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Study on the coupling role and forecasting of energy-economy-environment triple system based on system dynamics approach, taking Inner Mongolia autonomous region as an example

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The sustainable development of Inner Mongolia, particularly the coordinated development of energy, economy, and environment, plays a crucial role in shaping energy strategies and environmental protection policies for both Inner Mongolia and China. Based on this, the study focuses on the energy-economy-environment coupling in Inner Mongolia, employing system dynamics for multi-scenario simulations. The findings reveal: (1) the overall coupling coordination degree is improving, with the energy-environment friendly scenario yielding the best results; (2) industrial pollution and energy consumption are significant factors influencing coupling coordination; (3) addressing energy consumption and achieving carbon neutrality are long-term challenges for Inner Mongolia's sustainable development. Therefore, Inner Mongolia should optimize its industrial structure, promote high-tech and low-carbon industries, improve energy efficiency, develop renewable energy, and strengthen pollution control and carbon emission management to achieve sustainable development across its economy, energy, and environment.

KEYWORDS

inner Mongolia autonomous region, system dynamics, energy, economy, environment, coupling coordination, Inner Mongolia

1 Introduction

The Inner Mongolia Autonomous Region plays a pivotal role in China's energy sector due to its vast natural resources, including coal, natural gas, and renewable energy sources such as wind and solar power (Wu et al., 2023). As one of the nation's leading coal producers, Inner Mongolia has also made significant strides in expanding its renewable energy capacity, particularly in wind and solar energy (Wang et al., 2023; Zhang et al., 2023). However, despite these advancements, the region faces considerable challenges, including low energy efficiency, an over-reliance on coal, and severe environmental pollution (Elkhatat and Al-Muhtaseb, 2024; Yu and Liu 2022). This heavy dependence on coal as the dominant energy source has led to extensive air and water pollution, soil degradation, and accelerated desertification of grasslands (Zhang, 2020). Although Inner Mongolia's economy has grown rapidly, driven by resource-intensive industries, its economic structure remains overly dependent on energy production, limiting its long-term resilience and sustainability (Wu et al., 2024; Zhiyuan et al., 2024). Recent efforts to diversify the economy have fostered growth in the tertiary sector, especially in services, but environmental challenges continue to hinder the region's progress toward sustainable development (Hariram et al., 2023; Jiang et al., 2024). To address these issues, it is essential to further optimize the industrial structure, enhance energy efficiency, and implement more robust environmental protection measures (Yang et al., 2023; Zhu and Zhang 2021).

Research on the interconnections between energy, the economy, and the environment has garnered increasing attention due to its critical role in achieving sustainable development. Scholars have highlighted the complex interdependencies among these systems, where economic growth is typically accompanied by rising energy consumption and greater environmental pressures (Irfan et al., 2022; Liu et al., 2022). Regional studies reveal significant variations in the degree of coupling and coordination between these systems, which are influenced by local policies and development models. Research on the Yellow River Basins demonstrates notable spatial differences in coupling coordination (Li et al., 2024; Chen et al., 2023). Studies of other regions, such as Hebei Province and resource-dependent areas of China, further support the view that while overall coupling trends are improving (Cao et al., 2020; Wu et al., 2018), significant regional heterogeneity remains, and policy interventions are crucial for promoting coordinated development (Yan et al., 2019;Liu et al., 2021).

The application of system dynamics has proven to be an effective approach for studying the coupling and coordination between energy, the economy, and the environment (Mohammad et al., 2021). System dynamics modeling enables researchers to simulate the dynamic evolution of these systems, uncovering feedback loops and nonlinear interactions. Numerous studies have employed system dynamics to assess the impact of various development policies on regional sustainability (Wang Y. et al., 2023). Studies of Kunming and the Three Gorges Reservoir Area illustrate how balanced economic and environmental strategies can enhance the coordination between these systems (Cui et al., 2019; Cheng et al., 2024). Similarly, research in Northeast China and other resource-dependent regions has utilized system dynamics to predict trends in resource consumption and environmental impacts, underscoring the urgent need for effective resource management and environmental protection (Cao et al., 2023; Jiang et al., 2022; Ouyang et al., 2021).

This study uses system dynamics to examine coupling relationships and dynamic interactions among these systems, providing a scientific foundation for sustainable development. The research focuses on analyzing trends and influencing factors of the coupling coordination degree, investigating direct and indirect mechanisms by which indicators impact coordination, identifying key obstacles, and evaluating the effects of different policies on sustainability. The study's contribution lies in its system dynamics modeling, offering a comprehensive understanding of the coupling evolution in Inner Mongolia's energy-economy-environment systems, and providing insights into challenges and solutions for policy optimization. Through scenario analysis, this research supports the development of effective strategies to promote regional sustainable development.

2 Materials and methods

2.1 Data sources

The research area of this study is Inner Mongolia Autonomous Region, China, with data spanning from 2000 to 2021. The panel data are sourced from the China Statistical Yearbook, China Energy Statistical Yearbook, and Inner Mongolia Statistical Yearbook. Missing data were completed using interpolation methods. The carbon sequestration coefficient for each vegetation type refers to the "Accounting Standards for Total Ecological Product Value." Energy consumption and carbon emissions are converted based on the IPCC National Greenhouse Gas Inventory Guidelines, National Bureau of Statistics Standards of China, and the General Rules for Comprehensive Energy Consumption Calculation.

2.2 System dynamics model

2.2.1 Model introduction

System Dynamics, developed by Professor Forrester in the 1950s, is a widely used methodology for analyzing the behavior of complex systems over time. Leveraging a systems-thinking approach, system dynamics models dynamic feedback loops and interdependencies, using differential equations to describe the evolution of system variables. This allows researchers to identify patterns, delays, and non-linear behaviors within interconnected systems. A key advantage of system dynamics is its ability to reveal the internal structure and feedback mechanisms that drive system behavior, enabling hypothesis testing and scenario analysis through simulations. This makes system dynamics particularly valuable in fields like energy, economics, and environmental management, where understanding long-term dynamics and interactions is crucial. However, the methodology requires substantial domain knowledge and high-quality data for model calibration, as the accuracy of results depends heavily on input parameters and structural validity.

In this study, system dynamics is applied to analyze the complex interplay within the energy-economy-environment system of Inner Mongolia. By modeling the dynamic coupling of these subsystems, the study investigates feedback loops, trade-offs, and synergies, providing critical insights into their coordination. This approach enables scenario-based simulations to evaluate policy interventions, offering a scientific foundation for sustainable development planning. For Inner Mongolia, a region facing rapid economic transformation alongside significant environmental and energy challenges, the findings provide practical guidance for balancing economic growth with environmental protection and resource efficiency.

2.2.2 Model building

The energy-economy-environment system represents one of the most significant and complex subsystems within society. In this

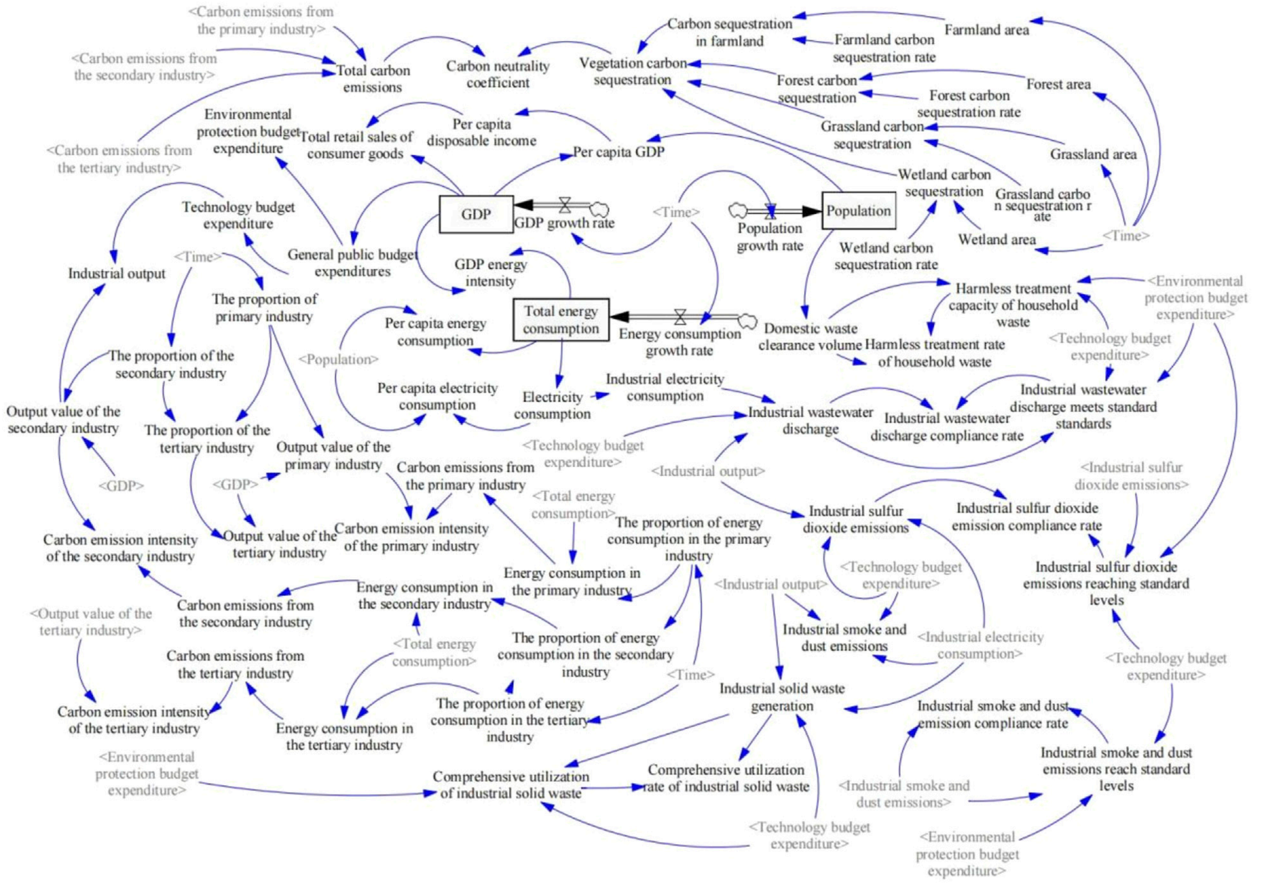

FIGURE 1
System dynamics model structure diagram.

study, key variables were selected for each subsystem as the primary focus of analysis, with additional related variables incorporated to enhance the model's comprehensiveness. Population, GDP, and total energy consumption were designated as stock variables, while all other variables were treated as flow variables. The economic activities of the region were categorized into three sectors: primary, secondary, and tertiary industries. For each sector, the model calculated metrics including proportion of GDP, output value, energy consumption, carbon emissions, and carbon intensity. Given the specific characteristics of Inner Mongolia, carbon sequestration by vegetation was estimated with a focus on farmland, forests, grasslands, and wetlands. For the environmental subsystem, the analysis prioritized indicators closely linked to the energy and economic systems, such as metrics related to residential and industrial activities and key targets for carbon neutrality. The system dynamics model constructed for this study is depicted in Figure 1.

2.2.3 Model parameter settings

In this study, the system dynamics model spans from the year 2000–2030, using annual time steps for simulation. Population, GDP, and total energy consumption, as key macroeconomic variables within the social system, are defined as stock variables, with their initial values set based on 2000 cross-sectional data. Growth rates for population, GDP, and energy consumption, as well as the output value proportions and energy consumption shares of the three main industrial sectors, are determined based on actual calculations and implemented using table functions. Other variables are influenced by their related variables, and a fitting equation is constructed through panel data to express them. Detailed parameter settings are presented in Table 1.

2.2.4 Validity testing

Before applying the system dynamics model, a validity test was conducted by comparing the simulation results with historical data from 2000 to 2021. The model is considered reliable if the average absolute error of the variables is below 20%. The validity test results showed that the average absolute error for all tested variables was below the 20% threshold, indicating that the model passed the validity test and can be regarded as relatively reliable. Detailed results are provided in Table 2.

2.2.5 Multi scenario simulation

In applying the system dynamics approach, multiple scenarios are distinguished by assigning different parameter values to key variables. By conducting multi-scenario simulations, the model reveals the system's evolutionary trajectory under varying conditions, enabling comparative analysis of development patterns across scenarios. This approach also provides a basis for forecasting optimal system development and offering practical

TABLE 1 Parameter settings table.

Parameter name	Parameter number	Parameter setting
GDP	A1	Initial value:1539.11
Population	A2	Initial value:2372
Total energy consumption	A3	Initial value:1788.53
Per capita GDP	A4	A1/A2
Per capita disposable income	A5	0.428182*A4
General public budget expenditures	A6	0.313687*A1-218.735
Total retail sales of consumer goods	A7	0.318929*A1-0.0221354*A5+180.368
Technology budget expenditure	A8	0.0071853*A6
Environmental protection budget expenditure	A9	53.5817*ln(A6)-302.964
Industrial output	A10	0.964946*Output value of the secondary industry-28.8415*A8
Total electricity consumption	A11	0.628718*A3-1217*ln(A3)+8281.22
Industrial electricity consumption	A12	0.891469*A11-26.1294
Domestic waste clearance volume	A13	0.142731*A2
Harmless treatment capacity of household waste	A14	0.237046*A13 + 2.97103*A8+1.01016*A9
Total amount of industrial wastewater discharge	A15	−3057.68*ln(A8)-6185.86*ln(A10)+11871*ln(A12)
Industrial wastewater discharge meets standard standards	A16	2649.95*ln(A8)+644.288*ln(A9)+19769.6*ln(A15)-188058
Industrial smoke and dust emissions	A17	−4.76125*A8+0.0149064*A10 + 30.554*ln(A12)-114.589
Industrial smoke and dust emissions reach standard levels	A18	−1.81801*A8+0.592494*A9+0.392729*A17-7.58169
Industrial sulfur dioxide emissions	A19	−6.12753*A8+0.0161984*A10 + 0.0102189*A12 + 135.507
Industrial sulfur dioxide emissions reaching standard levels	A20	0.31129*A8+0.125766*A9+0.945319*A19-29.566
Industrial solid waste generation	A21	155.272*A8+0.384959*A10 + 8.62528*A12
Comprehensive utilization of industrial solid waste	A22	−373.95*A8+40.5105*A9+0.0411153*A21 + 15830.2

guidance aligned with real-world conditions. In this study, three scenarios are defined: the current baseline scenario, the high economic development scenario, and the energy-environment-friendly scenario. These scenarios aim to identify a development model best suited to the unique conditions of Inner Mongolia.

In the most recent 5 years within the study period, Inner Mongolia has experienced an average GDP growth rate of approximately 7%, a population growth rate of around −1%, and an energy consumption growth rate of about 4%. Based on these trends, the current baseline scenario extends these values for simulation purposes. In the high economic development scenario, greater emphasis is placed on economic development. The GDP growth rate is increased by about half and set at 10%. This rapid economic growth is expected to attract population inflows and drive higher energy consumption (Yang et al., 2022). Accordingly, the population growth rate is set at 0.5%, and the energy consumption growth rate at 7.5%. The energy-environment-friendly scenario, in contrast, prioritizes the impact of energy consumption and environmental sustainability over accelerated growth. While maintaining the GDP growth rate at 7% to ensure steady economic development, this scenario reduces energy consumption growth to 2.0% and assumes a moderate population growth rate of 0.2%. This scenario seeks to balance economic development with sustainable energy use and environmental preservation. Detailed parameter settings for these scenarios are provided in Table 3.

2.3 Coupling coordination

This study adopts a multi system coupling coordination model to comprehensively analyze the coupling coordination scheduling of Inner Mongolia's energy-economy-environment system. The construction indicators and weights are shown in Table 4. The model construction process is as follows. To avoid numerical bias from subjective assignment, this study uses the entropy method for objective weight calculation. Due to inconsistencies in data units and dimensions, standardization is first performed. An offset of 0.01 is added to avoid zero values in the data. Positive and negative indicators are distinguished and processed as follows:

$$\mathbf{X_{ij}} = \left(\mathbf{x_{ij}} - \mathbf{min\,X_j}\right) \Big/ \left(\mathbf{max\,X_j} - \mathbf{min\,X_j}\right)$$

$$X_{ij} = \left(\max X_i - x_{ij}\right) \Big/ \left(\max X_j - \min X_j\right)$$

Where X_{ij} is the standardized value of the j-th indicator data in the i-th year, x_{ij} is the original value of the j-th indicator data in the

TABLE 2 Results of system dynamics validity test.

Variable name	The average absolute error between simulation data and historical data from 2000 to 2021
Farmland area	2.10%
Forest area	0.27%
Grassland area	0.85%
Wetland area	11.54%
Per capita GDP	1.20%
Per capita disposable income	8.02%
General public budget expenditures	9.86%
Total retail sales of consumer goods	14.65%
Technology budget expenditure	19.66%
Environmental protection budget expenditure	14.38%
Industrial output	3.51%
Total electricity consumption	14.67%
Industrial electricity consumption	15.56%
Domestic waste clearance volume	9.49%
Harmless treatment capacity of household waste	11.50%
Total amount of industrial wastewater discharge	17.11%
Industrial wastewater discharge meets standard standards	19.81%
Industrial smoke and dust emissions	17.16%
Industrial smoke and dust emissions reach standard levels	15.32%
Industrial sulfur dioxide emissions	5.40%
Industrial sulfur dioxide emissions reaching standard levels	11.38%
Industrial solid waste generation	8.98%
Comprehensive utilization of industrial solid waste	12.39%
Carbon emission intensity of the primary industry	4.19%
Carbon emission intensity of the secondary industry	5.73%
Carbon emission intensity of the tertiary industry	6.26%

i-th year, $\min X_j$ is the minimum value of the j-th indicator, and $\max X_j$ is the maximum value of the j-th indicator.

Secondly, use the entropy method to calculate the proportion of the j-th indicator value in the i-th year:

$$\mathbf{Y_{ij} = X_{ij} \Big/ \sum_{i=1}^{m} X_{ij}}$$

Calculate the entropy of indicator information again:

$$\mathbf{e_j = -k \sum_{i=1}^{m} \left(Y_{ij} * \ln Y_{ij} \right)}$$

Let $k = \frac{1}{\ln m}$, m is the number of years of evaluation, then the range of value for e_j is $0 \le e_j \le 1$.

Calculation of information entropy redundancy:

$$\mathbf{d_j = 1 - e_j}$$

Determination of indicator weights:

$$\mathbf{w_j = d_j \Big/ \sum_{j=1}^{n} d_j}$$

Calculate the comprehensive value using standardized data and weights:

$$\mathbf{u_j = w_j * Y_{ij}}$$

Finally, calculate the coupling degree and coupling coordination degree:

$$\mathbf{C = \sqrt[n]{u_1 * u_2 * u_3} \Big/ (u_1 + u_2 + u_3)}$$

$$\mathbf{T = \alpha u_1 + \beta u_2 + \gamma u_3}$$

$$\mathbf{D = \sqrt{CT}}$$

Where C is the coupling degree, and, $u_1\, u_2$ and u_3, is the comprehensive level of the three systems respectively; T is the comprehensive evaluation index of the three systems; $\alpha\, \beta$ *and* γ is the contribution of $u_1\, u_2$ and u_3. Therefore, it is considered that the three systems play an equal role and will be uniformly set at 1/3; D is the degree of coupling coordination, and a larger value of D indicates a higher degree of coordination among the three systems. According to the model setting, the larger the D value, the higher the coupling coordination degree. The interval division is shown in Table 5.

2.4 Grey correlation degree model

To further explore the factors influencing the coupling coordination degree between energy, economy, and environment, this study uses a grey correlation model to analyze the impact of each driving factor. The grey correlation model is a quantitative analysis method that assesses the degree of correlation between sequences based on the geometric similarity between the parent and child data sequence curves. The steps to construct the correlation model are as follows:

Firstly, based on selecting the corresponding sequence, set the coupling coordination degree of the three systems as the characteristic sequence, denoted as $D_0(m, t)$, and the data sequence of the driving factor indicator m in year t is denoted as $X_i(m, t)$. The standardized feature sequence and factor sequence are $D_0'(m, t)$ and $X_i'(m, t)$, and the specific formula for calculating the correlation coefficient is as follows:

TABLE 3 Multi scenario parameter setting table.

	GDP growth rate	Population growth rate	Energy consumption growth rate
Current baseline scenario	7.0%	−1.0%	4.0%
High economic development scenario	10.0%	0.5%	7.5%
Energy-environmental-friendly scenario	7.0%	0.2%	2.0%

TABLE 4 Evaluation index system and weights of energy-economy-environment composite system.

Primary indicators	Secondary indicators	Indicator impact direction	Weight
Energy	GDP energy intensity (10000 tons/billion yuan)	Negative	0.0978
	Per capita energy consumption (tons of standard coal per person)	Negative	0.1404
	Per capita electricity consumption (kWh/person)	Negative	0.1296
	Industrial electricity consumption (billion kW hours)	Negative	0.1461
	Electricity consumption per unit GDP (kWh/yuan)	Negative	0.0619
	Carbon emission intensity of the primary industry (10,000 tons/billion yuan)	Negative	0.1679
	Carbon emission intensity of the secondary industry (10000 tons/billion yuan)	Negative	0.1370
	Carbon emission intensity of the tertiary industry (10000 tons/billion yuan)	Negative	0.1188
Economic	Per capita GDP (yuan)	Positive	0.1599
	Per capita disposable income (yuan)	Positive	0.1873
	Total retail sales of consumer goods in society (100 million yuan)	Positive	0.1548
	General public budget expenditure (100 million yuan)	Positive	0.1700
	Industrial added value (100 million yuan)	Positive	0.1672
	GDP of the tertiary industry (100 million yuan)	Positive	0.1603
Environment	Industrial wastewater discharge compliance rate(%)	Positive	0.1425
	Industrial sulfur dioxide emission compliance rate(%)	Positive	0.0662
	Industrial smoke and dust emission compliance rate(%)	Positive	0.0956
	Comprehensive utilization rate of industrial solid waste(%)	Positive	0.1342
	Harmless treatment rate of household waste(%)	Positive	0.1351
	Carbon neutrality coefficient	Positive	0.4261

$$\mathbf{r_i(m,t)} = \frac{\mathbf{min}_{\mathbf{i,m,t}}\left|\mathbf{D_0'(m,t) - X_i'(m,t)}\right| + \boldsymbol{\rho}*\mathbf{max}_{\mathbf{i,m,t}}\left|\mathbf{D_0'(m,t) - X_i'(m,t)}\right|}{\left|\mathbf{D_0'(m,t) - X_i'(m,t)}\right| + \boldsymbol{\rho}*\mathbf{max}_{\mathbf{i,m,t}}\left|\mathbf{D_0'(m,t) - X_i'(m,t)}\right|}$$

where $max_{i,m,t}|D_0'(m,t) - X_i'(m,t)|$ and $min_{i,m,t}|D_0'(m,t) - X_i'(m,t)|$ represent the maximum and minimum absolute values of the driving factor indicators, respectively. ρ is the resolution coefficient, usually taken as 0.5

Finally, calculate its grey correlation degree:

$$\mathbf{H_i} = \frac{\mathbf{1}}{\mathbf{m}}\sum_{\mathbf{k=1}}^{\mathbf{m}} \mathbf{r_i(m,t)}$$

where H_i is the correlation degree, and the larger its value, the closer the correlation between this indicator and the coupling coordination degree of the three systems, which in turn indicates that this indicator has a greater driving effect on the coupling coordination degree.

2.5 Obstacle model

To identify the obstacles that affect the coordinated development level of the energy economy environment system

TABLE 5 Coupling coordination evaluation form.

D value	0 < D ≤ 0.2	0.2 < D ≤ 0.4	0.4 < D ≤ 0.6	0.6 < D ≤ 0.8	0.8 < D ≤ 1
Type	Severe imbalance	Moderate imbalance	Basic coordination	Moderate coordination	High quality coordination

coupling in Inner Mongolia, this article uses an obstacle degree model to calculate various indicators, and constructs a model as follows:

$$\mathbf{I_{ij} = 1 - X_{ij}}$$

$$\mathbf{Z_{ij}} = \left(\frac{\mathbf{I_{ij}W_{ij}}}{\sum_{\mathbf{ij=1}}^{\mathbf{n}} \mathbf{I_{ij}W_{ij}}}\right) \times \mathbf{100\%}$$

where I_{ij} is the deviation degree of the indicator; X_{ij} is the standardized value of the indicator; Z_{ij} is the obstacle level of the indicator; w_{ij} represents the contribution of the indicator. The larger the Z_{ij} value, the greater the hindering effect of this indicator on the improvement of system coupling coordination.

3 Results and discussion

3.1 Coupling coordination degree

As shown in Section 2.2.4, our model has small simulation errors on individual variables, and we also focus on the performance of the model in overall coupling coordination. Therefore, the historical real data and simulation data from 2000 to 2021 were processed in the same dimension to obtain their coupling coordination for each year, and their absolute errors were compared and calculated. The results are shown in Figure 2.

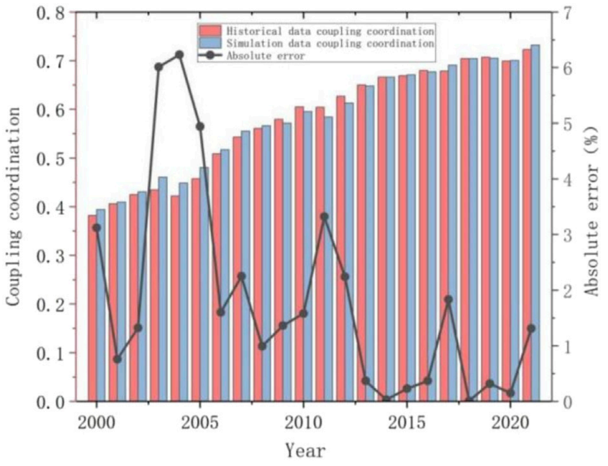

FIGURE 2
Coupling coordination degree and error verification from 2000 to 2021.

Figure 2 demonstrates that the annual absolute error remains below 7%, indicating a high level of accuracy in the model's simulation. Between 2000 and 2021, the overall coupling coordination degree of Inner Mongolia's energy-economy-environment system shows a clear upward trend. In 2000, the system was moderately imbalanced; from 2001 to 2010, it progressed to a basic coordinated state; and by 2011, it achieved moderate coordination. This suggests that, since the early 21st century, Inner Mongolia's economic development has increasingly aligned with local energy and environmental conditions.

Based on the good robustness of the system, the system dynamics model was applied to simulate multiple scenarios in Inner Mongolia Autonomous Region from 2022 to 2030. The coupling coordination degree of each scenario is shown in Figure 3.

Figure 3 illustrates that the overall coupling coordination degree across the three simulated scenarios shows a consistent upward trend, with the energy-environment-friendly scenario outperforming both the current baseline and high economic development scenarios. Between 2022 and 2024, no significant optimization is observed in the coupling coordination degree across all scenarios, as adjustments in the energy structure and environmental governance policies typically require time to produce measurable effects. Consequently, no substantial short-term improvements are noted (Zhang and Chen, 2018). The high economic development scenario, while maintaining moderate coordination, brings considerable energy consumption and environmental pressures, posing potential risks and challenges. From 2024 to 2026, the coupling coordination degree rises sharply, driven by stable economic growth, as the GDP growth rate helps the economic system converge towards the levels of the energy and environmental systems. This results in a significant improvement in the coupling degree of the economic system across all scenarios. Between 2026 and 2030, all scenarios exhibit stable growth, with the energy-environment-friendly scenario reaching high quality coordination state, attaining a coupling coordination degree of 0.8191.

3.2 Coupling degree of three subsystems

The coupling degree can indicate the comprehensive level of each subsystem, and the specific coupling degree of each subsystem is shown in Figure 4.

As shown in Figure 4, between 2000 and 2021, the energy system exhibited the highest coupling degree, followed by the environmental system, while the economic system, despite an overall upward trend, remained relatively low. The overall trend of the coupling degree between the energy system and the environmental system is relatively stable, but reached its minimum value in 2004. The main reason for this phenomenon is the rapid development of Inner Mongolia's economy, which has a strong dependence on resources, resulting in a significant increase in energy consumption and significant pressure on the energy and

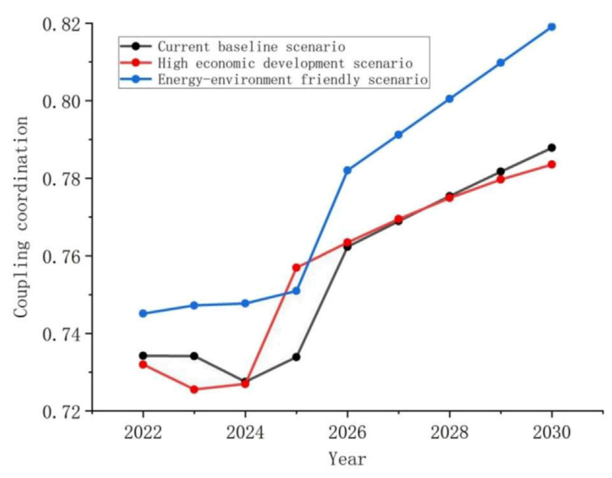

FIGURE 3
Coupled coordination of the three systems for 2022–2030 under three scenario simulations.

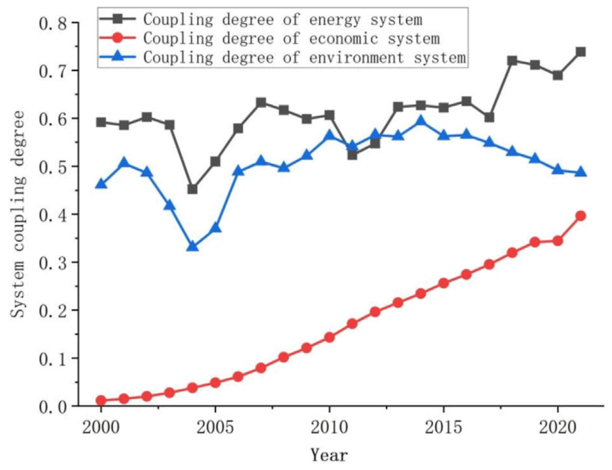

FIGURE 4
Coupling degree of three systems from 2000 to 2021.

environmental systems. Therefore, the coupling degree was relatively low at that time.

To further investigate the dynamics of different subsystems under varying scenarios, this chapter will compare and analyze the coupling degrees of the economic, energy, and environmental subsystems across three scenarios: the current baseline, high economic development, and energy-environment-friendly scenarios. The result is shown in Figure 5.

For the economic subsystem, the coupling degree under the baseline scenario consistently rises from 0.4521 in 2022 to 0.8155 in 2030, indicating stable economic growth driven by existing policies. In the high economic development scenario, the increase is even more pronounced, with the coupling degree reaching 1, signifying the powerful effect of policies focused on accelerating economic expansion. However, this rapid growth may lead to greater resource consumption and environmental strain. In contrast, under the energy-environment-friendly scenario, the coupling degree increases more modestly from 0.4500 to 0.7829, reflecting slower yet more sustainable economic growth. To achieve long-term coordinated development, policies must strike a balance by simultaneously promoting economic growth and enhancing resource management and environmental protection.

The coupling degree of energy subsystems varies significantly across different scenarios. The current baseline scenario shows a year-on-year decline, suggesting that existing policies do not sufficiently prioritize energy management and efficiency. In the high economic development scenario, the coupling degree decreases more sharply, indicating the strain rapid economic growth places on energy resources. In contrast, the energy-environment-friendly scenario shows a steady increase in the coupling degree, highlighting the effectiveness of policies aimed at enhancing energy efficiency. This variation reflects the differing levels of emphasis on energy conservation and environmental protection across the scenarios. It is recommended that, while pursuing economic growth, the government should establish stricter energy efficiency standards, promote clean energy technologies, and strengthen environmental protection measures to ensure the long-term coordination and sustainability of the energy subsystem.

The performance of the environmental subsystem's coupling degree is particularly notable across scenarios. Although the overall trend involves a brief period of decline followed by recovery and slight fluctuation, the changes are relatively moderate. The energy-environment-friendly scenario consistently maintains a higher level, suggesting that well-designed policies can effectively mitigate the environmental pressures associated with economic development. However, even in this scenario, the coupling degree of the environmental subsystem experiences a minor downward trend, reflecting the ongoing environmental impacts of economic growth. Factors such as rising energy consumption, overuse of natural resources, and increased pollution continue to exacerbate environmental pressures, negatively affecting ecosystems, air and water quality, and biodiversity.

To ensure sustainable and balanced development, a comprehensive set of policy measures is essential. These should include strengthening environmental protection and resource management, promoting the use of clean and renewable energy, improving energy efficiency, enhancing environmental monitoring and governance, and fostering innovation in green technologies. Collaboration among government, businesses, and society is crucial to creating a synergistic approach that achieves both economic growth and environmental preservation, ultimately aligning with long-term sustainability goals.

3.3 Grey correlation degree

Calculate the correlation degree between the secondary indicators and the coupling coordination of the three systems under each scenario using the grey correlation model, and rank them. The results are shown in Table 6.

Table 6 demonstrates that the strongest correlations are observed between the compliance rate of industrial sulfur dioxide emissions, carbon emission intensity in the primary industry, electricity consumption per unit of GDP, compliance rate of

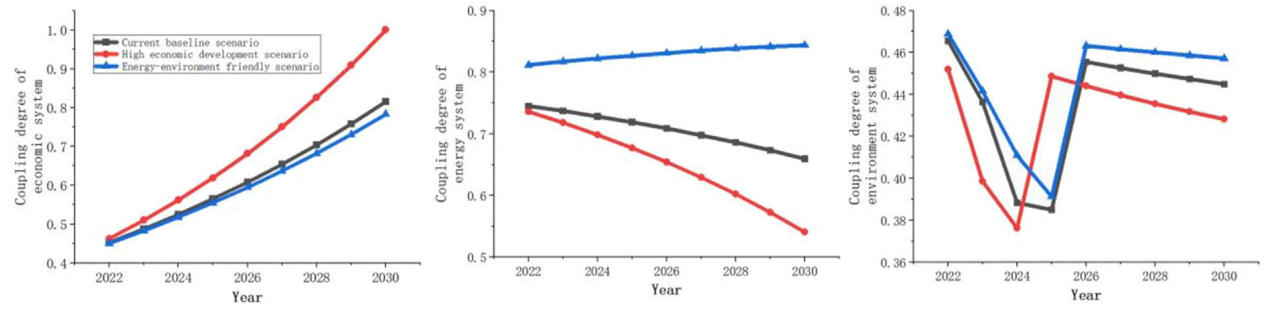

FIGURE 5
Coupling degree of each s. ubsystem under three scenario simulations from 2022 to 2030.

industrial smoke and dust emissions, and industrial electricity consumption. In contrast, the correlations among the six economic system indicators are relatively weaker. This is because environmental and energy system indicators directly impact environmental quality and resource efficiency, playing a critical role in influencing coupling coordination. In comparison, economic indicators have a more indirect effect, primarily mediating the relationship through variables such as energy consumption and environmental pollution, leading to a lower correlation. Nonetheless, these economic indicators were chosen for their capacity to reflect the broader level and quality of economic development, which has potential long-term effects on coupling coordination. Their inclusion allows for a more comprehensive evaluation of the interactions among the economic, energy, and environmental systems, thus offering valuable insights for policy formulation.

Notably, the compliance rate of industrial sulfur dioxide emissions consistently emerges as the most influential factor affecting the coupling coordination among the three systems, underscoring the critical importance of controlling these emissions. Likewise, the compliance rate of industrial smoke and dust emissions, along with industrial electricity consumption, are key factors, emphasizing the need to mitigate industrial pollution and manage energy consumption to enhance system coordination (Liu et al., 2016). Furthermore, the high correlation between electricity consumption per unit of GDP and carbon emission intensity in the primary industry across various scenarios highlights the essential role of improving energy efficiency and reducing carbon emissions in fostering the coordinated development of the energy, economy, and environmental systems (Wang et al., 2022). Therefore, strategies centered on controlling industrial pollution, optimizing energy efficiency, and reducing carbon emissions are pivotal for achieving the sustainable coupling and coordination of these three systems.

3.4 System obstacle level

This study calculated the obstacle level of secondary indicators from 2000 to 2030 across various scenarios using the obstacle level model. Corresponding years were selected at 5-year intervals, and indicators with higher obstacle levels were identified. The results are shown in Table 7.

The data in Table 7 indicate that the primary factors affecting the coupling coordination of Inner Mongolia's energy-economy-environment system vary by year and scenario but are consistently centered around industrial pollution, energy consumption, and carbon emissions. In 2000 and 2005, key obstacles included the compliance rate of industrial sulfur dioxide emissions, industrial wastewater discharge, the harmless treatment rate of household waste, the carbon emission intensity of the secondary industry, and GDP energy intensity. These indicators reflect significant challenges in managing industrial pollution and waste disposal during Inner Mongolia's rapid industrialization. For instance, in 2000, low compliance rates for sulfur dioxide and wastewater emissions highlighted the need for stricter pollution controls. By 2005, increasing carbon emissions in the tertiary sector and waste management became prominent issues, reflecting new environmental pressures. From 2010 to 2020, the focus of obstacles shifted toward carbon emissions and energy consumption. In 2010, the carbon emission intensity of the primary and tertiary sectors became significant, reflecting rising environmental impacts. By 2020, industrial and *per capita* electricity consumption, as well as *per capita* energy consumption, became major obstacles, highlighting challenges in managing energy demand. During this period, Inner Mongolia's GDP growth stabilized, but carbon emissions and energy consumption surged, with carbon emissions rising by 42% and electricity consumption increasing by 94%. Looking ahead to 2025 and 2030, industrial pollution and energy consumption remain major obstacles. In 2025, across different scenarios, factors like the compliance rate of industrial smoke and dust emissions, the utilization rate of industrial solid waste, industrial electricity consumption, and *per capita* energy consumption stand out as key challenges. For instance, in the baseline scenario, smoke and dust emissions and solid waste utilization reflect ongoing pollution control issues, while in the rapid economic growth scenario, energy consumption is the primary concern. Even under the energy-environment-friendly scenario, industrial pollution and energy use persist as obstacles. By 2030, indicators such as industrial electricity consumption, *per capita* energy use, the utilization rate of industrial solid waste, and the carbon neutrality coefficient remain critical obstacles. These issues persist under both the baseline and high economic growth scenarios, emphasizing the ongoing challenge of managing energy demand. Even under the energy-environment friendly scenario,

TABLE 6 Grey correlation ranking of various indicators under three scenario simulations.

Number	Current baseline scenario	High economic development scenario	Energy-environment-friendly scenario
1	Industrial sulfur dioxide emission compliance rate (0.8409)	Industrial sulfur dioxide emission compliance rate (0.8413)	Industrial sulfur dioxide emission compliance rate (0.8537)
2	Electricity consumption per unit GDP (0.7669)	Carbon emission intensity of the primary industry (0.7511)	Carbon emission intensity of the primary industry (0.7451)
3	Carbon emission intensity of the primary industry (0.7461)	Electricity consumption per unit of GDP (0.7208)	Electricity consumption per unit of GDP (0.7109)
4	Industrial smoke and dust emission compliance rate (0.6885)	Industrial smoke and dust emission compliance rate (0.7069)	Industrial smoke and dust emission compliance rate (0.7047)
5	Industrial electricity consumption (0.6682)	Industrial electricity consumption (0.6770)	Industrial electricity consumption (0.6840)
6	GDP energy intensity (0.6536)	GDP energy intensity (0.6588)	Per capita electricity consumption (0.6492)
7	Comprehensive utilization rate of industrial solid waste (0.6282)	Per capita electricity consumption (0.6567)	GDP energy intensity (0.6480)
8	Per capita electricity consumption (0.6200)	Per capita energy consumption (0.6285)	Comprehensive utilization rate of industrial solid waste (0.6335)
9	Per capita energy consumption (0.5947)	Comprehensive utilization rate of industrial solid waste (0.6259)	Per capita energy consumption (0.6096)
10	Carbon emission intensity of the secondary industry (0.5754)	Carbon emission intensity of the secondary industry (0.5792)	Carbon emission intensity of the secondary industry (0.5730)
11	Carbon emission intensity of the tertiary industry (0.5581)	Carbon emission intensity of the tertiary industry (0.5607)	Industrial wastewater discharge compliance rate (0.5624)
12	Industrial wastewater discharge compliance rate (0.5554)	Industrial wastewater discharge compliance rate (0.5556)	Carbon emission intensity of the tertiary industry (0.5595)
13	Carbon neutrality coefficient (0.5323)	Carbon neutrality coefficient (0.5383)	Carbon neutrality coefficient (0.5325)
14	Harmless treatment rate of household waste (0.5172)	Harmless treatment rate of household waste (0.5174)	Harmless treatment rate of household waste (0.5242)
15	Per capita GDP (0.4872)	GDP of the tertiary industry (0.4942)	GDP of the tertiary industry (0.5145)
16	Per capita disposable income (0.4872)	General public budget expenditures (0.4902)	General public budget expenditures (0.5093)
17	GDP of the tertiary industry (0.4682)	Total retail sales of consumer goods (0.4864)	Total retail sales of consumer goods (0.5074)
18	General public budget expenditures (0.464)	Industrial output (0.4829)	Industrial output (0.5025)
19	Total retail sales of consumer goods (0.4614)	Per capita disposable income (0.4732)	Per capita GDP (0.4809)
20	Industrial output (0.4583)	Per capita GDP (0.4732)	Per capita disposable income (0.4809)

energy efficiency and industrial waste management continue to pose challenges.

In the short term, Inner Mongolia must focus on reducing industrial energy consumption and controlling pollutants. In the long term, addressing broader energy consumption issues and progressing toward carbon neutrality will be key priorities, especially as the region aims to become an ecological demonstration province.

4 Conclusion

This study employs a system dynamics model to simulate the energy-economy-environment system in Inner Mongolia. The research results indicate that from 2000 to 2021, the overall coupling and coordination degree of the energy economy environment system in Inner Mongolia has increased, demonstrating the enhancement of the adaptability between economic development and energy environment. In the three scenario simulations, the coupling coordination degree of the energy environment friendly scenario is always better than other scenarios, especially reaching a high-quality coordination state by 2030, reflecting the significant effect of sustainable development policies.

For the coupling degree of each subsystem, from 2000 to 2021, the coupling degree between the energy system and the environmental system was relatively high, while the coupling degree of the economic system, although increasing, was relatively low. In different scenario simulations, the coupling degree of the economic subsystem increases the fastest under the high-speed economic development scenario, but it puts significant pressure on energy and the environment. The significant

TABLE 7 Obstacle factors and obstacle degree ranking in three scenarios.

Scenario	Year	1	2	3	4	5
Historical period	2000	Industrial sulfur dioxide emission compliance rate (0.1497)	Industrial wastewater discharge compliance rate (0.1220)	Harmless treatment rate of household waste (0.1041)	Carbon emission intensity of the secondary industry (0.0874)	Industrial smoke and dust emission compliance rate (0.0776)
	2005	Carbon emission intensity of the tertiary industry (0.0968)	Harmless treatment rate of household waste (0.0754)	GDP energy intensity (0.0728)	Carbon emission intensity of the secondary industry (0.0653)	Industrial wastewater discharge compliance rate (0.0648)
	2010	Carbon emission intensity of the tertiary industry (0.0677)	Carbon emission intensity of the primary industry (0.0519)	Electricity consumption per unit of GDP (0.0492)	Harmless treatment rate of household waste (0.0423)	GDP energy intensity (0.0407)
	2015	Carbon emission intensity of the primary industry (0.0515)	Carbon neutrality coefficient (0.0363)	Industrial output (0.0350)	Per capita disposable income (0.0349)	Per capita GDP (0.0349)
	2020	Industrial electricity consumption (0.0467)	Per capita electricity consumption (0.0445)	Per capita energy consumption (0.0441)	Electricity consumption per unit of GDP (0.0413)	Carbon neutrality coefficient (0.0385)
Current baseline scenario	2025	Industrial smoke and dust emission compliance rate (0.0899)	Comprehensive utilization rate of industrial solid waste (0.0608)	Industrial electricity consumption (0.0541)	Per capita electricity consumption (0.0532)	Per capita energy consumption (0.0517)
	2030	Per capita electricity consumption (0.0742)	Industrial electricity consumption (0.0729)	Per capita energy consumption (0.0689)	Comprehensive utilization rate of industrial solid waste (0.0608)	Carbon neutrality coefficient (0.0406)
High economic development scenario	2025	Comprehensive utilization rate of industrial solid waste (0.0604)	Industrial electricity consumption (0.0571)	Per capita electricity consumption (0.553)	Per capita energy consumption (0.0532)	Carbon neutrality coefficient (0.0398)
	2030	Industrial electricity consumption (0.0956)	Per capita electricity consumption (0.0884)	Per capita energy consumption (0.0781)	Comprehensive utilization rate of industrial solid waste (0.0604)	Carbon neutrality coefficient (0.0419)
Energy-environment-friendly scenario	2025	Comprehensive utilization rate of industrial solid waste (0.0915)	Industrial electricity consumption (0.0609)	Per capita energy consumption (0.0519)	Carbon neutrality coefficient (0.0488)	Industrial smoke and dust emission compliance rate (0.0389)
	2030	Comprehensive utilization rate of industrial solid waste (0.0609)	Industrial electricity consumption (0.0607)	Per capita energy consumption (0.0543)	Carbon neutrality coefficient (0.0397)	Industrial smoke and dust emission compliance rate (0.0173)

improvement of energy systems in energy and environmentally friendly scenarios reflects the positive role of energy-saving and environmental protection policies. The coupling degree of environmental systems is relatively stable in different scenarios, but the impact of economic growth on the environment persists.

The results of the grey relational analysis model show that the compliance rate of industrial sulfur dioxide emissions, industrial smoke emissions, and industrial electricity consumption are key factors affecting the coupling and coordination of the economic, energy, and environmental systems. In contrast, the correlation of economic system indicators is relatively weak, mainly through the coupling and coordination of energy consumption and environmental pollution, but their long-term potential impact cannot be ignored.

The results of the system obstacle degree model show that the coupling coordination of Inner Mongolia’s energy economy and environment system is mainly affected by industrial pollution, energy consumption, and carbon emissions, and over time, it shifts from industrial pollution to energy consumption and carbon emissions issues. From 2000 to 2020, Inner Mongolia faced challenges in pollution control, energy consumption, and carbon emissions during its rapid industrialization process, particularly in terms of industrial sulfur dioxide emissions, wastewater discharge, and energy use. In the future, industrial pollution control and energy management will remain major issues, and even in energy and environmentally friendly scenarios, energy efficiency and industrial waste management will face certain pressures.

Although the results of this study demonstrate the process and related influencing factors of the coordinated development of energy economy environment coupling in Inner Mongolia Autonomous Region, there are also some shortcomings. In the model construction, the included variables and data volume are not comprehensive enough, which may lead to the omission of some important factors. At the same time, the dynamic complexity of the model is insufficient, ignoring nonlinear effects and lag effects, and cannot fully reflect the real situation. However, the key obstacle revealed in the study is to ensure the core of coordinated development under the guidance of sustainable development goals. Based on this, this study proposes the following policy recommendations:

4.1 Optimizing economic development

Inner Mongolia should focus on upgrading its industrial structure by prioritizing high-tech industries and modern service sectors (You and Zhang, 2022). Establishing funds to support high-tech enterprises and creating innovation platforms will facilitate the transformation of traditional industries. Investment in scientific research and technological innovation should be increased, and industry-academia collaboration encouraged to strengthen the region's innovation capacity. Additionally, improving infrastructure and optimizing the investment environment are crucial for fostering sustainable economic growth (Dong et al., 2018).

4.2 Improving energy efficiency

Energy consumption is a key constraint on Inner Mongolia's development (Chen et al., 2021; Sun et al., 2018). Optimizing the energy structure and enhancing energy efficiency is critical. The region should reduce its reliance on energy-intensive industries, promote the development of low-carbon sectors, and adopt stricter energy efficiency standards. Encouraging the adoption of energy-saving technologies and expanding the use of renewable energy sources, such as wind and solar, will help optimize the power supply structure. Implementing a renewable energy quota system and electricity trading market will increase the share of renewable energy in overall consumption, thereby reducing both *per capita* energy consumption and the environmental impact.

4.3 Reducing industrial pollutant emissions

Industrial emissions remain a significant issue for Inner Mongolia's environmental quality (Guo et al., 2022; Zhang and Fan, 2022). The development of a circular economy should be promoted through legislation and financial support, encouraging enterprises to adopt cleaner production technologies. Stronger law enforcement, stricter emission standards, and enhanced pollution control measures are essential for improving the compliance rates for sulfur dioxide and dust emissions. Support for upgrading industrial waste management technologies and dust control systems will further reduce the environmental burden and contribute to green development.

4.4 Addressing carbon emissions

Under China's dual carbon targets, reducing carbon emissions is a priority for Inner Mongolia. The region should accelerate its transition away from high-carbon energy sources like coal and expand the development of renewable and clean energy, including wind, solar, and hydrogen (Li et al., 2023). Strengthening carbon market mechanisms and emission regulations will incentivize enterprises to lower their carbon footprints. Establishing a robust carbon trading market, setting emission quotas, and encouraging technological innovation in carbon management are critical steps toward achieving carbon neutrality.

By implementing comprehensive policy recommendations, Inner Mongolia can establish a coordinated and sustainable development model, achieving a balance between economic growth, environmental protection, and resource efficiency. Future research should further enrich the model variables and data dimensions, incorporate key factors such as society, technological innovation, and policy implementation, and enhance the analysis of nonlinear relationships and dynamic feedback mechanisms in the system. At the same time, research on regional heterogeneity should be refined to explore the coupling characteristics of different regions, and combined with scenario simulations over a longer time span, to comprehensively evaluate the effectiveness of policy implementation and provide more scientific guidance for the sustainable development of Inner Mongolia's energy economy environment system.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Data will be made available in request.

Author contributions

HZ: Conceptualization, Data curation, Formal Analysis, Investigation, Project administration, Visualization, Writing–original draft. YZ: Conceptualization, Data curation, Formal Analysis, Methodology, Writing–original draft. BH: Formal Analysis, Funding acquisition, Writing–original draft. YQ: Data curation, Funding acquisition, Project administration, Visualization, Writing–review and editing. LL: Formal Analysis, Funding acquisition, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1494691/full#supplementary-material

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