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Safety Evaluation of Sustainable Uranium Development in China Combined with an Analytical GAN Framework

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Abstract: Uranium is the basic raw material for nuclear energy and is quite highly regarded. Developing a safe supply of uranium is important for safeguarding sustainable nuclear development. The purpose of this study is to evaluate the sustainability of uranium development in China based on dynamic system modeling combined with GAN (Generative Adversarial Network) analysis. We considered eight essential indicators and 42 sub-indicators as part of a detailed quantitative description, and then developed a framework to evaluate and rank China-specific sustainability in light of the quantitative performance of five options for fuel cycle transition scenarios. We began by using KMO sample measurements and the Bartlett Test of Sphericity to determine the suitability of factor analysis and the fitness of the corrected model map and observation data. We then analyzed the roles of different representatives of the decision makers and their impacts on the overall ranking by applying GAN methods from a weighted perspective. Five transition scenarios identified are 1) Pressurized Heavy Water Reactors, 2) Mixed Light Water Reactor + Fast Reactor, 3) Mixed LWR+FR fuel cycle scheme with heterogeneous irradiation, 4) Mixed Pressurized Water Reactor + FR fuel cycle scheme with plutonium recycled directly and repeatedly, and 5) Sodium-cooled fast breeder reactor power plant. The results showed that scenario 1 is the most unsustainable and highly confrontational scenario with a high demand for uranium resources, the lowest sustainability and a high level of antagonism among departments. On the other hand, Scenario 5 requires more advanced technology but exhibits less antagonism among the departments, and thus it largely satisfies the basic requirements for uranium sustainability and low levels of antagonism. In this paper, a safety assessment index system for the uranium supply is computed using a GAN framework. This system plays a crucial role in the sustainable supply and development of uranium, and provides flexibility for coping with the evolution and inherent uncertainties of the necessary technological developments.

Key words: uranium; sustainable development; safety evaluation; index system

1 Introduction

As a clean, safe, highly-efficient and economical form of energy, nuclear power is the only non-fossil fuel energy in the world which can completely replace the energy from fossil fuels to meet the needs of large-scale industrial development (World Nuclear Association, 2017). To date, more than 450 nuclear power stations, located in no less than 30 countries, have been connected to the grid, representing a total installed capacity of more than 371.8 GW, or 17% of total power generation worldwide. All countries are committed to the large-scale development of nuclear power (Yan et al., 2011). Large-scale plans for nuclear power use and construction will inevitably affect the safety of the supply of uranium resources, and all countries have taken measures to ensure the sustainable development of nuclear power. Australia, Kazakhstan, Russia, the United States, Canada and other countries that are rich in uranium resources not only protect domestic use, but also carry out

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stringent export measures and foreign cooperation (Peng, 2017; Long et al., 2018). Japan, France and many other countries that have developed nuclear power must mainly rely on overseas development to accumulate uranium reserves and improve the utilization rate of uranium resources in creating a safe early warning system (Chol et al., 2016; Cai et al., 2019).

During decades of rapid economic development, China's growing demand for electricity has been supported mainly by increasing the use of high-carbon fossil fuel energy (with coal accounting for approximately 75 percent of China's energy). The country is now under great pressure to reduce greenhouse gas emissions (BP, 2019; IAEA, 2019a; IAEA, 2019b; IAEA, 2019c). Recently, eleven nuclear power plants generating 9.0782 million kW have begun commercial operations, and account for approximately 1.15 percent of China's installed electrical capacity. Imbalances between the supply and demand of uranium are not so prominent for the time being (IAEA, 2019d). However, China is beginning to transition from a nuclear strategy of moderate development to one of more active development, and it is currently targeting the deployment of 70 million kW by 2030. This means that two nuclear plants able to generate at least one million kW must be newly-built every year, so in the short term, demand for uranium will show explosive growth. At this time, however, domestic productivity and output of uranium are only 1040 and 750 tons, respectively (Zhao et al., 2011). Based on the current growth trend for domestic uranium productivity, the gap between the uranium supply and demand will reach more than 10 thousand tons by 2025, and more than 30 thousand tons by 2030. The development of the geological sciences in China, which began in the 1950s, has been hindered by various factors, among them are a lack of funding and technologies, difficulties in finding mining sites, and the depths at which mineral deposits are located. Recently, safety assessments for uranium resources have also recently become a major focus and focal point (IAEA, 2019e).

If the total installed capacity of nuclear power reaches 150–200 million kW in 2030, then the total installed capacity of nuclear power is expected to reach 300–400 million kW in 2050. Without the introduction of fast reactors and MOX fuel, an estimated 27–36 thousand tons of natural uranium will be needed in 2030, and 54–72 thousand tons will be needed in 2050, which is obviously a considerable demand (Liu et al., 2017; Yang et al., 2018). With the continuous expansion of China's nuclear power scale, the risks and uncertainties of uranium resource security will inevitably increase. In the long run, improving the utilization rate of uranium resources through technological progress is necessary to achieve the effective utilization of uranium resources (An, 2016; Long et al., 2019). The effective utilization of uranium resources is closely related to the choice of reactor type, especially the choice of fuel cycle. Nuclear fuel is "one pass" in a thermal reactor, and the utilization rate of uranium resources is about 0.6%. However, the closed cycle of the thermal reactor can increase the utilization rate of uranium resources up to 8%, almost increase from 20% to 30%, while the closed cycle of a breeder fast reactor can increase the utilization rate of uranium resources by 30–60 times (Ciuulla et al., 2016; Sungyeol Choi et al., 2016; Gorman et al., 2018).

However, the access of commercial fast reactors to the nuclear power market depends on many factors, including the maturity of technology, economy, supply of uranium resources, etc., and different stakeholders have different priorities. Some nuclear fuel cycle schemes may be more advantageous than other schemes, but not all of the decision makers will be satisfied with them. Therefore, the establishment of evaluation indicators, methods and evaluation models is of great significance for the sustainable development of uranium resources in China (Wen et al., 2019).

2 Data sources and research methods

The nuclear fuel cycle includes the front end, the irradiation stage and the back end. The front end includes uranium mining, ore processing, uranium extraction, conversion, enrichment, fuel manufacturing, etc., while the irradiation stage is the reactor stage, and the back end includes the temporary storage, cooling, packaging, transportation, geological disposal and recovery of spent fuel, etc. If the recycling plan is selected correctly, it will not only improve the utilization rate of uranium resources, but will also greatly reduce the generation and toxicity of radioactive waste, and at the same time, it will alleviate the contradiction between the supply and demand of uranium resources.

Underlying the primary context and constraints specific to China is the crucial need to draft a framework for making informed decisions regarding the initiation of a sustainable development roadmap for uranium resources. Such a framework should (a) be capable of using an integrated system for evaluation and obtaining information about the potential benefits and costs of the potential fuel cycle options, (b) find a balance of benefits, (c) make appropriate decisions to achieve stability, and (d) be capable of providing policy guidance for planning nuclear energy in China.

Here we have formulated evaluation indicator metrics for China-specific sustainability associated with five reference scenarios of fuel cycle transition options. We then established a GAN analysis framework that is connected with the quantitative performance of the five candidate options for the fuel cycle. We evaluated and ranked each of these five fuel cycle options to model and evaluate the sustainability of China-specific uranium resources. We also further analyzed the roles of different representatives of stakeholders and their impacts on the overall ranking of the options from the perspective of weight, and found a balance point among the corresponding decisions to maintain stability.

The choice of nuclear fuel cycle plays an important role in the economy of uranium mining. Therefore, this paper sets five scenarios according to the different options for recycling uranium mine resources, and evaluates the influences of various index factors on the sustainable development of uranium mine resources through the five scenarios.

Scenario 1: Pressurized Heavy Water Reactors (PHWR) with direct disposal of spent nuclear fuel.

Scenario 2: Mixed Light Water Reactor (LWR) + Fast Reactor (FR) fuel cycle scheme with homogeneous multiple recycling of transuranic fuel.

Scenario 3: Mixed LWR+FR fuel cycle scheme with heterogeneous irradiation of Minor Actinide targets.

Scenario 4: Mixed Pressurized Water Reactor (PWR) + FR fuel cycle scheme with plutonium recycled directly and repeatedly in a closed fuel cycle.

Scenario 5: Sodium-cooled fast breeder reactor power plant with the resulting plutonium repeatedly recycled as Mixed Uranium-Plutonium Oxide (MOX) fuels.

Based on the sustainability of uranium in the future, we have classified and determined eight key evaluation indicators including uranium supply, demand, price, technological readiness, environmental impact, strategy, political impact and management (Beims et al., 2019). These key indicators include 42 sub-indicators, and for more detailed quantitative descriptions see Table 1. Each indicator has its own characteristics and trade-offs (i.e., economic competitiveness but large generation of uranium wastes, high technological feasibility but low risk resistance, public acceptance but potential environmental risks, etc.). Then, we collected all these quantitative performance indicators and linked them with the output data from the five simulated reference fuel cycle scenarios to construct an overall indicator for assessing the sustainability of uranium.

There are always diverse stakeholders involved in the process of evaluating uranium resources. They each put forward individual preferences and opinions on the nuclear energy strategy which weigh the trade-offs and opinions within the strategic framework of decision-making in order to achieve a mutual compromise on the sustainable nuclear fuel cycle system in China. Considering the values (quantity) and preferences (quality) from diverse stakeholders, we further analyzed the role of different stakeholder representatives and their impacts on the overall ranking from the perspective of weight.

Based on extensive literature review and extensive consultation with experts, we used traditional questionnaire survey methods to provide stakeholders with a series of questionnaires. We conducted a weighting assumption analysis of the stakeholders to illustrate how the ranking differs according to their distinctive socio-political perspectives (Tomaž et al., 2011; Gao et al., 2017). Therefore, four types of stakeholders representing the particular biases toward nuclear energy which underlie each respective indicator were assumed as technical department, economic department, environmental department and social residents. All four representative stakeholders are assigned their own characteristic weighting values, between '0' (negligible) and '1' (important), according to their specific interest preferences. In order to avoid any subjective bias toward an indicator, before conducting hypothesis testing, we first used the Cronbach α to test the reliability and validity of the scale. Only high consistency can ensure that the measurement of a variable meets the research reliability requirements.

3 Establishment of the safety evaluation index of uranium resources in China

The core issue of the traditional definition of energy security is ensuring energy supply. As a non-renewable resource, the uranium mine determines that its mining is closely related to the resource environment. Traditional energy security ignores environmental protection and maintains ecological balance. Therefore, this paper adds environmental factors to the safety evaluation index system; that is, the safety evaluation of uranium resource sustainable development includes two aspects: uranium resource supply security and use safety. Supply security refers to the stability, economy and sustainability of the uranium resource supply (Zhang et al., 2014; Collins et al., 2017). The use safety means that the use and consumption of uranium resources should not pose a threat to human beings or their ecological environment. The continuous supply of uranium resources is the basic goal of resource security, embodied in the level of satisfaction and the economics of access; while the safety of uranium resource use is a higher goal pursued by national resource security, and reflected in the improvement of the quality of resources. This is the continuous improvement of the types and forms of resource use that are driven by technological development (André et al., 2014; Georges et al., 2017).

3.1 Data reliability and validity analysis

The security of the uranium resource supply is a matter of politics, military, economy, resources, man-made and many other factors. Its safety evaluation is also a complex system problem, and it is necessary to build a comprehensive and perfect indicator system that reflects its safety status (Li et al., 2015; Wang, 2019). Based on scientific evaluation of a large number of published studies and extensive consultation with experts, the index system initially established in this study is divided into eight aspects. Before conducting the hypothesis test, the study first tested the reliability and validity of the scale. In terms of reliability, this paper uses the cloned Bach coefficient (Cronbach α) to ensure that the high consistency of each variable meets the reliability requirements of the study. Reliability analysis of the published literature and expert opinions was carried out using Cronbach α coefficient, and the results are shown in Table 1.

By calculating the Cronbach α value of the evaluation reliability for each latent variable, the table above shows that they are all greater than 0.750, indicating that the measurement has a high reliability level for each variable.

Table 1 Confidence analysis of the overall indicator metrics for evaluating the resource safety of uranium in China

Key indicators	Sub-indicators	Cronbach α
Supply indicator	Resources (expected reserves, recovered reserves, recoverable reserves) ($X1$)	0.802
	Production volume (yield growth rate, storage-production ratio) ($X2$)	
	Imported uranium mine (import concentration, import share, external dependence) ($X3$)	
Demand indicator	Population growth ($X4$)	0.814
	Lifestyle of residents ($X5$)	
	Economic growth rate ($X6$)	
	Technological advancement ($X7$)	
	Production and consumption structure ($X8$)	
	Alternative levels of other energy sources ($X9$)	
	Supply and demand ratio of uranium resources ($X10$)	
	Uranium resource consumption intensity ($X11$)	
	Industrial structure ($X12$)	
Price indicator	Producer price ($X13$)	0.898
	International market price ($X14$)	
	Production cost ($X15$)	
	Marginal cost of mining technology ($X16$)	
	Tax rate ($X17$)	
Technical indicator	Mining rate ($X18$)	0.858
	Uranium comprehensive utilization rate ($X19$)	
	Science and technology contribution rate of uranium mining industry ($X20$)	
	Scientific and technological achievements conversion rate of uranium mining industry ($X21$)	
Environment indicator	Nuclear waste (spent fuel post-processing) stock ($Y1$)	0.856
	Uranium mine regional distribution ($Y2$)	
	Welfare loss ($Y3$)	
	Uranium mine depletion cost ($Y4$)	
	Environmental degradation cost ($Y5$)	
	Environmental pollution loss ($Y6$)	
Strategic indicator	Control of domestic uranium mines ($Y7$)	0.842
	Control of international uranium mines ($Y8$)	
	Strategic reserve for uranium mines ($Y9$)	
	Global development strategy ($Y10$)	
Political indicator	External relationship stability ($Y11$)	0.752
	Domestic political environment stability ($Y12$)	
	Uranium mining industry policy ($Y13$)	
	Consumption habits of nuclear power ($Y14$)	
Management indicator	Human resources ($Y15$)	0.791
	Equipment integrity rate ($Y16$)	
	Improvement rate of production safety system measures ($Y17$)	
	Safety of import transportation channel ($Y18$)	
	Influence control degree of import transportation channels ($Y19$)	
	Environmental safety ($Y20$)	
	Information identification and processing capabilities ($Y21$)	

In terms of validity, firstly, since each variable measurement is derived from the relevant results and opinions of domestic scholars, the scale can be considered to have good content validity. Secondly, the KMO sample measurement and the Bartlett Test of Sphericity were used to determine whether the sample is suitable for factor analysis. The results of this analysis are shown in Table 2.

Table 2 Factor analysis fitness test using KMO value and Bartlett's spherical test

Method	Variables	Value
Kaiser-Meyer-Olkin	KMO value	0.954
Bartlett's sphericity test	Approximate chi square	2136.125
	df	162
	Sig.	0.000

Using MATLAB software for exploratory factor analysis gives a KMO value of 0.954, which is very suitable for factor analysis; and the Bartlett hemispherical test value is 0.000, which is less than 0.001, supporting the exploratory factor analysis, and indicating that the data has good validity.

3.2 Path analysis of fitness between the index system and observation data

Given the above results, the following strategic indicators were used to measure the fit between the indicator system and the observation data: Chi-square value, significance value, adjusted goodness-of-fit index, goodness-of-fit index, root mean square error of approximation and CN value. The fitness of the initial model is shown in Table 3.

Table 3 Model fitness index

Chi-square value	*P* value	AGFI	GFI	RMSEA	CN
197.740	0.000	0.846	0.886	0.175	187

In the initial hypothesis model fitting indexes, $AGFI<0.9$, $GFI<0.9$, $RMSEA<0.5$, $CN<200$, and $P=0.000<0.05$, reach the level of significance, thereby rejecting the null hypothesis and assuming that the model does not fit the observation data. Thus, the model needs to be further revised. By referring to the correction index MI provided by AMOS, the covariation relationship between the error variables is increased. Following the correction, the adaptation degree of the model is shown in Table 4, wherein the Chi-square value is decreased, and the significance probability value is $P=0.076>0.05$, accepting the virtual reality. Assuming that the AGFI value is increased to 0.832, the GFI is increased to 0.938, the RMSEA is reduced to 0.029, and the CN value is increased to 194, indicating a better match between the corrected model map and observation data.

Table 4 Revised model fitness index

Chi-square value	*P* value	AGFI	GFI	RMSEA	CN
138.682	0.076	0.832	0.938	0.029	194

4 Construction of the evaluation index model for sustainable development of uranium resources in China

Analytic Hierarchy Process (AHP) is a system decision-making method that breaks down a problem into several levels of simpler problems which are then represented by a set of criteria or attributes. Relative to each sub-question, the AHP method is always applied to determine the relative weights of the evaluation indicators (coefficients), and the Decision Support System (DSS) is combined with the individual's point of view to obtain an overall relative weight option (priority) (Wang et al., 2010; Álvaro, 2018). The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) evaluation analysis method assumes that the selected option should be the shortest Euclidean distance of the positive ideal solution and the longest Euclidean distance of the negative ideal solution (Teresa, 2018; Gu, 2019). Both of these compromises are hypothetical and derived within the Euclidean distance concept. Because each of the departments involved in policy implementation have their own competing interests, they are confrontational. Therefore, the anti-neural network method is used to analyze the index weights based on AHP and TOPSIS (Helena et al., 2018). Table 5 shows the index weight data for stakeholder perspectives from various functional departments and the citizens.

Since the adversarial neural network model of the sine function has the statistical characteristics of memory recovery, we first construct an adversarial neural network model with generalized input and output functions:

$$x_i(t) = f(y_i(t)) = \sin\frac{y_i(t)}{\lambda}$$

$$y_i(t+1) = ky_i(t) + \sum_{j=1}^{n} \rho_{ij} \arctan\frac{x_j(t)}{\lambda} + \alpha_i - \rho_{ii}^*(t)a_{0i}$$

$$\left|\rho_{ii}^*(t+1)\right| = (1-\beta)\left|\rho_{ii}^*(t)\right|, \quad \lambda > 0, i = 1, 2, \cdots, n \qquad (1)$$

Among them, x and y respectively represent the neuron output values of X and Y in the sub-indicators in Table 2; and the decision made will only be stable when the balance point of X and Y is found, that is, when the balance point of the stakeholders is found. Therefore, under the sufficient condition of uniform asymptotic stability of time-varying weights, the global index will have asymptotic stability. ρ_{ij} represents the weight of the connection from the j-th neuron to the i-th neuron; α_i is the input deviation of the i-th neuron; k is the eurilemma attenuation factor; ρ_{ii} is self-connection weight and $\rho_{ii} = \rho_{ii}^*(t)$; β is the attenuation factor and $0 \leqslant \beta < 1$; and α_{0i} is the self-deviation of the i-th neuron.

Table 5 Weight values of evaluation indicators from the stakeholders' perspectives

Key indicators	Sub-indicators	Technical department	Economic department	Social resident	Environmental department
Supply indicator	Resources (expected reserves, recovered reserves, recoverable reserves) (*X*1)	0.225	0.337	0.013	0.004
	Production volume (yield growth rate, storage-production ratio) (*X*2)				
	Imported uranium mine (import concentration, import share, external dependence) (*X*3)				
Demand indicator	Population growth (*X*4)	0.007	0.122	0.006	0.003
	Lifestyle of residents (*X*5)				
	Economic growth rate (*X*6)				
	Technological advancement (*X*7)				
	Production and consumption structure (*X*8)				
	Alternative level of other energy sources (*X*9)				
	Supply and demand ratio of uranium resources (*X*10)				
	Uranium resource consumption intensity (*X*11)				
	Industrial structure (*X*12)				
Price indicator	Producer price (*X*13)	0.012	0.203	0.104	0.004
	International market price (*X*14)				
	Production cost (*X*15)				
	Marginal cost of mining technology(*X*16)				
	Tax rate (*X*17)				
Technical indicator	Mining rate (*X*18)	0.414	0.107	0.013	0.329
	Uranium comprehensive utilization rate (*X*19)				
	Science and technology contribution rate of uranium mining industry (*X*20)				
	Scientific and technological achievements conversion rate of uranium mining industry (*X*21)				
Environmental indicator	Nuclear waste (spent fuel post-processing) stock (*Y*1)	0.148	0.006	0.512	0.474
	Uranium mine regional distribution (*Y*2)				
	Welfare loss (*Y*3)				
	Uranium mine depletion cost (*Y*4)				
	Environmental degradation cost (*Y*5)				
	Environmental pollution loss (*Y*6)				
Strategic indicator	Control of domestic uranium mines (*Y*7)	0.009	0.103	0.073	0.049
	Control of international uranium mines (*Y*8)				
	Strategic reserve for uranium mines (*Y*9)				
	Global development strategy (*Y*10)				
Political indicator	External relationship stability (*Y*11)	0.012	0.015	0.062	0.078
	Domestic political environment stability (*Y*12)				
	Uranium mining industry policy (*Y*13)				
	Consumption habits of nuclear power (*Y*14)				
Management indicator	Human resources (*Y*15)	0.173	0.107	0.217	0.059
	Equipment integrity rate (*Y*16)				
	Improvement rate of production safety system measures (*Y*17)				
	Safety of import transportation channel (*Y*18)				
	Influence control degree of import transportation channels (*Y*19)				
	Environmental safety (*Y*20)				
	Information identification and processing capabilities (*Y*21)				

Note: Stakeholders only score the weight for key indicators.

Suppose h: R^n, since R^n is n-dimensional Euclidean space, the usual infinite norm assigned to R^n can be regarded as an iterative map or a neural network with continuous state, $h_\mu(x) = h(x, \mu)$, if the following conditions are true:

$$h(x_0, \mu_0) = x_0$$

$$h'_{\mu_0}(x_0) = -1$$

$$\alpha = \left[\frac{\partial^2 h}{\partial \mu \partial x} + \frac{1}{2} \frac{\partial h}{\partial \mu} \frac{\partial^2 h}{\partial x^2} \right] \Bigg|_{(x_0, \mu_0)} \neq 0$$

$$\beta = \frac{1}{3!} \frac{\partial^3 h}{\partial x^3}(x_0, \mu_0) + \left(\frac{1}{2!} \frac{\partial^2 h}{\partial x^2}(x_0, \mu_0) \right)^2 \neq 0 \quad (2)$$

Then a cycle occurs at (x_0, μ_0) , there is a curve $x(\mu)$ in the vicinity of μ_0 , $x(\mu)$ is a stable fixed point on one side of μ_0 , and an unstable fixed point after passing μ_0 ; and there is a smooth curve ξ tangent to the line $\{\mu_0\}$ at the point (x_0, μ_0) ; and ξ is a mapping iteration of μ to $\theta(x)$ function about x. When $\beta > 0$, the cycle is stable, and vice versa.

When the parameters are satisfied with $\rho > 0, k > 1, -1 < a_0 - \frac{a}{\rho} < 0$, and the parameter λ changes, there must be $\lambda = \lambda^*$ in the interval $\left(0, \frac{\rho}{k+1}\right)$, so that the period at $\left(\frac{y(t)}{\lambda^*}, \lambda^*\right)$ is stable.

Vectorizing the model as:

$$Y(t+1) = kY(t) + PX(Y(t)) + I - diag\{\rho_{11}, \rho_{22}, ..., \rho_{nn}\}I_0 \quad (3)$$

Among them, $diag\{\rho_{11}, \rho_{22}, ..., \rho_{nn}\}$ is the diagonal matrix.

$$X(Y(t)) = \Phi\left(\frac{Y(t)}{\lambda}\right) = \begin{bmatrix} f(y_1(t)) \\ f(y_2(t)) \\ \vdots \\ f(y_n(t)) \end{bmatrix} = \begin{bmatrix} \sin(\frac{y_1(t)}{\lambda}) \\ \sin(\frac{y_2(t)}{\lambda}) \\ \vdots \\ \sin(\frac{y_n(t)}{\lambda}) \end{bmatrix} \quad (4)$$

In addition:

$$Y(\mathrm{t}) = \begin{bmatrix} y_1(t) \\ y_2(t) \\ \vdots \\ y_n(t) \end{bmatrix}, \quad I = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix}, \quad I_0 = \begin{bmatrix} a_{01} \\ a_{02} \\ \vdots \\ a_{0n} \end{bmatrix},$$

$$P = \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_1 \\ \rho_{21} & \rho_{22} & \cdots & \rho_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \rho_{n1} & \rho_{n2} & \cdots & \rho_{nn} \end{bmatrix}$$

If P is a non-singular matrix, then:

$$\Phi\left(\frac{Y(t)}{\lambda}\right) = P^{-1}(diag\{\rho_{11}, \rho_{22}, ..., \rho_{nn}\}I_0 - I) \quad (5)$$

$$I' = \left[diag\{\rho_{11}, \rho_{22}, ..., \rho_{nn}\}I_0 - P^{-1}\Phi\left(\frac{Y(t)}{\lambda}\right) \right]' = \begin{bmatrix} a'_1 \\ a'_2 \\ \vdots \\ a'_n \end{bmatrix} \quad (6)$$

Due to the nature of the sine function, when $|a'_1| < 1$, there must be two different solutions to the equation on the interval of $[0, 2\pi]$, denoted as c_i^* and c_i^{**} $(i = 1, 2, ..., n)$.

At this stage, the existence and stability of the unique solution are judged by the input and output functions, which can be obtained from the GAN model:

$$f(y_i(t+1)) - f(y_i(t)) = -\alpha_i(t, x_i(t)) \times [b_i(t, x_i(t)) - \sum_{j=1}^{n} c_{ij}(t) f_j(x_j(t)) - \sum_{j=1}^{n} d_{ij}(t) f_j(x_j(t - \lambda_{ij}(t))) + I_i(t)]$$

$$(i = 1, 2, ..., n) \quad (7)$$

In addition, $\mu_i(t)$ is the given weight of the i-th indicator. When we aggregate the global preference information considering total indicators, a preference function determines the relevant preference extent by using the ranking relation. However, the antagonistic preferences between two options can be independently presented by different preference functions. The function determines the appropriate graphical representations of the preference function in line with the various types of indicators. So, we derive the antagonism function of $\mu_i(t)$ by calculating $\mu \alpha_i \gamma_i x_i^2$.

$$\mu \alpha_i \gamma_i x_i^2 = -(1-\mu)\frac{1}{\rho} \sum_{t=1}^{\rho} \left\{ x_i \alpha_i(t, x_i)[b_i(t, x_i) - \sum_{j=1}^{n} c_{ij}(t) f_j(x_j) - \sum_{j=1}^{n} d_{ij}(t) f_j(x_j) + I_i(t)] \right\}$$

$$= -(1-\mu)\alpha_i \gamma_i |x_i|^2 + (1-\mu)\frac{1}{\rho} \sum_{t=1}^{\rho} x_i \alpha_i(t, x_i) \times \left[\sum_{j=1}^{n} c_{ij}(t) f_j(x_j) - \sum_{j=1}^{n} d_{ij}(t) f_j(x_j) + I_i(t) \right] \quad (8)$$

$$= -(1-\mu)\alpha_i \gamma_i |x_i|^2 + \alpha_i \gamma_i |x_i| \left(\sum_{j=1}^{n} (c_{ij}^M + d_{ij}^M) p_j |x_j| + \sum_{j=1}^{n} (c_{ij}^M + d_{ij}^M) \beta_j + I_i^M \right)$$

$$\phi(\mu, x(t)) \neq 0$$

Then a stochastic gradient descent algorithm is used to evaluate the objective function in formula (8) based on the parameters of each tuple $\mu_i(t)$, and therefore, the mapping iteration can be obtained by the GAN model as follows:

$$|\mu_i(t)| = \left(\frac{1}{\varepsilon}\right)^t \max_{1\leqslant i\leqslant n}\{\sup_{-\tau<s<0}|\varphi_i(s)-\varphi_i(s)|\},\quad (i=1,2,\ldots,n) \tag{9}$$

As a result, there is a unique equilibrium solution $\left(\frac{y(t)}{\lambda^*},\lambda^*\right)$ in the evaluation system, and the global index is stable.

5 Evaluation index model of uranium resource safety in China

The above data were calculated by a model of neural network evaluation, which showed that the evaluation index model has good practicability. The evaluation results are in good agreement with the actual evolution of uranium supply security in China. In general, the uranium supply security situation is relatively poor in China, and it is currently being transformed into a highly dangerous state, which is inconsistent with the process of building a well-off society in all aspects. Uranium resources in China have huge discrepancies in spatial and temporal distribution, the level of economic development varies from place to place, and consumers' awareness of energy conservation is inconsistent, thus increasing the difficulty of achieving uranium supply safety.

Figure 1 shows the final rankings of the risk evaluation for the Potential dimension in eight indicator metrics in four departments using GAN methods. The perspective of each representative parameter is depicted at a corresponding location in the two-dimensional space as a radar chart. Despite some ranking differences in the nine parameter factors, the results obtained with the GAN methods were mostly well-coordinated and consistent. This is primarily owing to the great uncertainties underlying the benefits to the different departments, particularly regarding the high probabilistic safety risk and the low investment benefit of the advanced fuel cycle technologies.

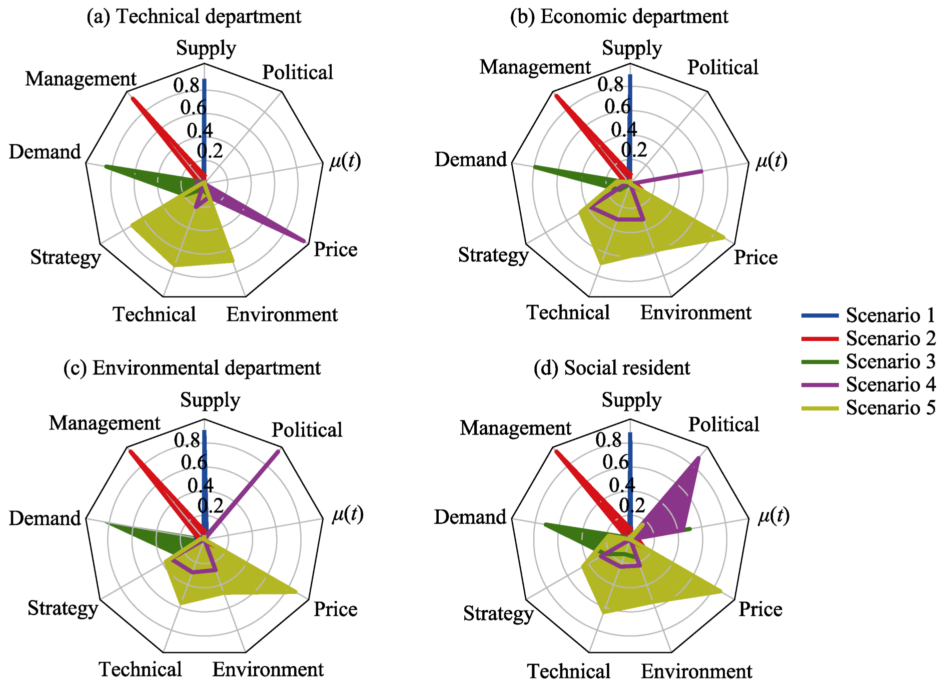

Fig. 1 The integrated system evaluation of the five scenarios, with influences based on indicator weights, by four different departments

The results show that scenario 1 is the most unsustainable and highly confrontational scenario, with high demand for uranium resource supply, the least sustainability and high antagonism among the departments. In contrast, scenario 5 requires higher technology but produces less antagonism among departments, which substantially satisfies the basic requirements underlying the current definition of uranium sustainability and low antagonism.

Accordingly, the technology department is more inclined to choose scenario 5, while social residents are more inclined to manage the security because they lack a secure sense of the latest technology, so they will give up scenario 5 and choose scenario 4. The economic department will be more inclined to choose scenario 5 under the condition of appropriate price.

The factors that have greater impacts on the safety of the uranium supply are mainly resource factors and import factors, as their cumulative weights are higher. Among the individual indicators, the strategic uranium reserve and storage-production ratio are the most important indicators, so they will mainly determine the utilization and benefit of uranium mine in China.

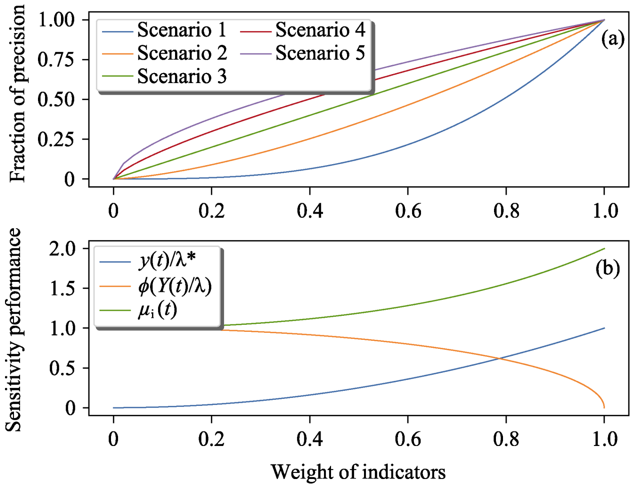

Fig. 2 The net ranking flows in the five scenarios as influenced by indicator weights using GAN methods, with respect to (a) Fraction of precision and (b) Sensitivity performance.

To perform a sensitivity analysis, we build (A) Fraction of precision and (B) Sensitivity performance, and analyze the sensitivity of the preference functions about three variables $\frac{y(t)}{\lambda^*}$, $\Phi\left(\frac{Y(t)}{\lambda}\right)$ and $\mu_i(t)$, the x-axis represents the weight of three indicators, the y-axis of A shows the fraction of precision for the five scenarios and the y-axis of B as the sensitivity performance, then adopted a probabilistic approach through a simulation using the four departments. It simulated the iteration of the weight values of an individual extreme preference-oriented indicator in the five scenarios within an assigned uniform probability distribution. Here, the same principle of equal importance of all indicators was likewise applied to ensure that the sum of all the indicator weighting values at the same level equaled ‘1’.

Fig. 2 shows the elimination of individual subjective bias for a defined inner range of distribution as 0.7835, with another line showing the outer limits of the distribution as 0.0583. The green line in the Fig. 2b marks the location of the assigned distribution. As a result, all rankings are generally stable in accordance with the assessment of the weighting values.

The ultimate goal of the uranium mine index evaluation is not only to determine the current status of the mined uranium supply security in China, but also to determine the leading factors which affect the safety of the mined uranium supply based on the results of the evaluation, and then propose targeted countermeasures to ensure the safety of the mined uranium supply and, ultimately, sustained and healthy economic development in China.

Through the analysis of the status of uranium resource use globally and in China, and the international situation, the main influencing factors of the uranium resource safety system are obtained, safety evaluation indicators are constructed, the current situation of uranium resource utilization is sorted out, and the interests of the state and enterprises are taken into account. At the same time, from the political, economic, cultural, military, social and other perspectives, a multi-perspective approach used fuzzy mathematical analysis to construct China’s uranium resource safety evaluation index model. This model dynamically reflects the supply and demand of China’s uranium resources, the timely control of uranium supply and demand, and the realization of the coordinated development of the uranium resource industry chain.

6 Discussion and policy implications

The uranium resource safety evaluation system can not only ensure the healthy and sustainable development of the national economy, but also achieve harmony and tolerance between people and nature, and enrich and expand the application scope of the index evaluation. The use of grounded theory and more advanced mathematical methods to obtain a safety evaluation index system and a dynamic balance model is a new exploratory approach, and a beneficial attempt for the safe use of uranium resources. The findings revealed by this approach lead to the following policy recommendations:

(1) On the premise of ensuring the sustainable development of uranium resources in China, it is necessary to comprehensively strengthen the exploration and development of domestic fissile nuclear energy mineral resources, and to fully utilize existing production capacity. At the same time, a number of new uranium mines should be constructed and planned so as to achieve and maintain a certain scale of natural uranium production capacity in China.

(2) Promote to enrich the reserve of resources, including the reserves of mineral deposits and uranium products, the total amount of which is the sum of those required for the scale of three years after the development of nuclear power.

(3) Take overall strategic planning and overall coordination, including foreign exploration and development of uranium resources as a priority development area; assist foreign and political parties and military parties in the face of corporate behavior; and establish joint mining groups, financial groups, and others. The industry should be coupled to form an overseas competitive industrial chain with strong competitiveness. It should actively participate in the international mineral resource pricing and construction of financial trading markets, so that China can compete and cooperate with existing monopoly forces in overseas investment and trade.

(4) Promote scientific and technological progress, continuously improve the utilization rate of uranium resources, accelerate the technological upgrading of the mixing and leaching production line, and tackle the research and development of the proven large-scale uranium deposits; pay attention to the research and evaluation of unconventional uranium resources, and pay attention to the research and development of extraction technology for salt-lake uranium resources, as well as the exploration of sea uranium extraction technology; achieve gradual resolution of uranium tailing slag re-extraction and reuse; and focus on research on the environmentally-sound treatment of mine solid wastes.

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基于对抗神经网络模型的中国铀资源可持续发展安全评价

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摘　要：随着我国经济的快速发展，以化石能源为主的能源结构对我国环境压力与日俱增。相比之下，核能具有安全、高效、清洁、可持续性等诸多优点。铀作为核能的基础物质，目前已经受到国际各界的高度重视。如何保证铀的安全供应也已成为核可持续发展的重要保障。本文的工作是在动态系统建模的基础上，结合生成式对抗网络（GAN）模型，对我国铀资源可持续发展进行综合评价。 采用 8 个基本指标和 42 个子指标进一步详细量化描述，本文通过制定一个框架，根据 5 种燃料循环过渡方案的量化绩效，在大量文献阅读和广泛征询专家意见的基础上，采用传统的问卷调查方法，对中国铀资源特有的可持续性进行评估和排名。首先利用 KMO 样本测量和 Bartlett 球度检验来确定因子分析的适用性和修正模型图与观测数据的适用性。然后从权重的角度分析了不同利益相关者代表所扮演的角色及其对综合排名的影响。结果表明，情景 1 对铀资源供应要求高，经济性最差，各部门之间的对抗性最大，对于协调和可持续发展会有更大的障碍，是最不可持续和高度对抗的情景。相反，情景 5 对技术的要求更高，各部门之间的对抗性更小，基本上满足了当前铀可持续性和低对抗性定义的基本要求。本文采用 GAN 框架计算铀供应安全评价指标体系，为铀的可持续供应和发展提供了灵活性，以应对技术发展的演变和内在不确定性。因此在进行铀资源可持续发展安全评价时需要进行博弈分析，找出影响铀矿供应安全的主导因素，协调各个部门及公众的利益关系，进而提出针对性对策，保障我国铀矿可持续安全和经济持续健康发展。

关键词：铀资源；可持续发展；安全评价；指标体系