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Research Article

Revealing the Synergetic Development Evolution Mechanism of Economic Growth, Energy Consumption, and Environment: An Empirical Analysis Based on Haken Model and Panel Data

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The purpose of this paper is to reveal the mechanism and process of the dynamic evolution of the economy-energy-environment (EEE) system and study the variables that determine the speed of system evolution and development. The innovation is to overcome the defect of single index by constructing a system evaluation index and reveal the regional EEE system's evolution mechanism based on Haken's synergetic theory to supplement a systematic perspective's empirical evidence. It selects 30 provinces, municipalities, and autonomous regions in China to empirically analyse the evolution mechanism of the EEE system from 2005 to 2019. The empirical results show that economic development is the order parameter of the evolution and development of the EEE system. In the process of system evolution, the economic development subsystem is the decisive factor in EEE system evolution. In terms of the positive feedback mechanism of order parameter combination, the EEE system forms a positive feedback mechanism for increasing economic development in the stage of evolution and development. The negative feedback mechanism of decreasing environmental pollution emissions is formed in the EEE system. The increase in pollutant emissions has a certain inhibitory effect on economic growth. The improvement in the economic development level has no promoting effect on pollutants, and economic development, in turn, reduces environmental pollution.

1. Introduction

Excessive energy consumption and rapid economic development cause a series of environmental problems, such as extreme events such as haze during spring and winter festivals [1]. The development of the economy, energy, and environment is seriously unbalanced. The importance of coordinated development and sustainable development of the economy-energy-environment (EEE) system has become increasingly prominent in the context of the deepening development of regional economic agglomeration [2].

The coordinated development of the economy, energy, and environment itself is a systematic project, and the evolution law is complex. It is necessary to understand the evolution law of complex systems and study the speed variables that dominate the evolution and development of the system to help the public and society address the problems associated with resource depletion, environmental pollution, and economic recession. Environmental pollution causes health damage in China [3, 4]. In light of the threats to energy and the environment in the process of China's economic development, it is important to explore the green collaborative development mechanism of the regional economy, energy, and environment based on system thinking, which has certain theoretical and practical significance for the realization of system coordination and sustainable development.

Several achievements have been made in the study of the evolution mechanism. In the research method, research focuses on the interaction between the individual elements of subsystems. It is necessary to investigate the dynamic evolution and interaction of energy, economy, and environment subsystems from the system science method, analyse the evolution process and interaction of the three subsystems, and summarize the essential law of system evolution from the evolution form of complex systems. From the perspective of self-organization theory, the symbiotic dynamic evolution of energy and environment complex systems and the interaction of subsystems need to be further studied. In terms of research objects, most studies start from a single region or city, and the dynamic evolution mechanism of the EEE system from the perspective of a multiagent needs to be further studied. From existing research on system modelling, research on the evolution mechanism and its law of EEE complex systems can provide a useful supplement for the theoretical system and research paradigm of the system evolution mechanism. Using the theory of system science to study the evolution mechanism of EEE complex systems is helpful in exploring the basic operation mechanism and provides a theoretical explanation in line with the actual evolution law. Based on the evolution characteristics of self-organization and the Haken model, the evolution process of interaction between different subsystems is analysed, which is helpful in revealing the evolution mechanism of the EEE system.

In view of this, this paper constructs the theoretical framework and model of EEE system evolution based on the Haken model, reveals the process and mechanism of system evolution, and provides a theoretical supplement for the study of system evolution. Based on evolution theory, complex system science, self-organization theory, and ecology theory, this study examines the green collaborative development mechanism of the EEE complex system, establishes the EEE system evolution model based on the synergetic Haken model, empirically studies the system evolution mechanism of China's provincial two stages, identifies the system order parameters, and analyses the dynamic evolution behaviour of complex systems.

The remainder of the paper is as follows: Section 2 constructs the theoretical framework of the evolution of the EEE complex system. Section 3 constructs the evolution model of the EEE complex system. Section 4 describes the data sources and variables. Section 5 conducts an empirical analysis. Section 6 concludes the paper.

2. Literature Review

2.1. Interaction between the Economy, Energy, and Environment Subsystems. Research on the evolution of the economy-energy-environment system has produced many results in the interaction of subsystems. Research on energy and environmental systems is based on the theory of sustainable development to realize the coordinated development of energy, the economy, and the environment. The research on the interaction of subsystems is based on energy and environmental economics. The essence is the interaction of the energy, economy, and environment (EEE). Among the systems that affect the environmental subsystem, the energy subsystem has the most obvious impact on the environmental system and directly affects the evolution and development of the environmental subsystem. The socioeconomic system indirectly affects the environmental subsystem. The main achievements include externality theory, public goods theory, and EKC theory [5, 6].

In the existing empirical research on the internal relationship and interaction of the economic, energy, and environmental systems, some scholars take time series data as samples and use cointegration analysis and causality tests to discuss the empirical relationship between the three, such as the dual relationship between the economy and the environment conforming to the environmental Kuznets curve hypothesis and the dual relationship between energy and the economy [5]. The results show an inverted U-shaped relationship between the economy and the environment and a two-way causal relationship between energy consumption and economic growth. The relationship between energy and the economy has been studied by scholars [6–8]. Later, with the development of spatial statistics and spatial econometrics, the spatial distribution of the economy, energy, and environment and empirical research considering spatial impact also became an important research direction [9].

2.2. Coupling and Coordination Relationship of Complex System. Other studies have launched a comprehensive discussion on the economy, energy, and environment system, mainly focusing on the measurement, evaluation, and temporal and spatial evolution analysis of the coordination degree of the economy, energy, and environment system [10–12]. Previous studies have found that the coordination level of China's economy, energy, and environment is still at a low level, with an unbalanced regional distribution and spatial agglomeration effects [1, 13–15]. Sun et al. studied the coordinated development level of the whole system and each subsystem based on the measurement model of the EEE system coordinated development level of the PLS-SEM method [16]. Su et al. used the spatial measurement method to evaluate the dynamic evolution trend of system coordination [11].

According to the literature on the coupling and coordination relationship, the research on the complex system of the economy, energy, and environment mainly focuses on the following directions. The first is to establish an index system to measure the coupling and coordination level of different research objects. The second type is empirical research based on measurements using econometrics, game models, and other methods [13]. The third category is to theoretically explore the causes of low-level coordinated development from the perspective of economics and complex system theory and put forward countermeasures from the perspective of policy planning [17].

2.3. Coevolution of Energy and Environmental Systems. The evolution mechanism of economic, energy, and environmental systems has also aroused interest in academic circles, and related research has been widely carried out [17–22]. Different models have been used to explore the evolution mechanism of energy and environmental systems, and some scholars have made innovations in methods such as multiobjective programming models, computable general equilibrium models, input-output models, and the Brusselator model [23–26]. The energy-economy-environment model complex giant system has self-organization characteristics. Dissipative structures and nonlinear models are used in the evolution process of the system, including logistic growth models, integrated econometric models, and models of the Energy Institute of National Development and Reform Commission [27–30]. Some scholars have used a computable general equilibrium model for system modelling. Other scholars have used the logic model to study the characteristics of the system evolution path. The system dynamics method is widely used in the study of system evolution. The self-organization evolution method was applied to the study of system evolution. Research on identifying order parameters is also gradually unfolding. Zhong et al. [31, 32] analysed the spatial and temporal pattern evolution and influencing factors of energy-environmental efficiency. Sheng et al. [33] analysed the regional convergence of energy-environmental efficiency.

The Haken model has also been gradually applied to research on the social economy, energy, environment, and technological innovation [34–37]. Zhang et al. established the evolution equation of the energy-economy-environment system based on the Haken model and found that there was no synergistic effect between improving energy efficiency and reducing pollutant emissions in the evolution process [38]. Bai-qing et al. [39] used the Haken model to study the synergistic relationship between economic development and the logistics industry. Zhu et al. [40] performed a synergistic analysis of the resilience and efficiency of the marine economy. Chen and Xu [41] evaluated water-energy-food system security based on the RF-Haken model. Yang et al. [14] used big data and the Haken model to analyse coordinated development between the metropolitan economy and logistics. Zhong et al. [42] revealed the nexus among energy-economy systems with the Haken model. Li et al. [43] established the research framework of coevolution and analysed the different effects of high-quality development on resource and environment driving mechanisms by using the Haken model. Tan and Kong [44] studied the driving mechanism of regional synergistic development based on the Haken model.

In summary, in the study of complex systems of the energy economy and environment, the evolution mechanism of the energy environment system has attracted extensive interest from scholars. Research on energy-economy-environment systems includes subsystem models, interaction calculations, and research on balance and coordinated development among systems [45]. Academic circles mainly focus on the EEE system from different angles, such as time series and cointegration. In the current research on the evolution mechanism of complex systems of energy, economy, and environment, many models lack comprehensive consideration of the dynamic evolution and interaction of the subsystems of these mechanisms. Even if the interaction of subsystems is considered, time series and cointegration models are often used from a macro-perspective. Few studies have investigated the symbiotic dynamic evolution and subsystem interaction of regional energy and complex environmental systems from the perspective of ecology and evolution theory. In terms of research objects, most studies start from a single region or city and lack analysis methods to form a systematic and feasible dynamic evolution mechanism of the complex system of energy and environment from a regional perspective. Research on the evolution mechanism and law of complex systems of economy, energy, and environment needs to be further deepened. Although the systematic method has achieved results in the EEE system, the theoretical system and research paradigm of the evolution mechanism of the complex system of energy economy and environment have not yet been formed. In view of this, using the theory of system science to deeply study the evolution mechanism of the complex system of energy economy and environment has a certain value, which is helpful to explore the basic operation mechanism of the evolution of the complex system of energy economy and environment, and then gives a practical theoretical explanation for the evolution law of the complex system of energy economy and environment on the basis of the basic operation.

3. Evolution Mechanism and Haken Evolution Model of EEE Complex System

Haken's synergetic theory provides a new method for describing the self-organization process by dividing variables into fast and slow variables. According to self-organization theory, the EEE system is an open and nonequilibrium self-organization system [46, 47]. Self-organization evolution means that, in the nonlinear range, through the transformation between subsystems and internal and external systems, the system evolves from disorder (high energy consumption, high emissions, and rapid development) to a new orderly state (low energy consumption, low emissions, and sustainable development). In this process, there are many subsystem variables. Slow variables dominate the evolution process of the system, command fast variables, and become the order parameters of the new system [34, 47]. Haken proposed a self-organizing evolution Haken model based on order parameters to study the evolution mechanism of the system.

Evolution theory, self-organization theory, complex system science, and ecology theory provide a theoretical basis for the study of the evolution mechanism of EEE complex systems [34, 47]. Evolution theory provides a method for research from "static equilibrium" to "dynamic evolution." The general analysis structure of system evolution is the "variation selection heredity" of Darwinism. Complex system theory holds that EEE systems need to exchange elements with external systems in addition to internal metabolic processes [48]. The exchange of elements with the outside of the system affects the entropy increase and the order degree of the system. This exchange process makes the system present a "Dissipative Structure" state and finally forms an orderly organizational system [49]. The EEE system includes three complexity adaptive systems, and there are cross-actions among them. At the same time, the evolution between systems is dynamic.

According to the principle of ecology, the EEE system consists of an energy subsystem, an economy subsystem, and an environment subsystem, forming an artificial ecosystem through the coupling effect. The system promotes the improvement of the economy and environmental systems through the process of energy utilization and maximizes the total system benefit. The EEE complex system includes three subsystems: the energy system, the economy system, and the environment system. The energy subsystem not only provides material guarantees but also determines the low pollution and low-carbon evolution and development of the EEE system from the source. First, system evolution is not a simple reorganization of the system diversity structure but a unity of new diversity. The spatiotemporal evolution of complex systems brings new unity of diversity and presents a metastable steady state (symmetry breaking) [47]. Second, energy, economy, and environmental systems have different characteristics and network structures. The three subsystems evolve dynamically during the process of interaction and mutual adaptation, forming a complex system. In the process of multiple interactions and mutual adaptation, the change in subsystem elements will change the evolution path of the other subsystems. The evolution path of the subsystem and complex system forms a "causal cumulative effect" through a "positive and negative feedback mechanism," which affects the evolution direction [48]. In this evolution process, the evolution path of "self-coupling" and "self-winding" and the feedback cycle provide the evolution power for the fluctuation of the system and form a self-organizing complex system under internal and external competition and cooperation. The EEE system is shown in Figure 1.

First, dynamic evolution is the evolutionary characteristic of the EEE complex system. The complex system is a dynamic process, and the evolution of the complex system of the main body at all levels follows the dynamic evolution path of "initial stage middle stage late stage." Under the change in internal dynamics and external conditions, driven by the order parameter, the complex system evolves from the state at $t-1$ to the state at time t along the dynamic evolution path [38]. The second is symbiosis. Symbiosis refers to the interaction between EEE complex systems within and between regions, and the factors between subsystems flow freely, which is reflected in the interaction. The third is infusibility. EEE systems interact with each other within and between regions and show the spatial characteristics of agglomeration and diffusion. The fourth is guidance. The subsystems and their factors in the EEE system have different effects on the evolution of the system. Some subsystems and their factors will become the dominant variables, leading to the evolution process of the system and the evolution of fast variables [48]. The evolution mechanism of EEE complex systems is shown in Figure 2.

Furthermore, we can obtain the evolution mechanism of the EEE system based on evolution self-organization theory: system self-organization evolution means that, in the process of system evolution, in the nonlinear range far from the equilibrium point, when the external conditions reach a certain threshold, the disordered state of the system evolves into a new ordered state through self-organization [48]. The self-organization process of an EEE system is a process in which the system evolves from disorder (high energy consumption, high emissions, and rapid development) to a new orderly state (low energy consumption, low emissions, and sustainable development) when it leaves the equilibrium state through the transformation between subsystems and internal and external systems under different conditions. The self-organization evolution of an EEE system depends on the interaction of subsystems and is the internal evolution mechanism of the system.

EEE Complex System Dynamic Evolution Mechanism. Evolution is the source power of the evolution of sustainable development systems, which reflects diversity in evolution. Evolution is the beginning of the system evolution, which shows the diversity and unity of the initial state. The premise of system evolution is self-growth, which confirms that the process of system evolution conforms to market and price mechanisms [34]. The self-regulation characteristic of a complex system reflects that the system appears to be a new state with a change in certain external conditions. The self-adjusting characteristics of the system drive the evolution of the system, and the evolution process depends on the positive and negative feedback cycles of the internal coupling mechanism and the changes in external conditions (environmental protection investment, environmental regulation, energy policy, etc.). The internal dynamics of the system evolution include the coupling, winding, and feedback mechanisms [47]. The coupling relationship between subsystems forms a positive and negative feedback cycle, which provides evolutionary power for the system evolution process. The evolution of the system promotes the multi-coupling of different levels among subsystems. Multiple network coupling, in turn, promotes system evolution.

EEE Complex System Overflow Mechanism. The spillover mechanism describes the spatial spillover effect of the evolutionary unit in an economic system. The self-replication of the EEE system is reflected in the demonstration and diffusion effects of the sustainable development mode, and the spillover effect of the new orderly state (low energy consumption, low emissions, and sustainable development) of system self-organization evolution is realized. When the EEE system changes into an orderly state of low energy consumption, low emissions, and sustainable development, it will affect the system evolution direction of other regions [46]. The regional system replicates the ordered system states of other regions and promotes the continuous evolution of the entire system.

EEE Complex System Guiding Mechanism. According to self-organization theory, when the external control variable reaches the threshold, the open nonlinear nonequilibrium system can mutate to a new ordered structure triggered by random fluctuations. The formation process of the EEE system is a self-organization evolution process from an old structure to a new structure. The influence of subsystems and their factors on the system is heterogeneous. When the

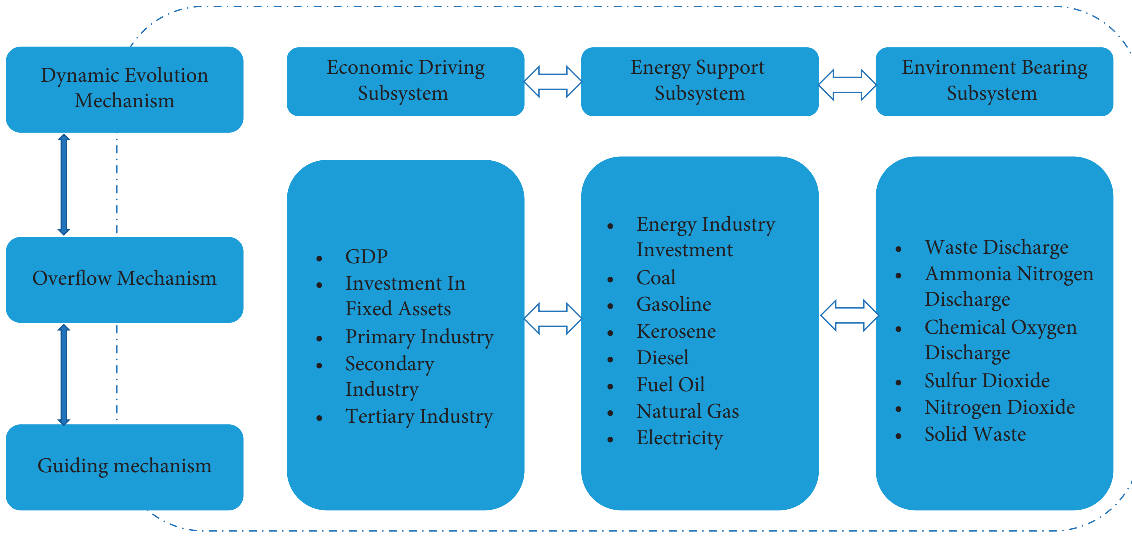

FIGURE 1: The EEE complex system and components.

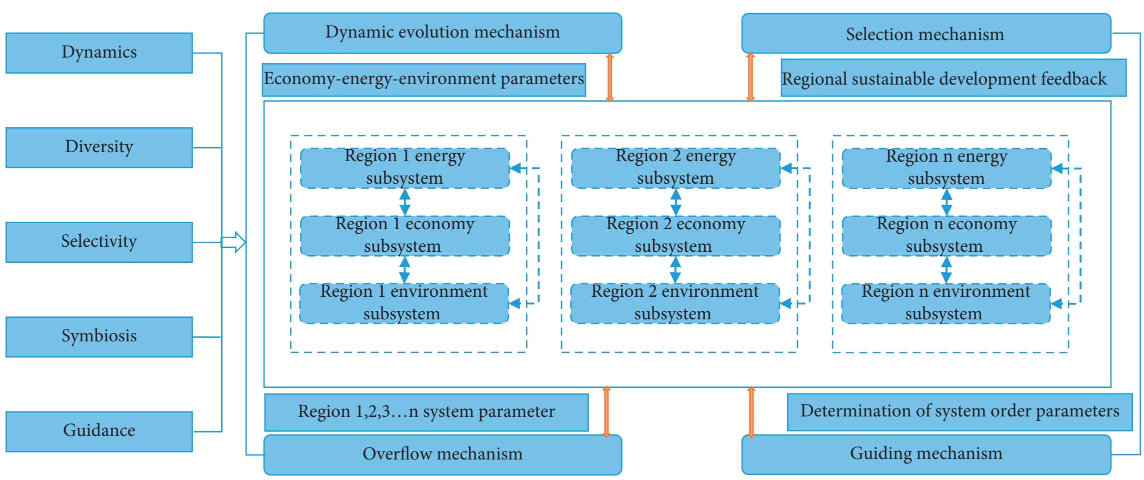

FIGURE 2: The evolution mechanism of the EEE complex system.

external control variable reaches the threshold, the open nonlinear nonequilibrium system can jump to a new ordered structure triggered by random fluctuations. By changing the parameters, the system is pushed through the linear instability point, and the exposure of this heterogeneity can be divided into fast and slow variables. The slow variable dominates the evolution process and dominates the fast variable, becoming the order parameter of the new system structure. Haken's synergetic theory is a representative theory of self-organization theory. Haken's synergetics pushes the system through the linear instability point by changing the parameters and distinguishes the fast variable from the slow variable [34, 47].

The interaction and coupling effects of the energy, economy, and environment subsystems in the EEE system constitute a multilevel structure system. According to synergetic theory, the control parameters of the system are divided into external and internal parameters [38]. The external parameters of the system represent the influence of external environmental factors on the internal system. The internal parameters of the system include the fast and slow variables. Slow variables dominate the evolution process of the system, command fast variables, and become the order parameters of the new system. The order parameter equation can be used to study the formation and evolution of ordered structures [46, 47, 50]. According to the self-organization evolution mechanism of order parameters, energy consumption is the direct factor of environmental pollution, economic development is an indirect factor of environmental development, and the interaction among economic development, energy consumption, and environmental pollution emissions dominates the evolution of the EEE system [51].

The Haken model can analyse the coevolution and evolution stages of the EEE system. The synergetic method is used to determine the linear instability point, eliminate the fast variables, and obtain the order parameter equation. q_1 and q_2 are the two state variables. Suppose that s_1 dominates the evolution of the system, the change in q_1 makes q_2 change rapidly, q_1 is the slow variable of the system, and q_2 is the fast variable of the system. q_1q_2 represents the interaction of variables [37, 38]. In addition, the evolution of the system is affected by random fluctuations. Therefore, the evolution process of the system is expressed as follows:

$$\dot{q}_1 = -\rho_1 q_1 - a q_1 q_2 + \tau_1, \tag{1}$$

$$\dot{q}_2 = -\rho_2 q_2 + b q_1^2 + \tau_2. \tag{2}$$

Here, s_1 and s_2 represent the states of the system. a, b, ρ_1, ρ, and 2 are the control parameters. τ_1 and τ_2 are the random terms. Equations (1) and (2) reflect the interaction between the energy and environment systems. Let $s_2 = 0$; then

$$q_2(t) \approx \frac{b}{\rho_2} q_1^2(t). \tag{3}$$

Substituting formula (3) into formulas (2) and (4) can be obtained:

$$q_1(t) \approx -\rho_1 q_1 - a\frac{b}{\rho_2} q_1^3(t). \tag{4}$$

This means that q_1 decides q_2 and s_1 dominates s_2, makes the system form an ordered structure, and dominates the evolution of the system. Thus, q_1 is the order parameter of the system. The equation of motion must satisfy the adiabatic approximation assumptions $\rho_2 > 0$ and $|\rho_2| \gg |\rho_1|$.

The Haken model is discretized into formula (5):

$$\begin{cases} q_1(t+1) = (1-\rho_1)q_1(t) - aq_1(t)q_2(t) + \varepsilon_1, \\ q_2(t+1) = (1-\rho_2)q_2(t) + bq_1(t)^2 + \varepsilon_2. \end{cases} \tag{5}$$

By integrating the opposite number of s_1, we can obtain the system potential function, that is, the coevolution trend function, which can be used to judge the state of the entire system:

$$v = 0.5 q_1 q_1^2 + \frac{ab}{4\lambda_2} q_1^4(t). \tag{6}$$

4. Data Sources and Variable Descriptions

According to the principle of data integrity and feasibility, the index system selects indicators from energy, economy, and environment system [37, 38]. Initially, the indicators for classification and screening are selected, the indicators representing the subsystem are selected, the weight is determined using the entropy method, and the final index system is established. Combining the above methods to determine the index weight can not only make full use of the sample data information but also reduce subjective bias.

Due to the lack of data and considering the applicability and availability, panel data are selected from 30 provinces, municipalities, and autonomous regions in China from 2005 to 2019. The data are obtained from the China Energy Statistical Yearbook and the China Statistical Yearbook. Economy subsystem indicators are measured from the stock and structure. The system index system is presented in Table 1.

To eliminate the dimensional difference, the normalization method is used to standardize the data, and the entropy method is used to measure the subsystem [52]:

$$s_i = \sum_{j=1}^{m} w_j I_j, \quad i = 1, 2, 3 \ldots m. \tag{7}$$

In equation (7), s_i is the subsystem of area i, and I_j is the standardized index data. The subsystems of energy, economy, and environment in region i are REN_{it}, REC_{it}, and REV_{it}, respectively. m is the number of indices of the subsystem, and w_j is the weight of index j. The entropy method is used to determine the weight w_j, and the formula for calculating the specific gravity of index i of the subsystem in region i is shown in

$$p_{ij} = \frac{I_{ij}}{\sum_{j=1}^{m} I_{ij}}, \quad i = 1, 2, 3 \ldots m. \tag{8}$$

The calculation formula of index entropy is shown in

$$E_j = -\left(\frac{1}{m}\right) \sum_{j=1}^{m} p_{ij} \ln p_{ij}, \quad 0 \le E_j \le 1. \tag{9}$$

The formula of index weight is shown in

$$w_j = \frac{(1-Ej)}{\sum_{j=1}^{n} (1-Ej)}, \quad 0 \le E_j \le 1. \tag{10}$$

5. Results and Discussion

5.1. Results

5.1.1. Spatial Distribution. Figures 3–5 summarize the change trend of EEE subsystems in China from 2005 to 2019. As seen from the figures, the development level of the economic subsystem has increased year by year. The time evolution trend of the environmental carrying subsystem and energy subsystem level is reflected in the inverted U-shaped time evolution mode of "rise-decline-rise."

First, the spatial emissions of the EEE system are described from a macroperspective. The comprehensive development level of subsystems reflects the characteristics of spatial distribution. Figures 3–5 show the EEE distribution of 30 provinces from 2005 to 2019. China's provincial EEE has obvious regional differences. In 2019, regions with a high economic subsystem index were concentrated in developed coastal areas, such as Guangdong, Jiangsu, Zhejiang, Shandong, Beijing, Shanghai, Fujian, Henan, Hubei, and Sichuan. Medium-level areas include Hunan, Anhui, Hebei, Chongqing, Tianjin, Shaanxi, Liaoning, Jiangxi, Inner Mongolia, and Yunnan. Low-level areas are distributed in Guangxi, Shanxi, Guizhou, Xinjiang, Jilin, Heilongjiang, Hainan, Ningxia, Gansu, and Qinghai. Regions with a high energy consumption subsystem index are concentrated in developed coastal areas, such as Shanghai, Guangdong, Jiangsu, Liaoning, Shanxi, Inner Mongolia, Zhejiang, Henan, Hubei, and Shanghai. Areas with moderate energy subsystems include Hebei, Sichuan, Anhui, Hunan, Fujian, Xinjiang, Guizhou, Shaanxi, Heilongjiang, and Jiangxi. Low-

Table 1: Construction of the economy-energy-environment index system.

Subsystem	Layer	Index
Energy support subsystem (REN)	Inventory	Energy industry investment ($x1$), coal consumption ($x2$), gasoline consumption ($x3$), kerosene consumption ($x4$), diesel consumption ($x5$), fuel oil consumption ($x6$), natural gas consumption ($x7$), and electricity consumption ($x8$)
Economy driving subsystem (REC)	Aggregate and structure	GDP index ($y1$), proportion of secondary industry ($y2$), proportion of tertiary industry ($y3$), and GDP per capita ($y4$)
Environment bearing subsystem (REV)	Water environment	Total amount of wastewater discharge ($z1$), ammonia nitrogen discharge ($z2$), and chemical oxygen demand discharge ($z3$)
	Atmospheric environment	Annual average emission of sulfur dioxide ($z4$) and nitrogen dioxide ($z5$)
	Solid waste	Solid waste and domestic waste ($z6$)

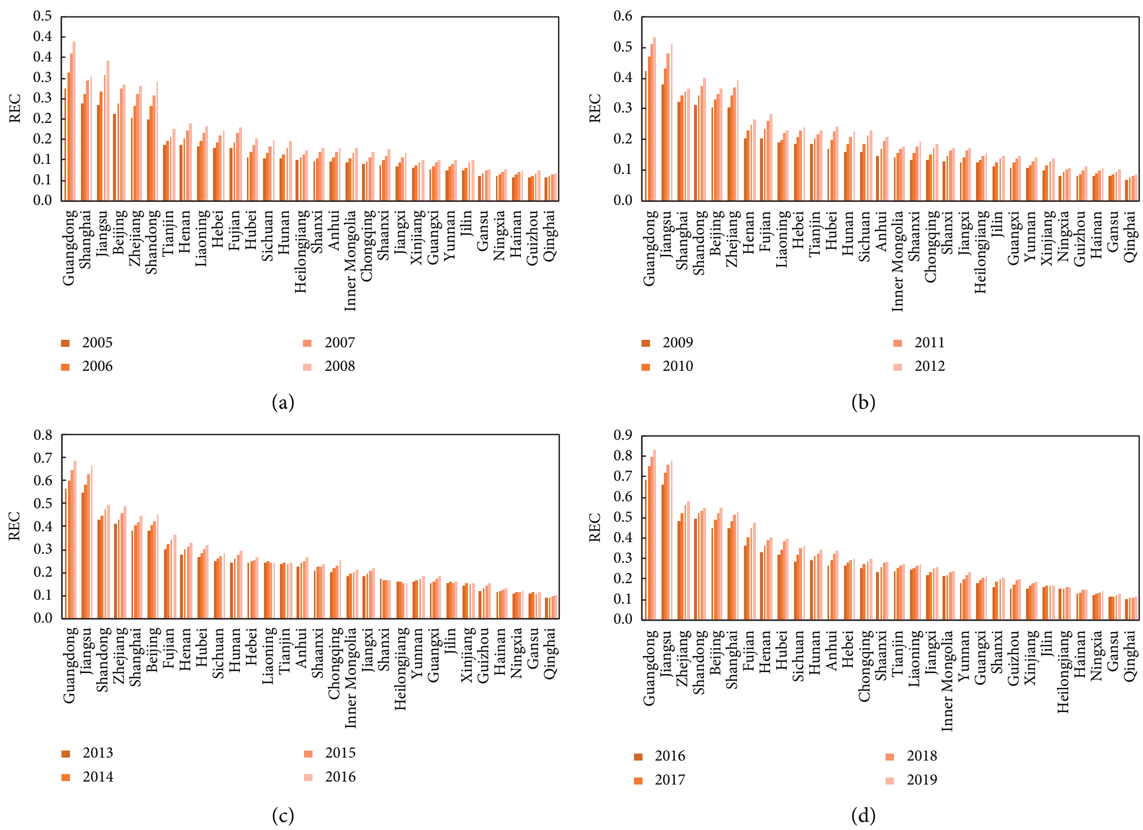

Figure 3: China's EEE subsystem-REC (2005~2019).

level areas of the energy subsystem are distributed in Yunnan, Guangxi, Chongqing, Tianjin, Jilin, Ningxia, Beijing, Gansu, Hainan, and Qinghai, and areas with high development levels of the environmental-bearing subsystem are concentrated in coastal developed areas. The areas with medium degrees of environmental carrying subsystems include Hubei and Hunan. The low-level areas of the environmental carrying subsystem are distributed in Qinghai, Gansu, and Ningxia.

The above differences may be spatially dependent. Energy consumption from multiple sources shows spatial differences and clusters at the same time. Overall, the economic system level of the eastern coastal provinces is higher than that of the central and western inland provinces. The spatial distribution characteristics of China's economic development can be described as "high in the East and low in the central and western regions." REV and REN do not seem to show an aggregation trend. REC seems to have an aggregation trend. The global Moran index was used to test the spatial autocorrelation and spatial clustering of provincial REC in China.

5.1.2. Exploratory Spatial Data Analysis. Spatial effects refer to a certain degree of spatial interaction between economic and geographical behaviours among regions, which is divided into spatial autocorrelation and spatial heterogeneity. Spatial heterogeneity refers to the regional imbalance in

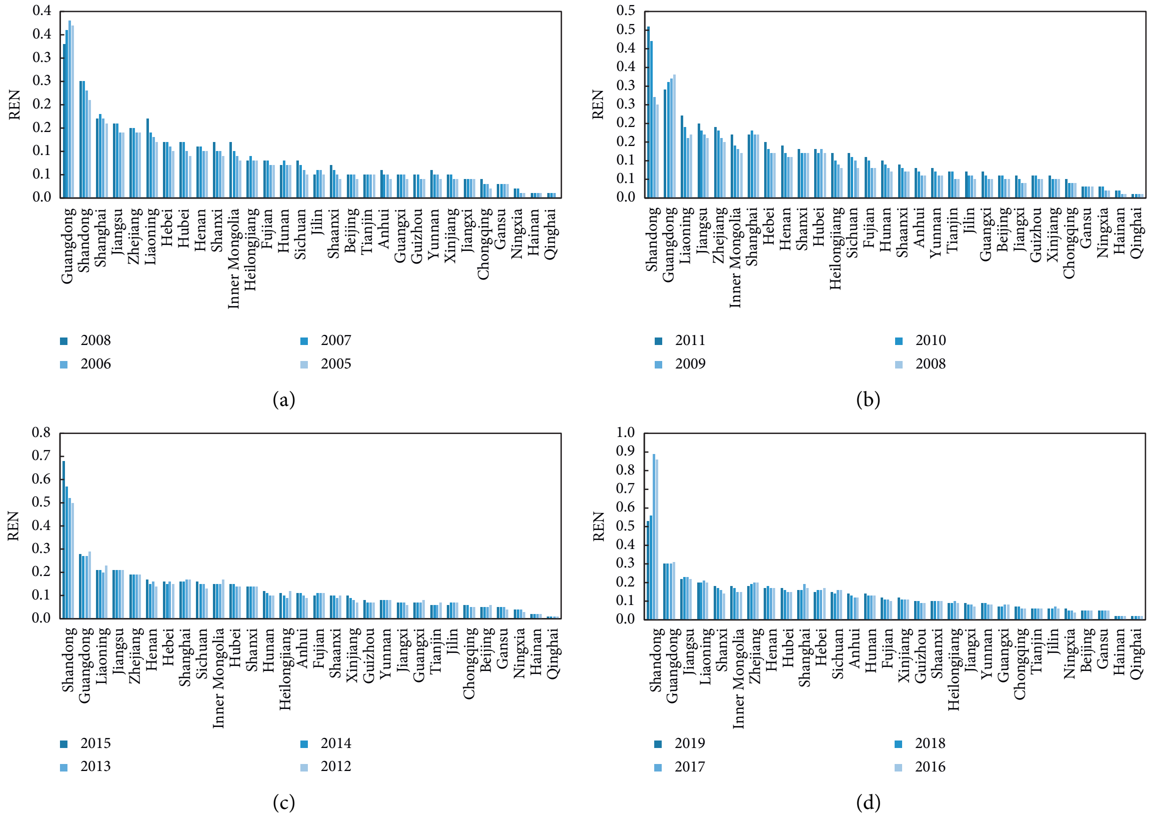

Figure 4: China's EEE subsystem-REN (2005~2019).

geographical space, which is manifested in economic and geographical structures such as centre and periphery, core and edge, and developed and backwards, and reflects the spatial heterogeneity of various indicators of economic and social development. This paper mainly uses the global spatial correlation test and local spatial correlation test to test the spatial effect of REC in China.

In this paper, Moran's I index method is used to test the global spatial correlation of China's provincial REC level. Global spatial autocorrelation refers to the cluster situation that depicts the spatial distribution of regional economic development from the whole regional space. Local indicators of spatial association (LISA) were used to test the local spatial correlation.

(1) Spatial Global Autocorrelation. In this section, the global spatial correlation index Moran's I and local Moran's I scatter diagram are used to test whether REC has spatial autocorrelation and cluster characteristics. According to the empirical results of the spatial feature analysis in Table 1, the global Moran's I indices calculated by the development level of China's interprovincial regional economic subsystem are positive. The significance test shows that the interprovincial economic system has spatial autocorrelation in geography, as shown in Table 2.

The economic system development of various provinces in China shows common spatial distribution characteristics, and REC shows positive autocorrelation in space. The spatial correlation feature of regional REC in China is that regions with higher development levels of economic systems tend to be adjacent to regions with higher development levels. Most provinces are in the first quadrant and the third quadrant, belonging to the type of H-H agglomeration and L-L low agglomeration. The spatial units falling into the first and third quadrants have a strong positive spatial correlation. The estimation result is consistent with the objective geographical and economic distribution, and it also proves that REC has a spatial correlation among regions.

(2) Local Spatial Correlation. To deeply study the cluster characteristics, this section uses local indicators of spatial association (LISA) to study the spatial pattern and cluster characteristics of REC.

LISA estimation results in Table 3 show that, in 2019, Jiangsu, Zhejiang, Shanghai, Fujian, and Anhui tend to be distributed in the first quadrant (H-H), showing a spatial distribution trend of high economic system development and a positive spatial correlation with other provinces; Hainan and Jiangxi are distributed in the second quadrant (L-H), and the provinces with low economic system development are surrounded by other provinces with high economic system development; Xinjiang, Inner Mongolia, and Gansu are distributed in the third quadrant (L-L), low in Xinjiang, Inner Mongolia, and Gansu, showing a negative spatial correlation with other provinces. Sichuan is distributed in the fourth quadrant (H-L), and the provinces with high economic system development are surrounded by other provinces with low economic system development.

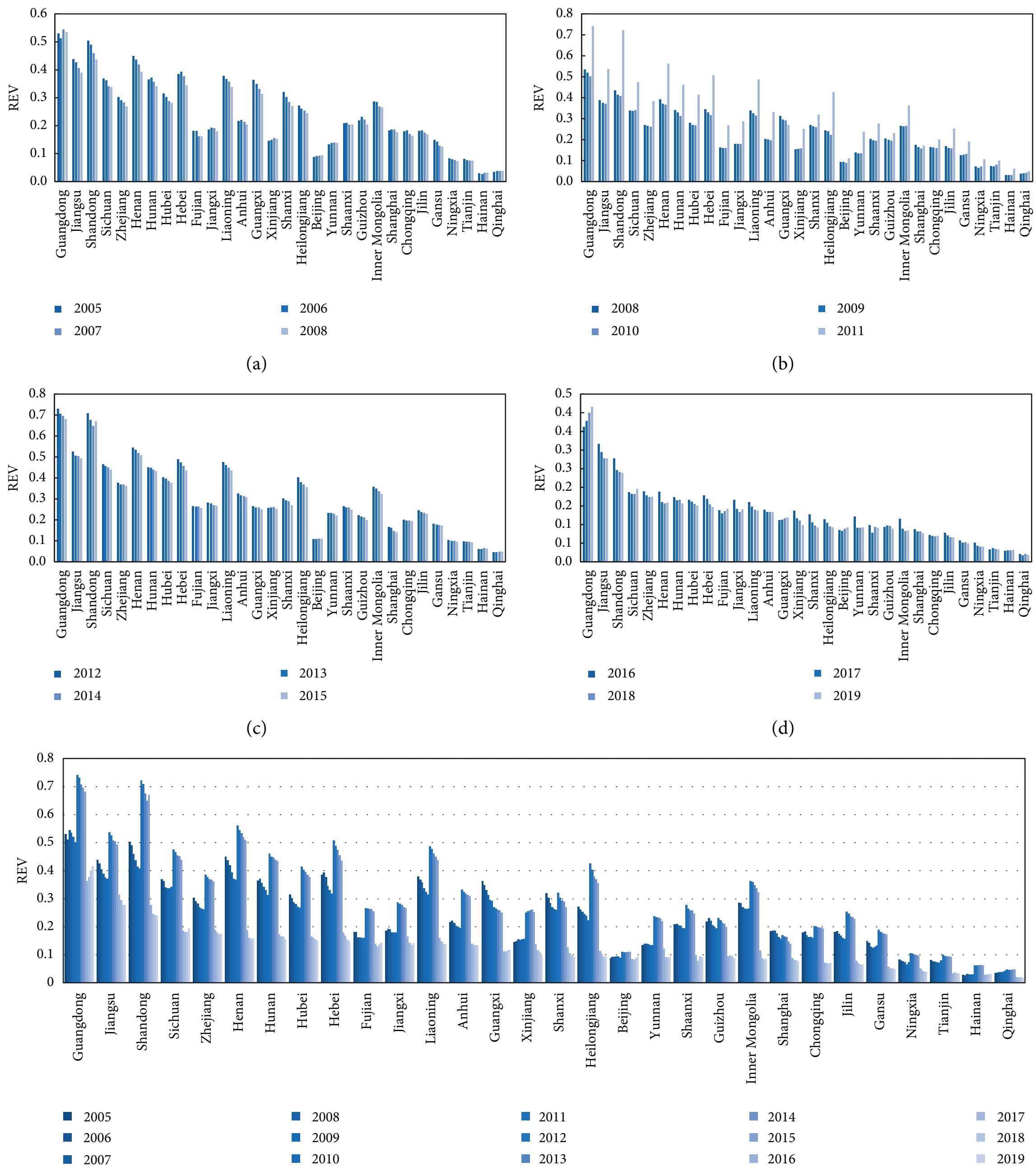

Figure 5: China's EEE subsystem-REV comparison (2005~2019).

Table 2: Moran's I statistics of China's REC.

Year	Moran's I	p value	sd	z value
2005	0.2712*	0.0180	0.1240	2.5100
2009	0.2579*	0.0180	0.1232	2.4206
2013	0.2584*	0.0190	0.1219	2.4473
2017	0.2605*	0.0190	0.1202	2.5042
2019	0.2629*	0.0180	0.1203	2.5209

Note. *Significance at the 5% level.

Table 3: Local spatial association pattern classification of REC.

Quadrant	Cluster	2005	2009	2013	2019
Quadrant I	H-H	Jiangsu**, Zhejiang*, Shanghai**, and Fujian*	Jiangsu**, Zhejiang*, Shanghai*, and Fujian*	Jiangsu**, Zhejiang*, Shanghai**, and Fujian*	Jiangsu**, Zhejiang*, Shanghai**, Fujian*, and Anhui**
Quadrant II	L-H	Anhui* and Hainan***	Anhui* and Hainan***	Anhui**, Hainan***, and Jiangxi*	Hainan*** and Jiangxi**
Quadrant III	L-L	Xinjiang*, Inner Mongolia*, Gansu*, Shanxi*, and Sichuan**	Xinjiang***, Inner Mongolia*, Gansu*, and Sichuan**	Xinjiang***, Inner Mongolia*, and Gansu*	Xinjiang***, Inner Mongolia**, and Gansu*
Quadrant IV	H-L	—	—	Sichuan**	Sichuan*

Note. (1) *Significance of 0.05; (2) **significance of 0.01; (3) ***significance of 0.001.

Table 4: Analysis results of system order parameter identification.

Num.	Model hypothesis	Equation of motion	Control parameters
(1)	$q_{1it} = REC_{it}$	$q_1(t) = 1.0245q_1(t-1) - 0.0480q_1(t-1)q_2(t-1)$	$\rho_1 = -0.0245$
		(0.0000^{***}) (0.0003)	$\rho_2 = 1 - 0.8276$
	$q_{2it} = \mathrm{REN}_{it}$	$q_2(t) = 0.8276q_2(t-1) + 0.0037q_1(t-1)^2$	$a = 0.0480$
		(0.0000^{***}) (0.8421)	$b = 0.0037$
(2)	$q_{1it} = \mathrm{REN}_{it}$	$q_1(t) = 0.9181q_1(t-1)$-$0.1592q_1(t-1)q_2(t-1)$	$\rho_1 = 1 - 0.9181$
		(0.0000^{***}) (0.0260^{*})	$\rho_2 = 1{-}1.0147$
	$q_{2it} = \mathrm{REC}_{it}$	$q_2(t) = 1.0147q_2(t-1) - 0.0194q_1(t-1)^2$	$a = 0.1592$
		(0.0000^{***}) (0.0039^{***})	$b = -0.0194$
(3)	$q_{1it} = \mathrm{REN}_{it}$	$q_1(t) = 0.7002q_1(t-1)$ $0.4253q_1(t-1)q_2(t-1)$	$\rho_1 = 1 - 0.7002$
		(0.0000^{***}) (0.0000^{***})	$\rho_2 = 1 - 0.7822$
	$q_{2it} = \mathrm{REV}_{it}$	$q_2(t) = 0.7822q_2(-1)$ $-0.2044q_1(t-1)^2$	$a = -0.4253$
		(0.0000^{***}) (0.0015^{***})	$b = -0.2044$
(4)	$q_{1it} = \mathrm{REV}_{it}$	$q_1(t) = 0.8987q_1(t-1)$ $-0.5496q_1(t-1)q_2(t-1)$	$\rho_1 = 1 - 0.8987$
		(0.0000^{***}) (0.0000^{***})	$\rho_2 = 1 - 0.8357$
	$q_{2it} = \mathrm{REN}_{it}$	$q_2(t) = 0.8357q_2(t-1)$ $0.0787q_1(t-1)^2$	$a = 0.5496$
		(0.0000^{***}) (0.0000^{***})	$b = 0.0787$
(5)	$q_{1it} = \mathrm{REC}_{it}$	$q_1(t) = 1.0220q_1(t-1)$ -$0.0447q_1(t-1)q_2(t-1)$	$\rho_1 = -0.0220$
		(0.0000^{***}) (0.0161^{**})	$\rho_2 = 0.2413$
	$q_{2it} = \mathrm{REV}_{it}$	$q_2(t) = 0.7587q_2(t-1)$ -$0.2508q_1(t-1)^2$	$a = 0.0447$
		(0.0000^{***}) (0.0769^{*})	$b = -0.2508$
(6)	$q_{1it} = \mathrm{REV}_{it}$	$q_1(t) = 0.9498q_1(t-1)$-$0.6039q_1(t-1)q_2(t-1)$	$\rho_1 = 1 - 0.9498$
		(0.0000^{***}) (0.0000^{***})	$\rho_2 = -0.0099$
	$q_{2it} = \mathrm{REC}_{it}$	$q_2(t) = 1.0099q_2(t-1)$-$0.0226q_1(t-1)^2$	$a = 0.6039$
		(0.0000^{***}) (0.0003^{***})	$b = -0.0226$

The estimation result is consistent with the objective geographical and economic distribution and proves that the development of the economic system has a spatial agglomeration effect among regions.

5.1.3. System Evolution Results. The system evolution model includes three variables: REN_{it}, REC_{it}, and REV_{it}. The Haken model is used to identify the order parameters of two variables. The steps of the empirical analysis are as follows: the model equation was constructed, the parameters were solved, the hypothesis of the model was tested, and the parameters of the system were determined. The results are shown in Table 4.

The parameters are obtained according to formula (5) and equation of motion:

$$\begin{aligned} REC_{(t)} &= 1.0220REC_{(t-1)} - 0.0447REC_{(t-1)}REV_{(t-1)} + 0.0129 \\ &\cdot \left(0.0000^{***}\right)\left(0.0161^{**}\right)\left(0.0000^{***}\right). \\ R^2 &= 0.9984;\ \text{adjusted}\ R^2 = 0.9982;\ F = 8415.769. \\ REV_{(t)} &= 0.7587REV_{(t-1)} - 0.2508REC^2_{(t-1)} + 0.0661 \\ &\cdot \left(0.0000^{***}\right)\left(0.0769^{*}\right)\left(0.0000^{***}\right), \\ R^2 &= 0.8616;\ \text{adjusted}\ R^2 = 0.8514;\ F = 84.0037. \end{aligned} \tag{11}$$

According to the R^2 and F test values, the fitting effect is better, and the regression effect is also very significant. As shown in Table 4, $\rho_1 = -0.0220$; $\rho_2 = 0.2413$; $a = 0.0447$; $b = -0.2508$; $|\rho_2| \gg |\rho_1|$. This indicates that REC decays slowly and represents the order parameter with small damping. REV is a fast variable, indicating rapid attenuation.

REC is the order parameter of REV. According to the pairwise comparison, REC is determined to be the order parameter of the evolution of the economy-energy-environment system. The indirect effect of the economic subsystem on the environmental subsystem is greatly promoted, and REC is the order parameter of evolution and development.

According to the control parameter results of evolution analysis, $\rho_1 = -0.0220 > 0$, indicating that the EEE system forms a positive feedback mechanism with increasing economic development; $\rho_2 = 0.2413 > 0$, indicating that the negative feedback mechanism of decreasing environmental pollution emission is formed in the EEE system, which strengthens the order of the system; $a = 0.0447 > 0$, indicating that environmental pollution hinders the economic subsystem; $b = -0.2508 < 0$, indicating that economic development can promote the reduction of environmental pollution.

5.2. Discussion. In this stage (2005~2019), the economic subsystem development REC is the order parameter of the sustainable evolution process of the EEE system, while the environmental pollution emission level is a fast variable. The comprehensive development of the economic subsystem is the decisive factor affecting the sustainable development of China's provincial EEE system. According to formula (5), $\rho_1 = -0.0220 < 0$ indicates that the EEE system has established a positive feedback mechanism for the continuous improvement of economic development between 2005 and 2019; $a = 0.0447 > 0$, indicating that the increase in pollutant emission has a certain inhibitory effect on economic growth, which verifies the negative impact of environmental pollution on economic growth; $\rho_2 = 0.2413 > 0$, indicating that a negative feedback mechanism for pollutant emission reduction is formed within the EEE system; $b = -0.2508 < 0$, indicating that the improvement of economic development level has not yet formed a promoting effect on pollutants, and economic development, in turn, reduces environmental pollution. The growth of output will lead to an increase in environmental protection investment and help reduce environmental pollution. The data of many developed provinces and cities also verify this conclusion. This conclusion is consistent with many existing single-factor research results. This paper verifies this point from the empirical study of system comprehensive indicators.

The above empirical analysis results show that, among the evolution and development factors of China's EEE system, the economic subsystem has a high impact on the environmental subsystem. The economic subsystem has become a slow variable and an order parameter for the evolution and development of the EEE system, and environmental pollution is a fast variable for the evolution and development of the system. The order parameter economic subsystem commands environmental pollution and dominates the evolution process of the EEE system [37, 38]. Economic development is a slow variable of environmental impact that reflects the indirect and direct impact of the economic subsystem on the environmental subsystem and dominates the evolution of the EEE system. This shows that adjusting the evolution and development of the EEE system through economic regulation is of great significance to realize sustainable development.

Most of the existing studies have verified the interaction between energy consumption, economic growth, and environmental pollution from the perspective of a single factor. For example, SO_2 emissions are used to characterize the pollution emission pressure of the environmental subsystem, and the overall energy consumption is used to measure the utilization degree of the energy system. The comprehensive index system constructed in this paper systematically evaluates the subsystems in EEE from multiple pollutant emissions and various economic growth indicators, which more comprehensively reflects the development level of the overall system and provides more accurate empirical research support. Based on the systematic perspective of multiple indicators, this paper finds that, among the factors of the evolution and development of China's EEE system, the economic subsystem has a great impact on the environmental subsystem, the economic subsystem has become the order parameter of the evolution and development of the EEE system, and environmental pollution is the fast variable of the evolution and development of the system. The order parameter economic subsystem commands environmental pollution and dominates the evolution process of the EEE system. Economic development is a slow variable of environmental impact that reflects the indirect and direct impact of the economic subsystem on the environmental subsystem and dominates the evolution of the EEE system. Zhang et al. [38] found that there is no benign synergistic effect between energy efficiency and pollutant emission intensity. Pollutant emission intensity has an inhibitory effect on energy efficiency, but the inhibitory effect is weakened. The research of Zhong et al. [42] is based on the Haken model and finds that economic growth and energy consumption are coordinated. In terms of spatial distribution, Tianjin and Hebei have not achieved complete coordination in subsystems and need to be improved. Beijing has realized the coordinated development of economic growth and energy consumption. Tianjin and Hebei have not yet achieved complete coordination in terms of subsystems and need to be improved. Li et al. [43] applied the Haken model and pointed out that high-quality development and environmental enforcement mechanisms are uncoordinated.

Previous studies have found that economic growth and energy consumption are coordinated. Some areas have not yet achieved complete coordination of subsystems and need to be improved [38, 42]. High-quality development and environmental law enforcement mechanisms are not coordinated. The level of green development in eastern China is relatively high, while there is still much progress in northern, eastern, western, and central China. Comparing the research of this paper with the existing research, it is found that the collaborative relationship of EEE gradually tends towards collaborative development, and the development level of the economic system has become the leading factor in directing the evolution of the EEE system.

Regulating the evolution and development of the EEE system through economic regulation is of great significance to realize sustainable development. The government should actively participate in regulation to reduce environmental pollution [53].

In the EEE system, the energy subsystem provides the production power for the economic subsystem, but the pressure on the environmental subsystem is the main source of environmental pollution. Energy consumption and pollution emissions are the key evolutionary behaviour of the EEE system. They are also the key links of environmental governance and energy conservation and emission reduction strategies after China's rapid economic development. The analysis results of these variables in this paper can reflect the evolutionary characteristics of the EEE system. As an order parameter, the economic development subsystem is a slow variable of environmental impact, which reflects the indirect and direct impact of the economic subsystem on the environmental subsystem and dominates the evolution of the EEE system. This shows that adjusting the evolution and development of the EEE system through economic regulation is of great significance to realize sustainable development. After 30 years of reform and opening up, green development has become a national strategy. Economic regulation includes industrial structure adjustment and promoting a high-quality economic development mode. Compared with China's early rising economy, the economy is relatively backwards, and the investment in environmental management and green development is insufficient. In terms of energy management, China's main response strategies mainly focus on the promotion of clean energy strategies.

In summary, economic regulation is the key factor determining the sustainable development of China's economy-energy-environment system, which plays a key role in reducing environmental pollution emissions. Since 2004, although China has put forward energy conservation and emission reduction policies and green development strategies and some regions have achieved the coordinated development of energy conservation, emission reduction, and economic development, to achieve overall coordinated development, we still need to increase investment in underdeveloped regions.

6. Conclusion

This paper makes a theoretical analysis of the coordinated evolution mechanism of the EEE system and empirically studies the green coordinated development mechanism of China's EEE system based on panel models by constructing a Haken model. It selects 30 provinces, municipalities, and autonomous regions in China to empirically analyse the evolution mechanism of the EEE system from 2005 to 2019. The conclusions are as follows.

First, economic development is the order parameter of the evolution and development of the economy-energy-environment system. Rapid economic development drives changes in environmental emissions and other control variables and promotes the evolution and development of the EEE system into the next stage of coevolution. During the evolution process of the EEE system, the economic subsystem is the key factor in determining the sustainable development of the EEE system.

Most of the existing studies have verified the interaction between energy consumption, economic growth, and environmental pollution from a single factor. The comprehensive index system constructed in this paper systematically evaluates the subsystems in EEE from the perspective of multipollutant emissions and multienergy utilization, which more comprehensively reflects the development level of the overall system and provides more accurate empirical research support. It is found that, among the evolution and development factors of China's EEE system, the economic subsystem has a greater impact on the environmental subsystem, and the order parameter has become a fast variable for the evolution and development of the EEE system, an order parameter to command environmental pollution and dominate the evolution process of the EEE system. Economic development is a slow variable of environmental impact, which reflects the indirect and direct impact of the economic subsystem on the environmental subsystem and dominates the evolution of the EEE system, indicating that economic regulation is of great significance to realize sustainable development.

Second, in the process of system evolution, the economic development subsystem is the decisive factor in EEE system evolution. In terms of the positive feedback mechanism of order parameter combination, the EEE system forms a positive feedback mechanism for increasing economic development in the stage of evolution and development. In terms of the negative feedback mechanism of environmental pollution, a negative feedback mechanism for decreasing environmental pollution emissions is formed within the EEE system. The increase in pollutant emissions has a certain inhibitory effect on economic growth, which verifies the negative impact of environmental pollution on economic growth. The improvement of the economic development level has not yet formed a promoting effect on pollutants, and economic development, in turn, reduces environmental pollution. The growth of output will lead to an increase in environmental protection investment and help reduce environmental pollution. The data of many developed provinces and cities also verify this conclusion. This conclusion is consistent with many existing single-factor research results. This paper verifies this point from the empirical study of system comprehensive indicators. With the improvement of economic development, the public and the government have increased their attention and regulation of environmental pollution, especially the management of high emission and heavy pollution enterprises.

The contributions are as follows. Firstly, using the theory of system science, this paper studies the evolution mechanism of the complex system of energy economy and environment, which is helpful to explore the basic operation mechanism of the evolution of the EEE complex system, and then gives a practical theoretical explanation for the evolution law of complex system. Secondly, this paper constructs the theoretical framework and model of the evolution of the EEE system and reveals the mechanism and process of the dynamic evolution so as to provide a theoretical supplement, expand the research perspective on the relationship between economy, energy, and environment, and help to further deepen it from the perspective of system theory. Thirdly, on the basis of evolution theory, complex system science, self-organization theory, and ecological theory, this paper deeply studies the EEE complex system, including evolution mechanism and empirical research. This paper establishes an energy-economy-environment system model based on the Haken model and panel data, identifies the system order parameters, analyses the dynamic evolution behaviour of complex systems, and supplements the empirical research of panel data.

Economic development is the decisive factor in the evolution of the EEE system, which determines environmental pollution reduction and sustainable development. Although the effect of environmental pollution control began to show in some developed regions of China, due to the migration of polluting enterprises and the pressure of economic development in underdeveloped regions, the negative feedback mechanism of environmental pollution emission and the synergistic effect of economic development, energy consumption, and environmental pollution reduction have not been formed on the whole. Therefore, in future system evolution, we should focus on the formation of a negative feedback mechanism of environmental pollution emissions to realize the green cooperation of economic growth, energy conservation, and emission reduction.

Data Availability

The data used to support the findings of the study can be obtained from the corresponding upon request.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

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