

Multi-attribute risk assessment on helium investment environment in host countries

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ABSTRACT

Helium is a critical raw material, but its distribution is extremely uneven. To better mitigate trade risks and get a steady and safe supply of helium, it is of the utmost importance to assess the risk associated with the investment environment in helium-rich countries. This paper establishes an indicator system including 22 indicators from five dimensions, which consist of: helium resource endowment, macro environment, operation risk, maritime risk and, bilateral relationships. The game theory model combined with variance coefficient theory and expert survey are presented to determine the combined weights. The results show that Kazakhstan, Russia and Qatar present the best comprehensive performance; Australia has the highest operation risk and, Poland and Algeria have higher maritime risk; resources endowment has the largest weight, followed by maritime risk. We provide suggestions of acquiring upstream helium-rich gas fields and purchase & sale agreement of bundled liquified natural gas (LNG) etc.

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1. Introduction

Helium (He) is the noble gas with the lowest boiling point, which has a number of remarkable properties (Jia et al., 2022), such as colorless and odorless, low density, low solubility, and enhanced chemical inertness, etc. Due to its unique properties, helium plays an irreplaceable role in modern high-tech fields, consequently is called the “golden gas” among rare gases. Helium is widely used in fields including cool magnetic resonance imaging (MRI) scanners, nuclear fusion and low-temperature experiments, semiconductor production, superconducting technology, as well as fiber optic communication. Given the non-substitutable commodity properties, the world has begun to re-examine its status. During the periods 2008–2018, the stable helium market experienced a number of supply shortages and unusually high prices. Helium suddenly became the focus of political attention, and thus it has been listed as critical mineral resource in many developed countries.

Helium is an exhaustible finite resource, and the distribution of global helium resources is extremely uneven. The helium resources worldwide are mainly distributed in the United States, Qatar, Algeria, Canada, and Russia, etc. (Fig. 1). The United States is the largest helium producing country. According to the United States Geological Survey (USGS, 2023), the average volume of recoverable helium in known natural gas reservoirs in the United States is estimated to be $84.9 \times 10^8 \text{ m}^3$. Apart from the United States, the helium resources worldwide are approximately 31.3 billion cubic meters. Among the global proven helium reserves, the United States has a reserve of $85.61 \times 10^8 \text{ m}^3$, accounting for 83% of the world, Algeria has a reserve of $18 \times 10^8 \text{ m}^3$, Russia has a reserve of $17 \times 10^8 \text{ m}^3$, and Poland has a relatively small reserve of $0.24 \times 10^8 \text{ m}^3$. Meanwhile, global helium is generally in short supply, with an average annual shortfall of about 50 million cubic meters. The United States is the largest producer of helium in the world and has established strategic reserves in the Cliffside gas field since the last century. By 1981, it had stored at least 1 billion cubic meters of helium. Before 2012, the helium production of the United States had been close to 80% of the global production, but after that, the output decreased at an annual rate of about 10%. With the continuous depletion of reserves in helium storage, the storage reservoir was declared shut down by September 30,

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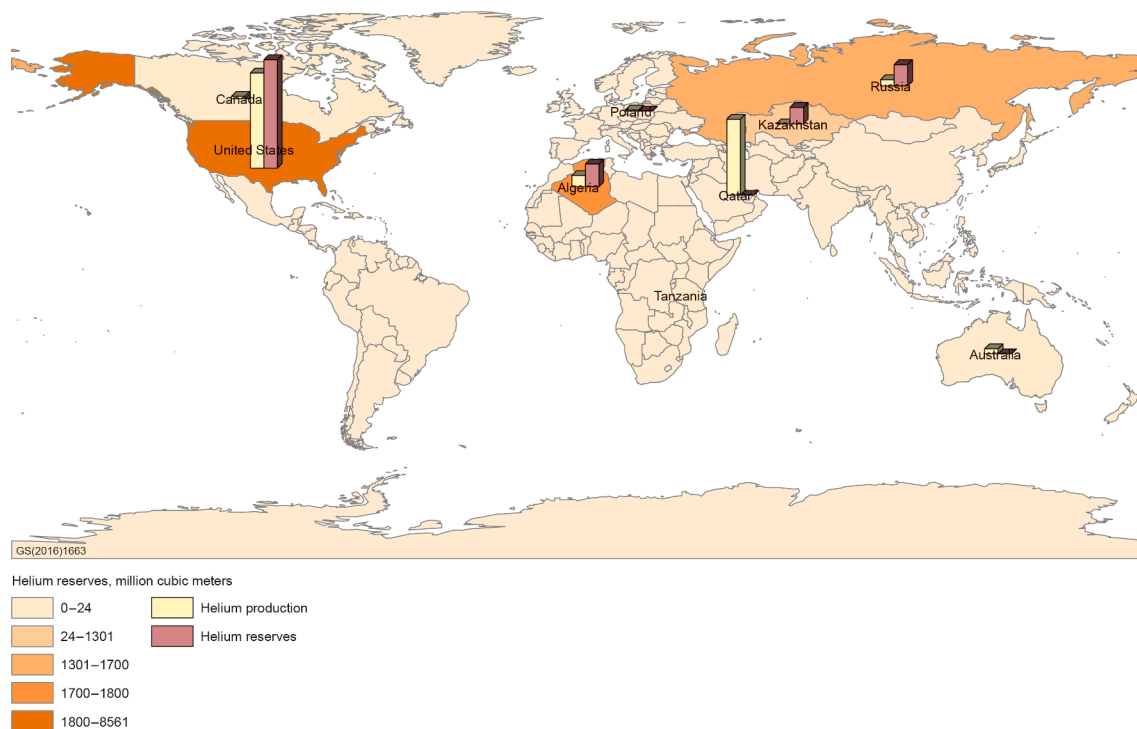


Fig. 1. Distribution of helium resources worldwide.

2022. Qatar is the second largest producer of helium, which is mainly separated from the flash gas of LNG in the northern gas fields.

In recent years, along with the rapid technological developments, emerging countries have to import a large amount of helium. China's helium reserves only account for 2% of the total global resources, but the demand is significant, accounting for 11% of the total global demand, and its external dependence is as high as 97.5%. With the rapid development of aviation, aerospace, and defense industry, the demand for helium is expanding, with an annual demand of about 22 million cubic meters, posing great risks to supply. Simultaneously, influenced by the reverse globalization and geopolitics conflicts, some traditional helium producing countries such as the United States and Russia are experiencing a depletion both in production and proven reserves. China faces a serious challenge securing helium. Therefore, assessing the helium investment environment and its potential has become particularly important. In recent studies, the assessment of the investment environment has mostly focused on oil and natural gas, and there has hardly been any research concerning helium. Given the importance of helium and the shortage supply situation, it is necessary to clarify the resource situation and investment environment in major helium-rich countries worldwide. Assessing the risk of investment environments in helium producing countries is of considerable important for the macro-layout of overseas investments by Chinese enterprises in order to better mitigate risks and enhance supply security.

The investment environment has always been a hotspot, and the main methods used for analyzing the investment environment include analytic hierarchy process (AHP), fuzzy comprehensive evaluation method, grey relationship analysis, entropy weight method, etc. Makipelto and Takala (2009) analyzed and evaluated the factors influencing investment decisions by AHP

for the energy industry in Finland. Su (2010) constructed a qualitative and quantitative evaluation system of oil and gas investment environment in the Central Asia Caspian Sea region using AHP and factor analysis. Zhao (2011) established an overseas oil and gas investment target selection model by a multi-level grey model. Wang and Mu (2014) evaluated the investment environment associated with oil in South American countries by AHP and cluster analysis. Olaru et al. (2014) conducted an investment risk assessment by the Monte Carlo method on Romanian energy investment projects. Qiu et al. (2015) extend the real options model to a multi-factor model with uncertainties of oil price, geology and engineering, to evaluate deepwater oil and gas exploration projects. Wang and Ding (2017) established an evaluation system by fuzzy clustering analysis and Kendall coordination coefficient to assess the investment environment in 40 major oil and gas producing countries. Wang et al. (2015) studied the investment environment by the super efficiency data envelopment analysis (SE-DEA) theory, constructed a potential measurement model by Theil index to study the variation trend of differences between different regions. Huang et al. (2017) analyzed the investment environment in the Democratic Republic of Congo using SWOT model, and concluded that the opportunities outweighed the risks. Han (2022) evaluated the investment environment in 18 key cities in China by the entropy weight method. Sun (2011) combines the evaluation of investment environment with contract types to design the indicators using the multi-objective program and risk decision matrix. With the goal of improving energy efficiency, Das and Atkinson (2011) constructed a risk-based decision-making model that combines energy efficiency improvement with risk management. Rajan and Vikas (2008) evaluated the investment risk by a weighted risk factor matrix and established a risk assessment model for oil host countries. Radukić and Stanković (2015) applied cluster analysis and variance analysis

to evaluate the local business environment in Serbia based on twelve criteria used in the NALED method. The assessment index focuses on macro environment and resource characters. [Chen and Lu \(2017\)](#) established an investment environment evaluation system that includes five indicators: political environment, security environment, macroeconomic development level, foreign investment environment, and infrastructure development level. [Wang \(2016\)](#) established a primary indicator system with nine major categories and modified the G1 model weighting with standard deviation. [Li and Deng \(2022\)](#) analyzed the investment environment in Asian member countries of OPEC from the perspectives of politics, economy, socio-cultural, and technological environment by the PEST analysis, but there was lack of quantitative evaluation. [Li and Deng \(2022\)](#) studied the investment environment in countries along the “the Belt and Road” with the help of the Delphi method and built an evaluating indicator system covering six aspects including social & economic development level, transportation infrastructure level, informatization level, strategic resource occurrence, political environment, and security environment. [Abba et al. \(2025\)](#) evaluated 40 multidimensional risk factors using the analytical hierarchy process to establish four investor groups for decentralized renewable energy investment in Nigeria: development finance institutions, domestic finance institutions, developers and impact investors. Some scholars adopted portfolio theory to measure the risk of multiple assets. [Vinel and Mortaz \(2019\)](#) used the Conditional Value-at-risk (CvaR) based portfolio approach to analyze strategic energy pooling for renewable energy in the US. [Lin et al. \(2024\)](#) developed a planning approach with CvaR for the extreme electricity price risk for energy system. [Zhang et al. \(2024\)](#) presented the optimal strategy towards carbon neutrality with consideration of multiple risk factors.

There has been a lot of research on the oil and gas investment environment, and a mature evaluation system has been established. However, there are several differences in investment risks between fossil energy and helium, including resource occurrence, segregation pattern, fiscal types, and so on. Our contribution is establishing an index of government take to quantify the contract attraction of host countries; helium production capacity index is developed with helium concentration of different raw material, the separating capacity of typical helium plants and the unit extraction cost. Since most helium is extracted from helium-rich natural gas reserves, the upstream cost index is presented according to the discovery and development costs of natural gas. At the same time, the maritime risk index is constructed by considering the shipping distance and the number of pirate attacks. Finally, the bilateral relationship coefficient is developed by the trade with China of each host countries.

This paper is organized as follows: Section 2 presents the literature review, Section 3 provides the index, methodology and data, Section 4 presents the assessment process and result analysis, and Section 5 concludes with recommendations.

2. Methodology

The evaluation of helium investment environment requires identifying various factors that affect helium investment and quantitatively analyze their consequences. This paper presents an evaluation index system, including helium resource endowment, macro investment environment, operation risk, maritime risks, and relations with China ([Fig. 2](#)), and adopts variation coefficient methods and game theory combined weighting model to establish investment environment evaluation model.

Correlation analysis is carried out on the selected indicators, and the correlation heat map of each indicator is drawn in [Fig. 3](#).

The results show that most of the correlation coefficients of each index are in the range of $[-0.5, 0.5]$, showing a weak correlation in general. However, the coefficients of “helium production” and “helium resources”, “factory capacity” and “unit helium extraction cost” are above 0.8, indicating a high correlation. Although these indicators are highly correlated, the dimensions of the response are different. The amount of helium resources reflects the endowments of resource countries and determines their potential supply capacity. Helium production reflects the actual extraction, separation, and refinery capacity in a nation. Plant capacity represents the ability and effectiveness to process raw gas; the unit helium extraction cost reflects the cost control ability of the plant, which is related to its profitability and market competitiveness. Therefore, we retain all five indicators to ensure the comprehensiveness and accuracy of the evaluation.

2.1. Evaluation model

The evaluation of investment environment in resource countries is the most important aspect of the zone selection for obtaining overseas helium assets. The selection of the target zone not only determines whether the enterprise can successfully get overseas helium production, but also determines the ability of the enterprise to smoothly operate overseas projects. The model is based on the following categories of factors affecting helium investment.

$$M = R \times \sum_{i=1}^n W_i \times X_i \quad (1)$$

where M is the comprehensive score of helium investment in resource countries; W_i denotes the weight of influencing factors in indicator i ; X_i denotes the evaluation score of influencing factors in indicator i ; R is the bilateral relation coefficient.

The determination of the score X_i of each factor requires further subdivision of the more specific indicators. The specific determination of each factor will be introduced in subsequent sections.

2.2. Determination of weight

The weight W_i is determined by the combined weighting methods based on the objective weight (W_1) and the subjective weight (W_2).

The objective weight is determined by the variance coefficient method, and its basic principle is that when conducting multi-indicator evaluation, the greater the degree of variation of all observed values of a certain indicator, the greater the contribution of the indicator to the imbalance, and it should be given a larger weight; on the contrary, it should be given a smaller weight. The variance coefficient can reflect the characteristics of indicator data and ensure the objectivity of the weight. At the same time, the weight of indicators can be continuously updated with the evolution of evaluation time and can also change with different combinations of evaluation indicators. Therefore, the variation coefficient is a dynamic method for determining weights, which facilitates the addition of new indicators for evaluation in the future. The subjective weight (W_2) can be determined by expert survey methods. The calculation of the objective weight (W_1) by the variation coefficient is as follows,

$$W_1 = \frac{V_{s_i}}{\sum_{i=1}^n V_{s_i}} \quad (2)$$

In the formula,

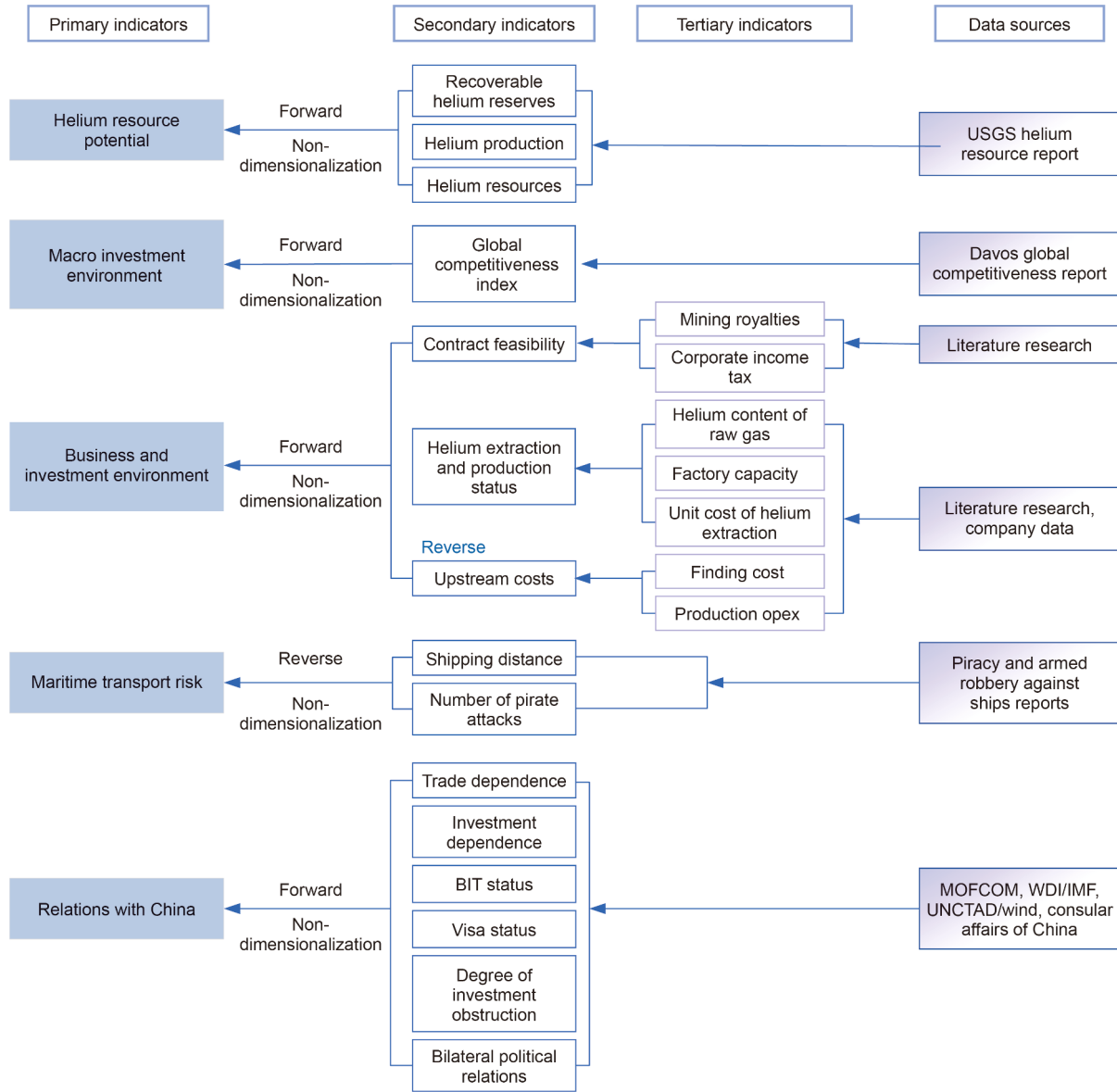


Fig. 2. Evaluation system of helium investment environment.

$$V_{S_i} = \frac{S_i}{\bar{X}_i} \quad (3)$$

$$S_i = \sqrt{\frac{\sum_{i=1}^{n_i} (X_i - \bar{X}_i)^2}{n_i}} \quad (4)$$

$$\bar{X}_i = \frac{\sum_{i=1}^{n_i} X_i}{n_i} \quad (5)$$

where X_{ij} is the observed value of the j th country under the i th indicator; V_{S_i} denotes the coefficient of variation of the i th indicator; $\bar{X}_i$ is the average of the observed values of the i th indicator; S_i denotes the standard deviation of the observed values of the i th indicator; n_i represents the number of the observed values of the i th indicator; n is the number of indicators.

2.3. Game theory combined weighting model

A game theory model is developed with the Nash equilibrium as the goal, treating the weights obtained by expert survey and variance coefficient method as the two parties. The combined weights are calculated by seeking the Nash equilibrium point. Introducing the linear combination coefficients α , the linear combination is presented as follows,

$$W = \alpha_1 W_1^T + \alpha_2 W_2^T \quad (6)$$

In order to minimize the deviation between the weighted result vector of the game theory model and that of the single method, deviation minimization is performed on each weight. The optimal weight coefficient is solved according to the following formula,

$$\min \left(\left\| \alpha_1 W_1^T + \alpha_2 W_2^T - W_1 \right\|_2 + \left\| \alpha_1 W_1^T + \alpha_2 W_1^T - W_2 \right\|_2 \right) \quad (7)$$

According to the differential property of the matrix, the first derivative condition of Eq. (7) is obtained,

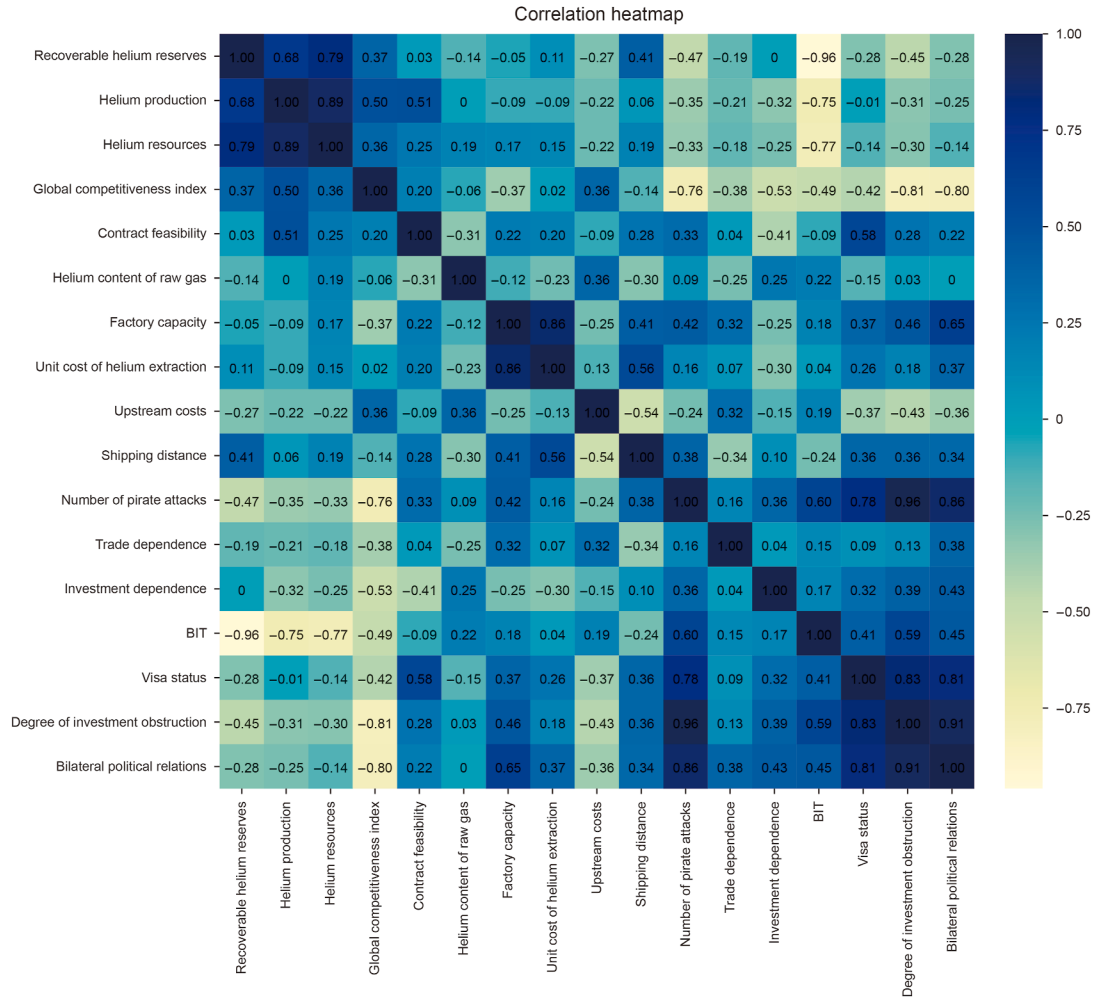


Fig. 3. Thermal diagram of the relationship between indicators.

$$\begin{bmatrix} W_1 W_1^T & W_1 W_2^T \\ W_2 W_1^T & W_2 W_2^T \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} W_1 W_1^T \\ W_2 W_2^T \end{bmatrix} \quad (8)$$

The linear coefficient is normalized to get the optimal combination weight W^* ,

$$W^* = \alpha_1^* W_1^T + \alpha_2^* W_2^T \quad (9)$$

where α_i^* is the normalized combination coefficient.

2.4. Data sources

This study mainly consists of five primary indicators, fifteen secondary indicators, and seven tertiary indicators for evaluating the helium investment environment.

The data in the helium resource endowment indicators, such as helium reserves, production, and resources are sourced from the Mineral Commodity Summaries published by the United States Geological Survey in 2022. The indicators of macro investment environment in resource countries are evaluated by the global competitiveness index published by Global Competitiveness Report of the World Economic Forum in Davos, Switzerland. The data of the helium operation risk in resource countries mainly comes from IHS and Wood Mackenzie. In the evaluation of maritime risks, the shipping distance is calculated by Netpas Distance software, and the risk of pirate attacks along the shipping route is

expressed by the number of pirate attacks reported in *Report on Piracy and Armed Robbery against Ships* published by the International Maritime Bureau. The indicators of relations with China comprise six dimensions: trade dependence, investment dependence, presence of Bilateral Investment Treaty (BIT), visa policy liberalization, degree of investment obstruction, and bilateral political relations. Specially, trade dependence metrics are obtained from World Development Indicators (WDI) and International Monetary Fund (IMF). Investment dependence indices are derived from United Nations Conference on Trade and Development (UNCTAD) statistics and Wind Financial Terminal. BIT status (signed/unsigned) is verified through official records of China's Ministry of Commerce. Visa policy details are extracted from the Consular Affairs Office of China's Ministry of Foreign Affairs website. Investment obstruction levels and bilateral political relations are quantified through Delphi method-based expert assessments. When calculating indicators, except for indicators such as cost and risk that need to be reversed and then dimensionless, other indicators are directly dimensionless. The dimensionless and positive processing methods for inverse indicator are as follows.

Dimensionless processing,

$$u_i = \frac{x_i}{\max\{x_i\}} \quad (10)$$

where x_i is the observed value of the indicator, and u_i is the standardized indicator value.

Positive processing of reverse indicator,

$$u_i = \frac{1}{x_i} \tag{11}$$

where x_i is the observed value of the indicator, and u_i is the standardized indicator value.

3. Evaluation for helium investment environment

3.1. Helium resource endowment

The recoverable helium reserves, helium production, and helium resources are chosen to represent resource endowment from USGS statistics (Table 1). The United States is the largest helium resource country in the world, with both reserves and production ranking first. The total helium reserves of the United States, Algeria, and Russia account for 99% of the world, the North America is the main supplier of helium, and the helium production of the United States and Qatar account for over 80% of the world.

3.2. Macro investment environment in host countries

This study chose the Investment Environment Evaluation Method of the World Economic Forum in Davos, Switzerland-Global Competitiveness Report to reflect the macro investment environment in resource countries. This index has a wide survey scope, fast update frequency, and strong correlation with the helium industry.

The global competitiveness index consists of four major categories and twelve sub items (“pillars”), and the twelve indicators are: “Institutions”, “Infrastructure”, “ICT Adoption”, “Macroeconomic Stability”, “Health”, “Skills”, “Product Market”, “Labor Market”, “Financial System”, “Market Size”, “Business Dynamism”, and “Innovation Capability”. The weights of these twelve indicators are the same, each accounting for 8.3% (100%/12) of the final result. This paper directly utilizes the global competitiveness data published in the Global Competitiveness Report (Table 2).

3.3. Helium operation risks in resource countries

3.3.1. Evaluation of the contract feasibility

The regulation and control of domestic helium by governments of resource countries are mainly reflected in helium contracts.

Table 2
Macro investment environment in helium-rich countries.

Country	Competitiveness index
United States	83.7
Algeria	56.3
Australia	78.7
Canada	79.6
Poland	68.9
Qatar	72.9
Russia	66.7
Tanzania	48.2
Kazakhstan	62.9

Therefore, the evaluation of the helium operation environment risks is centered on the feasibility of helium contracts.

The widely-used comprehensive indicator reflecting the attractiveness of fiscal and tax provisions is the government take of the resource country. It combines factors such as bonus, royalty, profit-sharing oil, taxation at all levels, and government equity participation into one indicator, which refers to the proportion of government take to distributable income throughout the entire lifecycle of the oilfield. “Government take” includes both the income of the government and the national oil company of the resource country. The government take is expressed as a percentage, and the calculation formula is:

$$\text{government take(\%)} = \frac{\text{royalty} + \text{income tax}}{\text{gross revenue}} \tag{12}$$

The government take is calculated by a quick-look method. We calculate the deduction and distribution of various payments proportionally based on the contract terms, setting the project revenue at 100%. If the royalty and profit-sharing ratio in the contract are progressive sliding ratios, the average level of the government take throughout the entire project life cycle shall be used for calculation. This method can quickly calculate the proportion of the government take to revenue in international cooperation projects, which is simpler than cash flow simulation, but can yield roughly the same results.

The royalty and corporate income tax rates of the helium-rich countries are shown in Table 3. The royalty of Poland is replaced by a 3% conventional natural gas royalty, while the royalty of Qatar has yet to be found. The net income of helium companies in each country is calculated by a quick-look method as follows.

Table 1
Resource endowment of host countries.

Country	Recoverable helium reserves ^a , 10 ⁶ m ³	Production ^b , 10 ⁶ m ³	Helium resources ^c , 10 ⁶ m ³
United States	8561	75	17057.01
Algeria	1800	9	8200
Australia	NA	4	3634
Canada	NA	2	2000
Poland	24	1	300
Qatar	NA	60	10,100
Russia	1700	5	6800
Tanzania	NA	NA	2780
Kazakhstan	1301	NA	NA

^a The data is from USGS, 2023. Among them, 8500 million cubic meters of recoverable helium resources in the United States are extracted from natural gas, and 61 million cubic meters are strategic reserves. The recoverable helium reserves in Kazakhstan come from the announcement of related party transactions of Intercontinental Oil and Gas Co., Ltd. NA indicates that there is currently no helium reverse statistics available.

^b The data is from USGS, 2023. NA indicates that there is currently no helium production statistics available.

^c The data is from USGS, 2023. The helium resources in the United States include an estimated average volume of 8.49 billion cubic meters of recoverable helium in known geological natural gas reservoirs, the remaining 60.7 million cubic meters in federal helium inventories, an average reserve of 4.33 billion cubic meters in the Central Continental region, 4.11 billion cubic meters in the Rocky Mountains region, 52.7 million cubic meters in the central and northern regions, 12.5 million cubic meters in the Gulf Coast region, and 1.11 million cubic meters in the Alaska region. The helium resources in Tanzania come from “The principles of helium exploration”. The helium resources in Australia come from “A case study of helium recovery from Australian natural gas”. NA indicates that there is currently no helium resource statistics available.

3.3.2. Production capacity of helium extraction in host countries

The evaluation of the helium extraction project mainly considers the investment, production capacity, and helium concentration of feed gas of the helium plant. One helium plant is selected from each of the nine resource countries for illustration. There is currently no production of helium extraction plant in Kazakhstan. The unit helium extraction cost is a better indicator with a smaller value, therefore, it needs to be subjected to positive processing. The investment in helium extraction plants in Poland, Tanzania, and Kazakhstan is unknown, so the unit helium extraction cost is temporarily set at 0. The situation of each plant is shown in Table 4.

3.3.3. Upstream cost of gas source

The sum of finding cost, production and operation costs of natural gas is used to represent the upstream costs of helium as shown in Table 5 (see Table 6).

3.4. Maritime risks of helium

When constructing maritime risks, two main factors should be considered. First, the shipping distance from the resource country to ports in China, which is a key factor affecting the magnitude of shipping risks. The longer the shipping distance, the greater the shipping risks occurred. Second, the number of pirate attacks in the seas and straits that the shipping route passes through. The more pirate attacks occur in the straits or seas that the route passes through, the more dangerous the route is. The shipping distance from the resource country to China is calculated by Netpas Distance software; the risk of pirate attacks along the shipping route is expressed by the number of pirate attacks reported in *Report on Piracy and Armed Robbery against Ships* published by the International Maritime Bureau.

$$TRR_i = \frac{D_i}{D_{\max}} + \left(\frac{tRisk_i - tRisk_{\min}}{tRisk_{\max} - tRisk_{\min}} \right) \quad (13)$$

where TRR_i denotes the maritime risks of helium from resource country i to China; D_i represents the distance from resource country i to China; $D_{\max}$ denotes the maximum distance from the resource country to China; $tRisk_i$ is the risk of pirate attacks from resource country i to China; $tRisk_{\max}$ and $tRisk_{\min}$ represent the maximum and minimum risks of pirate attacks from resource country i to China, respectively.

The maritime risk is a better indicator with a smaller value, therefore, it is subjected to positive and dimensionless processing. Since the products can be transported by land from Russia and Kazakhstan to China, so the maritime risk value is 0, and when calculating positively, their maritime risk score is 1.

3.5. Relations with China

Indicator of relations with China constitutes a pivotal determinant of foreign direct investment flows. Enhanced bilateral relations with China demonstrably facilitate Chinese capital inflows, necessitating its incorporation as a critical analytical dimension.

This composite index encompasses six operationalized components: trade dependence, investment dependence, BIT status, visa facilitation policies, investment obstruction level, and bilateral political relations.

Trade and investment dependence quantify the ratio of China-host country bilateral trade/investment volumes to the host nation's total external trade/investment. Elevated values reflect greater reliance of the host country on Chinese economic engagement. BIT status is codified through a tripartite classification: 1.0 (ratified and enforced), 0.5 (signed pending ratification), and 0.0 (no agreement). Ratified BITs substantively mitigate regulatory risks for Chinese enterprises under international law. Visa facilitation policies inversely correlate with administrative barriers, where higher scores denote streamlined visa procedures for Chinese nationals. Investment obstruction level and bilateral political relation metrics are derived through modified Delphi technique with expert panels. Low barrier scores and higher affinity scores correspond to improved investment climates. Full methodological specifications, including indicator normalization procedures and Delphi implementation parameters, are systematically presented in Table 7.

4. Ranking results and discussion

The evaluation system of investment environment in major helium resource countries worldwide is established based on an amount of collected data. We substitute the calculation results of each sub item into Eq. (1) through the various indicator weights, and obtain the comprehensive evaluation scores and rankings (Table 9). From the weight results, the resource endowment of helium is the indicator with the highest weight, which indicates that helium resources occupy the primary factor in the investment process. Kazakhstan, Russia, and Qatar emerge as the top-performing nations based on composite index evaluations, demonstrating superior scores in multidimensional assessments (Fig. 4). While these nations dominate the overall rankings, secondary analysis reveals distinct comparative advantages in specific indicator dimensions among other economies.

4.1. Resource endowment and maritime risk are the key factors

In our paper, the objective weight of each index is calculated by the variation coefficient method, and the subjective weight is determined by the expert survey, and finally the game theory combined weighting model is adopted to calculate the combined weight (Table 8).

Primary index weight results are shown in Fig. 5. Resource endowment accounts for the largest weight of 46.64%, demonstrating that helium resource potential is the most critical factors to consider in investment selection. The second largest index is maritime risk. Since helium is mostly transported by sea, the level of maritime risk will affect the stability of the helium supply chain and the returns of investors. Nations exhibiting optimal performance metrics—particularly Kazakhstan and Russia—demonstrate substantially reduced maritime-related vulnerabilities, with

Table 3
Quick-look method for obtaining government take of helium-rich countries.

	United States	Algeria	Australia	Canada	Poland	Qatar	Russia	Tanzania	Kazakhstan	
A	100	100	100	100	100	100	100	100	100	Annual total revenue Royalty
B	6	20	1	4.25	3	0	3	3	10	
C	94	80	99	95.75	97	100	97	97	90	Corporate income tax Government take
D	21	26	30	38	19	10	20	30	20	
E	27	46	31	42.25	22	10	23	33	30	

Table 4
Production situation of helium extraction in resource countries^a.

Country	Plant	Total investment, USD 10 ⁴	Production capacity, 10 ⁴ m ³ /year	Helium concentration of feed gas, mol%	Unit helium extraction cost, USD 10 ³ /ton
United States	DOE Canyon	13,400	605.92	0.3	22.12
Algeria	Skikda	8700	1581.44	Low pressure 4, high pressure 6 ^b	5.50
Australia	Darwin	3337.5	511.28	3	6.53
Canada	Battle creek	2416.7	154	0.80	15.69
Poland	Odolanow	NA	300 ^c	0.40 ^d	NA
Qatar	RAS Laffan Helium I	11,500	1739.36	2.00	6.61
Russia	Amur	1,270,000 ^e	6000	0.24	211.67
Tanzania	Helium One	NA	2800 ^f	NA	NA
Kazakhstan	NA	NA	NA	NA	NA

^a Unless otherwise specified, the data comes from "A case study of helium recovery from Australian natural gas". NA indicates there is currently no data available.^b The helium content data of the feed gas of Skikda helium extraction plant comes from "Large scale helium liquefaction and considerations for site services for a plant located in Algeria". The average value is taken as 5 during calculation.^c The production capacity of the Odolanow helium extraction plant in Poland comes from USGS, The Mineral Industry of Poland.^d The helium content in the feed gas of the Odolanow helium extraction plant in Poland comes from "Helium Extraction from LNG End Flash".^e The investment data for Amur helium plant in Russia comes from <https://www.hydrocarbons-technology.com/projects/amur-gas-processing-plant-amur-region/>.^f The production capacity data of Helium One in Tanzania comes from "Global Helium Industry Chain Analysis and China's Response Strategies".**Table 5**
Scores and rankings of upstream costs of helium-rich countries.

Country	Finding cost, USD/m ³	Operation costs, USD/m ³	Upstream cost, USD/m ³
United States	0.06	0.45	0.51
Algeria	0.26	0.34	0.60
Australia	1.96	1.05	3.01
Canada	0.02	0.75	0.78
Poland	0.09	0.71	0.80
Qatar	0.21	0.49	0.69
Russia	0.39	0.26	0.65
Tanzania	0.21	0.27	0.48
Kazakhstan	0.06	0.69	0.75

Table 6
Maritime risks of resource countries.

Country	Shipping routes	Shipping distance	Number of pirate attacks	Maritime risks
United States	United States-Pacific Ocean-China	10,328	0	0.796
Qatar	Qatar-Strait of Hormuz-Malacca Strait-China	6380	38	1.442
Canada	Canada-Sanak Reef South-Tsugaru Strait-Tsushima Strait-China	5095	0	0.393
Poland	Poland-Gibraltar Strait-Mediterranean-Suez Canal-Gulf of Aden-Yemen-Malacca Strait-China	11,415	40	1.880
Russia	–	–	–	–
Algeria	Algeria-Mediterranean-Suez Canal-Malacca Strait-China	9173	40	1.707
Kazakhstan	–	–	–	–
Australia	Australia-Indonesia-China	3851	16	0.697
Tanzania	Tanzania-Malacca Strait-China	6235	38	1.431

Note: The number of pirate attacks is sourced from International Maritime Bureau (2022).

Table 7
Relations between helium-rich countries and China.

Country	Trade dependence	Investment dependence	BIT status	Visa status	Degree of investment obstruction	Bilateral political relations
United States	0.141	0.012	0	0	0.2	0.314
Algeria	0.071	0.147	1	0.4	0.8	0.796
Australia	0.308	0.017	1	0	0.3	0.4
Canada	0.081	0.002	1	0	0.3	0.271
Poland	0.061	0.003	1	0.4	0.7	0.486
Qatar	0.161	−0.009	1	1	0.8	0.757
Russia	0.219	−0.005	1	0.8	0.8	0.943
Tanzania	0.405	0.048	1	0.4	0.8	0.871
Kazakhstan	0.23	0.187	1	1	0.8	0.85

this enhanced security profile stemming directly from their capacity for direct land-based transportation linkages. Poland occupies the lowest position in the ranking attributable to its limited

resource endowments and elevated maritime transportation risks, consequently being excluded from priority consideration in investment decision-making processes.

Table 8
Weight values of each indicator.

Primary indicators	Secondary indicators	Tertiary indicators	Subjective weight	Objective weight	Combination weight
Resource endowment	Recoverable helium reserves	–	0.40	0.41	0.50
	Helium production		0.25	0.37	0.28
	Helium resources		0.35	0.22	0.23
Macro investment environment	Global competitiveness index	–	–	–	–
Helium operation risks	Contract feasibility	Royalty	0.30	0.12	0.11
	Production capacity of helium extraction project	Corporate income tax			
		Production capacity	0.30	0.55	0.50
		Helium content of feed gas			
	Upstream cost	Unit helium extraction cost	0.40	0.32	0.39
Helium shipping risks	Shipping distance	Discovery cost			
	Number of pirate attacks	Production and management costs			
Relations with China	Trade dependence	–	0.10	0.15	0.12
	Investment dependence	–	0.05	0.35	0.19
	BIT status	–	0.10	0.09	0.10
	Visa status	–	0.10	0.22	0.16
	Degree of investment obstruction	–	0.25	0.10	0.18
	Bilateral political relations	–	0.40	0.10	0.26

Table 9
Comprehensive scores and rankings of helium investment environment in resource countries.

Country	Helium resource endowment	Macro investment environment	Helium operation risks	Maritime transport risk	Relations with China	Total score	Ranking
Kazakhstan	0.062	0.751	0.747	1.000	1.085	0.530	1
Russia	0.209	0.797	0.84	1.000	0.912	0.528	2
Qatar	0.419	0.871	0.847	0.272	0.854	0.431	3
Algeria	0.253	0.673	0.82	0.23	0.876	0.340	4
Tanzania	0.044	0.576	1.000	0.275	0.930	0.296	5
America	1.000	1.000	0.978	0.493	0.245	0.213	6
Australia	0.075	0.94	0.369	0.564	0.469	0.163	7
Poland	0.01	0.823	0.737	0.209	0.583	0.160	8
Canada	0.04	0.951	0.681	1.000	0.323	0.159	9
Subjective weight	0.54	0.07	0.14	0.25			
Objective weight	0.20	0.30	0.25	0.25			
Combination weight	0.47	0.12	0.16	0.25			

As shown in Fig. 6, helium resources, reserves and production still occupy the highest proportion among the sub-indicators, indicating that the sustainability and sufficiency of helium resources are crucial for investors. The global competitiveness index has a relatively high weight of 11.82%. This index reflects the comprehensive strength of resource countries in economic, political, scientific and technological aspects. The United States and Australia are at the forefront in the term of the global competitiveness index and have significant advantages in the fields of helium development, technological innovation, market access and so on.

4.2. Helium resources and investment choice analysis

From a multi-criteria assessment perspective, the prioritized sequence of analytical outcomes is systematically tabulated in Table 9. The Kazakhstan demonstrates optimal composite performance within the evaluation framework, primarily attributable to its stable macroeconomic investment climate, minimized maritime transportation risks, and robust Sino-centric diplomatic relations. While Kazakhstan's helium resource potential score

remains suboptimal in initial evaluations, progressive exploratory initiatives within Kazakh geological basins reveal substantial untapped exploitation potential. The 2011 technological achievement appraisal conducted by the China Petroleum and Chemical Industry Federation (CPCIF) in Beijing for the research project “Helium Enrichment Mechanisms and Resource Assessment in the Suk Gas Field, Chu-Sarysu Basin, Republic of Kazakhstan” established critical benchmarks. This pioneering systematic evaluation quantified helium resources through indirect volumetric methodology, calculating three-tiered geological reserves at $21.89 \times 10^8 \text{ m}^3$ with recoverable reserves reaching $13.01 \times 10^8 \text{ m}^3$, categorizing Suk Field as a world-class helium reservoir. The subsequent Petroleum and Natural Gas Exploration and Development Contract between Suk Energy and Kazakhstan's Central Exploration and Development Commission formalized a 25-year developmental timeline. Economic modeling under current Chinese helium import pricing indicates phased development feasibility: Phase I could yield $10 \times 10^6 \text{ m}^3$ annually, escalating to more than $30 \times 10^6 \text{ m}^3$ in Phase I + II, with helium-specific economic valuations projecting USD 800 million and USD 2.9 billion respectively. Russia's secondary positioning in the ranking mirrors Kazakhstan's advantages in

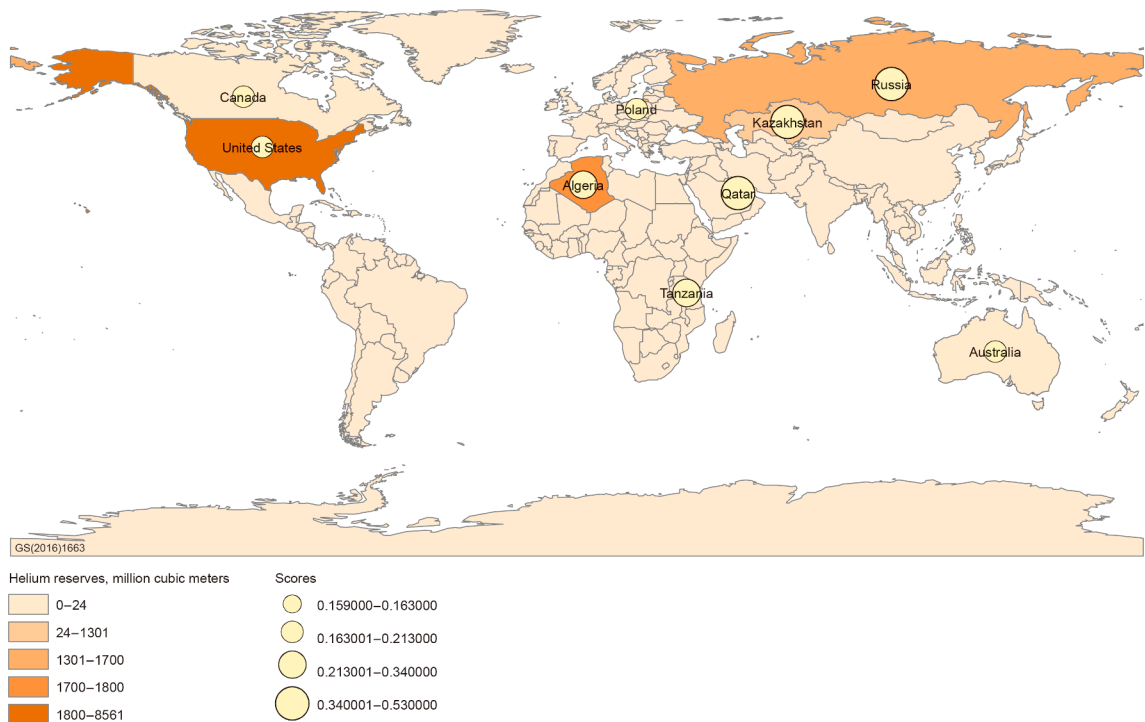


Fig. 4. Distribution of global helium resources and comprehensive scores of resource countries.

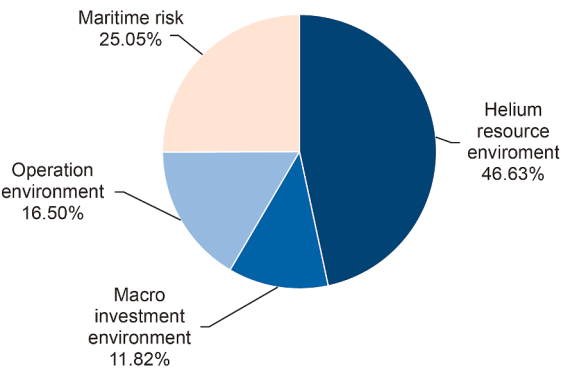


Fig. 5. Index weights of first-level indicators.

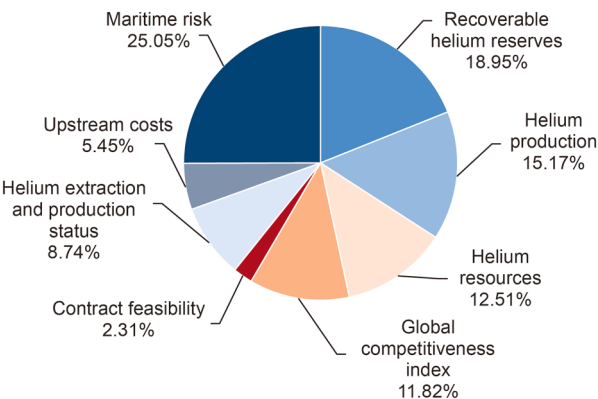


Fig. 6. Index weights of sub-index.

macroeconomic stability and maritime risk mitigation, collectively positioning both nations as prime collaborative investment targets.

While other nations demonstrate limited comprehensive competitiveness within the evaluative framework, their distinctive advantages across specific metrics warrant analytical attention. The United States maintains substantial proven helium reserves. Canada and Poland exhibit optimized regulatory frameworks for foreign direct investment. Algeria demonstrates enhanced operational efficiency in helium value-chain integration. Tanzania displays strategic bilateral diplomatic congruence with China.

5. Conclusion and recommendations

5.1. Conclusions

As a rare strategic resource, helium plays an irreplaceable role in several fields. The distribution of helium resources worldwide is uneven, and the level of development varies, so risk assessment of helium investment environment is of great significance for effectively accessing to helium resources. This paper develops an assessment index system and evaluation model by introducing the game theory model combined with variance coefficient theory and expert survey. The investment environment in nine helium producing countries is appraised. The primary conclusions are as follows.

- (1) The comprehensive index system is established including resource endowment, macro environment, operation risk, maritime risk, and relations with China. The index of after-tax profits is developed to quantify the contract attraction

of host countries. The helium production capacity index is presented with helium concentration of different raw gas, the separating capacity of typical helium plants and the unit extracting cost. Since most helium is extracted from helium-rich natural gas reserves, the upstream cost index is presented according to the discovery and development costs of natural gas. At the same time, the maritime risk index is constructed by considering the shipping distance and the number of pirate attacks. Finally, the relations with China is developed by the trade and political relations between China and host countries.

- (2) The comprehensive evaluation framework identifies Kazakhstan as the highest-ranked nation, followed sequentially by Russia and Qatar. Distinct risk profiles emerge across the evaluated jurisdictions. Qatar and Algeria demonstrate economic stability coupled with optimized operational environments. Tanzania and Kazakhstan exhibit strategic bilateral diplomatic congruence with China, albeit constrained by elevated resource uncertainty. Notably, current geopolitical conflicts introduce elevated risk factors in Russia, despite substantial untapped resource potential and strong bilateral engagement metrics with China. Techno-economic analysis reveals operational cost advantages in Qatar and Algeria, where boil-off gas (BOG) from LNG processing is utilized for helium refinement, achieving production cost reductions compared to conventional extraction methods.

5.2. Policy recommendations

The evaluation of the investment environment helps us seize opportunities and respond to risks and challenges. To generate efficiently sound strategies for selecting target countries for overseas helium investment, we provide the following policy recommendations based on aforementioned results:

Geopolitical stability and institutional continuity constitute fundamental prerequisites for sustainable international partnerships in helium development. The future joint development of helium projects should focus on the countries with potential rich resources and consistently lower risk, such as Kazakhstan and Tanzania. For helium trade cooperation, the focus should be on the countries with abundant natural gas and mature joint processing techniques of LNG and helium, such as Qatar and Algeria.

Due to different risk characteristics among countries, China should take effective measure to avoid the shortcomings. For the countries with geopolitical risk, such as Russia, stuck in conflicts, we should seize opportunities to enter upstream helium-rich gas fields and form a partnership through joint venture agreement. For the countries owning an unstable bilateral relationship with China, such as Qatar and Algeria, we should establish a risk warning system and exemption purchase contract to prevent losses.

Diversified supply system should be built to maintain the safety and stability of China's helium supply. We should actively respond to changes in the helium market, carry out multi-field cooperation around Qatar, Russia, Tanzania and other countries along the "Belt and Road", and establish long-term and stable supply relations, so as to reduce our dependence on the western country-owned or funded companies. Increase support for domestic helium enterprises such as G-Gas and Shanghai Jiyang, actively cultivate domestic helium market players, and encourage enterprises to participate in international cooperation. Meanwhile, a minimum guarantee mechanism for the purchase of crude helium and helium storage reservoirs should be established by the governments.

However, there are a certain of limitations in our approach and results. Some uncertainties lie in the policies and regulations for helium investment in host countries. In future research, the volatility of time series of helium investment risk can be quantified, and the change trend of country-specific risk will be modelled.

CRedit authorship contribution statement

Xu Zhao: Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Qing Wang:** Writing – review & editing, Funding acquisition. **Zi-Yi Zhang:** Writing – review & editing, Visualization, Validation, Software, Resources, Data curation.

Declaration of competing interest

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

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