GOSPODARKA SUROWCAMI MINERALNYMI – MINERAL RESOURCES MANAGEMENT

2026 Volume 42 Issue 1 Pages 93–117

DOI: 10.24425/gsm.2026.158273

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Assessment of China's nickel resource supply security based on the CRITIC-TOPSIS Model

Introduction

Mineral resources are not only the key material foundation for economic and social development but also an important safeguard for national security and national economic development (Wu 2014). Currently, China is in a new stage of socialist construction, where transformations in economic growth patterns and power sources are profoundly affecting the situation of mineral resource security (Cheng et al. 2018; Zuo et al. 2021). The deepening globalization, intensifying technological advancements, and industrial chain competitions, as well as continuous changes in the international political and economic landscape, have led to constant adjustments in the supply and demand dynamics of the global mining market (Wang et al. 2018; Yan et al. 2021). Frequent occurrences of "grey

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rhinoceros" and "black swan" events, as well as the rise of anti-globalization sentiments and resource nationalism, have significantly increased the uncertainty of resource supply disruptions (Wu and Xue 2019; Hong 2018). These changes necessitate a reexamination of the connotations and requirements of mineral resource security and the exploration of ways to achieve coordinated development between mineral resource exploitation and socio-economic conditions in a turbulent international environment (Yu 2021, 2023). Nickel, in particular, as a strategic mineral resource with unique physicochemical properties, is widely used in the defense industry, renewable energy, and high-tech fields. It is a foundational material for national economic construction and is known as the "industrial vitamin" due to its extensive application in the stainless steel industry (Wu et al. 2020; Yu 2019). However, as the largest consumer and importer of nickel resources globally, China faces challenges such as high demand, high external dependence, and volatile prices, all of which pose direct threats to China's nickel resource security. Therefore, objectively understanding the impact of new global changes on nickel resources, deeply analyzing the new domestic economic security needs under the new normal, and identifying the main factors affecting China's nickel resource supply security have become important prerequisites for alleviating the pressure on China's nickel resource supply and ensuring resource security.

The origin of research on mineral resource supply security dates back to World War I, initially focusing on ensuring the stable supply of key raw materials (Ray 1984; Anderson 1988; Harker and Lutz 1990; Sovacool et al. 2012). As the global resource landscape and political-economic landscape continue to evolve, the interactions between mineral resources and social, economic, and environmental factors throughout their lifecycle have become increasingly complex, making mineral resource security issues more multidimensional and dynamic (Glöser et al. 2015; Werner et al. 2023). Consequently, contemporary mineral resource supply risks involve not only environmental, economic, and social factors but are also closely related to macro-factors such as geopolitics (Shen et al. 2004; Hatayama and Tahara 2015; Que and Yan 2024). Given the diversity and complexity of factors influencing mineral resource risks, the academic community has gradually shifted towards adopting quantitative methods for resource security research. Researchers have established a series of evaluation indicators for mineral resource supply security to systematically analyze the sources of supply security, influencing factors, and mitigation strategies. Common evaluation indicators for mineral resource supply security include geological risks (Hatayama and Tahara 2015; Zhu et al. 2021), technological risks (Gulley et al. 2018), economic risks (Hatayama and Tahara 2015; Gunnarsdottir et al. 2022), geopolitical risks (Rosenau-Tornow et al. 2009; Hatayama and Tahara 2015; Zhou et al. 2020), regulatory risks (Zhang et al. 2018; Zuo et al. 2021), and social risks (Gulley et al. 2018; Jasiński et al. 2018; Zhu et al. 2020).

Early evaluation models for mineral resource supply security primarily employed qualitative methods, resulting in non-quantifiable outcomes with strong subjectivity and failing to objectively reflect the degree of risk associated with key indicators (Hu et al. 2004, 2005). To enhance the objectivity of evaluation results, scholars have introduced quantitative evaluation methods. Common evaluation models include the Analytic Hierarchy Process (AHP) (Zheng and Kai 2007), which hierarchically structures problems and constructs judgment matrices to calculate weights and derive results. Although it is systematic and can combine qualitative and quantitative analyses, it has high subjective dependence and requires strict consistency checks. The Fuzzy Comprehensive Evaluation Mode (Hu et al. 2022), based on fuzzy mathematics membership theory, can handle fuzzy and uncertain problems and offers flexible evaluation, but the determination of membership functions is subjective and requires high-quality data. The Grey Relational Analysis Model judges impacts based on the correlation of development trends between factors, requires low sample sizes, and is computationally simple, but it ignores factor weights and is affected by data distribution. The BP Neural Network Model is trained using the backpropagation algorithm (Ruan et al. 2018), has self-learning and strong nonlinear mapping capabilities, and can be used for predictive evaluation, but it requires long training times and is prone to local optimal solutions. As research progresses, scholars have gradually recognized the limitations of single models and begun attempting to integrate multiple models for wider application, such as the Dempster-Shafer-fuzzy AHP Model, the AHP-TOPSIS Model, the SWOT-AHP Model, the Fuzzy TOPSIS Model, and others (Pahlavani et al. 2020; Fang et al. 2021; Amiri et al. 2024).

Although domestic and foreign scholars have conducted detailed research on mineral resource supply security and achieved some results, there are inevitably some issues:

1. Research primarily focuses on energy minerals, with relatively low attention paid to the security of important solid non-energy minerals, especially nickel resource supply security. Research outcomes on nickel resource supply security are scarce, mainly concentrating on trade security or analyzing nickel resource supply security from a single perspective, lacking systematic evaluations.
2. The selection of evaluation indicators does not consider the current national development context and situational requirements, as well as the characteristics of nickel ore.
3. Research methods often adopt subjective weighting methods limited by evaluators' experience, failing to ensure the objectivity of comprehensive evaluation results.

To address these three issues, this paper establishes an evaluation index system for nickel resource supply security in line with China's national development conditions from three dimensions: global supply stability, domestic economic security, and co-existence of optimal. The CRITIC-TOPSIS model is employed to enhance the objectivity and authenticity of evaluations. By assessing the nickel resource supply security situation and evolutionary trajectory through evaluation results, this paper deeply analyzes supply risk points and proposes forward-looking policy recommendations to strengthen China's nickel resource supply security, promote sustainable nickel resource development, and enhance supply chain resilience.

1. Research method

1.1. Indicator system

Early definitions of mineral resource supply security emphasized a country's ability to consistently obtain resources at reasonable price levels (Leung 2011), along with factors such as technological advancements (Sebitosi 2008; Ang et al. 2015), energy efficiency improvements (Kemmler and Spreng 2007), geopolitics (Leung 2011; Sharifuddin 2014), and environmental risks (Luo and Huan 2010; Blum and Legey 2012). With rapid economic development and constant changes in both domestic and international situations, the risks to mineral resource supply security mainly originate from various aspects, including resource production, consumption, circulation, environmental protection, and international trade (Galos et al. 2021). Therefore, in the context of China's new development paradigm and considering the characteristics of nickel resources, this study summarizes the factors to consider for nickel resource supply security as follows: with national resource security as the goal and harmonious coexistence as the principle, it is necessary to coordinate national security with global common security. This involves not only considering the stability or effectiveness of domestic supply and price affordability or volatility but also taking into account global environmental governance and sustainable development issues, while comprehensively considering the dual synergy between national institutions and market forces (Figure 1).

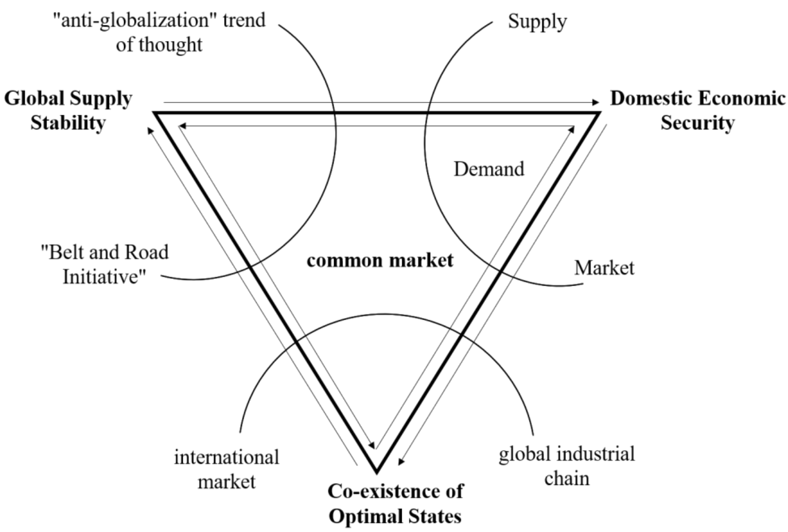

Fig. 1. Model of China's nickel resource supply security system

Rys. 1. Model chińskiego systemu bezpieczeństwa dostaw niklu

Table 1. Indicator System and Calculation Method for Assessing Security Risks of Nickel Resources in China

Tabela 1. System wskaźników i metoda obliczania oceny ryzyka bezpieczeństwa zasobów niklu w Chinach

Primary indicator	Secondary indicator	Tertiary indicator	Indicator direction	Indicator description	Indicator calculation and data sources	Unit
Global Supply Stability (GSI)	Resource Endowment	Resource Supply Potential (GSI01)	+	The recoverable life of global remaining resources is used to reflect the degree of resource supply security	$GSI01 = \sum \frac{R}{P}$ R represents the global nickel reserves, and P represents the global nickel production. Data on global nickel reserves and production are sourced from the USGS.	Years
	Resource Country Risk	Social Development Level (GSI02)	+	Impact of the resource country's socio-economic development status on resource supply	$GSI02 = \sum HDI_i \cdot \frac{P_i}{P}$ The Human Development Index (*HDI*) published by the United Nations Development Programme (UNDP) is selected to measure the socio-economic development level of resource-producing countries. i represents a nickel-producing country, P_i denotes the nickel production of that country, and HDI_i represents the Human Development Index of the country that produces nickel. *HDI* data are sourced from the "Human Development Index", and historical nickel production data are sourced from the USGS.	HDI
		Mining Policy Maturity (GSI03)	+	Completeness of the resource country's mining regulations, environmental regulations, and tax management systems	$GSI03 = \sum PPI_i \cdot \frac{P_i}{P}$ The Policy Perception Index (*PPI*) published by the Fraser Institute is selected to quantify the policy and regulatory risks in global resource development. PPI_i represents the Mining Policy Insight Index of nickel-producing countries. *PPI* data is sourced from the "Annual Survey of Mining Companies".	PPI
		Environmental Risk (GSI04)	+	Under the background of international trade, the risks posed by the environmental regulations of resource countries to the global resource supply	$GSI04 = \sum EPI_i \cdot \frac{P_i}{P}$ It is measured using the Environmental Performance Index (*EPI*) released by Yale University. A higher score on the index indicates a lower risk in global nickel supply. *EPI* data is sourced from the "Environmental Performance Index".	EPI

Primary indicator	Secondary indicator	Tertiary indicator	Indicator direction	Indicator description	Indicator calculation and data sources	Unit
Global Supply Stability (GSI)	Geopolitics	Global Governance Capability (GSI05)	+	Active participation of resource countries in global governance can reduce geopolitical risks in resource supply	$GSI05 = \sum WGI_{i,n} \cdot \frac{P_i}{P} \quad (n = 1, 2, ..., 6)$ We select six governance dimensions recorded by the World Bank: Voice and Accountability, Political Stability and Absence of Violence, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption. Using the share of nickel production in nickel-producing countries as weights, we calculate the weighted average to obtain the annual global resource governance indicator. In the formula, *n* represents the governance index of nickel-producing country *i* in the *n*-th dimension released by the World Bank. WGI data is sourced from the "Worldwide Governance Indicators".	WGI
		Global Supply Concentration (GSI06)	–	The degree of concentration of resource supply sources	$GSI06 = \sum \left(\frac{P_i}{P}\right)^2$ This paper calculates the global supply concentration of nickel mines using the HHI index.	HHI
		Production-Consumption Balance (GSI07)	+	Matching degree between global resource supply capacity and demand capacity	The matching degree between global nickel supply and consumption is measured by the ratio of global nickel production to consumption. When the ratio is greater than 1, there is a global nickel surplus; when it is less than 1, there is a supply shortage. The consumption data of nickel is sourced from "China Nonferrous Metals Industry Yearbook".	–
Domestic Economic Security (DSI)	Supply	Domestic Resource Supply Potential (DSI01)	+	Domestic remaining resource life	Measured by the domestic nickel reserve-to-production ratio, which reflects the potential for resource supply. A higher reserve-to-production ratio indicates a higher degree of supply security and stability. China's nickel resource reserves and production data are sourced from the USGS.	Years
		Relative Resource Abundance (DSI02)	+	The degree of abundance of the country's mineral reserves	The ratio of a country's per capita reserves to the world's per capita reserves indicating the country's mineral resource abundance. The higher the abundance, the stronger the supply capacity. China's and the world's reserve data are sourced from the USGS.	–

Primary indicator	Secondary indicator	Tertiary indicator	Indicator direction	Indicator description	Indicator calculation and data sources	Unit
Domestic Economic Security (DSI)	Supply	Domestic Reserve Share of the World (DSI03)	+	Relative position of domestic resource endowment globally	This indicator is quantified by the ratio of domestic reserves to global reserves. The data for domestic and global reserves are sourced from the USGS.	%
		Nickel Ore Production as a Percentage of the World (DSI04)	+	Relative position of domestic supply capacity globally	The ratio of China's nickel ore production to the world's total production. The data for China's nickel ore production and the global total production are sourced from the USGS.	%
		Refined Nickel Production as a Percentage of the World (DSI05)	+		The ratio of China's refined nickel production to the world's total production. The data for global refined nickel production are sourced from the "World Metal Statistics Yearbook". China's refined nickel production data are sourced from the China Nonferrous Metals Industry Association.	%
		Substitutability (DSI06)	–	Potential for resources to be substituted by other resources in end-use sectors	Due to nickel's unique properties, there are limited options for substitutes. Ju et al. (2022) assessed the non-substitutability of nickel mines and concluded that nickel can only be partially substituted. Generally, the difficulty of substitution is divided into four levels: 0 represents that complete substitution can be easily achieved without increasing additional costs; 0.3 represents low substitution costs; 0.7 represents a higher substitution cost or a larger performance loss; 1 indicates that substitution is impossible. Therefore, this paper sets the substitutability of nickel at 0.7.	–
		Recyclability (DSI07)	+	Scrap recovery rate	According to the UNEP "Recycling Rates of Metals", the scrap recovery rate of nickel is greater than 70%, which the author calculates as 0.7.	%
	Demand	Apparent Consumption Growth Rate (DSI08)	–	Domestic demand growth	$SI08 = \frac{(AC_n - AC_{n-1})}{AC_{n-1}}$ AC_n represents the apparent consumption of nickel in the n-th year. Reflecting domestic demand growth, nickel apparent consumption data is sourced from the "Comprehensive Statistics and Price Bulletin of Production, Supply, and Sales of Major Mineral Products in China".	%

Primary indicator	Secondary indicator	Tertiary indicator	Indicator direction	Indicator description	Indicator calculation and data sources	Unit
Domestic Economic Security (DSI)	Demand	Per Capita Nickel Resource Consumption (DSI09)	–	Actual domestic consumption of nickel resources	This represents the actual consumption of nickel resources domestically. A higher value indicates greater demand for nickel resources, potentially leading to supply shortages and increased insecurity in the nickel resource supply. The consumption data of nickel is sourced from "China Nonferrous Metals Industry Yearbook".	–
		Production-Consumption Gap (DSI10)	+	Domestic production's ability to meet demand	Represented by the difference between the sum of domestic nickel ore and refined nickel production and the apparent consumption of nickel.	t
		Price Volatility (DSI11)	–	Year-on-year change in domestic resource prices	$SI011 = \frac{(p_n - p_{n-1})}{p_{n-1}}$ p_n represents the domestic market price of nickel in the *n*-th year. Nickel price data for China is sourced from Wind database, using the average price of Nickel 1# from the Chang Jiang Nonferrous Metals Market as a measure. The price on the first trading day of each month is taken as the monthly price, and the average of these 12 monthly prices is used as the annual trading price of nickel in China to measure the average annual change in nickel prices in China.	–
		External Dependence Ratio (DSI12)	–	Ratio of net imports to apparent consumption	Represented by the proportion of net nickel imports to apparent consumption. The import data is sourced from the United Nations Comtrade Database.	–
	Market	Nickel Ores and Concentrates Import Concentration (DSI13)	–	Diversity of import sources	$DSI13 = \sum \left(\frac{M_{i,o}}{M_o} \right)^2$ $M_{i,o}$ represents the quantity of nickel ores and concentrates o imported by China from the *i*-th country, and M_o represents the total import volume of nickel ores and concentrates *o*. Nickel ores and concentrates are classified under HS code 260400 in the United Nations Comtrade Database, and the Herfindahl-Hirschman Index (HHI) is used to measure import concentration.	HHI

Primary indicator	Secondary indicator	Tertiary indicator	Indicator direction	Indicator description	Indicator calculation and data sources	Unit
Domestic Economic Security (DSI)	Market	Nickel-bearing Materials Import Concentration (DSI14)	–		$DSI14 = \sum\left(\frac{M_{i,q}}{M_q}\right)^2$ $M_{i,q}$ represents the quantity of nickel-bearing raw material q imported by China from the i-th country, and M_q represents the total import volume of nickel-bearing raw material q. Raw materials classified under HS codes 7501, 7502, 7503, 7504, 7505, 7506, 7507, 7508, etc., in the United Nations Comtrade Database, are evaluated for import concentration using the Herfindahl-Hirschman Index (HHI).	HHI
	Technology	Geological Research Level (DSI15)	+	Degree of geological exploration investment	Represented by the ratio of geological exploration investment to GDP. Geological exploration investment data is sourced from the “China Mineral Resources Report”. GDP data is sourced from the National Bureau of Statistics of China.	–
		Applied Technology Competitiveness (DSI16)	+	Reflects technological level in high-end applications of nickel	Represented by the ratio of authorized patents in high-end nickel application fields to the total number of authorized patents for nickel domestically. Greater applied technology competitiveness indicates a stronger ability to convert resource advantages into economic advantages. Data on authorized patents in high-end nickel application fields and the total number of authorized patents for nickel in China are sourced from the China National Intellectual Property Administration.	–
Co-existence of Optimal States (CEI)	Openness	Price Correlation (CEI01)	–	Correlation coefficient between domestic and foreign resource prices	Calculated using the DCC-GARCH model (Zhu et al. 2018). Greater price volatility indicates lower security.	–
		Market Openness (CEI02)	Neutral	Resource equity of foreign enterprises in China	Currently, the main nickel mining enterprises in China are Jinchuan Group, Jien Nickel Industry, Henghao Mining, and Xinjiang Xinxin Mining, all of which are wholly Chinese-owned enterprises. Foreign enterprises have not yet obtained the right to develop nickel mines in China. Therefore, this paper quantitatively evaluates the openness of China’s nickel resource development based on the investment guidance policies related	–

Primary indicator	Secondary indicator	Tertiary indicator	Indicator direction	Indicator description	Indicator calculation and data sources	Unit
Co-existence of Optimal States (CEI)	Openness				to nickel and its main ore types (copper, cobalt) in several editions of the "Catalog of Industries for Guiding Foreign Investment" (2007, 2011, 2015, 2017) issued by the National Development and Reform Commission and the Ministry of Commerce. Among them, encouraged development is marked as 1, and restricted development is marked as 0. After checking, the 2015 edition of the "Catalog of Industries for Guiding Foreign Investment" abolished the investment restrictions on foreign enterprises entering the copper and nickel materials sector, so this indicator is marked as 1 from 2015 onwards and 0 for years before 2015.	–
		Overseas Market Development Degree (CEI03)	Neutral	Resource equity obtained by domestic enterprises overseas	$CEI03 = \frac{\sum S_m \cdot P_m}{P}$ S_m represents the ownership share of Chinese enterprises in the development of foreign nickel mine m, P_m represents the output of that mine, and P represents the global nickel production. This paper calculates China's nickel equity abroad based on the ownership share of Chinese enterprises in overseas nickel mines to measure the overseas market development degree. Data on global nickel mine production and shareholding enterprise shares are sourced from S&P Global Market Intelligence.	%
		International Raw Material Transformation Indicator (CEI04)	Neutral	A country's ability to transform mineral raw materials into high-value-added downstream products in international trade	$CEI04 = \frac{\Sigma_a X_a - M_a}{\Sigma_a X_a + M_a}, \quad a = 1, 2, 3$ Drawing on the quantification method proposed by Daw (2017) $a = 1, 2, 3$ represent upstream nickel ore, midstream raw materials, and downstream nickel-bearing products, respectively. X_a represents China's export value in stage a, and M_a represents the import value in that stage. Based on the above formula, the value range of CEI04 is [–1, 1]. CEI04 takes a value of 1 if and only if a country achieves a net export in the global full industrial chain trade of nickel mines; CEI04 takes a value of –1 if and only if a country is a net importer in the global full industrial chain trade of nickel mines.	TIM

Based on the analysis of factors influencing nickel resource supply security, the selection principles for indicators are fully considered as follows:

1. The indicator should be relevant to the corresponding theme.
2. The indicator can be measured using available data and updated periodically.
3. The indicator should be transparent.
4. The selected indicators should avoid overlapping, double-counting, and correlation between indicators. In this study, the nickel resource supply security indicator system is divided into three levels (Table 1).

The primary indicators include three dimensions: Global Supply Stability (GSI), Domestic Economic Security (DSI), and Co-existence of Optimal States (CEI). The secondary indicators cover eight key areas, while the tertiary indicators are further refined into 27 specific indicators (Table 1). Global Supply Stability (GSI) measures the external risks faced by strategic mineral resources due to factors such as resource distribution and international relations, assessing the combined global risk profile of strategic mineral resources through global resource endowments, resource country risks, and geopolitical environments. Domestic Economic Security (DSI) reflects the supporting role of strategic mineral resources in the sustainable economic development of a country, covering four dimensions: supply, demand, market, and technology. Co-existence of Optimal States (CEI) emphasizes a broad perspective of security by placing strategic mineral resources within the global industrial chain to achieve coordinated development between domestic and international markets, measured by indicators such as price correlation, market openness, overseas market development, and international raw material conversion.

1.2 Evaluation method

Considering the availability of data for evaluating nickel resource supply security, the authors have set the research period for China's nickel resource security from 2011 to 2022. Given the diversity and complexity of the data related to nickel resource supply security evaluations, in order to make the evaluation results more objective and accurate, a CRITIC-TOPSIS model is established to evaluate the nickel resource supply security capacity. The CRITIC method is used to determine the weight values of the evaluation indicators, and then the TOPSIS model is employed to evaluate the merits of the evaluation objects, thereby determining the mineral resource security capacity. This approach not only objectively describes the importance of each indicator's contribution to nickel resource supply security capacity but also avoids the subjectivity of human factors. The CRITIC weighting method, proposed by Diakoulaki et al., is an objective weighting method that reflects the information content of indicators based on their contrast intensity and conflict between indicators. The greater the contrast intensity and conflict, the higher the indicator weight. This method considers both correlation weights and information weights, demonstrating certain advantages (Lin et al. 2024). The TOPSIS model is a comprehensive analysis method that uses approximation to ideal solutions to determine the ranking of evaluation objects. Its core idea involves studying and analyzing the distance between the optimal and worst solutions for the target problem, calculating the closeness of the evaluation indicators to the ideal solution, sorting the closeness of each evaluation indicator, and determining the evaluation effect (Halicka and Gola 2024; Hussain et al. 2024; Xiang and Xiang 2024). The combination of CRITIC and TOPSIS can accurately evaluate the superiority and inferiority relationships among multiple objects, effectively handle the correlations and conflicts among indicators, and is suitable for the complex multi-indicator decision-making scenario of this study. It takes into account both the objective weights of the indicators and provides comprehensive evaluations of the alternatives, resulting in more comprehensive and reliable outcomes.

1. Establish the original evaluation indicator matrix

Assuming there are *n* evaluation grades for comprehensive evaluation of *m* evaluation indicators, the original matrix is:

$$X = \left(x_{ij}\right)_{nm} \quad \left(i = 1, 2, \dots, n; \quad j = 1, 2, \dots, m\right) \tag{1}$$

2. Consistency trend processing

To ensure that all indicators have the same direction, consistency trend processing is required for the evaluation indicators, which involves converting high-preference indicators into low-preference indicators or vice versa. In practical applications, the latter approach is often adopted, where the original low-preference indicator data is inverted using the following formula:

$$X'_{ij} = \frac{1}{x_{ij}} \tag{2}$$

3. Indicator normalization processing

To eliminate the dimension of indicator measurement units, the original data matrix after consistency trend processing is normalized, converting the original data into numbers between 0 and 1.

The formula for positive indicators is:

$$X_{ij} = \frac{\left(X'_{ij} - \min\left(X'_{ij}\right)\right)}{\left(\max\left(X'_{ij}\right) - \min\left(X'_{ij}\right)\right)} \tag{3}$$

The formula for negative indicators is:

$$X_{ij} = \frac{\left(\max\left(X'_{ij}\right) - X'_{ij}\right)}{\left(\max\left(X'_{ij}\right) - \min\left(X'_{ij}\right)\right)} \tag{4}$$

The normalized data matrix is:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nm} \end{bmatrix} \tag{5}$$

4. Calculate the optimal and worst solutions

In the normalized data matrix A, define the vector composed of the maximum values of each index (the optimal solution vector) as the optimal solution A^+. Define the vector composed of the minimum values of each index (the worst solution vector) as the worst solution A^-. Then:

$$A^+ = \left(a_{i1}^+, a_{i2}^+, a_{i3}^+, \ldots, a_{im}^+\right) \tag{6}$$

$$A^- = \left(a_{i1}^-, a_{i2}^-, a_{i3}^-, \ldots, a_{im}^-\right) \tag{7}$$

5. Determine the indicator weights

Using the CRITIC method, calculate the standard deviation σ_j for the j-th indicator:

$$\sigma_j = \sqrt{\frac{\sum_{i=1}^{n}\left(x_{ij} - \bar{x}_j\right)}{n-1}} \tag{8}$$

Calculate the information carrying capacity E_j for indicator j:

$$E_j = \sigma_j \cdot \sum_{i=1}^{n}\left(1 - r_{ij}\right) \tag{9}$$

Where r_{ij} represents the correlation coefficient between indicators i and j, and the larger E_j, the greater the weight it occupies. Calculate the weight W_j:

$$W_j = \frac{E_j}{\sum_{i=1}^{n} E_j} \tag{10}$$

6. Calculate the Euclidean distance

Calculate the distances between the optimal and worst solutions and each evaluation object, denoted as D_i^+, D_i^-, , respectively:

$$D_i^+ = \sum_{j-1}^{m} W_j \left(a_{ij}^+ - a_{ij}\right)^2 \tag{11}$$

$$D_i^- = \sum_{j-1}^{m} W_j \left(a_{ij}^- - a_{ij}\right)^2 \tag{12}$$

7. Calculate the comprehensive evaluation index

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \tag{13}$$

Where the value of C_i ranges from 0 to 1. The larger the value of C_i, the closer the i-th evaluation object is to the optimal level, indicating stronger nickel resource supply security capacity; the smaller the value of C_i, the closer the ith evaluation object is to the worst level, indicating weaker nickel resource supply security capacity.

2. Result analysis

The calculated weights of the evaluation indicators are presented in Table 2. Among the primary indicators, Domestic Economic Security holds the highest weight, exerting the greatest influence on the security of nickel resource supply. Within Global Supply Stability, the secondary indicator with the largest weight is geopolitics, and the tertiary indicator with the largest weight is the global governance capability, ranging between 0.01 and 0.11 in weight. For Domestic Economic Security, the secondary indicator with the largest weight is supply, and the tertiary indicator with the largest weight is domestic resource supply potential, ranging between 0.01 and 0.12 in weight. Openness is the only secondary indicator under co-existence of optimal, and among its included indicators, price correlation has the largest weight, ranging between 0.04 and 0.08. Therefore, the most critical factors affecting the security of tin resource supply in China are domestic resource supply potential (0.12), global geopolitical risks (0.11), and nickel ore market price fluctuations (0.08).

The calculated evaluation results for the security of nickel resource supply in China are shown in Figure 2. Analysis reveals the following:

From the comprehensive evaluation of supply security, the overall security index (SSI) indicates a general downward trend in nickel resource security since 2011. Between 2011 and 2013, China's self-sufficiency rate for nickel ore was low, primarily relying on imports. From 2014 to 2015, Indonesia's nickel ore export ban further exacerbated fluctuations in the international market, increasing security risks. Between 2016 and 2018, domestic policy support and technological advancements reduced dependence on imports, lowering security risks.

Table 2. Indicator Weights Table

Tabela 2. Tabela wag wskaźników

Primary indicator	Weight	Secondary indicator	weight	Tertiary indicator	weight
Global Supply Stability (GSI)	0.32	Resource Endowment	0.09	Resource Supply Potential	0.09
		Resource Country Risk	0.06	Social Development Level	0.03
				Mining Policy Maturity	0.02
				Environmental Risk	0.01
		Geopolitics	0.17	Global Governance Capability	0.11
				Global Supply Concentration	0.04
				Production-Consumption Balance	0.02
Domestic Economic Security (DSI)	0.43	Supply	0.20	Domestic Resource Supply Potential	0.12
				Relative Resource Abundance	0.02
				Domestic Reserve Share of the World	0.02
				Nickel Ore Production as a Percentage of the World	0.01
				Refined Nickel Production as a Percentage of the World	0.01
				Substitutability	0.01
				Recyclability	0.01
		Demand	0.12	Apparent Consumption Growth Rate	0.02
				Per Capita Nickel Resource Consumption	0.01
				Production-Consumption Gap	0.01
				Price Volatility	0.03
				External Dependence Ratio	0.05
		Market	0.08	Nickel Ores and Concentrates Import Concentration	0.04
				Nickel-bearing Materials Import Concentration	0.04
		Technology	0.03	Geological Research Level	0.02
				Applied Technology Competitiveness	0.01
Co-existence of Optimal States (CEI)	0.25	Openness	0.25	Price Correlation	0.08
				Market Openness	0.07
				Overseas Market Development Degree	0.06
				International Raw Material Transformation Indicator	0.04

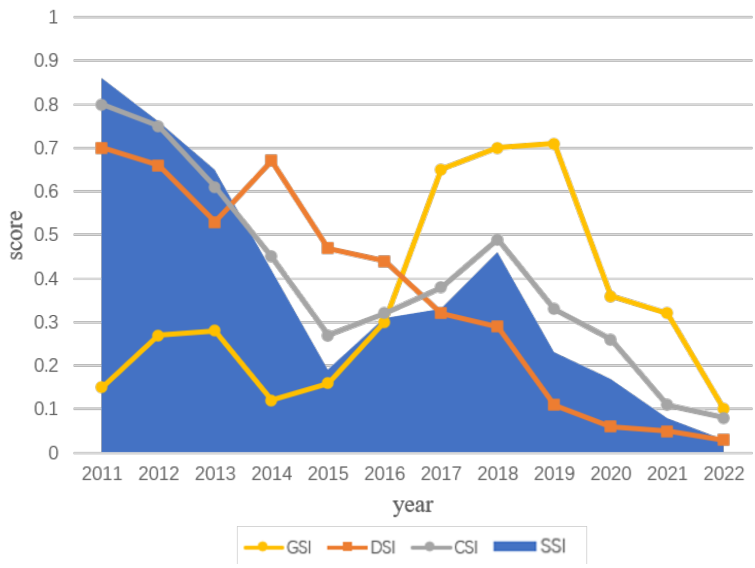

Fig. 2. Evaluation results of Global Supply Stability (GSI), Domestic Economic Security (DSI), Co-existence of Optimal States (CEI), and Overall Security Index (SSI) for nickel resources in China from 2011 to 2022

Rys. 2. Wyniki oceny globalnej stabilności dostaw (GSI), krajowego bezpieczeństwa gospodarczego (DSI), współistnienia stanów optymalnych (CEI) oraz ogólnego wskaźnika bezpieczeństwa (SSI) dla zasobów niklu w Chinach w latach 2011–2022

From 2019 to 2022, Western countries suppressed China's nickel resource investments and supply chains through means such as "decoupling and disintegration" and "collective pressure", leading to a sharp increase in nickel resource supply risks.

From the three dimensions of supply security: Global Supply Stability (GSI): Nickel resource global supply stability showed an upward trend in 2011. However, starting in 2019, due to the global pandemic, many resource countries suspended nickel ore mining, resulting in reduced global supply and a rapid decline in supply stability. Domestic Economic Security (DSI): It increased in 2014, closely related to China's implementation of the "Energy Development Strategic Action Plan", which increased the demand for nickel for fuel cells. However, as demand grew, domestic supply-demand imbalances gradually intensified, leading to increased supply risks and a continuous decline in domestic economic security. Co-existence of Optimal States (CEI): The trend of this indicator is basically consistent with the overall security index (SSI), reflecting the importance of coordinated development of domestic and foreign nickel resources in enhancing overall security.

From an international and domestic perspective: Internationally, Indonesia implemented a policy in January 2014 banning the export of laterite nickel ore, resulting in minimal nickel ore exports to China in 2015 and 2016. However, domestic production demand remained high during this period, prompting increased procurement from the Philippines. Indonesia and the Philippines, based on their own development needs, introduced policies in October 2019 to control nickel ore exports and mining, creating significant uncertainty in supply in 2020. Additionally, China has maritime disputes with Indonesia and potential disputes with the Philippines, which could lead to structural imbalances in nickel metal supply. Furthermore, the United States passed the Inflation Reduction Act, providing tax credits for electric vehicle consumers. If the electric vehicle contains battery components manufactured or assembled by "foreign entities of concern", the tax credit will be immediately revoked. Foreign entities such as China and Russia, which produce key minerals like nickel for export to the United States for use in clean energy vehicles, will not be eligible for consumer purchase subsidies. Domestically, with China's rapid economic development, the new energy vehicle industry began to expand rapidly from 2014, significantly increasing nickel demand. However, China's nickel resource reserves are limited and unevenly distributed, primarily in Gansu, Inner Mongolia, and Xinjiang. To address the domestic nickel resource supply-demand situation, the Ministry of Natural Resources released the "National Mineral Resources Plan (2016–2020)" in 2016 to promote the development and utilization of nickel resources. In recent years, the government has also strengthened support for nickel resource geological exploration, increased the allocation of mining rights, improved mining management systems, and activated the mining market, issuing relevant documents such as the "Opinions of the Ministry of Natural Resources on Several Matters Concerning Deepening the Reform of Mineral Resources Management" and the "Notice on Further Improving the Registration Management of Mineral Resources Exploration and Mining". However, due to limitations in China's nickel resource endowment and exploration and mining technology, the growth trend of China's nickel reserves is not significant. China's nickel mine production growth rate exceeds the reserve growth rate, and the overall reserve-to-production ratio has been decreasing year by year, with a high degree of external dependence. This has led to increasingly severe nickel resource supply-demand contradictions in China.

3. Result validation

When studying the security of China's energy supply, Song et al. (2019) argue that the trend in the energy supply security index is unaffected by changes in indicator weights, indicating the rationality of the evaluation indicator model. Based on this perspective, to validate the rationality of our model, this paper conducts a sensitivity analysis on the security of nickel resource supply using an alternative scenario with unequal weights.

Specifically, in this paper, the weights for global supply stability, domestic economic security, and Co-existence of Optimal States are set to 20%, 60%, and 20%, respectively. In this setting, domestic economic security is assigned a higher weight to highlight the critical role of domestic supply stability in nickel resource security, which aligns with the emphasis on the importance of supply stability in energy supply security evaluations (Feygin and Satkin 2004; Ang et al. 2015).

By comparing the changes in China's nickel resource supply security index values between the two scenarios depicted in Figure 3, it is evident that the index values under the alternative scenario are consistently lower than their corresponding values under the baseline scenario. Moreover, their trends over time remain consistent, indicating that the current evaluation index model is effective in estimating the level of supply security for China's nickel resources.

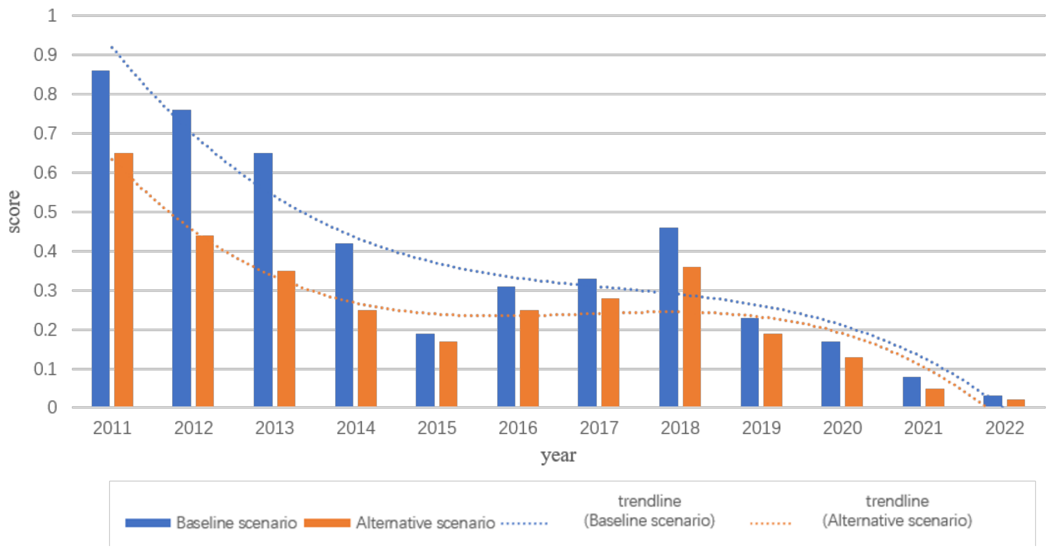

Fig. 3. China's Nickel Resource Supply Security Index under baseline and alternative scenarios

Rys. 3. Wskaźnik bezpieczeństwa dostaw niklu w Chinach w scenariuszach bazowym i alternatywnym

4. Conclusion

1. Under the background of China's new development pattern, and in combination with the characteristics of nickel resources, research shows that the supply security of nickel resources aims at national resource security, follow co-existence of optimal states, makes overall plans for the security of national strategic mineral resources themselves, and global common security. Through the joint efforts of various types and levels of entities, and based on the principle of mutual benefit in trade or investment, it aims to achieve a sustainable survival situation for the development of mineral resources.
2. Based on comprehensive factors affecting nickel resource supply security, this study established an evaluation index system for China's nickel resource supply security from three dimensions: global supply stability, domestic economic security, and co-existence of optimal states. Analysis shows that domestic economic security is crucial to the supply

security of nickel resources, and domestic resource supply potential, global geopolitical risks, and nickel ore market price fluctuations are the most critical factors affecting China's tin resource supply security.

3. Using the CRITIC-TOPSIS model, the level of safe supply of nickel resources from 2011 to 2022 was evaluated. Compared to other models, the CRITIC-TOPSIS model is not only applicable to comprehensive evaluation problems involving multiple indicators and multiple objects, but it also objectively describes the degree of importance of each indicator's contribution to the security of nickel resource supply capacity. The results indicate that China's nickel resource security level exhibits a fluctuating upward trend, with significant risks at both the overall level and across the three dimensions. Upon verification, the construction of the evaluation index system for nickel resource supply security is scientifically reasonable, and the evaluation model used is relatively appropriate, effectively assessing the security level of nickel resource supply in China.
4. According to the evaluation results of nickel resource supply security, it is found that China's nickel resource supply is currently facing enormous challenges. On the one hand, China has poor nickel resource endowments, low exploration and mining technology levels, and rising economic development demands, which exacerbate the contradiction between nickel resource supply and demand. On the other hand, foreign countries continuously adopt various means to suppress China's nickel resource investments and supply chains, establishing nickel resource supply alliances independent of China, further exacerbating the instability of China's nickel resource supply.

5. Countermeasure suggestion

1. Increase overseas mining investments in nickel resources

As the globalization trend of the world's mining market continues to strengthen and China's economy rapidly develops, the demand for nickel resources will further expand in the future. With the support of national opening-up policies, it is necessary to strengthen international cooperation, establish overseas nickel resource development bases, cultivate powerful multinational mining companies, and actively participate in nickel ore investment matters in other countries to obtain long-term stable supply channels. China's nickel resource imports are highly concentrated, with imports from Indonesia and the Philippines accounting for more than 90% of total imports, making China vulnerable. Therefore, China can expand the sources of nickel resource imports and seek potential cooperation opportunities with neighboring countries such as Russia and Australia, which are rich in nickel resources, to diversify import channels.

2. Enhance domestic nickel resource exploration efforts

Nickel resources are buried deep, with extremely complex mineralization conditions and difficult extraction. In recent years, China's own nickel ore production growth has been very slow. With the rapid development of the national economy, especially in the fields of stainless steel in the steel industry and new energy vehicle batteries, the supply-demand gap is widening, and the supply-demand contradiction is prominent. It is necessary to increase investment in nickel resource exploration, introduce policies to incentivize geological exploration units and enterprises, study nickel mineralization laws and key controlling factors, build new exploration models, innovate new exploration and survey models and methods for typical new areas and old mining areas, independently develop a batch of exploration equipment, strengthen exploration efforts around and in the depths of existing mines, and increase nickel resource reserves.

3. Improve China's global allocation of nickel resources

Laterite nickel ores account for about 60% of the global total, with Indonesia, the Philippines, and New Caledonia being major producers and occupying an important position in global production. In recent years, the United States, in conjunction with Indonesia, the Philippines, and other Western countries, has continuously implemented "decoupling and chain-breaking" against China, undermining the stability of the nickel supply chain, resulting in an annual increase in the supply-demand gap in China's nickel industry and a lack of international discourse power. China should strengthen exchanges and cooperation with countries in Asia and Oceania through platforms such as the China Mining Congress and the China-ASEAN Mining Cooperation Forum, promote the signing of memoranda of understanding for cooperation and project cooperation agreements, build an independent and controllable overseas transportation system, and consolidate the bottom line for nickel resource security.

4. Improve the nickel resource reserve system

The current international situation is complex and volatile, and the nickel resource supply faces many risks and instabilities. China should improve its mineral resource reserve system to promote smooth and sustainable economic development and ensure a long-term stable supply of nickel resources. It is necessary to rapidly increase the scale of nickel product reserves, intensify imports, and establish a full industrial chain nickel reserve base in the central and western regions. Increase nickel production capacity reserves, establish production capacity reserves and mobilization mechanisms, and rapidly expand production capacity in extreme situations. Accelerate the implementation of nickel ore reserve projects to ensure the fastest construction and commissioning in emergencies. Encourage capable enterprises to actively assume social responsibility, establish corporate reserve systems, and contribute to stabilizing market conditions in the region and the country.

5. Improve nickel smelting and production technology

Domestic nickel ore resources generally have low grades, multiple associated components, and are difficult to process, which greatly restricts the development of China's nickel industry. Therefore, researching how to improve the extraction technology of low-grade nickel ore, continuously developing new beneficiation and smelting processes, and improving the economic benefits of nickel resources play a crucial role in the sustainable utilization of nickel ore resources and the healthy development of the national economy. It is necessary to focus on researching nickel resource extraction technology, continuously developing new processes and technologies based on the characteristics of laterite nickel ores, and making full use of nickel ore resources. Encourage enterprises to increase R&D investment to form a production process of reduction, reuse, and recycling, improving the utilization efficiency of nickel resources.

This study was funded by Geological Survey Project of China.

The Authors have no conflict of interest to declare.

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ASSESSMENT OF CHINA'S NICKEL RESOURCE SUPPLY SECURITY BASED ON THE CRITIC-TOPSIS MODEL

Keywords

nickel resources, supply security, CRITIC-TOPSIS Model,
Evaluation Index System, sustainability

Abstract

With the accelerated development of the new energy vehicle industry, China's demand for nickel resources has been increasing, and its external dependence has remained high for a long time. In the context of the new international development pattern and security environment, it is essential to systematically evaluate the security of China's nickel ore resource supply. Based on China's new development background and situational requirements, this paper constructs an evaluation index system for nickel resource supply security from three dimensions: global supply stability, domestic economic security, and co-existence of optimal, from the perspectives of national resource security and sustainable development, combined with the characteristics of nickel resources. The CRITIC-TOPSIS model is adopted to evaluate the level of secure nickel resource supply from 2011 to 2022. The construction of the evaluation index system for nickel resource supply security has been proven scientifically reasonable, the method used is relatively appropriate, and the evaluation results are credible. The results indicate that China's nickel resource supply capacity has generally declined since 2011, with the main influencing factors being domestic resource supply potential, global geopolitical risks, and nickel ore market price fluctuations. Therefore, it is imperative to enhance domestic nickel resource exploration efforts, increase overseas mining investments in nickel resources, improve China's global allocation of nickel resources, and elevate nickel resource reserve capabilities and smelting and production technologies.

OCENA BEZPIECZEŃSTWA DOSTAW NIKLU W CHINACH W OPARCIU O MODEL CRITIC-TOPSIS

Słowa kluczowe

zasoby niklu, bezpieczeństwo dostaw, model CRITIC-TOPSIS,
system indeksów oceny, zrównoważony rozwój

Streszczenie

Wraz z przyspieszonym rozwojem przemysłu nowych pojazdów elektrycznych popyt Chin na zasoby niklu rośnie, a ich zależność od dostawców zewnętrznych utrzymuje się na wysokim poziomie od dłuższego czasu. W kontekście nowego wzorca rozwoju międzynarodowego i bezpieczeństwa środowiska niezbędna jest systematyczna ocena zabezpieczenia dostaw rudy niklu w Chinach. W oparciu o nowe uwarunkowania rozwojowe Chin i wymagania sytuacyjne niniejszy artykuł konstruuje system indeksów oceny bezpieczeństwa dostaw niklu w trzech wymiarach: globalnej stabilności dostaw, krajowego bezpieczeństwa gospodarczego oraz współistnienia warunków optymalnych z perspektywy krajowego bezpieczeństwa zasobów i zrównoważonego rozwoju, w połączeniu z charakterystyką zasobów niklu. Model CRITIC-TOPSIS został przyjęty do oceny poziomu bezpieczeństwa dostaw niklu w latach 2011–2022. Konstrukcja systemu indeksów oceny bezpieczeństwa dostaw niklu została naukowo udowodniona, zastosowana metoda jest stosunkowo odpowiednia, a wyniki oceny są wiarygodne. Wyniki wskazują, że potencjał Chin w zakresie zasobów niklu generalnie spadł od 2011 roku, a głównymi czynnikami wpływającymi na niego są krajowy potencjał podaży, globalne zagrożenia geopolityczne oraz wahania cen na rynku rudy niklu. Dlatego konieczne jest zintensyfikowanie krajowych działań w zakresie eksploracji zasobów niklu, zwiększenie zagranicznych inwestycji w górnictwo niklu, poprawa globalnej alokacji zasobów niklu przez Chiny, a także zwiększenie potencjału rezerw niklu oraz technologii wytopu i produkcji.