)>120

TABLE 4 Classification of lithium content in coal seams of some mining areas in China.

Classification	Province	Coalfields/mining areas/mine fields	Average value
Extra high lithium-content coal	Inner Mongolia	Heidaigou Coal Mine in Junger Mining Area, Guanbanwusu Coal Mine in Junger Mining Area	143,264
	Shanxi	Pingshuo Mining Area, Anjialing Coal Mine in Pingshuo Mining Area, Antaibao Coal Mine in Pingshuo Mining Area, JingGong No.1 Underground Coal Mine In Pingshuo Mining Area, JingGong No.2 Underground Coal Mine in Pingshuo Mining Area, Jincheng Mining Area, Xishan Coalfield	128, 152, 238, 230, 144, 141, 139, 176, 188, 286
	Chongqing	Nantong Mining Area	131
	Guang Xi	Fusui Coalfield	188
High lithium-content coal	Inner Mongolia	Jungar Mining Area, Harwusu Coal Mine in Junger mining Area, Zhuozi Mountain Coalfield	114, 116, 105
	Shanxi	Anjialing Coal Mine of Pingshuo Mining Area, Antaibao Coal Mine of Pingshuo Mining Area, JingGong No.2 Underground Coal Mine of Pingshuo Mining Area, Jing Gong No.3 Underground Coal Mine of Pingshuo Mining Area, Shenghui Coal Mine of HuoXi Coalfield	117, 116, 113, 96, 94
	He Nan	ShaanMian-Jiyuan Xin'an Mine in Henan	83
	Chongqing	Nanwu Mining Area	96
Medium lithium-content coal	Henan	Guhanshan Mine in Jiaozuo	48
	Guizhou	Liuzhi-Shuicheng Coal Field	28

part of Hebei Province. It includes the coal bearing belt at the north edge of North China, the Yimeng coal bearing belt, the northern Xian Province coal bearing belt, the western Xian Province coal bearing belt, and the western edge of the Erdesian basin coal bearing belt (Zhu et al., 2016). ii. the Qilian-Qinling metallogenic belt. This metallogenic belt contains the western Henan, central Shaanxi, Gansu, and Qinghai Province, including Songqi coal bearing belt, Weibei coal bearing belt, west edge of the Erdos Basin coal bearing belt, Qilian coal bearing belt and the Chaibei coal bearing belt. The lithium outlier in coal seams is mainly distributed in the Permian coal beds of Shandong and Henan Province. iii. the metallogenic belt in Sichuan, Yunnan, Guanxi Province. This metallogenic belt is located in the southwestern part of China, mainly including Sichuan, Chongqing, Guangxi, Guizhou, and contains Longmenshan inverted depression coal bearing belt, uplift coal bearing belt in central and southern Sichuan, Kangdian fault uplift coal bearing belt, fold coal bearing belt in eastern Yunnan, and the Youjiang fold coal bearing belt. The lithium outlier in coal seams is mainly distributed in the Permian seams in Chongqing, Guangxi and Guizhou (Liao et al., 2020).

Lithium content in various mining areas was analyzed with consideration of aforementioned delineation of metallogenic belts of coal-hosted lithium and grades of lithium content in coal seams (Table 3). It is found that extra high lithium-content coal, high lithium-content coal, and medium lithium-content coal are distributed in all metallogenic belts (Table 4). The extra high lithium-content coal is distributed in the metallogenic belt at the southern foothill of Yin Shan and in Qilian-Qinling and is concentrated in Junger Mining Area in Inner Mongolia, Pingshuo Mining Area in Shanxi, Nantong Mining Area in Chongqing, and Fusui Coalfield in Guangxi. The high lithium-content coal is distributed in the metallogenic belt at the southern foothill of Yin Shan and in Qilian-Qinling, covering Junger Mining Area in Inner Mongolia, Pingshuo Mining Area in Shanxi, ShaanMian-Jiyuan Xin'an Mine, and Nanwu Mining Area in Chongqing. The medium lithium-content coal is distributed in the metallogenic belts in Qilian-Qinling and in Sichuan-Guizhou-Guangxi, covering Guhanshan Mine in Henan and Liuzhi-Shuicheng Coalfield in Guizhou. According to the requirements of content ω(Li_d)>50 μg/g for lithium extraction in the standard, the average content of 50 μg/g in extra high and high lithium-content coal meet the requirements for extraction, while the average content less than 50 μg/g cannot meet the requirements for extraction. The metallogenic belts of lithium in coal seams at the southern foothill of Yin Shan and in Qilian-Qinling have the potential of lithium development and extraction. In addition, according to previous research, China's Junger Coalfield, Ningwu Coalfield, and Qinshui Coalfield have great potential in commercial development of lithium in coal seams. The predicted lithium resources in Junger Coalfield is about 3 million tons; The associated lithium ore reserves in coal seam No. 9 in Pingshuo Coalfield is about 560,000 tons (Dai et al., 2014); the resource of Li_2O in No. 15 coal seam in Qinshui Basin is 55,600 tons (Lei et al., 2022). Thus, the belts with development potential are distributed in Junger Mining Area in Inner Mongolia, Pingshuo Mining Area, Ningwu Coalfield, Qinshui Coalfield in Shanxi, ShaanMian-Jiyuan Xin'an Mine in Henan, and Nantong Mining Area in Chongqing.

7 Conclusion

1. China's lithium resources in coal seams are mainly hosted in the Carboniferous Permian coal in North China and secondarily in the Late Permian coal in South China. They are less concentrated in smaller range in the Permian strata of Qilian-Qinling.
2. Coal-hosted lithium is often enriched in aluminum containing minerals. Lithium in coal seams generally occurs in inorganic matter, with a small part occurring in organic matter. These inorganic minerals are kaolinite, boehmite, chlorite family minerals, quartz, calcite, pyrite, and amorphous clay minerals.
3. Lithium enrichment in coal seams is caused by stable supply of aluminum and lithium-bearing minerals and special structural and geological factors such as continuous weathering-denudation. The enrichment patterns vary in different metallogenic belts. Some lithium only occurs in the rock or is enriched both in rock and coal.
4. Based on previous delineation of metallogenic belts of coal-hosted lithium and grades of lithium content in coal seams, the metallogenic belts at the southern foothill of Yin Shan and in Qilian-Qinling have the potential of lithium development and extraction, covering Junger Mining Area in Inner Mongolia, Pingshuo Mining Area, Ningwu Coalfield, Qinshui Coalfield in Shanxi, Shanmian-Jiyuan Xin'an mine in Henan, and Nantong Mining Area in Chongqing. This finding provides the insight into theoretical study and exploration and development of lithium in coal seams. It is recommended to focus on these two metallogenic belts in exploration and carry out geological survey in Junger Mining Area in Inner Mongolia and Pingshuo Mining Area in Shanxi. In addition, a comprehensive survey of metal elements associated with coal, gangues, and argillaceous rocks in coal seams should be conducted in all large-scale coal fields in China. In such a survey, attention should be paid to aluminous strata. In addition to lithium, other resources which include germanium, gallium, rare earth and other scattered rare metals should also be surveyed so as to find their new metallogenic prospects and ensure the sustainable exploration and development of these resources. It is suggested that belts for development and utilization of lithium and other scattered rare metals in coal seams should be strategically proposed in China as soon as possible with scientific planning and optimization of resources. In this way, associated elements in coal can be utilized to support comprehensive development of strategic emerging mineral resources. And last but not least, industrial structure should be adjusted and improved through the horizontal synergy of multiple industries, the vertical extension of the industrial chain, and the improved waste recycling system. Large poly-generation strategic bases should be established to extract strategic metals from coal, so as to promote the utilization of multiple resources and efficiency in resource utilization, waste recycling, and by-product utilization. In doing so, environmental pollution can be reduced, and the efficient use of clean energy and strategic transformation can be promoted.

Author contributions

CL: Conceptualization, Writing–original draft, review and editing; TZ: Writing–review and editing, Supervision, Funding acquisition; GW: Conceptualization, Formal analysis; DC: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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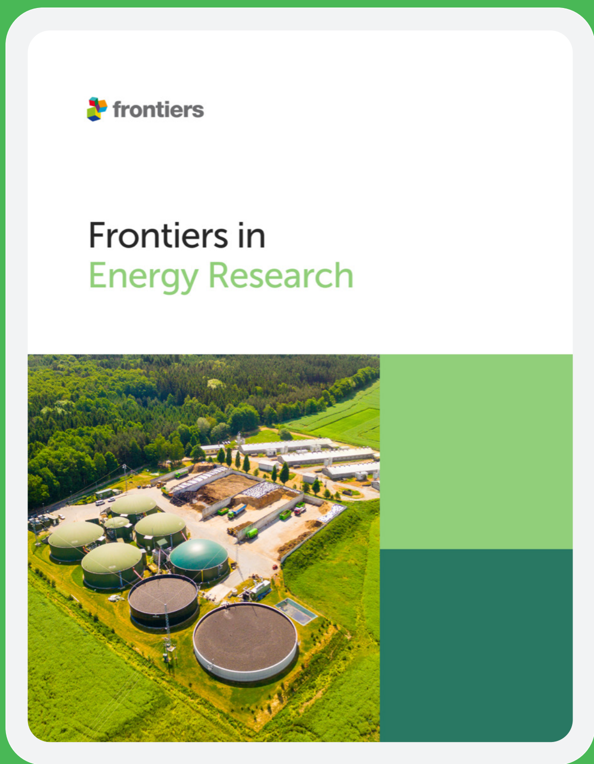

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