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Security Measure of Traditional Fossil Energy in China Based on Combination Weighting of Game Theory–Catastrophe Progression Model

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Abstract

The security level of traditional fossil energy sources is closely related to national development, particularly amid a complex and volatile international environment and the rising demand for global environmental governance. This study addressed China's traditional fossil energy security, considering internal factors, such as system structures, and external threats. A positive–negative two-directional evaluation index system including five aspects—resource, market, efficiency, environment, and economy—was proposed. This system integrates an index weighting method that combines the anti-entropy weight method and level-based weighting assessment method. A security measure evaluation method for Chinese traditional fossil energy based on the catastrophe progression model was also established. The security measure for three traditional fossil energy resources—petroleum, natural gas, and coal—was studied. Results show that under the hard constraints of "carbon peaking and carbon neutrality" in China, the clean and efficient utilization of coal is strategically vital significance. Optimizing coal use leverages China's resource advantages, reduces pressure on petroleum resources, ensures energy security, and protects the ecological environment. The overall security level of China's major fossil energy resources—petroleum, natural gas, and coal—presents an evident upward trend, indicating an improvement in the security status of China's energy.

Keywords: energy security; combination weighting of game theory; catastrophe progression model; fossil energy; carbon emission reduction

Introduction

In the past decade, the total consumption of fossil energy in China increased from 4.17 billion tons of standard coal in 2013 to 5.72 billion tons in 2023, which supported the national economic growth by nearly 6%, with an average annual growth rate of 3.2% [1]. In the energy consumption structure, coal-fired power generation accounts for 60% of total coal consumption. In 2023, clean power consumption accounted for 17.9% of total energy consumption. Coal-fired power generation comprised 33%, calculated as 55.3% × 60%. Thus, electric power represented 51.1% of the total energy consumption. Under the policy of carbon peaking and carbon neutrality, large-scale electrification is needed in fields such as industry, architecture, and transportation [2]. In 2023, coal consumption accounted for 55.3% of the total energy consumption, declining by 12.1 percentage points in comparison with that in

2013. The proportion of non-fossil energy consumption continued to grow, and that of non-fossil energy consumption was 17.9% in 2023, which was 7.7% higher than that in 2013 [3].

Nowadays, energy security in China faces numerous challenges. First, resource demand is high, with energy supply pressure remaining elevated for a long time [4]. The period after the reform and opening-up has witnessed rapid economic development and an enormous economic volume. The circumstances require increased energy support alongside serious energy threats induced by energy undersupply. Second, the energy structure is unbalanced. Coal resources are abundant, but oil and natural gas resources are relatively scarce. In China, which is the world's largest importer of crude oil and natural gas, the huge energy import directly lowers the level of energy security [5]. Third, China still lags behind developed countries in energy exploitation technology. Since this century began, energy revolutions in developed nations have guaranteed stable energy supplies. By contrast, China continues to face higher energy demand than supply, accompanied by a relatively high level of external dependence. Fourth, the international situation is turbulent. Petroleum and natural gas are strategic resources affecting economic, political, military, and social development worldwide. As a major importer, China always regards energy cooperation as an important factor in external development [6]. Since the Belt and Road Initiative has been proposed, China has strengthened exchange and cooperation with Western Asian countries, but the frequent political risk in this region impedes energy cooperation with the countries along the Belt and Road. These energy issues jointly affect the security of traditional fossil energy sources in China, making it urgent to accurately measure energy security and put forward countermeasures that consider the current complicated international situation and the new development pattern.

Literature review

In general, energy security evaluation has been investigated by establishing evaluation index systems. Energy security evaluation systems that are internationally recognized include those developed by the Joint Energy Security of Supply Working Group (JESS) in the U.K., International Energy Agency (IEA), and Asia-Pacific Energy Research Center (APERC). Among which, the JESS mainly focuses on natural gas and electricity. This model assumes that the energy market is a free market and that the price is a direct factor affecting consumers and suppliers. The IEA believes that the fossil energy endowments in different regions quite vary and that a single enterprise only slightly influences the market price. Therefore, the market influence of energy endowments in different countries and regions is the basis affecting energy security. Accordingly, an energy security evaluation model composed of price risk index and supply interruption risk index has been put forward [8]. With the continuously expanding energy demand of the Asia-Pacific region, the APERC has built a rating system including five energy supply security indices—diversity of primary energy demand, dependence on net import, low-carbon energy demand index, dependence on petroleum net import, and dependence on petroleum import from the Middle East. This system evaluates potential supply risk, energy resource diversity, and import dependence according to the actual situation in the Asia-Pacific region [9].

Basing on these frameworks, numerous scholars have established energy security evaluation index systems. Adomako et al. built an energy security evaluation system containing 44 indices in 11 dimensions; they further evaluated the natural gas import source of Asia using the Herfindahl–Hillman index (HHI) method [10]. Rochedo et al. reevaluated the "4A" framework. They believed that energy security should include four dimensions—usability, affordability, technological development and efficiency, sustainability, and supervision and governance, so they divided the four dimensions into 18 indices [11]. Ainou et al. refined the evaluation method for regional energy security and put forward policy suggestions for improving energy independence by analyzing the external energy reliance of certain countries [12]. Using 36 years of historical data from 25 countries, Ren et al. analyzed the reliability of international energy security risk indices using 29 variables from eight angles [13]. Alola et al. established an index system including petroleum dependence, market liquidity, and transportation risk; they evaluated the petroleum supply in Southeast Asia via principal component analysis [14]. Schaeffer et al. established 27 indices divided into nine groups from the perspectives of economy, energy, and environment to evaluate the energy security index of each country [15].

Many methods are available to measure energy security in China and abroad. According to different integrated index processing methods, energy security evaluation focuses on various dimensions. In evaluating the diversification degree of energy utilization based on single indices, energy security has been generally evaluated using the Shannon–Weiner index in combination with information theory [16]. The degree of energy trading markets has been usually measured through the HHI [17]. However, as energy issues become increasingly complicated, single indices are inadequate to reflect core problems in evaluating the overall energy security. Consequently, a growing number of scholars have started relevant estimation and evaluation based on integrated evaluation indices [18].

Saraiva et al. carried out an energy security evaluation from the dimensions of payability, availability, and technical characteristics [19]. Basso et al. established a three-dimensional energy security evaluation system containing 26 indices by using the system method tailored to the new normalcy of energy development in China [20]. Simas et al. constructed an energy security evaluation index system focused on the surplus, gap, and current status of energy supply, and they conducted an energy security evaluation of energy resources and consumption from the perspective [21]. Bogdanov et al. established a regional-level energy security evaluation system using the entropy weight TOPSIS method; they analyzed and compared energy security from three aspects—energy supply, demand, and utilization [22]. Portugal-Pereira et al. constructed an energy security evaluation index system from four dimensions, namely, energy industry development, supply capacity, utilization level, and environmental impact, to evaluate and analyze energy security [23]. Cergibozan et al. constructed an energy security evaluation index system including seven dimensions, such as energy production, consumption, environment, and efficiency. They used fuzzy analytic hierarchy process and GRA-TOPSIS model to evaluate energy security [24]. In the studies on energy types, Ren et al. constructed an energy security evaluation system including three dimensions—pressure, state, and response—to evaluate and predict coal security [25]. Cherp et al. assessed security on the source of oil imports by constructing an evaluation system including resources, politics, military affairs, and transportation [26]. Narula et al. evaluated natural gas energy security by constructing an evaluation system with four dimensions: availability, usability, bearing capacity, and affordability [27]. Ghabour et al. built a policy evaluation system including taxation, energy structure, and market for the coal industry [28]. Moreira et al. constructed an evaluation system from 11 indices from four dimensions: availability, economy, cleanliness, and sustainability; they used entropy TOPSIS method to quantitatively evaluate primary energy security [29].

To sum up, the relevant research methods with regard to single-index evaluation have advantages in clearly and intuitively examining and evaluating the influences of core target factors on energy security. However, such methods fail in the overall evaluation of energy security and cannot systematically analyze the relationship between different influencing factors. Comparatively, integrated evaluation methods are capable of overall energy security measurement, but their applicability remains controversial in the academic circles. Nevertheless, the evaluation methods based on integrated indices have become the mainstream choice in the current research on energy security issues in face of various increasingly complicated influencing factors in China and abroad. From this angle, a security evaluation index system for traditional fossil energy in China was constructed in this study.

Methodology

In this study, China's traditional fossil energy security was measured by using a combination weighting method of game theory and the catastrophe progression method. Before the evaluation using the catastrophe progression method, the weight of each index was calculated using combination weighting based on game theory.

Establishment of energy security evaluation index system

The influencing factors involved in energy security are very complex, so a scientific and reasonable energy security evaluation index system should be constructed to analyze relevant issues. Drawing on domestic and foreign literature, this study selected a total of 19 indices across five dimensions—resource, market, environment, utilization efficiency, and economic security—to address China's traditional fossil energy security needs. The evaluation index system is presented in Table 1.

Table 1. Evaluation index system for energy security measure of China's traditional fossil energy

Objective layer	Second-level index	Symbol	Third-level index	Symbol	Index calculation
Security measure of traditional fossil energy in China	Resource	A1	Per capita energy quantity	A11	Total energy quantity/population size
			Reserves/production ratio	A12	Recoverable reserves/produced quantity
			Proportion of reserves	A13	Domestic energy reserves/world energy reserves
			Energy type	A14	Types of domestic main fossil energy sources
	Market	A2	External dependence	A21	(Import-export)/demand
			Concentration of energy import	A22	Energy import volume of top 3 countries/total import volume
			Supply/demand ratio	A23	Energy production/energy consumption
			Energy self-sufficiency	A24	Energy consumption/ (energy import volume—energy export volume)
			Concentration of energy production	A25	Energy production of top three provinces/national total output
	Efficiency	A3	Energy consumption intensity	A31	Annual energy consumption/GDP
			Proportion of scientific research input into energy	A32	Scientific research input into energy/GDP
			Energy processing and conversion efficiency	A33	Output quantity/input quantity
	Environment	A4	Proportion of non-fossil energy in consumption	A41	Non-fossil energy consumption/total energy consumption
			Proportion of environmental pollution investment	A42	Environmental pollution treatment investment/GDP

		Sulfur dioxide emission intensity	A43	Sulfur dioxide emission/GDP
		Carbon emission intensity	A44	Carbon dioxide emission/GDP
Economy	A5	Oil price	A51	Average retail price of gasoline and diesel
		Natural gas price	A52	Price of household natural gas in provincial capitals
		Coal price	A53	Price of industrial coal in provincial capitals

Combination weighting method based on game theory

According to the established evaluation index system for traditional fossil energy security in China, a combination weighting method based on game theory was put forward. First, the objective weight of each index was calculated using the anti-entropy weight (AEW) method. Second, the subjective weight of each index was solved via level-based weight assessment (LBWA). Finally, an optimization solution model of combination weighting was established through game theory, aimed at minimizing the heterogeneity between objective and subjective weight results.

Objective weighting method based on AEW

In this study, the objective weight of each index was determined using AEW method. Entropy, which is a concept used to measure the disorder of thermodynamic systems, has been introduced into information theory. If there are *m* possible states in the system and the appearance probability of each possible state is $p_j (j = 1, 2, \cdots, m)$, then entropy can be defined as follows:

$$h = -\sum_{j=1}^{m} p_j \ln(p_j) \tag{1}$$

Where $0 \le p_j \le 1$ and $\sum_j p_j = 1$.

Under the AEW method, for the multi-attribute decision problem to be studied, the number of to-be-evaluated objects is *m* and the number if indices is *n*. Thus, the index value can be expressed as $x_{ij} (i=1,2,...,n, j=1,2,...,m)$, and the corresponding decision matrix can be written as $X = [x_{ij}]_{n\times m}$. Hence, the anti-entropy value of each index can be expressed as follows [27]:

$$w_{1i} = h_i / \sum_i h_i \tag{2}$$

Subjective weighting method based on LBWA

LBWA method is a subjective weighting method proposed by Serbian scholars Mališa Žižović and Dragan Pamučar in 2019 [28]. This method first determines the most important index in the index system (i.e., optimal index), then divides other indices into different levels according to their importance relative to the optimal index. Finally, this method judges the importance of each index within the level to determine the importance ranking of all indices. Through the ranking step of index importance, this method can effectively deal with the ranking inconformity that may be caused by a large number of indices. Consequently, it simplifies the comparison of index importance through the judgment of index importance within the level. Gaining attention from relevant scholars in recent years, LBWA has been applied to various multi-attribute decision fields, such as evaluation of renewable energy substitution schemes and decision on the position of offshore wind farms. In this study, the subjective weights for the credit risk evaluation indices of new energy power generation enterprises were determined through LBWA. The basic steps involved are as follows:

STEP 1: Determination of the optimal index. According to expert opinions, the index with the greatest importance in the index set is defined as the optimal index.

STEP 2: Index level division. The remaining indices except the optimal index are divided into different levels according to their importance on the following basis:

S1 Level: This level includes indices with the same importance as the optimal index or the indices with the importance below twice (twice not included) lower than that of the optimal index are collected into this level.

S2 Level: This level includes indices with the importance twice or triple (triple not included) lower than that of the optimal index are divided into this level.

SK Level: This level includes indices with importance ranging from K to (K+1) times lower than that of the optimal index are classified into this level.

Through this index level division, the importance of indices can be roughly defined. Assuming that the importance of a random index can be expressed as $S(C_i)$, for the level $S_k (k=1,2,...,K)$ to which this index belongs, the following can be satisfied:

$$S = S_1 \cup S_2 \cup \cdots \cup S_K$$

For any $p,q \in \{1,2,...,K\}$, if $p \neq q$, then $S_p \cap S_q = \varnothing$.

STEP 3: Index importance level judgment. In any layer $S_k = \left\{C_{1,k}, C_{2,k}, ..., C_{N_k,k}\right\}$, the optimal index $C_{B,k}$ within the layer is defined to compare the importance of other indices within this layer relative to this optimal index. The result is denoted as $I_{i_k,k}$, $I_{i_k,k}$, indicating the importance of the i_k th index in the kth layer relative to the optimal index. The greater the importance of the i_k th index, the smaller the value of $I_{i_k,k}$. $I_{i_k,k}$ is an integer within the interval of $[0,1]$. Especially when $k=1$, $C_{B,1}=C_B$ and $I_{B,1}=0$. r is a constant determined by the index importance ranking result, and

$$r = \max\left\{|S_1|, |S_2|, ..., |S_K|\right\},$$

where $|S_k|$ denotes the number of indices in the set S_k.

STEP 4: Determination of LBWA elasticity coefficient. Constant r represents the maximum difference in the judgment of index importance within the layer. According to the r value, the elasticity coefficient of LBWA is generally assigned according to the study by Mališa Žižović, Dragan Pamučar, and Ali Ebadi Torkayesh et al.

STEP 5: Calculation of the influence function. The influence function $f\left(C_{i_k,k}\right)$ of each index is calculated as follows:

$$f\left(C_{i_k,k}\right) = \frac{r_0}{k \cdot r_0 + I_{i_k,k}} \tag{3}$$

where $C_{i_k,k}$ represents the i_k th index in the kth layer.

STEP 6: Calculation of index weights. According to $f\left(C_{i_k,k}\right)$, the weight of the optimal index can be expressed as:

$$w_B = \frac{1}{\sum_{k=1}^{K}\sum_{i_k=1}^{N_k} f\left(C_{i_k,k}\right)} \tag{4}$$

Furthermore, the weight of other indices is $w_{i_k,k} = f\left(C_{i_k,k}\right) w_B$.

On this basis, the subjective weights of all indices under the LBWA method are obtained as w_{2i}.

Combination weighting method based on game theory

Considering the data dependence of the objective weighting method and the subjectivity of the subjective weighting method, the combination weighting method was adopted in this study to determine index weights. On the one hand, this approach can avoid too subjective experience-based judgments made by experts. On the other hand, it can prevent unreasonable weight allocation induced by neglecting index attributes during objective weighting so as to acquire more effective index weights.

In this study, the basic principle of combining subjective and objective weighting is to minimize the heterogeneity between subjective and objective weight results. A simple weighted average of subjective and objective weights can reduce the heterogeneity of subjective and objective weights to a certain extent, but it does not fully minimize it. Therefore, game theory was applied to the combination of subjective and objective weights, allowing both types of weights to contribute meaningfully to the evaluation process and further balance their differences through a reasonable weight allocation coefficient. The basic steps of the combination weighting method based on game theory are as follows:

If the weight vector $W_l=(w_{1,l},w_{2,l},...,w_{n,L})$ $(l=1,2,...,L)$ of n indices is calculated through L types of weighting methods, the basic weight set $W=\{W_1,W_2,...,W_L\}$ can be acquired accordingly. The combination weight is then defined as a linear combination of L basic weights, i.e.,

$$W_{inte}=\sum_{l=1}^{L}\alpha_l W_l \tag{5}$$

Where a_l is the allocation coefficient of the lth basic weight. The linear combinations of L basic weights are infinitely many. To find the optimal combination weight W_{inte}^* therein, the basic weight allocation coefficient in Formula (9) was optimized by following game theory, aiming to minimize the heterogeneity (deviation) between the optimal combination weight and all basic weights. The optimized formula can be expressed as:

$$\min\sum_{l=1}^{L}\left\|\left(\sum_{l=1}^{L}\alpha_l W_l\right)-W_l\right\|_2 \tag{6}$$

Where $\|U\|_2$ is the two-norm of vector U, a_l is a variable to be decided on, and $\sum_{l=1}^{L}\alpha_l$. a_l^* can solve the optimal value of Formula (10) using mature MATLAB commercial solver. Thus, the combination weight based on game theory can be expressed as follows:

$$W_{inte}^*=\sum_{l=1}^{L}\alpha_l^*\times W_l \tag{7}$$

Specifically, two basic weights are combined in this study: W_1 is the objective weight based on AEW; W_2 is the subjective weight based on LBWA. The weight after combination reaches the minimum deviation from the subjective and objective weights, thus balancing the index importance reflected by subjective and objective weights. That is, the combination weight can not only reflect the attribute of the index itself but also effectively utilize the original data information of the index.

Basic model of catastrophe progression evaluation method

Catastrophe model

In the catastrophe progression evaluation model, assuming that one catastrophe type has a potential function $f(x)$, $f'(x)=0$ is set to solve the profile of equilibrium, and $f''(x)=0$ is set to solve the odd point set equation of the profile of equilibrium. $f'(x)=0$ and $f''(x)=0$ are solved to obtain the bifurcation point set equation, which is the research emphasis and core of catastrophe theory. The target system will experience a catastrophe when the control variable meets the bifurcation point set equation.

(1) Derivation of bifurcation equation. Taking the cusp catastrophe model for example:

The potential function of the cusp catastrophe model is set as $f(x)=x^4+Bx^2+Cx$, and

$4x^3+2Bx+C=0$ is obtained given $f^{'}(x)=0$; $f^{''}(x)=0$ is set to obtain $12x^2+2B=0$. The bifurcation point set equations $B=-6x^2$ and $C=8x^3$ in the decomposed form of the cusp catastrophe model can be acquired by solving $f^{'}(x)=0$ and $f^{''}(x)=0$. These bifurcation point set equations are merged to obtain the bifurcation equation $8B^3+27C^2=0$ of the cusp catastrophe model.

Similarly, the bifurcation point set equations of other catastrophe models can be acquired as follows:

(2) The bifurcation point set equations in the decomposed form of the swallowtail catastrophe model $f(x)=x^5+Bx^3+Cx^2+Dx$ are $B=-6x^2$, $C=8x^3$, and $D=-3x^4$.

(3) The bifurcation point set equations in the decomposed form of the butterfly catastrophe model $f(x)=x^6+Bx^5+Cx^3+Dx^2+Ex$ are $B=-10x^2, C=20x^3, D=-15x^4, E=4x^5$.

(4) The bifurcation point set equations in the decomposed form of the shed catastrophe model are $B=-x^2, C=2x^3, D=-2x^4, E=4x^5, F=-5x^6$. The shed catastrophe model is not a primary catastrophe model (state dimension = 1 and control dimension = 5), but it has been frequently utilized in catastrophe progression evaluation models.

Dimensionless processing of evaluation indices

Evaluation indices were mainly divided into two types: qualitative and quantitative indices. The latter were subjected to dimensionless processing through the range transformation method, and the former were transformed into quantitative indices using the Delphi method or questionnaire method. According to the difference in evaluation indices, quantitative indices could be divided into positive indices and negative ones. The greater the value of positive indices, and the smaller the value of negative indices. The conversion formulas for positive and negative indices are given in Formulas (8) and (9):

$$\delta_{ij}^{+}=\frac{x_{ij}-\min x_j}{\max x_j-\min x_j} \tag{8}$$

$$\delta_{ij}^{-}=\frac{\max x_j-x_{ij}}{\max x_j-\min x_j} \tag{9}$$

Normalization formula for catastrophe model

Taking the cusp catastrophe model for example, $B=-6x^2$ and $C=8x^3$ are solved, and $x_B=\sqrt{-\frac{B}{6}}$ and $x_C=\sqrt[3]{\frac{C}{8}}$ are obtained, where x_B corresponds to the x value of B and x_C to that of C . To combine with fuzzy mathematical membership functions, the value ranges of control variables were made the same as those of state variables, and their values were all limited within $[0,1]$. Hence, $B=6B^{'}$ and $C=8C^{'}$ are set to obtain $x_B=\sqrt{B^{'}}$ and $x_C=\sqrt[3]{C^{'}}$. Subsequently, the values of $B^{'}$, C' , and x were all confined within [0,1], realizing the combination of the catastrophe model and fuzzy mathematics. The normalization formulas for the cusp catastrophe model were acquired as $x_B=\sqrt{B}$ and $x_C=\sqrt[3]{C}$. The normalization formulas for other catastrophe models can be solved in a similar way, as seen in Table 2:

Table 2. Normalization formulas for common catastrophe models in catastrophe progression method

Catastrophe type	Control dimension	Potential function	Normalization formula

Fold catastrophe	1	$f(x)=x^3+Bx$	$x_B=\sqrt{B}$
Cusp catastrophe	2	$f(x)=x^4+Bx^2+Cx$	$x_B=\sqrt{B},x_C=\sqrt[3]{C}$
Swallowtail catastrophe	3	$f(x)=x^5+Bx^3+Cx^2+Dx$	$x_B=\sqrt{B},x_C=\sqrt[3]{C},x_D=\sqrt[4]{D}$
Butterfly catastrophe	4	$f(x)=x^6+Bx^5+Cx^3+Dx^2+Ex$	$x_B=\sqrt{B},x_C=\sqrt[3]{C},x_D=\sqrt[4]{D},x_E=\sqrt[5]{E}$
Shed catastrophe	5	$f(x)=x^7+Bx^6+Cx^5+Dx^3+Ex^2+Fx$	$x_B=\sqrt{B},x_C=\sqrt[3]{C},x_D=\sqrt[4]{D},x_E=\sqrt[5]{E},x_F=\sqrt[6]{F}$

Selection principle of catastrophe decision

In the comprehensive evaluation for the security measure of China's traditional fossil energy using the catastrophe progression method, two principle guide system catastrophe decisions: "complementation" and "non-complementation." These principles are in accordance with the influencing directions of control variables on the state variable. The complementation principle refers to the complementary effect of control variables on the state variable in the system. The value of intermediate state variable x denotes the mean value for the initial mutation sequence of control variables. Hence, $x=(x_1+x_2+\cdots+x_n)/n,n\le 5$. The non-complementation principle means that all control variables in the system have no effects on the state variable. The value of intermediate state variable x is the minimum value of the state variable. Thus, $x=min\{x_1,x_2,\cdots,x_n\},n\le 5$, where x is the state variable and $x_1,x_2,\cdots,x_n$ represent the catastrophe progression values of lower-layer control variables $1,2,3,\cdots,n$, respectively.

Result Analysis and discussion

In the empirical data of this study, domestic recoverable energy reserves, world recoverable energy reserves, domestic energy production, world total energy production, energy production output, energy consumption, and energy price in each year all came from *BP Statistical Review of World Energy*. Recoverable reserves, produced quantity, population size, GDP, and environmental pollution treatment investment were derived from *China Statistical Yearbook*. Energy production, total production, energy processing and conversion output, and energy processing and conversion input came from *China Energy Statistical Yearbook*. The total energy import volume was derived from *Yearbook of China's Mining Industry*. The security measure of traditional fossil energy in China was taken as the study object for evaluation, and evaluation indices were scored using the combination weighting method based on game theory. The scores of 1, 3, 5, 7, and 9 represent the security levels under different circumstances, and the higher the score, the better the security level.

Weight determination for indices at each level

In terms of security of traditional fossil energy in China, five aspects—resource, market, efficiency, environment, and economy—were comprehensively evaluated, and the security level of traditional fossil energy in China was determined. According to the established evaluation model composed of combination weighting of game theory–catastrophe progression method, the weight of each index was determined using the combination weighting method of game theory. The weight value of each third-level index was calculated, as seen in Table 3.

Table 3. Calculation methods through combination weighting method based on game theory

Objective layer	Second-level index	Symbol	Third-level index	Symbol	AEW weight	LBWA weight	Comprehensive weight	Ranking
Security measure of traditional fossil energy in China	Resource	A1	Per capita energy quantity	A11	0.0763	0.0772	0.0770	3
			Reserves/production ratio	A12	0.0752	0.0419	0.0540	9
			Proportion of reserves	A13	0.0144	0.0738	0.0524	11
			Energy type	A14	0.0146	0.0619	0.0448	13
	Market	A2	Concentration of energy production	A21	0.0411	0.0126	0.0229	18
			Concentration of energy import	A22	0.0257	0.0466	0.0391	15
			Supply/demand ratio	A23	0.0492	0.0317	0.0381	16
			External dependence	A24	0.0321	0.0695	0.0560	8
			Energy self-sufficiency	A25	0.0199	0.0705	0.0523	12
	Efficiency	A3	Energy consumption intensity	A31	0.0617	0.0555	0.0578	7
			Proportion of scientific research input into energy	A32	0.0841	0.0184	0.0422	14
			Energy processing and conversion efficiency	A33	0.0895	0.0338	0.0540	10
	Environment	A4	Proportion of non-fossil energy in consumption	A41	0.0335	0.0795	0.0629	6
			Proportion of environmental pollution investment	A42	0.0952	0.0457	0.0637	5
			Sulfur dioxide emission intensity	A43	0.0227	0.0172	0.0192	19
			Carbon emission intensity	A44	0.0289	0.0403	0.0362	17
	Economy	A5	Coal price	A51	0.0814	0.0550	0.0646	4

	Natural gas price	A52	0.0702	0.0850	0.0798	2
	Oil price	A53	0.0841	0.0838	0.0840	1

Determination of catastrophe system type

Catastrophe types were classified according to the catastrophe progression method. The catastrophe system type for indices at each level in the evaluation index system was determined. The catastrophe system type corresponding to the designed evaluation index system for the security measure of traditional fossil energy in China is listed in Table 4.

Table 4. Weights of evaluation indices for traditional fossil energy security in China and catastrophe system types

Evaluation objective	Catastrophe type	Second-level index	Combination weight	Catastrophe type	Third-level index	Combination weight
Security measure of traditional fossil energy in China	Shed catastrophe	Resource	0.2802	Butterfly catastrophe	Per capita energy quantity	0.0770
					Reserves/production ratio	0.0540
					Proportion of reserves	0.0524
					Energy type	0.0448
		Market	0.2198	Shed catastrophe	Concentration of energy production	0.0229
					Concentration of energy import	0.0391
					Supply/demand ratio	0.0381
					External dependence	0.0560
		Efficiency	0.3288	Swallowtail catastrophe	Energy self-sufficiency	0.0523
					Energy consumption intensity	0.0578
					Proportion of scientific research input into energy	0.0422
					Energy processing and conversion efficiency	0.0540
					Proportion of non-fossil energy in consumption	0.0629
		Environment	0.1713	Butterfly catastrophe	Proportion of environmental pollution investment	0.0637
					Sulfur dioxide emission intensity	0.0192
					Carbon emission intensity	0.0362
			0.3802		Coal price	0.0646

	Economy	Swallowtail catastrophe	Natural gas price	0.0798
			Oil price	0.0840

Evaluation through catastrophe progression method

(1) According to the requirements of evaluation objectives, 15 relevant experts from colleges and universities and those dedicated to the field of energy security were invited to score the security evaluation of traditional fossil energy in China according to specific evaluation criteria. The index evaluation criteria and values are listed in Table 5. A high security level indicates the optimal state, meeting 90% of the requirements specified in the evaluation criteria. A relatively high security level satisfies 70% of the requirements. An intermediate security level meets 50% of the requirements, and a relatively low security level meets 30% of the requirements. A low security level denotes the poorest state, completely failing to meet the preset requirements.

Table 5. Index evaluation criteria and values

Evaluation level	Excellent	Good	Medium	Ordinary	Poor
Evaluation criterion	High security level	Relatively high security level	Medium security level	Low security level	Extremely low security level
Corresponding evaluation value	9	7	5	3	1
Corresponding evaluation level	[9, 10)	[7, 9)	[5, 7)	[3, 5)	[1, 3)

(2) Dimensionless evaluation indices. The mean value of expert scoring data for each index was taken, the dimensionless processing of positive indices was realized through Formula (1), and that of negative indices was implemented as per Formula (2). The calculation results are listed in Table 6. The symbol (+) indicates that the index of the next level abides by the "complementation" principle, whereas (−) means that the index of a relatively low level follows the "non-complementation" principle.

Table 6. Index scores and dimensionless values

Evaluation object	Second-level index	Third-level index	Mean value of expert scoring			Dimensionless value		
			Petroleum	Natural gas	Coal	Petroleum	Natural gas	Coal
Security measure of traditional	Resource	Per capita energy quantity	5.07	4.93	5.53	0.0333	0.9667	0.2667
		Reserves/production ratio	4.27	5.40	6.93	0.6333	0.2000	0.9667
		Proportion of reserves	7.47	6.93	5.93	0.2333	0.9667	0.4667
		Energy type	5.60	6.80	6.67	0.3000	0.9000	0.8333

fossil energy in China	Market	Concentration of energy production	5.80	3.67	5.33	0.4000	0.3333	0.1667
		Concentration of energy import	5.00	6.27	6.67	0.0000	0.6333	0.8333
		Supply/demand ratio	5.60	7.87	7.20	0.3000	0.4333	0.1000
		External dependence	5.73	4.00	8.60	0.3667	0.5000	0.8000
		Energy self-sufficiency	6.87	7.93	8.87	0.9333	0.4667	0.9333
	Efficiency	Concentration of energy production	5.67	4.47	8.27	0.3333	0.7333	0.6333
		Proportion of scientific research input into energy	4.60	5.87	3.33	0.8000	0.4333	0.1667
		Energy processing and conversion efficiency	4.07	6.60	3.67	0.5333	0.8000	0.3333
	Environment	Proportion of non-fossil energy in consumption	5.33	7.80	5.27	0.1667	0.4000	0.1333
		Proportion of environmental pollution investment	8.07	5.73	4.07	0.5333	0.3667	0.5333
		Sulfur dioxide emission intensity	5.93	8.47	6.67	0.4667	0.7333	0.8333
		Carbon emission intensity	6.60	6.13	8.87	0.8000	0.5667	0.9333
	Economy	Coal price	8.67	4.80	3.60	0.8333	0.9000	0.3000
		Natural gas price	8.87	6.07	7.47	0.9333	0.5333	0.2333
		Oil price	8.53	5.13	6.93	0.7667	0.0667	0.9667

(3) Calculation of membership function value of catastrophe progression

First, the resource index in the second-level index system for the security evaluation of China's traditional fossil energy included four third-level indices. They belonged to butterfly catastrophe. The index importance ranking was A11>A12>A13>A14, and the system was a complementation-type catastrophe system. Hence,

$$x_{A1}^{1} = \frac{1}{4}(\sqrt{A11}+\sqrt[3]{A12}+\sqrt[4]{A13}+\sqrt[5]{A14}) = \frac{1}{4}(\sqrt{0.0333}+\sqrt[3]{0.6333}+\sqrt[4]{0.2333}+\sqrt[5]{0.3000}) = 0.6306$$

The second-level index (market) for the security evaluation of China's traditional fossil energy contained five third-level indices, belonging to shed catastrophe. The index importance ranking was A24>A25>A22>A23>A21, and the system belonged to a complementation-type catastrophe system. Thus,

$$x_{A2}^{1} = \frac{1}{5}(\sqrt{A24} + \sqrt[3]{A25} + \sqrt[4]{A22} + \sqrt[5]{A23} + \sqrt[6]{A21}) = 0.6454$$

The second-level index (efficiency) in the security evaluation of China's traditional fossil energy included three third-level indices, belonging to swallowtail catastrophe. The index importance ranking was A31>A33>A32. The system was a complementation-type catastrophe system, so,

$$x_{A3}^{1} = \frac{1}{3}(\sqrt{A31}+\sqrt[3]{A33}+\sqrt[4]{A32}) = 0.7780$$

The second-level index (environment) in the security evaluation of China's traditional fossil energy contained four third-level indices, belonging to butterfly catastrophe. The index importance ranking was A42>A41>A44>A43, and the system was a non-complementation type catastrophe system. Therefore,

$$x_{A4}^{1} = \min(\sqrt{A42},\sqrt[3]{A41},\sqrt[4]{A44},\sqrt[5]{A43}) = 0.5503$$

The second-level index (economy) in the security evaluation of China's traditional fossil energy included three third-level indices, belonging to swallowtail catastrophe. The index importance ranking was A53>A52>A51, and the system belonged to a non-complementation type catastrophe system. Consequently,

$$x_{A5}^{1} = \min(\sqrt{A53},\sqrt[3]{A52},\sqrt[4]{A51}) = 0.8756$$

Second, for the objective system, the overall objective of security evaluation of China's traditional fossil energy included five second-level indices, belonging to shed catastrophe. The index importance ranking was A5>A3>A1>A2>A4. The system was thus a complementation-type catastrophe system, and the security evaluation result of China's traditional fossil energy (petroleum) is depicted as follows:

$$x_{A}^{1} = \frac{1}{5}(\sqrt{A5} + \sqrt[3]{A3} + \sqrt[4]{A1} + \sqrt[5]{A2} + \sqrt[6]{A4}) = 0.8926$$

According to the above calculation method and steps, the security evaluation result of China's traditional fossil energy (natural gas) is expressed as:

$$x_{A}^{2} = \frac{1}{5}(\sqrt{A1} + \sqrt[3]{A5} + \sqrt[4]{A3} + \sqrt[5]{A4} + \sqrt[6]{A2}) = 0.9080$$

The security evaluation result of China's traditional fossil energy (coal) is

$$x_{A}^{3} = \frac{1}{5}(\sqrt{A1} + \sqrt[3]{A5} + \sqrt[4]{A3} + \sqrt[5]{A4} + \sqrt[6]{A2}) = 0.9131$$

Result analysis

The ranking of the main factors with the highest security level of China's traditional fossil energy obtained through the combination weighting method of game theory was: oil price (0.0840) > natural gas price (0.0840) > natural gas price (0.0798) > per capita energy quantity (0.0770) > coal price (0.0646). This ranking indicates that special attention should be paid to the price of energy sources in the security evaluation of China's traditional fossil energy to prevent the mutations during evaluation [30]. The security evaluation of China's traditional fossil energy is greatly affected by the economical indices of traditional fossil energy sources, but it is only slightly influenced by factors such as supply/demand ratio (0.0381) > carbon emission intensity (0.0362) > concentration of energy production (0.0229) > sulfur dioxide emission intensity (0.0192).

Based on the calculation results, the security evaluation results of China's traditional fossil energy sources—petroleum, natural gas, and coal—were sorted. Their security levels were ranked as coal > natural gas > petroleum. The security level of petroleum is the lowest, which is ascribed to the failure of domestic petroleum resources to meet demands and the increasing external dependence. Therefore, seeking stable and reliable crude oil from overseas markets should be top priority. China, an important petroleum consumer and producer in the world, is not an OPEC member in terms of production or an IEA member in terms of consumption.

Conclusion

The energy strategy of China should shift from the past "passive defense" into "active output" given the increasingly enhanced comprehensive national strength and the continuous improvement of its international economic and political influence. China should proactively expand diversified energy import channels in the international market and ensure stable energy input. The measurement results reveal that the domestic energy reserve remains crucial to energy security. China is a large energy consumer with relative scarcity of resources. Therefore, external energy cooperation has always been the key to carrying out foreign trade and economic activities and guaranteeing the supply of energy resources. In addition, China has developed rapidly in fields such as new energy industry, energy finance, and energy technology, so efforts should be exerted to proactively promote external export and pursue cooperation in different markets on the basis of the abovementioned aspects. Doing so forms a virtuous circle of development of the energy industry. China must persist in the path of clean and efficient coal utilization given its characteristics of energy resource endowments. This choice conforms to the current basic national and energy contexts. Under the hard constraints of carbon peaking and carbon neutrality goals, the clean and efficient coal utilization is of great strategic significance for China to exert its advantages in coal resources. It can relieve the pressure on petroleum resources, ensure energy security, and protect the ecological environment. In conclusion, the three major fossil energy sources in China—petroleum, natural gas and coal—demonstrate high security level.

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