Analysis of Supply-Demand Characteristics and Security Scenario Simulation of China's Uranium Resources

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Abstract: To systematically evaluate the security of China's uranium resource supply and demand and its evolutionary trends, and to address the pressure of uranium resource security posed by nuclear power expansion under the dual carbon goals, geographic spatial analysis methods and system dynamics are integrated for a comprehensive analysis. First, indicators including location quotient, spatial mismatch index, supply-demand matching degree, and coordination degree were employed to quantitatively characterize the supply-demand pattern of China's uranium resources. Second, a system dynamics model encompassing five dimensions of uranium resource security was constructed, and three institutional resilience scenarios—low, medium, and high—were designed to conduct dynamic simulations of uranium resource security from 2008 to 2050. The results show that: (1) The center of gravity of China's uranium supply has shifted northward, while consumption in East China and South China remains dominant. The supply-demand mismatch between the north and the south continues to widen, and the coordination degree has remained in a state of long-term imbalance. (2) The system dynamics simulation results indicate that although proven uranium reserves have continued to grow, the security assurance period has been declining since 2015, and external dependence has remained at a high level over the long term. The development of nuclear power has led to significant carbon dioxide emission reductions; however, the accumulated volume of spent fuel has continued to expand. (3) A comparison across different institutional resilience scenarios reveals that, under a high-institutional-resilience scenario, a robust supply structure characterized by "domestic production increase, overseas equity supplementation, and import diversification" can be established, whereas, under a low-institutional-resilience scenario, import scale becomes uncontrolled and system vulnerability is significantly enhanced. Therefore, in accordance with the supply-demand characteristics of China's uranium resources, a region-specific security strategy is proposed: promoting in-situ leaching uranium mining technology in the sandstone-type uranium areas of Northwest China, strengthening mine decommissioning and remediation efforts in the hard-rock areas of South China, and optimizing the layout of strategic reserves along the eastern coastal areas.

Keywords: Uranium Resource Security; System Dynamics; Supply-demand Characteristics; Spatial Mismatch; Dual Carbon Goals

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1 Introduction

Resource security constitutes a critical component of the national security framework. In the context of the “dual carbon” goals, nuclear power—as a base-load energy source—has gained increasing strategic significance. Meanwhile, given that uranium is the primary fuel for nuclear power development, the stability of its supply directly affects the safety and sustainability of the nuclear power system. From a geographic perspective, uranium resource security entails several structural challenges, including uneven resource distribution, supply–demand imbalances, and supply chain vulnerabilities. Given the high geographical concentration of global uranium resources and escalating geopolitical risks, approaching the issue solely from a supply–demand balance perspective no longer suffices to capture its evolving dynamics [1]. In recent years, China’s nuclear power capacity has grown substantially, accompanied by a rapid surge in uranium demand. The combination of sluggish domestic production growth and heavy reliance on imports has created a complex set of challenges for uranium resource security [2].

According to data from the International Atomic Energy Agency (IAEA), there were over 400 nuclear power reactors worldwide in 2023, with a total installed capacity of nearly 400 million kilowatts, and this figure is projected to increase further in the coming years. China’s nuclear power sector has also entered a phase of accelerated growth, as its share of both installed capacity and electricity generation continues to rise, positioning it as a key pillar of the country’s energy transition. Globally, uranium resources are highly concentrated in a few countries, and the supply system remains vulnerable to geopolitical and trade fluctuations. Domestically, China’s uranium resources consist primarily of sandstone-type deposits in the north and hard-rock-type deposits in the south, with a pronounced spatial mismatch between resource-rich areas and nuclear power–consuming regions [3]. Therefore, it is necessary to integrate geographic perspectives with a systems-evolution approach in order to systematically analyze the current status and dynamic changes of China’s uranium resource security.

Existing research on uranium resource security has been approached from various dimensions. Xing Wanli [4] analyzed the supply and demand pattern of uranium resources in China and identified key security issues, including rising external dependence and highly concentrated import sources. Fang Jianchun [5] estimated China's peak uranium production using a Hubbert curve and STELLA model, projecting a peak around 2065 under the most optimistic scenario and highlighting the widening gap between domestic supply and demand. Luo Shihua [6] assessed the decarbonization pathways of China's power sector under the 2060 carbon neutrality target, demonstrating that nuclear power plays an indispensable role in achieving a cost-effective and reliable low-carbon electricity supply. Xiao Xinjian and Jiang Kejun [7] evaluated the feasibility of China's nuclear power development under the global 1.5 ℃ target, highlighting the challenges of uranium resource supply and the need for optimized deployment. On the international front, Sébastien Joel Guembou Shouop [8] analyzed the impact of the nuclear power renaissance on uranium resource security, while Brenda Huerta-Rosas [9] examined changes in uranium supply and demand and their implications for the global energy landscape from a market perspective. System Dynamics (SD) is a quantitative method for simulating stock–flow–feedback dynamics in complex systems. In security research, SD has been applied to nuclear security culture assessment and policy intervention [10]; in management and resource-related fields, it has been used for privatization investment [11], ETS–CCER coupling [12], and resilience assessment of China's oil import system under external shocks [13]. Nevertheless, the application of SD to dynamic simulations that incorporate spatial heterogeneity into uranium resource security analysis remains relatively limited.

Overall, existing research lays an important foundation for understanding uranium resource security, yet several shortcomings persist. First, insufficient attention has been paid to the spatial heterogeneity and geographic patterns of uranium resources. Second, there is a lack of a comprehensive research framework that integrates spatial analysis with dynamic simulation. Third, institutional factors are largely treated at a qualitative level, without systematic quantitative analysis.

2 Study Area and Data Methods

2.1 Overview of the Study Area

Due to differences in tectonic evolution, ore-forming conditions, and resource development histories, China’s uranium resources exhibit pronounced spatial regional differentiation. Overall, the northern region is predominantly characterized by sandstone-type uranium deposits hosted

in Mesozoic–Cenozoic sedimentary basins, whereas the southern region is dominated by granitic and volcanic-type deposits. Among these, the sandstone-type, granitic-type, volcanic-type, and carbonaceous–siliceous mudstone-type deposits constitute the "four major types" of uranium deposits in China, accounting for over 90% of the nation's total proven reserves [14]. Substantial differences exist among these regional deposit types in terms of resource scale, development conditions, and mining costs, which consequently affect regional resource security and development potential.

This study takes mainland China as the model domain, with a simulation period covering 2008–2050. The year 2008 is designated as the base year; the period 2009–2023 is used for model calibration and historical validation, while 2024–2050 serves as the forecasting and adjustment period. The model operates with an annual time step. In addition, a nearly five-year interval (2019–2023) was selected for dynamic back-testing against historical data.

2.2 Data Sources

The data used in this study are primarily sourced from international organization databases, industry annual reports, and national statistical data. Data on uranium resources and reserves are derived from the IAEA's Uranium Resources, Production, and Demand; nuclear power operation and trade data are sourced from the WNA and the China Nuclear Energy Development Report; socioeconomic data are sourced from the China Statistical Yearbook; and indicators related to institutional resilience are sourced from the China Nuclear Energy Development Report and other sources. To ensure data consistency, data from different sources were standardized in this study. Missing data were supplemented using linear interpolation and subjected to multiple validations to ensure they remained within reasonable ranges and maintained consistent trends.

2.3 Research Methods

2.3.1 Geospatial Analysis Methods

To quantify the spatial mismatch between uranium supply and demand in China, this study adopts several analytical metrics, including the Location Quotient (*LQ*), Spatial Mismatch Index (*SMI*), Supply–Demand Matching Degree (*SDMD*), Supply–Demand Coordination Degree (*SDCD*), and the Herfindahl–Hirschman Index *(HHI)*.

(1) Location Quotient

The Location Quotient (LQ) measures the relative specialization and concentration of uranium resources in a given region compared with the national average. The formula is as follows:

$$LQ_i = \frac{q_i/q}{Q_i/Q} \tag{1}$$

In the equation, q_i represents the uranium reserves of a region, and q represents the total national uranium reserves; Q_i represents the land area of a region, and Q represents the total national land area. $LQ_i > 1$ indicates that the region's uranium resources are relatively concentrated, and its level of specialization exceeds the national average; conversely, $LQ_i < 1$ indicates the opposite.

(2) Spatial Mismatch Index

The Spatial Mismatch Index, grounded in spatial mismatch theory, is employed to reveal the misalignment of factor development at a micro level. In this study, we apply this index to measure the direction and magnitude of spatial mismatch between uranium reserves and nuclear power consumption across subregions. The calculation formula is:

$$SMI = \left(\frac{\mathrm{R_i}}{\mathrm{R_t}} - \frac{\mathrm{C_i}}{C_t}\right) \tag{2}$$

In the equation, R_i represents the uranium reserves in the i-th region, R_t represents the total national uranium reserves, C_i represents nuclear power consumption in the i-th region, C_t represents total national nuclear power generation, and SMI_i represents the spatial mismatch index for the i-th region. The sign of this value indicates the direction of the mismatch: $SMI_i > 0$ indicates that the region has a surplus of resources; conversely, it is a region with a relative scarcity of resources. The absolute value of SMI_i reflects the degree of mismatch; the larger the absolute value, the more severe the spatial mismatch.

(3) Supply-Demand Matching Degree

The Supply–Demand Matching Degree (*SDMD*) assesses the alignment between uranium supply and consumption in each region. The calculation is as follows:

$$SDMD_i = \frac{S_i - D_i}{(S_{max} - D_{max})/2} \tag{3}$$

S_i represents the supply of uranium resources in the i-th region, D_i represents the consumption of uranium resources in the i-th region, and S_{max} *and* D_{max} represent the maximum supply and maximum demand across all regions, respectively. When SDMD > 0, there is a supply surplus; conversely, there is a supply deficit. When SDMD = 0, supply and demand are in balance.

(4) Supply-Demand Coordination Index

The Supply–Demand Coordination Index *(SDCD)* measures the level of coordination and equilibrium between the uranium supply system and the demand system in each region. The formula is:

$$SDCD_i^t = \sqrt{C_i^t \times T_i^t} \tag{4}$$

$$C_i^t = \frac{2\sqrt{S_i^t \times D_i^t}}{S_i^t + D_i^t} \tag{5}$$

$$T_i^t = \frac{S_i^t + D_i^t}{2} \tag{6}$$

S_i^t represents the supply of uranium resources in the i-th region in year t, D_i^t represents the consumption of uranium resources in the i-th region in year t, C_i^t represents the coupling degree between the supply system and demand system, and T_i^t represents the comprehensive efficiency index of supply and demand, and $SDCD_i^t$ is the supply-demand coordination index. The value of $SDCD_i^t$ ranges from [0, 1]; a value closer to 1 indicates greater coordination between supply and demand, while a value closer to 0 indicates greater imbalance. When $SDCD_i^t$ > 0.8, coordination is considered high; between 0.6 and 0.8, it is considered basic; between 0.5 and 0.6, it is considered marginal; and below 0.5, it is considered imbalanced.

(5) Herfindahl–Hirschman Index

The Herfindahl–Hirschman Index *(HHI)* measures the degree of concentration of uranium supply sources or import origins; higher values indicate greater concentration and thus higher supply risk [15]. The formula is:

$$HHI = \sum_{i=1}^{N} S_i^2 \tag{7}$$

In this formula, N represents the total number of import source countries. The HHI value ranges from 0 to 10000; a higher value indicates greater concentration of import sources. It is generally considered that the larger the HHI, the higher the market concentration, and the more vulnerable the supply chain is to shocks caused by policy changes in a single source country or geopolitical conflicts.

2.3.2 System Dynamics Simulation Method

From the perspective of security science, uranium resource security can be defined as the ability of a system to maintain critical supply functions under internal disturbances or external shocks. In this study, we define uranium resource security as the capacity to sustainably meet the uranium demand for nuclear power development under stable economic and political conditions. This capacity is further decomposed into five dimensions: resource endowment, supply chain, technological substitution, independent innovation, and institutional resilience.

The model focuses on the dynamic relationship between resource supply and demand. Based on this, we construct an SD model centered on “resource supply and demand security”. According to variable attributes, the model includes four main categories—state variables, flow variables, auxiliary variables, and constants, as listed in Table 1.

Table 1 Main variables of the model

Variable Type	Variable Name	Variable Type	Variable Name
State Variables	Cumulative proven uranium resources in China	Auxiliary Variables	Work efficiency
	Uranium resource inventory		Uranium exploration completed workload
	Total population		Uranium price
	Total GDP		Uranium exploration investment
	Cumulative nuclear power installed capacity		Nuclear power construction investment
	Cumulative spent fuel accumulation		Uranium Demand
	Cumulative CO_2 emission reductions		Import volume
Rate Variables	Newly identified uranium resources		Overseas equity uranium production
	Population growth		Unit nuclear power capacity
	GDP growth		Nuclear (thermal, wind, hydro, solar) power generation
	Number of operating nuclear power units		GDP per capita
	Annual CO_2 emission reductions		Nuclear power revenue
	Annual spent fuel increase		Uranium Production
Constants	Spent fuel generation ratio per unit nuclear power capacity		Nuclear Power Operating Hours
	CO_2 emission coefficient		

Using the above variables, this paper develops a causal feedback structure for China's uranium resource security system, as shown in Figure 1.

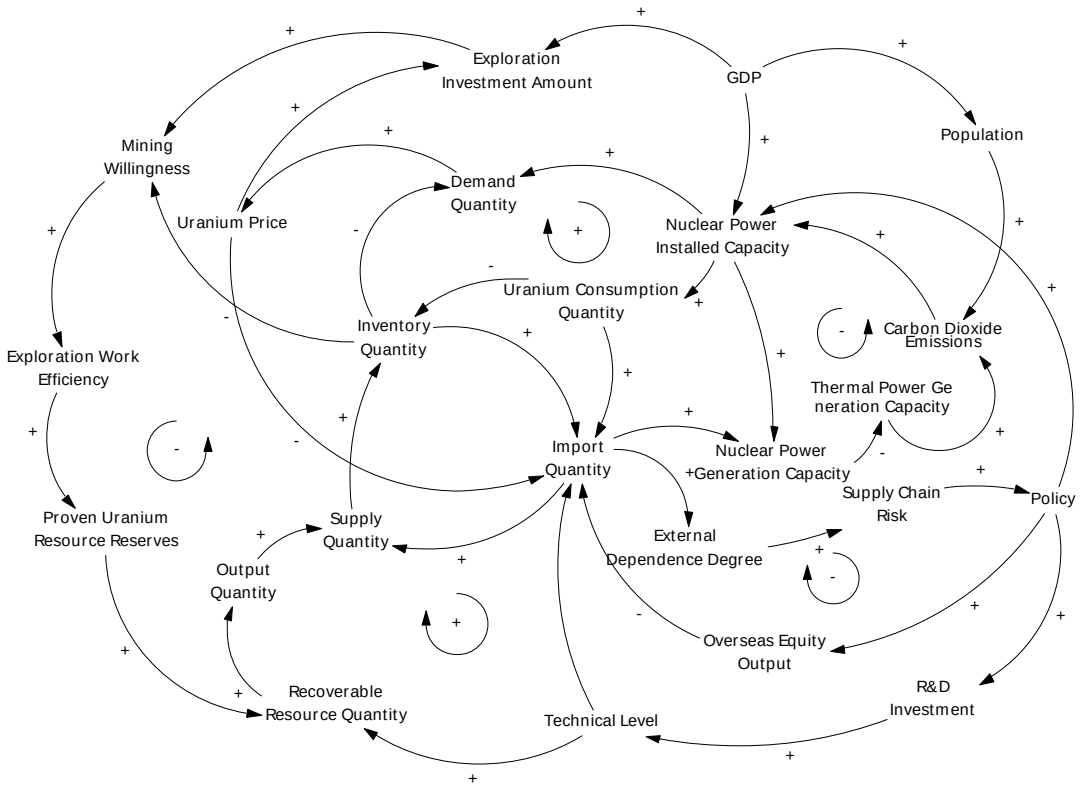


Figure 1 Causal Loop Diagram of China’s Uranium Resource Security

3 Analysis of the Characteristics of Uranium Resource Supply and Demand in China

3.1 Spatial Characteristics of Uranium Resource Supply in China

The spatial distribution of China’s proven uranium reserves is highly uneven, exhibiting an overall pattern of "abundant in the north and scarce in the south, abundant in the west and scarce in the east." In contrast, nuclear power consumption is heavily concentrated in the eastern coastal regions, creating a significant spatial mismatch between supply and demand. This mismatch forms the geographical foundation for constructing a uranium resource security model.

Considering the distribution pattern of uranium resources, deposit types, and regional development conditions, this study divides the study area into four major spatial units for uranium supply, as illustrated in Figure 2.

(1) North China and Northeast China

Resources are highly concentrated in Inner Mongolia, Shaanxi, Hebei, Liaoning, and other provinces. Inner Mongolia alone accounts for nearly half of the nation’s total resources. Sandstone-type deposits predominate in this region, which offers favorable development conditions and a high share of production capacity. However, long-distance transportation increases logistics costs and supply chain vulnerabilities.

(2) The Northwest Region

Uranium resources in this region are mainly distributed in Xinjiang and Gansu, consisting predominantly of sandstone-type deposits. These resources are shallowly buried and of moderate grade, resulting in low mining costs and considerable potential for large-scale production. Nevertheless, mining conditions are constrained by arid climate, ecological fragility, and water scarcity.

(3) East and South China

Resources are primarily distributed in Jiangxi, Hunan, Zhejiang, Guangdong, and other areas, and are mainly

composed of granite-type and volcanic-type hard-rock uranium deposits. The ore bodies are small, scattered, and characterized by complex burial patterns, leading to relatively higher mining costs.

(4) Southwest China

Resources are primarily distributed in Sichuan, Yunnan, Guangxi, and other regions, consisting mainly of black shale-type uranium deposits. Development conditions in this area are relatively complex.

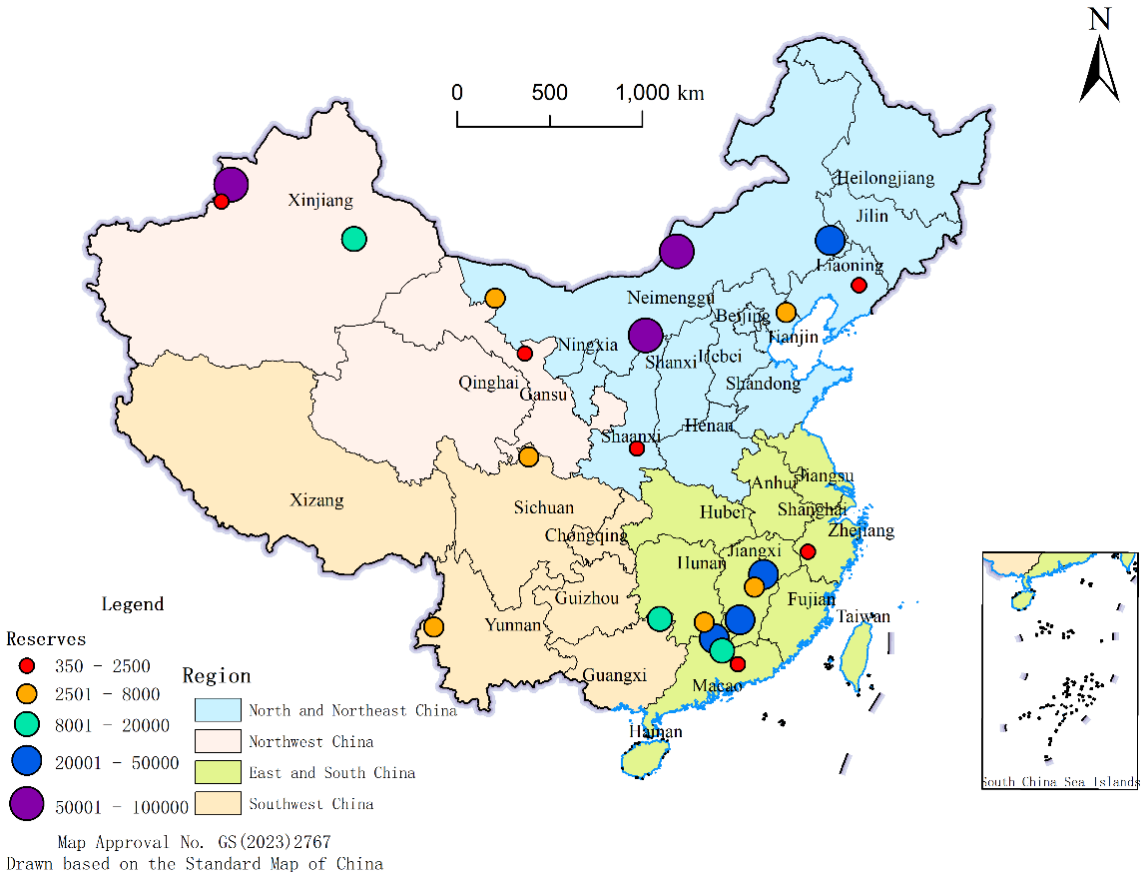


Figure 2 Spatial Distribution of Uranium Supply in China

In terms of spatial distribution, uranium resources in northern China are widely hosted in Mesozoic–Cenozoic sedimentary basins, such as the Ili Basin and the Tuha Basin in Xinjiang. These basins form an important sandstone-type uranium resource belt spanning the Northwest and northern North China. Uranium mining in the northern regions primarily employs in-situ leaching (ISL) technology. This method features stable ore bodies, relatively low mining costs, a high degree of automation, and large production capacities at individual mines. According to the IAEA's *Uranium Resources, Production and Demand* (2024 edition), approximately 64% of China's proven uranium resources are suitable for ISL mining, and these are predominantly concentrated in the northern basin areas.

In contrast, uranium deposits in southern China are mainly granite-type and volcanic-type hard-rock deposits, distributed largely across the Nanling Metallogenic Belt at the junction of Jiangxi, Guangdong, and Hunan provinces. Due to smaller ore body sizes, complex burial conditions, and higher mining costs, overall production efficiency and capacity in this region are relatively limited. Between 2019 and 2022, several conventional uranium mining centers in the south ceased operations or closed due to resource depletion or high costs, leading to a marked decline in uranium production. By the end of 2023, production from these southern conventional mining centers accounted for only about 10% of the national total. As uranium mining technology in the north continues to improve and large-scale sandstone-type deposit development accelerates, the northern region has gradually become the mainstay of China's uranium resource supply system [16].

Table 2 Regional Location Quotients of China (2013–2023)

Region	2013	2015	2017	2019	2021	2023
North China and Northeast China	1.12	1.37	1.44	1.50	1.56	1.65
The Northwest Region	0.55	0.48	0.50	0.52	0.54	0.61
East and South China	3.21	2.78	2.60	2.45	2.30	2.00
Southwest China	0.24	0.25	0.24	0.22	0.21	0.18

China's uranium resource supply exhibits a clear north–south divergence across the four regions. In North and Northeast China, the LQ index rose steadily from 1.12 in 2013 to 1.65 in 2023, indicating a continuous strengthening of the region's resource advantage. This has supported the formation of large-scale sandstone-type uranium deposits across the country, centered on basins such as Ordos, Erlian, and Yili. In East and South China, the LQ declined from 3.21 to 2.00 over the same period, though it remains well above 1, suggesting that the region still holds a resource advantage. However, its relative position in the national supply landscape has continued to weaken, a trend closely linked to the gradual closure of mines in the region due to resource depletion and high extraction costs. In the Northwest region, the LQ ranges between 0.48 and 0.61, below the national average. Nevertheless, recent breakthroughs in deep exploration in areas such as the Tarim Basin in Xinjiang indicate considerable future supply potential. The Southwest region, with an LQ of only 0.18, is considered a uranium-poor area. The specific LQ values for each region are presented in Table 2.

3.2 Spatial Characteristics of Uranium Resource Demand

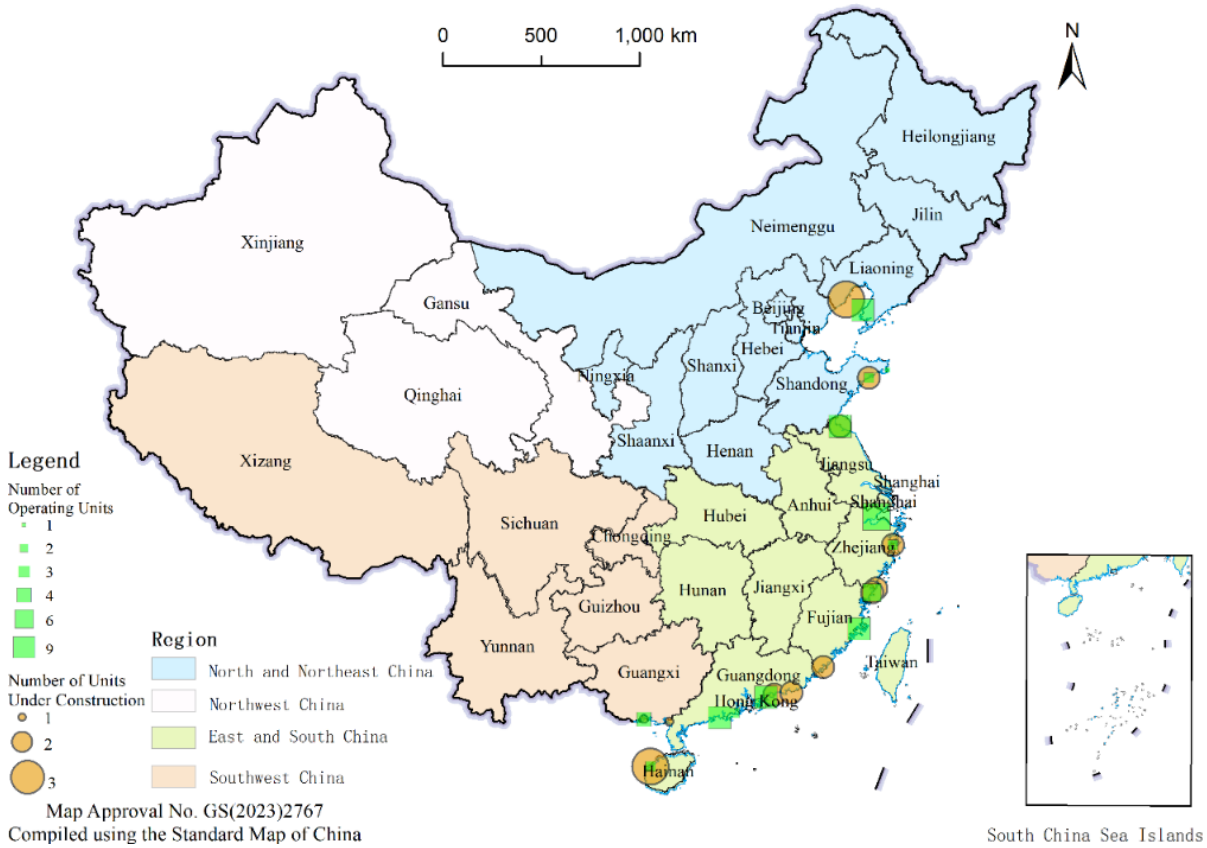


Figure 3 Spatial Distribution of Uranium Demand in China (Nuclear Power Installed Capacity)

In terms of uranium consumption, the spatial distribution of China's uranium resource demand—reflected by operational and under-construction nuclear power generating capacity—is presented in Figure 3. In studies on uranium resource security, nuclear power represents the main source

of uranium demand and provides accessible, continuous data. Therefore, this paper uses nuclear power generating capacity as a proxy for uranium consumption demand. The distribution of nuclear power exhibits a pronounced coastal pattern. As of the end of 2023, China had 55 operational nuclear power units and 24 under construction, with a total installed capacity of approximately 52.2 million kilowatts, primarily concentrated in the eastern coastal regions [17]. The combined nuclear power installed capacity of Guangdong, Zhejiang, and Fujian provinces accounts for over 70% of the national total [18]. In addition, Shandong, Jiangsu, Guangxi, and Hainan are expected to become key regions for future nuclear power capacity expansion. Coastal provinces have become the core areas for nuclear power development in China, owing to their strong industrial bases, substantial electricity demand, and favorable cooling water conditions.

Calculations of regional shares of nuclear power consumption reveal that China's nuclear power consumption distribution remains concentrated in the southeastern coastal areas, while the consumption share of North and Northeast China has shown a trend of increasing year by year. Although the consumption share of East and South China has declined since 2013, these regions still dominate national consumption by a large margin. In North and Northeast China, the consumption share has increased notably, but nuclear power generation remains concentrated in Liaoning and Shandong provinces. Demand in Southwest China remains weak, while Northwest China has no installed nuclear power capacity, resulting in a consistently zero consumption share. Overall, the pattern of consumption concentrated in the southeastern coastal regions is unlikely to change fundamentally in the short to medium term. The specific consumption shares for each region are presented in Table 3.

Table 3 Regional Share of Nuclear Power Consumption in China (2013–2023)

Region	2013	2015	2017	2019	2021	2023
North China and Northeast China	5.66%	8.56%	14.38%	14.38%	14.57%	16.04%
The Northwest Region	0%	0%	0%	0%	0%	0%
East and South China	94.34%	91.44%	85.62%	85.62%	80.97%	78.23%
Southwest China	0%	0%	0%	0%	4.45%	5.74%

3.3 Characteristics of Spatial Mismatches Between Supply and Demand

We calculated the SDMD and SDCD for each subregion over the period 2013–2023, as presented in Table 4.

Table 4 Regional Supply-Demand Matching, Coordination, and Spatial Mismatch Index (2013–2023)

Region	indicator	2013	2015	2017	2019	2021	2023
North China and Northeast China	SDMD	+0.88	+1.16	+1.11	+1.17	+1.30	+1.37
	SDCD	0.28	0.34	0.39	0.42	0.47	0.48
	SMI	+28.62	+33.42	+29.67	—	+33.24	+34.58
The Northwest Region	SDMD	+0.50	+0.48	+0.54	+0.58	+0.61	+0.70
	SDCD	—	—	—	—	—	—
	SMI	+16.20	+14.20	+14.56	—	+15.77	+17.78
East and South China	SDMD	-1.15	-1.29	-1.30	-1.33	-1.27	-1.38
	SDCD	0.37	0.38	0.42	0.44	0.48	0.51
	SMI	-51.21	-54.17	-50.70	—	-50.04	-51.39
Southwest China	SDMD	+0.20	+0.22	+0.24	+0.24	+0.06	-0.03
	SDCD	—	—	—	—	0.76	0.91
	SMI	+6.40	+6.55	+6.47	—	+1.04	-0.98

In summary, the supply and demand of uranium resources in China exhibit the following characteristics:

(1) The supply–demand gap between the north and south continues to widen. In North and Northeast China, the SDMD increased from +0.88 to +1.37, while the SMI rose from +28.62 to +34.58, indicating that the northern region's resource advantage and resource scale have continued to strengthen. In East and South China, the SDMD remained between –1.15 and –1.38, and the absolute value of the SMI consistently exceeded 50, showing no sign of improvement. The trend of polarization—with a surplus in the north and a shortage in the south—has become more pronounced.

(2) The level of resource coordination between the north and south remains low. Although the SDCD of North and Northeast China relative to East and South China

has increased, the growth rate has been slow and has not exceeded 0.6, placing it only within the marginally coordinated range. During the same period, the SMI revealed that positive mismatch in North and Northeast China continued to widen, while negative mismatch in East and South China remained severe, further indicating that the supply–demand structures of these two regions are at a low level of coordination. In contrast, the Southwest region achieved a relatively high SDCD of 0.91 with an SMI approaching 0. However, its combined reserves and consumption account for less than 10% of the national total, so its contribution to overall improvement remains limited.

Calculations based on available data show that the HHI index rose from 3,962 in 2008 to 5,516 in 2023 (n=2), and has remained above 5,000 since 2020. This indicates a high concentration of import sources and significant geopolitical risks [19]. Collectively, the above geospatial analyses point to substantial risks to China's uranium resource security.

4 Dynamic Simulation of China's Uranium Resource Security

4.1 Data Assumptions and Historical Validation

This study follows the policy direction of the "Dual Carbon" goals and references the *China Nuclear Energy Development Report (2026)* and the *Study on China's Nuclear Power Development Plan* to establish scenario-based settings for key model parameters [20]. The exogenous variables in the model mainly include nuclear power installed capacity. Based on forecasts from UxC Consulting and expert assessments of China's nuclear power installed capacity by 2035, we validated the simulation values for the corresponding years. Population and economic growth parameters were primarily derived from publicly available sources such as the *China Statistical Yearbook*, with the specific settings presented in Table 5.

Table 5 Simulation Settings of Exogenous Variables

Year	Uranium Import Index	Population Growth Rate (%)	GDP Growth Rate (%)	Uranium Price (RMB/t)	Uranium Demand for Nuclear Power(t)	Nuclear Power Investment (million RMB)
2030	0.800	0.00009	0.045	80	22600	2000
2040	0.700	0.009	0.034	120	43400	4000
2050	0.600	0.0009	0.032	150	55000	6000

Based on the above benchmarks and assumptions, this paper constructs a stock-flow model of China's uranium resources, as shown in Figure 4.

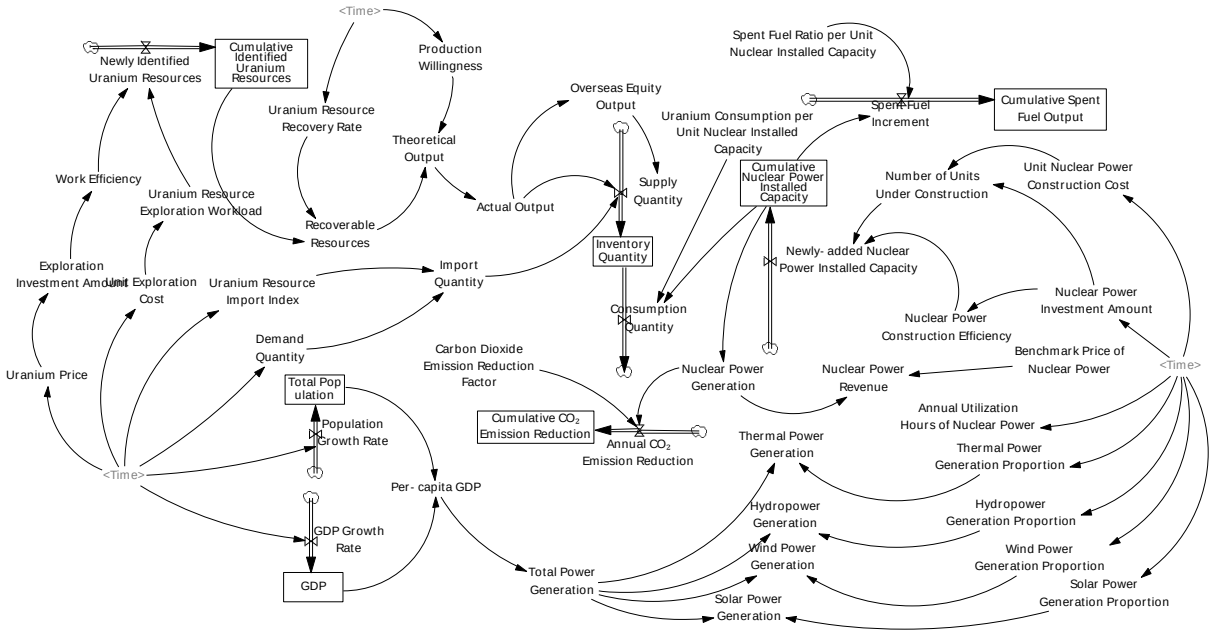


Figure 4 Stock-Flow Diagram of China's Uranium Resource Security

To verify the reliability of the model, we conducted a goodness-of-fit test using historical data from 2008 to 2023, with the results presented in Table 6. The model outputs are generally consistent with the trends in historical actual data, with relative errors all kept within a reasonable range and high fitting accuracy for key variables. Furthermore, sensitivity analysis indicates that the model is sensitive to nuclear power investment intensity and the import index, but relatively insensitive to population and GDP growth. This suggests that the evolution of the uranium resource system is primarily influenced by the pace of nuclear power expansion and the degree of reliance on overseas sources [21].

Table 6 Validity Verification of the Uranium Resource Model

Parameter	Fitting	2019	2020	2021	2022	2023
Uranium resource reserves (t)	Actual value (t)	344000	341750	339500	372600	405700
	Simulated value (t)	369975	356525	354275	352025	385125
	Relative error (%)	7.56	4.32	4.36	-5.53	-5.08
Uranium production (t)	Actual value (t)	1600	1600	1540	1550	1600
	Simulated value (t)	1604.72	1606.25	1607.03	1569.08	1600.54
	Relative error (%)	0.30	0.39	4.35	1.23	0.03
Uranium imports (t)	Actual value (t)	12817.32	16484.99	13538.94	12246.39	14516.27
	Simulated value (t)	12817.30	16485.00	13538.90	12246.40	14516.20
	Relative error (%)	-0.01	-0.01	-0.01	0.01	-0.01
Cumulative nuclear power installed capacity (10,000 kW)	Actual value (10,000 kW)	3758.40	4333.40	4563.40	4793.40	5028.40
	Simulated value (10,000 kW)	3985.59	4563.44	4791.73	4981.54	5220.22
	Relative error (%)	6.05	5.31	5.00	3.93	3.82
Nuclear power generation (100 million kWh)	Actual value (100 million kWh)	3483.50	3662	4075	4177	4449
	Simulated value (100 million kWh)	3146.23	3492.40	3738.51	3793.94	4056.11
	Relative error (%)	-9.68	-4.63	-8.26	-9.17	-8.83

4.2 Analysis of Simulation Results and Scenario Analysis

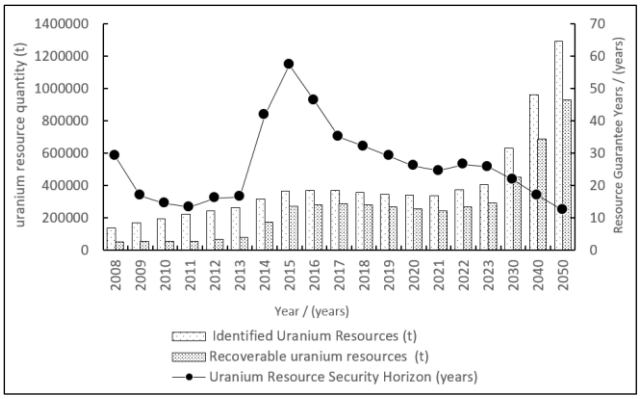


Figure 5 Analysis Results of China's Uranium Resource Endowment (2008–2050)

The analysis of China's uranium resource endowment, as shown in Figure 5, indicates that both China's proven reserves and recoverable resources have continued to increase at a significant rate, indicating that exploration efforts in regions such as Northwest and North China have yielded substantial results. Based on current trends, it is projected that China's uranium reserves and recoverable resources will continue to grow through 2050, suggesting that the country's uranium exploration and development system possesses a certain degree of sustainability. However, it should be noted that China's uranium resource security horizon has been declining continuously since 2015, and is projected to drop to approximately 10 years by 2050, reflecting a gradual weakening of the country's static resource security capacity.

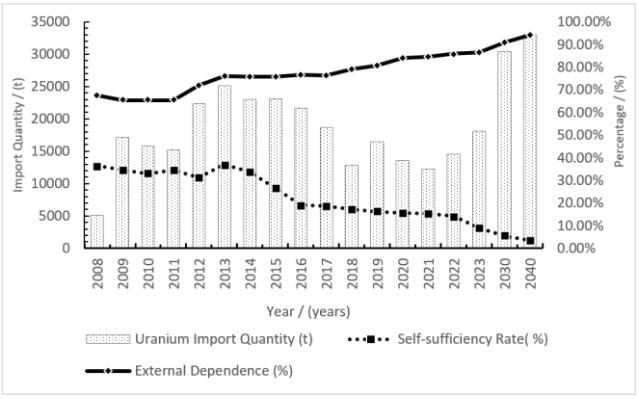


Figure 6 Analysis Results of China's Uranium Supply Chain Security (2008–2050)

The analysis of China's uranium supply chain security, as shown in Figure 6, illustrates the deteriorating trend in

this dimension. China's uranium imports have generally fluctuated at high levels, and are projected to continue increasing from 2030 to 2050, with the country's dependence on foreign sources remaining persistently high. The steadily declining self-sufficiency rate in uranium resources reflects a significant and persistent gap between domestic resource supply and nuclear power demand. In addition, due to the pronounced spatial mismatch between supply and demand, natural uranium and nuclear fuel products must rely on long-distance, cross-regional transportation. Against the backdrop of extreme weather events, geopolitical conflicts, and sudden public emergencies, the vulnerability of the supply chain is expected to increase further.

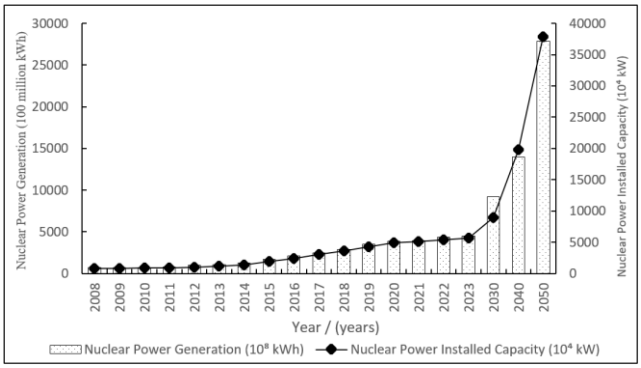


Figure 7 Evaluation of China’s Technological Substitution Security(2008–2050)

The analysis of China's technological substitution security, as shown in Figure 7, indicates that while technological substitution has led to improved efficiency, it may also result in the accumulation of waste. Uranium consumption per unit of electricity generated—a key indicator of uranium resource utilization efficiency—reflects the level of progress in nuclear fuel cycle and nuclear power technologies. Overall, this indicator has shown a fluctuating trend; as technology continues to advance, uranium resource utilization efficiency is expected to improve. Furthermore, by 2050, CO_2 emission reductions resulting from nuclear power development are projected to reach a high level, providing significant support for achieving China's "dual carbon" goals. At the same time, however, the expansion of nuclear power capacity will also lead to the rapid accumulation of spent fuel. Simulation results show that China's spent fuel inventory has continued to grow since 2008 and is projected to reach a considerable level by 2050. The long-term accumulation of spent fuel will place greater demands on nuclear waste treatment capacity, environmental safety, and long-term storage systems, and will gradually become a major factor constraining the sustainable development of nuclear energy in China.

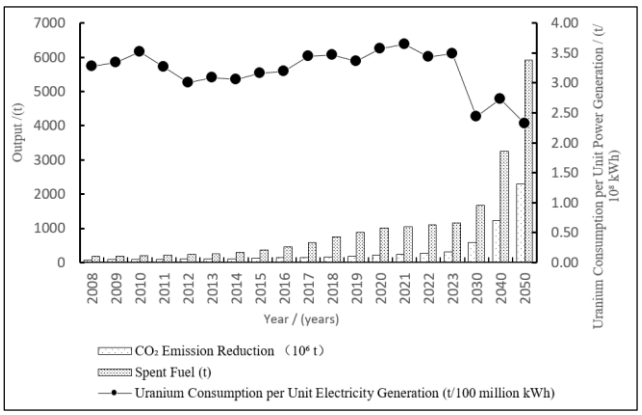


Figure 8 Analysis Results of China’s Innovation Autonomy Security (2008–2050)

The analysis of China's innovation autonomy security, as shown in Figure 8, indicates that both nuclear power installed capacity and electricity generation have increased in tandem, signaling an improvement in China's level of localization and self-reliance. In recent years, breakthroughs in key technologies such as the "Hualong One" and "Guoyu No. 1" have enabled China to achieve self-reliance and independent control over third-generation nuclear power equipment and nuclear fuel cycle technologies, providing crucial support for the security of the nuclear energy industry chain. It is projected that by 2050, both nuclear power installed capacity and electricity generation will continue to grow, and the strategic position of nuclear power within the energy mix will be further strengthened.

The simulation results across the four dimensions mentioned above indicate the following: resource endowment faces the contradiction of increasing reserves but declining supply security; supply chain risks continue to intensify due to import dependence and spatial mismatches; technological substitution exhibits a double-edged sword effect, with improved efficiency on one hand and waste accumulation on the other; and independent innovation serves as a critical safety buffer.

Since institutional factors are difficult to quantify directly, this paper characterizes the level of institutional resilience by adjusting key parameters. Referring to the parameter ranges commonly used in existing policy simulation studies, we set low institutional resilience (S1) and high institutional resilience (S2) at 0.7 times and 1.3 times the baseline value (S0), respectively. Specifically, the exploration-to-production conversion coefficient and production willingness reflect resource development efficiency;

production delay reflects the project approval cycle; nuclear power construction efficiency reflects the speed of plan implementation; and the import index reflects the ability to regulate import dependence [22]. In the S1 scenario, the model simulates inefficient approvals, slow conversion, and insufficient overseas expansion. In the S2 scenario, it simulates efficient implementation, enhanced coordination, and improved overseas security. The specific parameter settings are presented in Table 7.

Table 7 Parameter Settings for Three Institutional Resilience Scenarios

Parameter	S1	S0	S2	Adjustment Basis
Exploration-to-production conversion coefficient	Baseline × 0.7	Baseline value	Baseline × 1.3	Institutional influence on mineral rights approval and conversion efficiency of exploration results
Production willingness	Baseline × 0.7	Baseline value	Baseline × 1.3	Institutional influence on capacity utilization rate and management efficiency
Production delay (years)	2	1	1	Institutional influence on project approval and construction management efficiency
Nuclear power construction efficiency	Baseline × 0.7	Baseline value	Baseline × 1.3	Institutional influence on the implementation speed of nuclear power planning
Import index	1.2 / 1.3 / 1.4	0.8 / 0.7 / 0.6	0.6 / 0.4 / 0.2	Institutional influence on the capacity to regulate import dependence

By conducting simulations based on parameters from three predefined scenarios, we can obtain dynamic trends and projections regarding the security of China's uranium resources. The simulation results for the three scenarios show significant differences, revealing the regulatory and central role of institutional resilience in China's uranium resource security system.

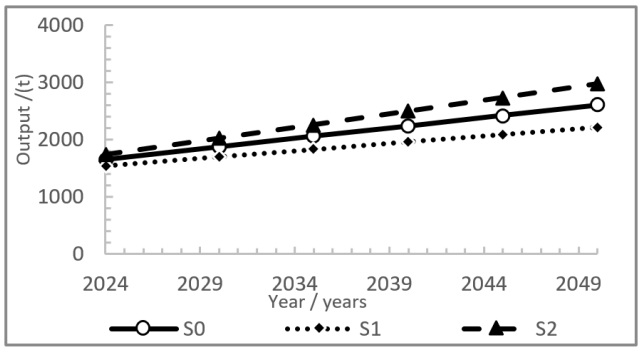


Figure 9 Comparison of China’s Uranium Production Forecasts under Three Scenarios

A comparison of China's uranium production under the three scenarios is presented in Figure 9. Under the high institutional resilience scenario (S2), the growth rate of domestic uranium production is significantly faster than in the other scenarios. This is primarily due to improved efficiency in converting exploration investments into production and a shorter cycle for releasing production capacity, which together significantly enhance resource development capabilities. In contrast, under the low institutional resilience scenario (S1), resource development efficiency is lower, domestic production growth is relatively slow, and it becomes difficult to meet the growing demand driven by the rapid expansion of nuclear power.

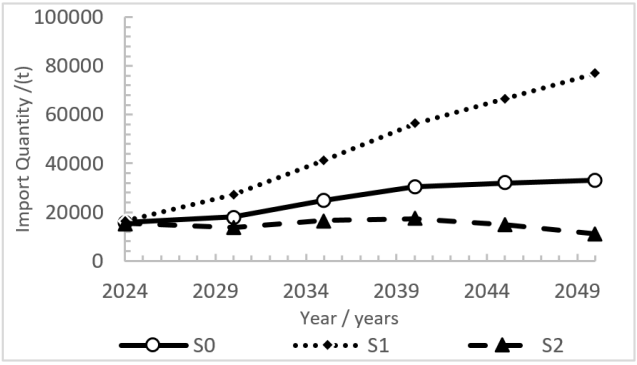


Figure 10 Comparison of China’s Uranium Import Forecasts under Three Scenarios

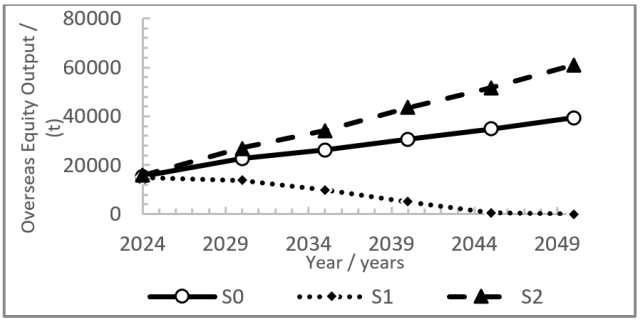


Figure 11 Comparison of China’s Overseas Equity Uranium Production Forecasts under Three Scenarios

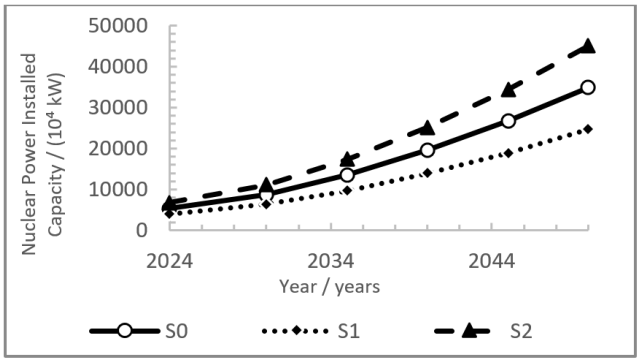


Figure 12 Comparison of China's Nuclear Power Installed Capacity Forecasts under Three Scenarios

A comparison of import volumes under different institutional conditions is presented in Figure 10. In the low institutional resilience scenario, due to insufficient growth in domestic supply capacity, the scale of imports expands rapidly, external dependence continues to rise, and system vulnerability increases markedly. In the high institutional resilience scenario, as domestic supply capacity and overseas equity resources improve in tandem, the level of import dependence is effectively controlled, forming a security structure characterized by "domestic production growth, overseas supplementation, and import diversification." Overseas equity uranium production under different institutional conditions is further compared in Figure 11. In the high institutional resilience scenario, capabilities for overseas resource development and international cooperation are significantly enhanced, and production from overseas equity resources gradually increases, alleviating domestic resource pressures to a certain extent. In the low institutional resilience scenario, however, the ability to secure overseas resource assets is weak, and the impact of international market fluctuations on the stability of domestic supply chains is more pronounced.

The results for China's nuclear power installed capacity under different institutional resilience scenarios are compared in Figure 12. In all three scenarios, nuclear power installed capacity exhibits a sustained growth trend. Under the high institutional resilience scenario (S2), installed capacity grows at the fastest rate and is projected to reach approximately 465,000 megawatts by 2049. This is primarily due to optimized approval processes, enhanced industrial chain coordination, and improved policy safeguards, which collectively provide efficient support for the large-scale development of nuclear power. Under the baseline scenario (S0), installed capacity grows steadily, reaching approximately 340,000 megawatts by 2049, reflecting the typical pace of development within the existing institutional framework. Under the low institutional resilience scenario (S1), growth is the slowest, reaching only about 250,000 megawatts by 2049, as issues such as low approval efficiency and insufficient policy stability constrain industrial expansion. Overall, high institutional resilience can effectively resolve development challenges and drive the high-quality development of the nuclear power industry; conversely, low institutional resilience will delay the process of low-carbon energy transition. Based on the above analysis, the key characteristics of uranium resource security under the three institutional resilience scenarios are summarized in Table 8.

Table 8 Comprehensive Comparison of Uranium Resource Security Characteristics under Three Scenarios

Comparison Dimension	S0 (Baseline)	S1 (Low Resilience)	S2 (High Resilience)
Domestic production	Steady growth	Sluggish growth	Rapid growth
Import volume	Continuously rising	Uncontrolled increase	Steady decline
Overseas equity production	Steady growth	Continuous shrinkage	Rapid growth, becoming a core component
Nuclear power installed capacity	Steady growth	Slowest growth	Rapid increase
Supply structure	Slowly optimizing	Single-source import dependence	Diversified and self-reliant structure
System resilience	Moderate	Extremely low	Highest

A comparison of the three scenarios reveals the following patterns. Under the low institutional resilience scenario (S1), domestic production growth is sluggish, import volumes grow rapidly and become difficult to manage, overseas equity interests shrink, and the system exhibits high vulnerability. Under the baseline scenario (S0), all indicators remain stable, but external dependence remains persistently high. Under the high institutional resilience scenario (S2), domestic production and overseas equity interests increase in tandem, import dependence is effectively controlled, and a diversified and robust supply structure is formed. This structure aligns with China's "three-thirds" security strategy: approximately one-third from domestic development, one-third from overseas equity mines, and one-third through imports, while adhering to the "four-in-one" framework.

This indicates that institutional resilience does not directly increase resource reserves, but by optimizing development efficiency, supply structure, and risk resilience, it

becomes a core soft power within the security system. However, the high institutional resilience scenario still faces a stockpile gap during the transition period, suggesting that institutional capacity building must be advanced in tandem with strategic reserve mechanisms and should be designed with differentiation to account for the spatial heterogeneity of China's uranium resources.

5 Conclusions and Policy Recommendations

5.1 Conclusions

By integrating geospatial analysis methods with system dynamics modeling to study China's uranium resource security, this paper reaches the following main conclusions: (1) China's uranium supply and consumption exhibit a significant spatial mismatch. Although North China and Northeast China, as well as East China and South China, are all resource-rich regions, the supply center has shifted further northward, while the consumption center remains anchored along the southeastern coast. The extreme difference in SDMD reaches 2.75, and the trend of polarization continues to intensify; the supply–demand coordination in both core regions remains within the imbalanced range. In addition, the proportion of China's uranium imports continues to expand, and the HHI index remains within the high-risk range.

(2) Simulation results from the SD model show that China's uranium resource security horizon has been declining continuously since 2015, indicating a gradual weakening of static security capacity. External dependence has remained persistently high over the long term, posing significant supply chain risks. While nuclear power development has been accompanied by improved uranium utilization efficiency and substantial emission reduction benefits, the accumulation of spent fuel continues to expand, imposing growing pressure on resource security.

(3) Comparative simulations under three institutional resilience scenarios—low (S1), baseline (S0), and high (S2)—reveal that institutional resilience exerts a significant regulatory effect on domestic production, import dependence, and overseas equity production. Under the high institutional resilience scenario (S2), the system forms a robust three-pronged structure characterized by "domestic production growth as the mainstay, supplemented by overseas interests, and reduced import dependence," with the fastest growth in nuclear power installed capacity. Under the low institutional resilience scenario (S1), import volumes grow rapidly and become difficult to control, overseas equity interests shrink, and system vulnerability is significantly increased. Institutional resilience does not directly increase resource reserves, but by optimizing exploration-to-production conversion efficiency, production capacity release cycles, and coordination capabilities with overseas partners, it becomes a core soft power for ensuring security. Institutional capacity building must be advanced in coordination with strategic reserve mechanisms and must also be adapted to the spatial distribution characteristics of China's uranium resources.

5.2 Policy Recommendations

Based on the above conclusions, the following policy recommendations are proposed:

(1) Northwest Sandstone-Type Uranium Concentration Zone

This region is characterized by an arid climate, scarce water resources, and a fragile ecological environment. Priority should be given to promoting green CO_2+O_2 in-situ leaching technology for uranium extraction, so as to avoid groundwater contamination and surface damage caused by conventional mining methods. A GIS-based dynamic groundwater environmental monitoring platform should be established to enable real-time early warning and risk management during the mining process. Through the synergy of technological upgrading and ecological monitoring, a win-win outcome for resource development and environmental protection can be achieved.

(2) South China Hard-Rock Uranium Deposit Distribution Area

This region contains numerous abandoned mines from historical operations and faces significant environmental remediation challenges, with high economic and environmental costs for further capacity expansion. Therefore, the policy focus should shift from capacity expansion to "residual ore recovery and mine decommissioning and remediation." Geographic information technology should be utilized to conduct suitability assessments for land reclamation in mining areas, and ecological restoration and land reuse should be implemented on a case-by-case basis. At the same time, enterprises should be encouraged to employ technological means to recover uranium resources from residual ores, thereby revitalizing existing reserves and reducing new environmental pressures.

(3)Eastern Coastal Nuclear Power Load Centers

This region has a high concentration of nuclear power capacity, but is vulnerable to marine disasters such as typhoons, storm surges, and sea-level rise, and is geographically distant from the resource-producing areas in the northwest. The geographical distribution of strategic natural uranium reserves should be optimized by establishing regional reserve centers around major nuclear power bases and setting up emergency transportation mechanisms. In addition, climate resilience should be incorporated into the site selection assessment for reserve facilities, so as to reduce the risk of supply chain disruptions caused by disasters.

6 Limitations and Future Directions

This study effectively simulates the long-term evolution of uranium resource security under the interaction of multiple factors using a system dynamics model. However, the model still has certain limitations, and future research could be deepened in the following areas:

(1) Expanding the model's scope. This study concentrates on key links in the domestic supply chain. Future work could incorporate the production decisions and trade strategies of major uranium-exporting countries, or introduce environmental carrying capacity constraints, so as to better reflect complex real-world conditions.

(2) Analysis of parameter uncertainty. Data for some key parameters—such as production volumes from overseas equity interests—are missing. Due to commercial confidentiality, precise historical data could not be obtained. Although the parameter simulation method used in this study was cross-validated, some uncertainty still exists. If more detailed data become available in the future, model accuracy could be further improved.

(3) Refinement of policy instruments. Policy factors in the model are represented by a composite index. Although this study has established an indicator system, the measurement of some secondary indicators still relies on expert scoring, which introduces some subjectivity. In future work, the Delphi method or fuzzy comprehensive evaluation could be introduced to enhance objectivity.

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