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Original Research

Stability Evaluation and Spatial-Temporal Evolution of Regional Economic-Energy-Environment System in the Context of Carbon Neutrality: A Case Study in East China

Sile Hu[1], Dunnan Liu[1], Ming Zhong[2], Guanhai Shi[2], Na An[2*], Fan Wu[2], Hang Fan[1]

[1]North China Electric Power University, Beijing, China
[2]China Huaneng Group, Ltd., Beijing, China

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Abstract

With the proposal of China's dual-carbon goal, the contradiction between regional economic development, energy consumption, and environmental governance is increasingly acute, and the stability of the economy-energy-environment (3E) system is increasingly prominent, which is an inevitable choice to effectively promote the green and low-carbon transformation of China's economy. Based on the stability of the 3E system, an index system was constructed from three dimensions: availability of the energy-resource system, coordination of the energy-economic system, and sustainability of the energy-ecosystem. Based on the principal component analysis and mature-element extension evaluation model, the stability and spatio-temporal evolution characteristics of the 3E system in East China were systematically evaluated. The results show that, firstly, from the spatial dimension, the coordination degree of the energy economic system is good in the economically developed A region, while the energy utilization efficiency is low in the economically less developed B region, and the sustainability of the energy ecosystem is relatively poor. Secondly, in terms of time dimension, Jiangxi, Jiangsu, and Shandong are the regions with rising fluctuations, Shanghai and Anhui are the regions with decreasing fluctuations, and Zhejiang and Fujian are the regions with relatively stable fluctuations, which is conducive to realizing the common vision of regional green and low-carbon development, breaking the geographical and information gap between provinces, and gradually forming a community of 3E system coupling and coordinated development.

Keywords: dual carbon target, energy-economy-environment system, stability evaluation model

*e-mail: anna2024115@163.com

Introduction

How to balance energy shortages, high-quality economic development, ecological environmental protection, and sustainable development is a focus problem plaguing all countries [1]. To attain global sustainable development in the 21st century, it is imperative for all nations to foster a low-carbon economy [2]. Despite the fact that China's traditional extensive development model has facilitated its remarkable economic growth, it has also incurred substantial costs on resources and the environment [3]. China surpassed the United States in 2005 as the world's largest emitter of carbon dioxide. Confronting the increasingly grave issue of global climate change, China has put forward ambitious goals to strive for carbon peaking by 2030 and achieve carbon neutrality by 2060 [4]. In the pursuit of the "dual carbon" objective, China is confronted with the imperative to effectively address and harmonize two crucial relationships: economic development and carbon emissions, carbon emission reduction, and national energy security, thereby achieving sustainable development of the energy-environment-economic system. From an energy systems perspective, China confronts a dual challenge encompassing both energy scarcity and the transformation of its energy structure. Over recent years, China has witnessed a steady growth in energy imports, with net imports escalating from 50 million tons of standard coal in 2000 to 1.12 billion tons in 2020. Furthermore, as of 2021, China's foreign energy dependence rate stands at 20.6% [5]. From an environmental system perspective, the significance of environmental issues such as haze pollution, ecological damage, and resource depletion resulting from energy consumption and economic development cannot be underestimated. From an economic system standpoint, China is currently transitioning from a traditional extensive development model characterized by high input, high consumption, and high pollution to enhancing total factor productivity and improving the quality of economic growth. The relationship between "dual carbon" and ecosystem protection has a great impact on the stable development of the regional energy-economy-environment system. [2, 3].

East China, encompassing Shanghai, Jiangsu, Anhui, Zhejiang, Shandong, Fujian, and Jiangxi provinces and cities, stands as one of the most economically vibrant regions in China. According to the data from the National Bureau of Statistics, in 2022, the economic contribution of these seven provinces and cities accounted for 38.25 percent of China's total output [6]. However, being densely populated with a population exceeding one-third of China's total population, East China faces significant energy demand and often encounters substantial energy gaps. Moreover, due to varying levels of economic development among these seven provinces in East China, there exist notable disparities in terms of energy structure, energy utilization efficiency, and environmental protection status, leading to regional heterogeneity [7]. Therefore, this study focuses on 7 provinces and cities in East China as research subjects, quantifies and assesses the stability of the 3E system in East China, and analyzes the spatio-temporal evolution trend of its stability based on the evaluation results. This analysis aims to provide a valuable reference for expediting China's achievement of carbon neutrality.

The potential marginal contributions of this paper are as follows: (1) From the research perspective, different from the previous research that focused on the coordination of 3E systems, this paper focuses on the stability of 3E systems and builds a 3E system stability evaluation model, which enriches and expands the existing research results and also contributes to the inspiration of future research related to 3E systems. (2) In terms of research content, this paper constructs an index system from three dimensions: energy-resource system availability, energy-economic system coordination, and energy-ecosystem sustainability. Based on the principal component analysis and mature-element extension evaluation model, this paper systematically evaluates the stability and spatio-temporal evolution characteristics of the 3E system in East China. (3) From the perspective of research value, based on the stability evaluation of 3E systems in East China, this paper further explains the reasons for the difference in 3E stability between different provinces in East China and the problems existing in each system, providing valuable policy references for the coordinated development of 3E systems in various provinces.

Literature Review

At present, the problem of environmental pollution has been widely discussed by many scholars at home and abroad. Due to the complex relationship among energy, economy, and environment, scholars have explored the relationship among 3E systems, specifically as follows:

In the realm of economic-environmental studies, Grossman and Krueger [8] proposed the renowned Environmental Kuznets Curve (EKC), which illustrates an inverted U-shaped relationship between environmental quality and economic development. A study conducted by Yousefi-Sahzab et al. [9], utilizing data from Iran, confirmed a significant positive correlation between CO2 emissions and economic growth in all sectors except for agriculture. Ou et al. [10] investigated the driving factors and pattern changes of carbon emission growth in Guangdong, China, from a consumption perspective. Odhiambo's research demonstrates a unidirectional causal relationship between economic growth and carbon dioxide emissions in sub-Saharan African countries over both short and long-term periods [11]. For the study of energy-environment systems, Lu et al. [12] employed the gray theory to assess the varying degrees of influence that different types of energy consumption exert on environmental quality. Akhmat et al. [13] conducted research using countries from the South Asian Association for Regional Cooperation as samples and found that energy consumption is a significant driving factor behind the increase in environmental pollutants in SAARC countries. Regarding the study of energy-economy systems, Acheampong's research results demonstrate an interdependent relationship between energy consumption and economic growth [14]. Lin [15] measured the energy efficiency and economic growth quality across various provinces in China, exploring their relationship, with empirical results indicating a clear U-shaped correlation between energy efficiency and economic growth quality. Furthermore, some scholars have examined the relationship between energy intensity, energy consumption, and economic output growth rate [16, 17].

Currently, the research framework of the energy-environment-economy system has gained widespread acceptance, and numerous scholars have integrated this 3E system with various analytical tools, yielding fruitful research outcomes. Cui et al. [3] established a VAR model for the 3E system in Shaanxi Province, China, and examined the dynamic relationship among energy, economy, and environment through impulse response analysis and variance decomposition techniques. The findings indicate that a positive shock to economic growth will have a negative impact on energy consumption. Utilizing a simultaneous equation model and drawing on panel data from 58 countries, Saidi and Hammami [18] demonstrated that energy consumption positively influences economic growth while concurrently resulting in elevated pollution levels. Aydin and Cetintas [19] utilized the panel smooth transition regression (PSTR) model to demonstrate that when the proportion of renewable energy in energy consumption falls below a certain threshold, economic growth exhibits a detrimental effect on the environment and exacerbates environmental pollution. Conversely, when the proportion surpasses this threshold, economic growth mitigates environmental pollution. Zhang et al. [20] investigated the spatial effects of China's economic growth and energy consumption on environmental pollution using a spatial econometric model. Ye et al. [21] proposed a nonlinear interactive gray multivariable model based on dynamic compensation to forecast China's 3E system, revealing steady increases in carbon emissions, total energy consumption, and GDP for China. Mu et al. [22] employed a combination of the gray correlation analysis method and the entropy weight method to examine the correlation and synergy within urban economy-energy-environment systems. Zhang et al. [23] developed a comprehensive and comparative 3E system evaluation and optimization management approach, which was applied in an empirical study involving the key cities within China's three major economic circles. Li et al. [24] investigated the correlation between the digital economy and 3E efficiency in EU countries, based on a comprehensive evaluation of system efficiency. Lei and Xu [25] employed the coupling coordination degree model to assess the level of synchronized development between the economy and the environment. Subsequent investigations revealed that China's energy consumption structure transformation significantly facilitated the harmonious advancement of its economic and environmental systems.

The efficient use of energy is an important basis for promoting China's low-carbon and clean transformation and is also the key to promoting the stable development of regional 3E systems. Regarding the definition and evaluation of low-carbon economies and energy systems, Zhang et al. [26] developed an energy-saving evaluation index system for low-carbon industrial development by selecting energy consumption indicators, emission reduction indicators, technical indicators, etc., based on the analysis of domestic and foreign theories on the evaluation of low-carbon industrial development. This system aims to comprehensively optimize the layout of the industrial structure and promote the transformation and upgrading of traditional industries. Ye et al. [27] assessed the low-carbon development situation of Sichuan Province by considering 30 evaluation indicators for low-carbon development across six aspects, including economic development, social progress, energy consumption, low-carbon emissions, carbon sink capacity, and environmental carrying capacity. In terms of the research on the relationship between low-carbon economies and energy development, Veton et al. [28] studied the impact of stock market development on low-carbon economies and pointed out that technological innovation plays a driving role in promoting regional low-carbon development. Hu et al. [29] studied China's low-carbon development within the framework of economy, energy, power, and environment. They also projected China's economic growth, energy and power demand, renewable energy generation, energy conservation, and emission reduction until 2030. Xing et al. [30] creatively propose the concept of a low-carbon digital economy from the perspectives of resource flow, digital flow, and energy flow. They investigate the synergistic effect of low-carbon digital development by constructing a collaborative model for economic and social development. Taking China as an example, Pan et al. [31] used a dynamic recursive computable general equilibrium (CGE) model to study the coupling effects of fossil energy right trading (FET), renewable energy certificate trading (RECT), and renewable energy subsidies (RES) on green finance policies in a low-carbon economy. Hosein et al. [32] investigated the potential of long-term renewable energy (RE) planning and climate policy for facilitating the Northern Territory's transition to a low-carbon economy by 2050. Sustainable economic growth was analyzed through three scenarios: business as usual (BAU), high industrial growth (HIG), and renewable energy exports (REE). Zhou et al. [33] studied the role of renewable energy output (REO), green technology innovation (GTI), and financial development (FD) in carbon emission levels in four emerging Asian countries from 2010 to 2021. Wang et al.'s study [34] considers patents related to energy alternatives as a crucial technical factor influencing the low-carbon economy. Their research demonstrates that the utilization of clean energy can enhance the level of development in the low-carbon economy, thereby highlighting the significance of energy-alternative technologies.

Many scholars have carried out in-depth research on energy security, environmental pollution, embodied value, and other aspects, aiming to improve the coordination and stability of the energy security system, the economic system, and the environmental system. Early studies on energy security primarily focused on the stability of energy supply and price [35]. Subsequently, with changing climate conditions, scholars also began to emphasize the security of energy utilization [36]. From the perspective of influencing energy security, Sana et al. [37] used the panel data of 40 major energy-consuming economies in Asia, the Americas, Europe, and Africa from 1996 to 2021 and adopted the cross-sectional enhanced autoregressive distributed lag model to study the impact of conflict on energy security risks. Lee et al. [38] revealed the adverse impact of ICT on energy demand and energy security. Wang et al. [39] found that the relationship between monetary policy and energy security has been significantly enhanced since the 2008 financial crisis. The more developed an economy is, the more likely it is to face energy security challenges resulting from changes in monetary policy. From the perspective of energy production system security, Kuzior et al. [40] pointed out that the economic security system relies on the concept of circular economy through the 3R model. Wei et al. [41] clarified the internal relationship between environmental characteristics and carbon emission effect characteristics and established an experimental method based on carbon dioxide emission impact characteristics and urban environmental characteristics. Meng et al. [42] introduced a new framework to quantify the Marine economic security of China's regional Marine sector and designed a multi-dimensional index system from the dimensions of industry, science and technology, ecology, and administration to provide information for strategic governance reform. At the same time, there is still significant room for improvement in China's energy security, and the factors that pose a threat to energy security persist over a long period of time. Therefore, it remains necessary to implement effective measures to enhance China's energy security level and propel its development toward a higher level [43-45]. Zang et al. [46] constructed an energy security evaluation index system with a total of 18 indicators from five dimensions, including energy supply, energy consumption, energy economy, energy environment, and energy transportation, and evaluated and predicted Inner Mongolia's energy security from both time and space dimensions according to the constructed energy security evaluation index system. Xu et al. [47] emphasize that in order to enhance China's energy security, it is imperative to focus on four key aspects: bolstering energy exploration and development, optimizing the energy structure, enhancing energy efficiency, and establishing diversified channels for energy supply.

In terms of evaluation methods, the current research has made varying improvements to previous subjective weighting methods, including the entropy weight-TOPSIS method [48-50], the grey correlation TOPSIS method [51-53], and the enhanced AHP-FCE method [54-56].

Through a comprehensive literature review, it becomes evident that the current research on 3E systems primarily focuses on the coordination analysis within these systems and the internal relationships among subsystems. Despite the growing significance of energy issues, scholars have predominantly conducted studies on energy supply and utilization in relation to system security. Unfortunately, there is a dearth of research examining the stability analysis between energy systems and other systems from a holistic perspective encompassing aspects such as economy and environment. In light of this gap, this study integrates the concept of a low-carbon economy to establish a dynamic evaluation method for constructing a multi-system interconnection index system that assesses the development stability of the energy-economy-environment (3E) system in East China.

The subsequent sections of this paper are structured as follows: Section 3 presents the design of a stability evaluation model for the 3E system and establishes a comprehensive evaluation model by integrating principal component analysis and matter element extension. In Section 4, an analysis is conducted on the results of regional stability evaluation and sensitivity in East China. Finally, Section 5 provides a summary along with prospects.

Method

3E System Stability Evaluation Model

Evaluation Index System

Drawing on previous literature and considering the coupling relationship between the energy system, the economic system, and the environmental system, this paper defines the stability of the 3E system as ensuring affordable energy supply to support national economic development while promoting sustainable development through low-carbon practices. This concept encompasses three key aspects: the availability of energy resources, the coordination of the energy-economic system, and the sustainability of the energy-ecosystem. Therefore, the pressure-state-response (PSR) model was used as our analytical framework to analyze the complex relationship among the three variables, as illustrated in Fig. 1.

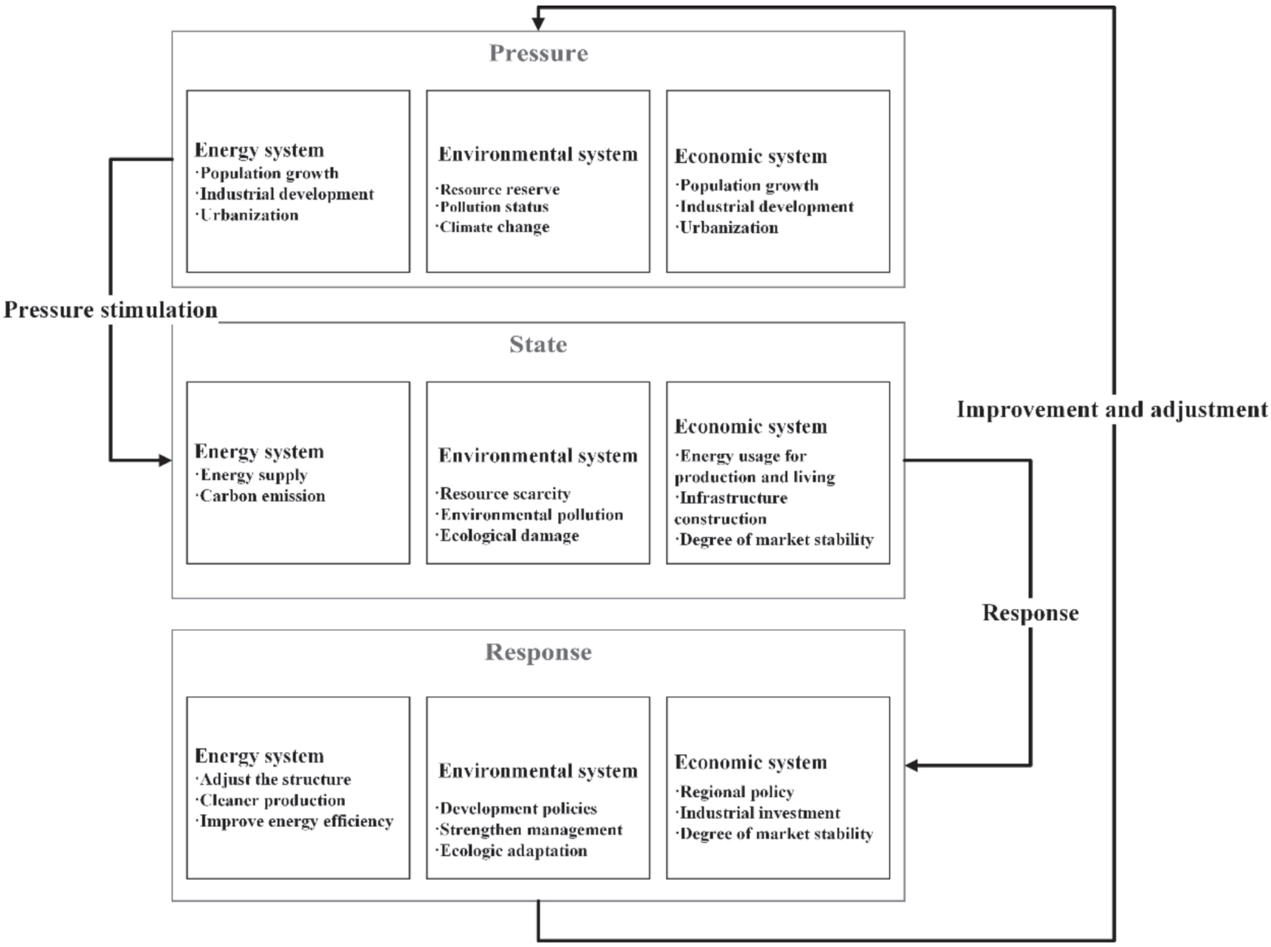


Fig. 1. 3E system stability analysis framework based on PSR.

The 3E system, as shown in Fig. 1, is influenced by various factors, specifically "pressure". Among them, the energy system is affected by resource supply pressure, the economic system is influenced by demand pressure, and the environmental system is impacted by ecological pressure. These pressures result in consequences such as an intensifying contradiction between the supply side and the demand side, a growing problem of environmental pollution, and unbalanced development. At this juncture, under the guidance of top-level policies, relevant measures should be proposed to promote the sustainable development of regional green investment. Therefore, this paper prioritizes system stability and establishes a 3E system stability evaluation index from three dimensions: availability of energy-resource systems; coordination between energy-economic systems; and sustainability of energy-ecosystems (as depicted in Fig. 2).

(1) Energy-resource system availability

As shown in Fig. 2, this indicator reflects the energy supply capacity of the 3E system and its ability to handle interruptions in energy supply. However, the pressure caused by resource security and continuous energy production mainly includes three indicators: self-sufficiency rate, energy production diversity index, and reserve-to-production ratio. The specific calculation expressions are as follows:

– Self-sufficiency rate: This refers to the degree of self-sufficiency of a country or region in energy production and consumption, which is calculated as follows:

$$S = \frac{R_{TP}}{R_{TC}} \tag{1}$$

Where S is self-sufficiency rate; R_{TP} is total energy production, and R_{TC} is total energy consumption.

– Energy production diversity index: This refers to the index used to measure the diversity of a country or region's energy production structure. The specific calculation expression is as follows:

$$H_p = -\sum_{i=1}^{N} P_i^p \cdot \ln(P_i^p) \tag{2}$$

Where H_p is the energy production diversity index; P_i^p is the proportion of the i energy type in the total energy production, and N is the number of energy types.

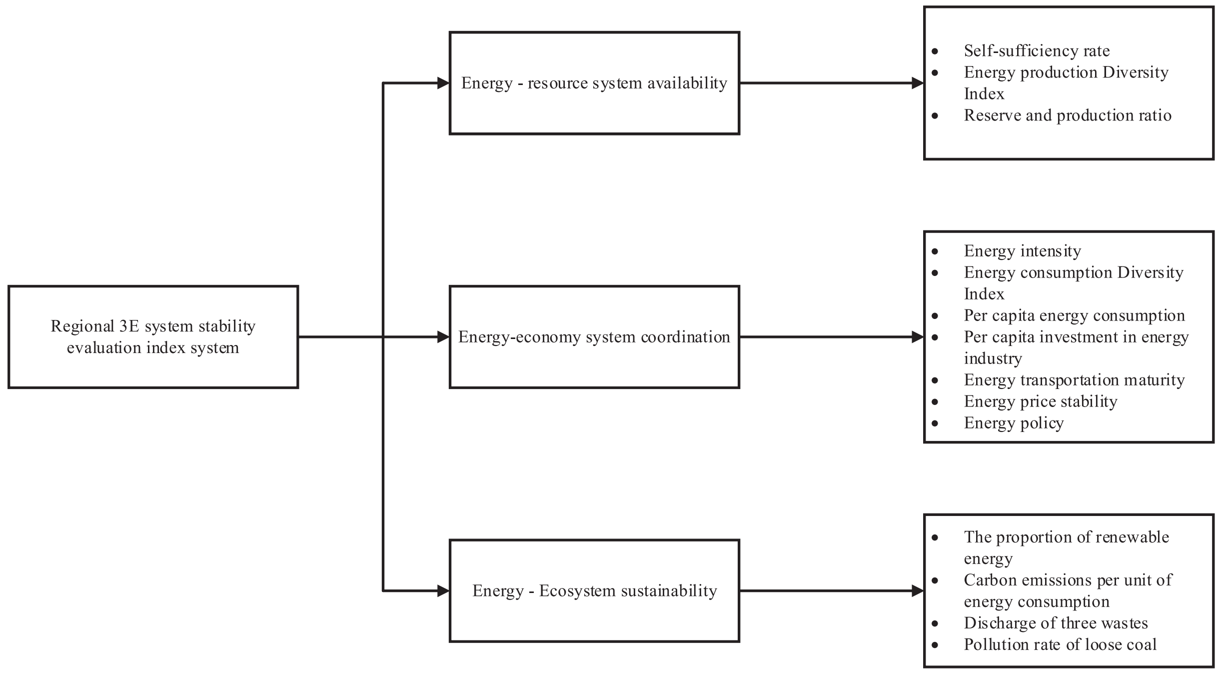


Fig. 2. Stability Evaluation Index System of the Regional 3E System.

– Reserve and production ratio: This refers to the index used to measure the relationship between the reserves of a certain energy resource and the annual production. The specific calculation expression is as follows:

$$RP = \frac{R_R}{R_{TC}} \tag{3}$$

Where RP is the reserve and production ratio and R_R is the proved reserves in the region.

(2) Coordination of the energy-economy system

As can be seen from Fig. 2, this index is affected by the instability of the energy market, the volatility of energy prices, the uncertainty of investment funds, *etc*., resulting in the imbalance of the energy-economy system. In general, within the 3E system, it indicates the degree of coordination between the economic system and processes such as energy conversion, processing, transportation, and consumption. The lower the degree of coordination, the more it indicates that either the energy supply cannot meet regional economic development or the regional economic development cannot afford to use energy. This includes seven indicators such as energy intensity, energy consumption diversity index, per capita energy consumption, per capita investment in the energy industry, energy transportation maturity, energy price stability, and energy policy. The specific calculation expression is as follows:

– Energy intensity: This refers to the amount of energy consumed per unit of gross national product or unit output; the specific calculation expression is as follows:

$$EI = \frac{R_{TC}}{R_{GDP}} \tag{4}$$

Where EI is energy intensity and R_{GDP} is unit gross national product.

– Energy consumption diversity index: This refers to the proportion of different types of energy in the total energy consumption. The specific calculation expression is as follows:

$$H_C = -\sum_{i=1}^{M} P_i^c \cdot \ln(P_i^c) \tag{5}$$

Where H_C is the energy consumption diversity index; P_i^c is the proportion of the i energy type in the total energy consumption, and M is the total number of energy types.

– Per capita energy consumption: This is used to reflect the energy utilization efficiency, the energy consumption level, and people's living standards in a country or region and is also an important indicator to measure energy consumption. The specific calculation expression is as follows:

$$E_{per} = \frac{R_{TC}}{R_{POP}} \tag{6}$$

Where E_{per} is per capita energy consumption, and R_{POR} is the population of the area.

– Per capita investment in the energy industry: This is used to measure the average investment level of each person in the energy industry of a region. The specific calculation expression is as follows:

$$C_{per}^{i} = \frac{C_{TI}}{R_{POP}} \quad (7)$$

Where C_{per}^{i} is per capita investment in the energy industry, and C_{TI} represents total investment in the energy industry.

– Energy transportation maturity: To reflect the diversity and cleanliness of a country or region's energy structure in the field of transportation, the specific calculation expression is as follows:

Where C_{et} stands for energy transportation maturity, $R_{i,j}$ is the mileage of the i mode of transportation, and R_{AREA} is the area.

$$C_{et} = \frac{\sum(R_{i,j})}{R_{AREA}}, i, j = 1, 2, 3 \quad (8)$$

– Energy price stability: This is an important indicator that reflects the health and stability of a country or region's energy market and is of great significance to the economy, energy security, environment, and other aspects. It refers to the degree and frequency of energy price fluctuations in the energy market.

– Energy policy: A set of strategies, regulations, measures, and programs to achieve specific energy goals.

(3) Energy-Ecology system sustainability

As can be seen from Fig. 2, in the 3E system, this index mainly includes four indicators, such as the proportion of renewable energy, carbon emissions per unit of energy consumption, discharge of three wastes, and the pollution rate of loose coal, due to the impact of large-scale use of fossil energy on the environment. The specific calculation expression is as follows:

– The proportion of renewable energy: This refers to the proportion of renewable energy in the entire energy production and consumption system. The specific calculation expression is as follows:

$$CE = \frac{R_{total}^{CE}}{R_{TP}} \quad (9)$$

Where CE is the proportion of renewable energy, and R^{CE}_{total} is renewable energy consumption.

– Carbon emissions per unit of energy consumption: This is used to evaluate the relationship between energy utilization efficiency and carbon emission levels, reflecting the impact of energy consumption on the environment. The specific calculation expression is as follows:

$$CO = \frac{R_{co_2}}{R_{TP}} \quad (10)$$

Where CO is carbon emissions per unit of energy consumption, and R_{CO_2} is carbon dioxide emissions.

– Discharge of three wastes: This refers to the three kinds of waste emissions generated in the process of energy production and consumption, namely waste gas, wastewater, and solid waste. The specific calculation expression is as follows:

$$W_{co} = \frac{\sum(W_{i,j})}{R_{TP}}, i, j = 1, 2, 3 \quad (11)$$

Where W_{co} is the discharge of three wastes, and $W_{i,j}$ is the discharge of type i waste.

– Pollution rate of loose coal: This refers to the degree of environmental pollution caused by loose coal combustion in the process of energy production and consumption. The specific calculation expression is as follows:

$$W_{lc} = \frac{R_{llc}}{R_{lc}} \quad (12)$$

Where W_{lc} is the pollution rate of loose coal, R_{llc} is the domestic consumption of raw coal, and R_{lc} is the raw coal consumption in the terminal energy system.

Principal Component Analysis-Matter Element Extension Comprehensive Evaluation Model

The Index Weight Was Determined by Principal Component Analysis

Principal component analysis (PCA) is a statistical method for dimensionality reduction. By means of an orthogonal transformation, the original random vector whose components are correlated is transformed into a new random vector whose components are not correlated. The specific calculation steps are as follows:

Step 1: By collecting and investigating related data on energy, economy, and other provinces in East China, the stability evaluation index value of the 3E system is calculated. The specific matrix is obtained as follows:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (13)$$

Where X is the 3E system stability evaluation index matrix.

Step 2: Compute the eigenvalues λ_1, λ_2, ..., λ_n of the score matrix and determine the corresponding eigenvector e_i(i = 1, 2, ..., n) associated with the eigenvalue λ_i.

Step 3: Each eigenvalue corresponds to a principal component, corresponding to the contribution rate of the principal component, as follows:

$$p_i = \frac{\lambda_i}{\sum_{i=1}^{n} p_i} \tag{14}$$

Among them, it is necessary to determine the number of eigenvalues with eigenvalues greater than 1 and the sum of contribution rates greater than 80%.

Step 4: The principal component F_1, F_2, ..., F_n is extracted and a model for the principal components is established as follows:

$$F_z = \overline{\omega_1} x_1 + \overline{\omega_2} x_2 + \cdots + \overline{\omega_m} x_m \tag{15}$$

Where x_1, x_2, ..., x_m is the value of m evaluation indicators.

Step 5: According to the above steps, the weight of the i indicator is calculated as follows:

$$\overline{\omega_i} = \frac{p_i e_i}{\sum_{i=1}^{n} p_i} \tag{16}$$

Where $\overline{\omega_m}$ is the weight of each indicator.

Comprehensive Evaluation of Matter-Element Extension

The core idea of matter-element extension analysis is to introduce the concept of matter-element, which is a kind of mathematical object between a mathematical entity and a fuzzy concept. The main idea of matter-element analysis is to describe things as ordered triples (N, C, V), where N represents the things of matter-element, C represents the characteristics of matter-element, and V represents the magnitude of matter-element. The triples are called crop elements, indicating the degree of uncertainty or fuzziness. By using matter elements, fuzzy or uncertain data can be modeled and analyzed. The specific steps are as follows:

Step 1: Determine the matter element. It consists of 14 evaluation indexes, such as the self-sufficiency rate and the diversity index of energy production.

Step 2: The matter-element matrix (R = (N, C, V)) was determined to calculate the stability evaluation index value of the 3E system in the provinces of East China.

$$R = (N、C \quad V) = \begin{bmatrix} R & C_1 & v_1 \\ & & \\ & C_n & v_n \end{bmatrix} \tag{17}$$

Where R is the n-dimensional matter element, which contains 3E system stability evaluation indexes and data.

Step 3: Determine the classical domain. The classical domain consists of the interval where the matter-element characteristics (indicators) and their magnitude value are to be evaluated, as follows:

$$R_{0j} = (N_{0j}、C_i \quad V_i) = \begin{bmatrix} R_{0j} & C_1 & v_{0j1} \\ & & \\ & C_n & v_{0jn} \end{bmatrix} \tag{18}$$

Where R_{0j} is the classical domain, where, j = 1, 2, 3; N_{0j} is the data set of the 3E system stability evaluation index j; C_i is the characteristic of N_{0j}; V_i is the quantitative value interval specified by N_{0j} for the stability evaluation index of the 3E system.

Step 4: Determine the classical section domain. 3E The section domain of system stability evaluation is represented by R_p as follows:

$$R_p = \left[N_p, C, V_p\right] = \begin{bmatrix} N_p & C_1 & v_{p1} \\ & & \\ & C_n & v_{pn} \end{bmatrix} \tag{19}$$

Where N_p is the complete set of stability evaluation indexes for the 3E system to be evaluated.

Step 5: Calculate the distance of the 3E system stability evaluation index to the classical domain matter element and the node domain matter element, as follows:

$$p\left(c_{ij}, \left\langle a_{jk}, b_{jk} \right\rangle\right) = \left| c_{ij} - \frac{a_{jk} + b_{jk}}{2} \right| - \left| \frac{b_{jk} - a_{jk}}{2} \right| \tag{20}$$

Step 6: Combined with the principal component analysis method, the weight of the 3E system stability evaluation index is determined, and the correlation degree is obtained, as follows:

$$K_{oj} = \sum_{i=1}^{m} \overline{w}_i p_{ij}, j = 1, 2, ..., n \tag{21}$$

Where $\overline{w}_i$ is the weight of the 3E system stability evaluation index.

Step 7: The stability score of the 3E system in East China is as follows:

$$K_q(p_0) = \max\left\{K_j(p_0)\right\}, j = 1, 2, \ldots, m \tag{22}$$

Where $K_q(p_0)$ is the maximum value of $K_j(p_0)$ of each level of close degree in the stability evaluation of the 3E system. The stability of provinces in East China is divided into five levels, namely I, II, III, IV, and V. A higher evaluation result for a province in East China indicates stronger availability of the energy-resource system, better coordination of the energy-economic system, and greater overall stability of energy-ecosystem sustainability. It also suggests a higher anti-risk ability.

Evaluation Method Flow Chart

In this paper, a combination of principal component analysis and the matter-element extension method is proposed to evaluate the stability of the 3E system in East China. The specific process is shown in Fig. 3.

Example Analysis

Basic Data

In order to verify the validity and scientificity of the proposed stability model, this paper takes East China (Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, and Shandong) as an example to analyze, and the research results provide ideas for other regions.

As the economic center of China, East China has abundant resources and strong economic vitality, playing a crucial role in China's development. To assess the stability of the 3E system in East China, data for each evaluation index were obtained from the National Statistical Yearbook (2011-2020) and the National Energy Statistical Yearbook (2011-2020).

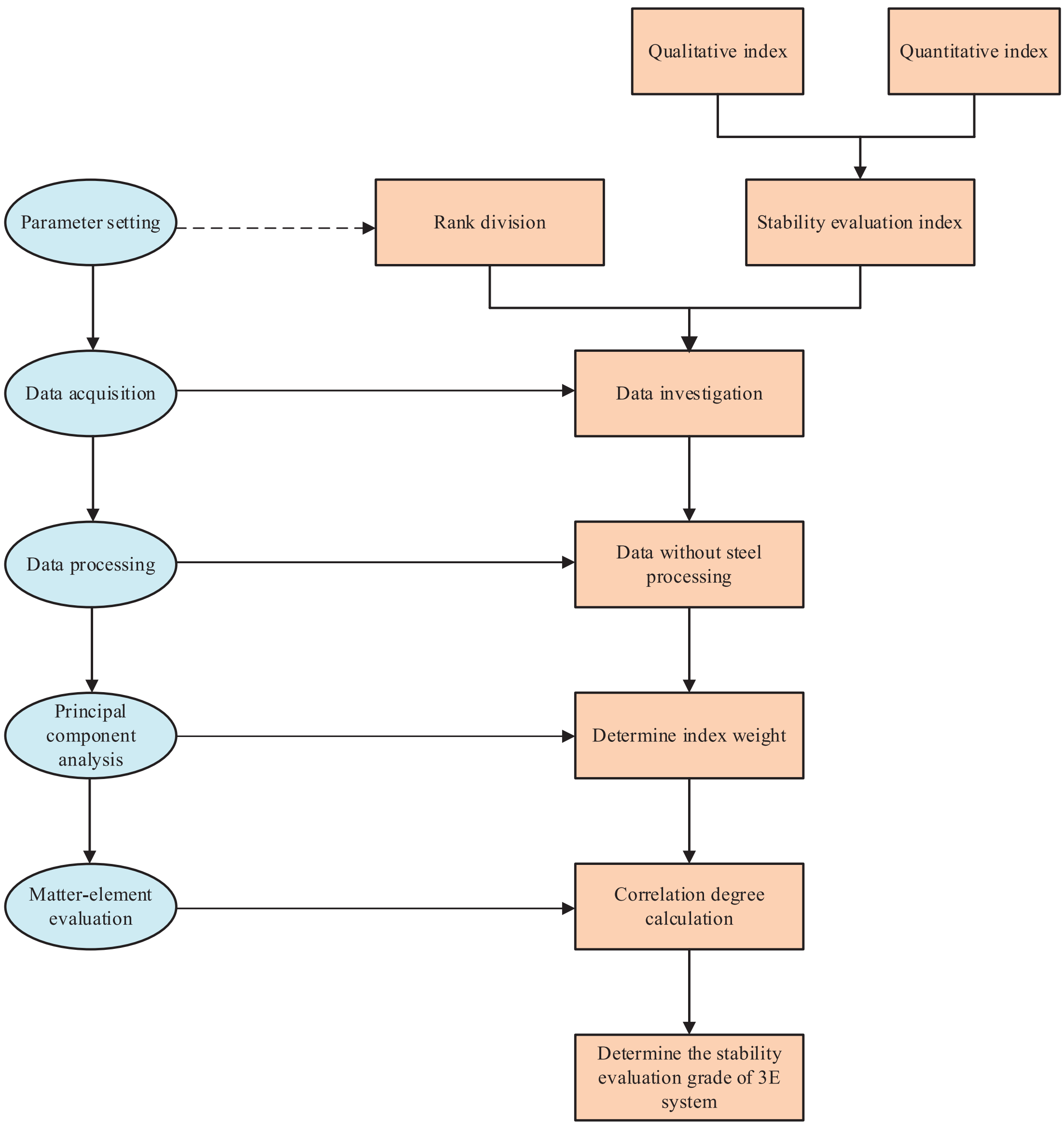


Fig. 3. Flowchart of the proposed method.

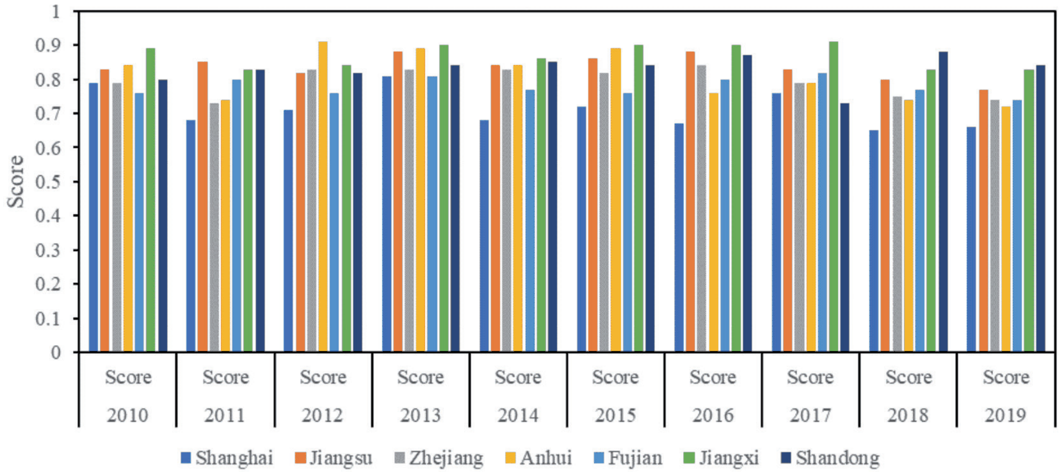


Fig. 4. Stability evaluation results of the 3E system in East China.

Model Calculation Results

The stability evaluation method of the 3E system proposed in this paper is used to calculate the East China region, and the evaluation results are shown in Fig. 4.

The stability levels of the 3E system among the seven provinces and cities in East China are relatively close, as shown in Fig. 4, with specific evaluation levels presented in Table 1. Based on the annual stability evaluation results of the 3E system, overall stability in East China increased from 2011 to 2014, with an average annual growth rate of 3%, attributed to China's vigorous development of wind power, photovoltaic, and other renewable energy sources. However, from 2016 to 2019, overall stability gradually declined in East China. Among the different provinces and cities in East China, Anhui, and Jiangsu have higher stability evaluation levels and are considered regional leaders, whereas Fujian and Shanghai have lower stability evaluation levels.

The stability distribution of the 3E system in various provinces in East China is shown in Fig. 5 when combined with Fig. 4.

Table 1. Stability evaluation results of the 3E system in East China.

Region	2010		2011		2012		2013		2014	
	Score	Level	Score	Level	Score	Level	Score	Level	Score	Level
Shanghai	0.79	IV	0.68	IV	0.71	IV	0.81	V	0.68	IV
Jiangsu	0.83	V	0.85	V	0.82	V	0.88	V	0.84	V
Zhejiang	0.79	IV	0.73	IV	0.83	V	0.83	V	0.83	V
Anhui	0.84	V	0.74	IV	0.91	V	0.89	V	0.84	V
Fujian	0.76	IV	0.80	IV	0.76	IV	0.81	V	0.77	IV
Jiangxi	0.89	V	0.83	V	0.84	V	0.90	V	0.86	V
Shandong	0.80	V	0.83	V	0.82	V	0.84	V	0.85	V
Region	2015		2016		2017		2018		2019	
	Score	Level	Score	Level	Score	Level	Score	Level	Score	Level
Shanghai	0.72	IV	0.67	IV	0.76	IV	0.65	IV	0.66	IV
Jiangsu	0.86	V	0.88	V	0.83	V	0.80	IV	0.77	IV
Zhejiang	0.82	V	0.84	V	0.79	IV	0.75	IV	0.74	IV
Anhui	0.89	V	0.76	IV	0.79	IV	0.74	IV	0.72	IV
Fujian	0.76	IV	0.80	IV	0.82	V	0.77	IV	0.74	IV
Jiangxi	0.90	V	0.90	V	0.91	V	0.83	V	0.83	V
Shandong	0.84	V	0.87	V	0.73	IV	0.88	V	0.84	V

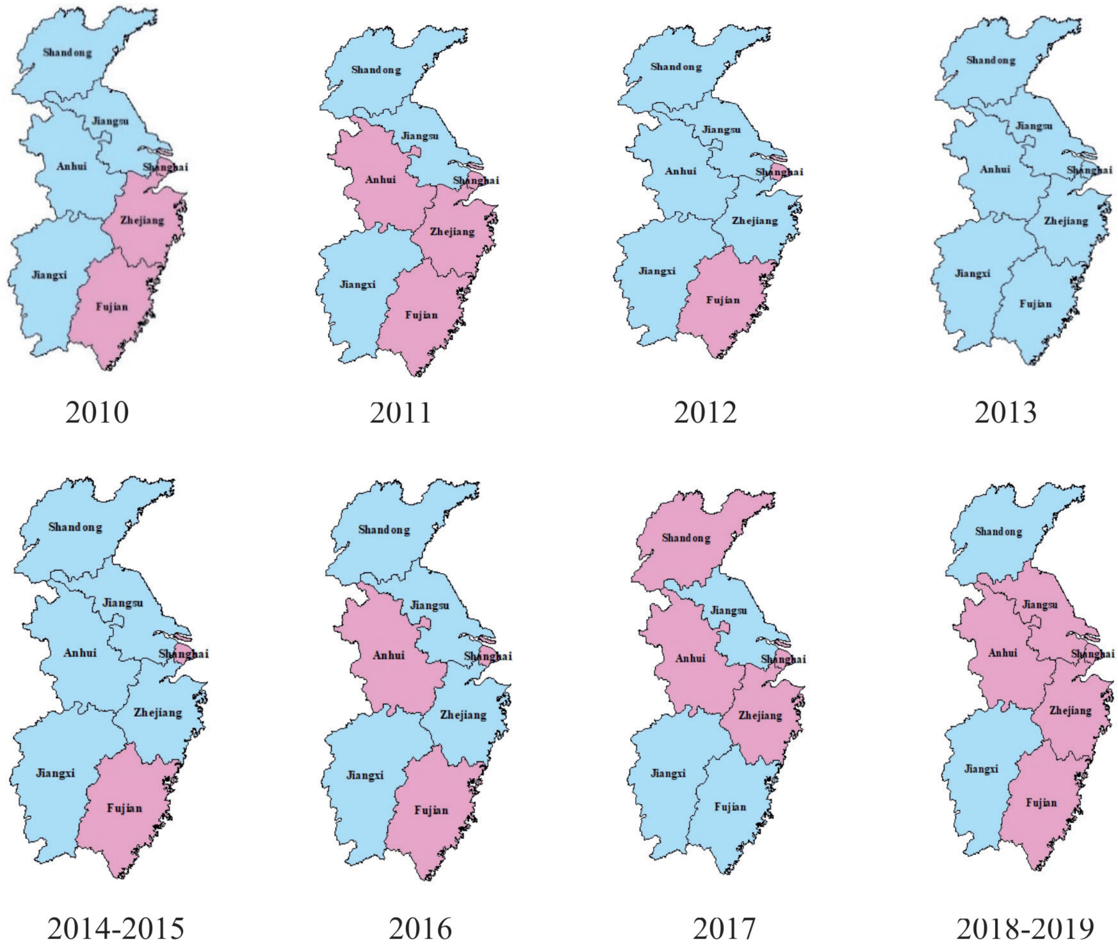


Fig. 5. The spatial evolution of 3E system stability in East China.

Sensitivity Analysis

In order to analyze the influence of evaluation indexes on the stability of the 3E system, the single factor rotating OAT method is adopted in this paper. This method carries out sensitivity analysis on the weight of the main change stability evaluation index and the proportional adjustment of the weight of other stability evaluation indicators. The specific calculation expression is as follows:

$$\begin{cases} W_{C_m}^p = W_{C_m}^0 + W_{C_m}^0 \cdot p, 1 \le m \le n \\ W_{C_i}^p = \dfrac{1 - W_{C_m}^p \cdot W_{C_i}^0}{1 - W_{C_m}^0}, i \ne m, 1 \le i \le n \end{cases}$$

$$R_{C_m}^p = W_{C_m}^p \cdot A_m + \sum_{i \ne m}^{n} W_{C_i}^p \cdot A_i$$

$$MACR^p = \frac{1}{N} \sum \left| \frac{R_{C_m}^p - R_0}{R_0} \right| \times 100\% \tag{23}$$

Where $W^p_{C_m}$ is the weight of stability evaluation index C_m after change; $W^0_{C_m}$ is the initial weight of stability evaluation index C_m; p is the change amplitude of stability evaluation index C_m; $W^p_{C_i}$ is the weight of C_i of other stability evaluation indexes after change; $W^0_{C_i}$ is the initial weight of other stability evaluation indexes C_i; $R^p_{C_m}$ is the weight of stability evaluation index C_m after the weight is changed. A_m, A_i the risk status of the main change stability evaluation index and other stability evaluation indexes; $MACR^p$ is the absolute average rate of change.

Taking the above stability evaluation results in East China for further analysis and taking 2019 as an example, the change rate of the evaluation results is much lower than that of the weight. Under the condition that the index weight changes by 5% and 10%, the overall change rate of the evaluation results fluctuates between -1% and 1%, which proves the stability of the stability evaluation system of the 3E system in this paper. The results are as follows:

(1) The evaluation results showed an approximate linear increase with the increase in the absolute value of the weight change rate, and each stability evaluation index had different change rate values.

(2) For the same evaluation factor, when the absolute value of the weight change rate is the same, its sensitivity is the same.

Space-Time Evolution Analysis of Stability

The Time Evolution of the Stability of Each Province and City

According to the results of the 3E system evaluation in the East China region, the evolution situation can be divided into three types, namely, the fluctuation rising situation, the relatively stable situation, and the fluctuation decreasing situation, as shown in Figs 6, 7, and 8.

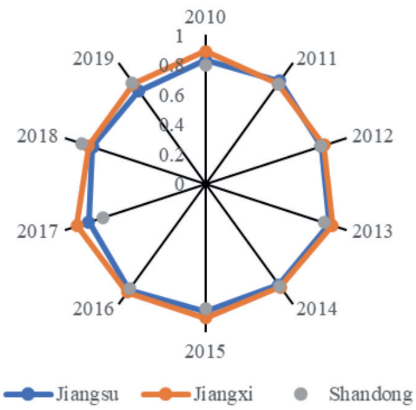


Fig. 6. The fluctuation rising situation.

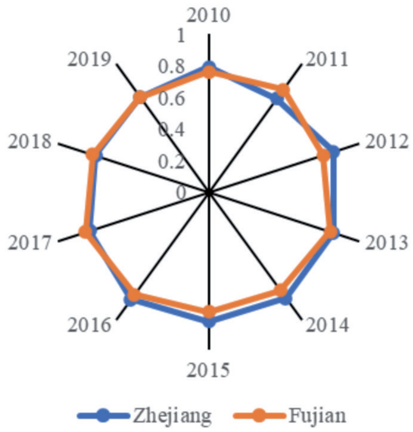


Fig. 7. The relatively stable situation.

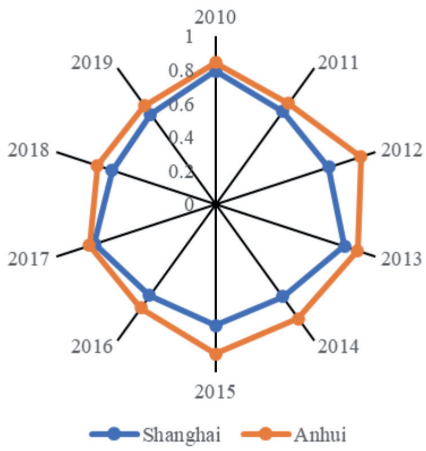


Fig. 8. The fluctuation decreasing situation.

(1) The fluctuation rising situation - Jiangxi, Jiangsu, and Shandong

The situation involves three provinces: Jiangxi, Jiangsu, and Shandong. The 3E system exhibits strong stability but shows a fluctuating trend. The upward trend in the region can be attributed to the positive indicators in these provinces. From an energy-economy coordination perspective, Jiangxi Province maintains a consistently excellent level of energy consumption per unit GDP at the national level, with non-fossil energy expected to account for over 18.0% of total energy consumption. In Jiangsu Province, the local energy supply is relatively balanced; by the end of 2023, electricity consumption reached 783.3 billion KWH, representing a 5.9% increase compared to previous years. Shandong Province has accelerated structural adjustments and transformations in its energy industry while promoting green and low-carbon energy consumption and supply. During the sample period, there was a significant decrease of approximately 34%.

(2) The relatively stable situation in Zhejiang, Fujian

This situation involves Zhejiang and Fujian provinces; the 3E system is relatively stable and has little fluctuation. The main reason for this stability in the two provinces lies in their perfect regional top-level design and minimal changes in energy supply and consumption. In particular, Zhejiang Province has made overall considerations for energy supply and demand, accelerating the upgrade of its energy structure, and resulting in significant improvements in both energy structure optimization and utilization efficiency. On the other hand, Fujian Province has capitalized on its natural resources to expedite the development of nuclear power, wind power, and photovoltaic power generation. Clean energy installed capacity has become the primary component of new power installations within the province, with an increase of 9.16 million kilowatts accounting for 88% of total new power installations.

(3) The fluctuation decreasing situation in Shanghai, Anhui

This situation involves two regions: Shanghai and Anhui. The 3E system is relatively stable but not strong, showing a trend of decreasing volatility. The main reason for the instability of the 3E system in these two regions is their heavy reliance on energy supplies from other provinces, resulting in a significant reduction in self-sufficiency rates. Among them, Shanghai, as China's international metropolis, continues to experience an expansion in total energy consumption with a "V" shaped growth rate; however, it heavily depends on other provinces and cities for its energy needs. On the other hand, Anhui province primarily relies on coal consumption as its main source of energy while also supplementing it with various other forms of energy consumption. Consequently, coal consumption holds an absolute advantage in terms of energy usage within the province. Therefore, there has been insufficient improvement regarding the availability of energy resources systemically, sustainability within both provinces' energy-ecosystem and stability within their respective energy-economic-environment systems.

Spatial Evolution of the Stability of Provinces and Cities

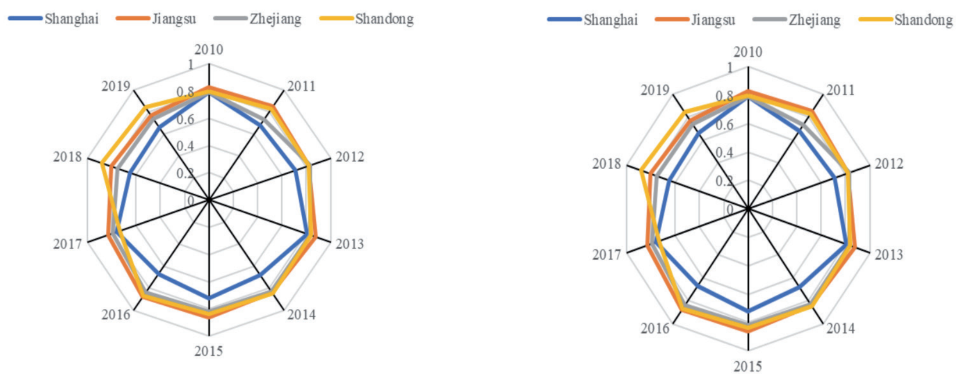
To evaluate the spatial evolution trend of 3E system stability in East China, it is divided into two categories based on the level of regional economic development: Class A regions and Class B regions. Category A includes Shanghai, Jiangsu, Zhejiang, Shandong, and the other four provinces determined by the regional GDP level of China as a whole. Class B regions have a slightly lower economic development level compared to Class A regions and include Jiangxi, Fujian, Anhui, and the other three provinces. For horizontal comparative analysis, refer to Fig. 9.

(1) The spatial evolution trend of 3E system stability in the Class A region is relatively stable with little fluctuation, and the coordination of the energy economic system is good. The stability order of the 3E system in this region is Jiangsu > Shandong > Zhejiang > Shanghai. In terms of regions, compared with other provinces, the Jiangsu 3E stability system has a higher evaluation index value, mainly due to the balance between ecological sustainability and economic coordination, which strictly controls the continuous rise of carbon emissions, loose coal pollution, and other indicators, optimizes the energy structure, and improves the comprehensive energy utilization rate. Although Shandong Province has abundant energy reserves and good economic coordination, its energy consumption is still dominated by fossil fuels, resulting in serious environmental pollution and poor ecological sustainability. Zhejiang Province, as a typical power-receiving grid, faces a serious shortage of local energy demand and supply, resulting in poor availability of the energy-resource system. However, it exhibits good economic coordination and ecological sustainability. Shanghai, like Zhejiang Province, has relatively scarce local resources. In the face of continuous growth in per capita energy consumption, the coordination of the energy-resources system has been at a low level. Therefore, it is necessary to strengthen the coupling development of multiple types of energy and gradually improve the comprehensive energy utilization rate while reducing environmental pollution emissions. This will help improve the stability of the regional 3E system in an orderly manner.

(2) The spatial evolution trend of 3E system stability in the Class B region is relatively poor, which is reflected in the low energy utilization rate. The stability order of the 3E system in this type of region is Jiangxi > Anhui > Fujian. In terms of regions, Jiangxi Province still relies on fossil energy to maintain regional energy efficiency levels despite the presence of large energy-consuming industries, resulting in a lack of stability in the regional 3E system. However, the province is easily influenced by stability evaluation indexes such as energy intensity and loose coal pollution rate, which further highlights the issue of the low energy utilization rate in the region. Anhui Province is rich in various types of energy resources and has strong energy availability. However, due to problems such as low regional energy efficiency and serious environmental pollution, regional economic coordination and ecological sustainability are poor. Fujian Province's performance in terms of energy availability, ecosystem sustainability, and economic coordination is not satisfactory, resulting in a low evaluation of the regional 3E system's stability.

Conclusions and Policy Recommendations

Based on the data on energy, economy, and environment in East China from 2010 to 2019, the stability evaluation index system of the energy-economy-environment system (3E system) in East China was



Class A area 3E stability evaluation distribution map

Class B area 3E stability evaluation distribution map

Fig. 9. Distribution of 3E stability evaluation in Class A and Class B areas.

constructed based on the principal component-matter-element extension evaluation model, and the stability evaluation situation and spatio-temporal evolution trend of provinces and cities in East China were analyzed, providing a solid scientific basis for the government to formulate policies. Specific research conclusions are as follows:

(1) As China's strong province in economic development, East China has strong economic coordination and ecological sustainability. However, with the high energy demand, the demand for the availability of energy resources is large, which affects the stability evaluation of the regional 3E system.

(2) According to the spatio-temporal evolution results, from the stability evaluation results of the time dimension, the fluctuation rising situation > the relatively stable situation > the fluctuation decreasing situation. From the perspective of spatial stability evaluation results, the 3E system stability evaluation results of the Class A region are higher than those of the Class B region (3E system stability evaluation results).

(3) On the whole, the 3E stability evaluation of East China is mainly affected by the self-sufficiency rate, energy intensity, loose coal pollution rate, and other indicators. It should be combined with regional resource endowment to coordinate the development of multiple types of energy, optimize the energy structure, and improve the comprehensive utilization rate of energy.

The research presented in this paper has the following policy implications: First, it is imperative to expedite the layout of the new energy industry and promote clean energy utilization. In response to the energy shortage in East China, diversifying the energy supply through renewable sources such as photovoltaic power generation and wind power should be pursued. Particularly given its advantageous location along China's eastern coast, East China possesses immense potential for offshore wind energy. Consequently, governmental support for new energy sectors like photovoltaics and wind power should be intensified by encouraging relevant enterprises to advance their technological capabilities while providing corresponding preferential policies pertaining to financing. Second, enhancing energy efficiency and implementing clean technologies are imperative. Encouraging innovation in green technology is a crucial step towards achieving sustainable development and ensuring the stability of the 3E system. The presence of numerous universities in East China offers a favorable technical environment for enterprises to engage in collaborative endeavors related to green technology innovation. Third, it is advisable to enhance environmental governance. Strengthening the supervision and regulation of pollutant discharge, particularly in relation to air pollution, water pollution, and solid waste control, is crucial. Encouraging enterprises to adopt cleaner production technologies, expanding the pollution control industry chain, and promoting green development are essential measures. Last, the seven provinces located in East China should bolster coordination and collaboration across different provinces concerning energy, environment, and economic advancement. This can be achieved by promoting trans-regional energy interconnection, augmenting both energy transmission capacity and comprehensive utilization capacity.

Although this paper constructs a relatively scientific and reasonable evaluation model to analyze the stability and spatio-temporal evolution characteristics of the 3E system in East China, there are inevitably some limitations inherent in this study. For instance, the research sample selected for investigation is limited to East China, which represents one of the most economically active regions in China and holds significant research significance. However, it should be noted that the less developed western region has not been taken into account, particularly regarding the evident resource disparities between the eastern and western regions. This aspect warrants further exploration in future studies.

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Conflict of Interest

The authors declare no conflict of interest.

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