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Research article

Integrated assessment and influencing factor analysis of energy-economy-environment system in rural China

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Abstract: With China's economic growth, energy-economy-environment (3E) issues in rural areas have become more prominent. As key areas for energy consumption and environmental protection, analyzing the influencing factors of the 3E system in rural areas is crucial. We constructed and analyzed the rural 3E model using clustering and examined the relationship between scientific and technological talent, the economic level of rural residents, and 3E development through principal component regression. The findings showed: (1) Overall improvement in 3E development, with coastal and non-coastal areas showing significant differences; (2) room for energy improvement, rapid economic growth, and more balanced environmental development in some regions; (3) scientific and technological talent and economic level significantly impacted 3E development; and (4) in coastal areas, talent development had a greater impact, while in non-coastal areas, both talent and economic development had comparable effects. Moreover, 1-unit increase in talent development in coastal areas boosted 3E development by 0.12 units, while in non-coastal areas, talent and economic level increased 3E development by 0.04 and 0.06 units, respectively.

Keywords: rural areas; energy-economic-environmental (3E) systems; cluster analysis; principal component analysis

1. Introduction

With China's economic development, contradictions between energy consumption, economic growth, and environmental protection in rural areas have intensified, leading to energy shortages, pollution, and ecological degradation, which constrain rural economic development and affect farmers' quality of life [1]. Research on the influencing factors of the energy-economy-environment (3E) system in rural China is of great practical significance. The 3E system in rural China is a complex and interconnected system, influenced by factors such as energy supply methods, economic development levels, environmental awareness, policies, technological progress, demographic changes, and climate change. These factors interact and constrain each other, forming a dynamic system. The energy supply mode plays a key role in 3E system development, with traditional biomass energy impacting the environment and energy efficiency, while clean energy reduces environmental burdens and improves efficiency. Economic development significantly impacts the 3E system by improving infrastructure, promoting technological progress, and raising environmental awareness. The promotion of environmental protection requires efforts from the government, social organizations, and rural residents. Additionally, policy formulation, technological innovation, demographic trends, and climate change adaptation all influence the sustainable development of the 3E system in rural areas. A deep analysis of these factors is needed to promote sustainable rural development, helping to identify bottlenecks and providing a scientific basis for governments and relevant departments to formulate effective policies and measures [2]. In the context of the 14th Five-Year Plan, which emphasizes prioritizing agriculture and rural revitalization, the importance of this study is further highlighted. In rural areas, the balance between energy consumption, economic development, and environmental protection is key to achieving sustainable development. Energy shortages, which not only restrict rural economic growth but also affect farmers' livelihoods, are particularly prominent. Moreover, the ecological environment faces serious threats due to inadequate environmental protection measures and awareness. To address these issues, a comprehensive analysis of the factors affecting the rural 3E system from multiple perspectives is needed, including government policies, changes in rural industry structure, increased environmental awareness among farmers, and the promotion of scientific and technological innovations [3].

The core areas of energy and economics research include energy supply and demand, energy markets, energy policy, and the energy-environment nexus. In these areas, in-depth discussions have been conducted, focusing on the supply and demand of traditional and renewable energy sources, the functioning of energy markets, the impact of energy policies on the energy economy, and the balance between energy and the environment [4]. However, research on the 3E in rural areas remains insufficient and lacks focus on the specificity and complexity of rural areas. The main focus of energy and environmental research has been placed on energy efficiency, technological innovation, and energy policy [5]. Energy and environmental efficiencies have been identified as key indicators of the relationship between economic development, energy consumption, and environmental impacts, with technological innovation being emphasized as central to solving energy and environmental problems [6]. In rural areas, energy and environmental issues are linked not only to the conflict between energy consumption and pollution but also to the balance between ecological protection and economic development. Researchers should focus on the design and implementation of 3E policies and the role of technological innovation in improving energy-environmental efficiency. Existing research has not sufficiently addressed these issues in rural areas. We aim to fill this gap by studying the three aspects of 3E and offer policy suggestions for rural areas to support their sustainable development.

Scholars have provided various insights on these topics from different perspectives. Li et al. (2023) found that the overall level is high, but there are regional differences [7]. Li et al. (2023) pointed out that EU countries with different levels of economic development should adopt different strategies to ensure the simultaneous development of their digital economy and 3E efficiency [8]. Yu et al. (2022) studied the coupling problem of economy-energy-environment-technology co-ordinated development and its temporal evolution characteristics in four provinces (regions) of the Northeast region [9]. Ma et al. (2022) reviewed the research progress on the relationship between 3E from a spatial perspective [10]. Zhang et al. (2022) empirically analysed the relationship between the digital economy, energy efficiency and carbon emissions [11]. Yang et al. (2021) reviewed the research on integrated performance evaluation of 3E of solid waste resourcing [12]. Li et al. (2021) studied the coordinated development of 3E, science and technology in the Beijing-Tianjin-Hebei region [13]. Luo et al. (2020) analysed the degree of coupled 3E coordination between provinces in China and found that there are regional differences and fluctuations over time [14]. Tang et al. (2020) studied the influence mechanism of interprovincial eco-efficiency and found that it was influenced by multiple factors such as energy structure, industrial structure, and technology level [15]. Yan et al. (2019) constructed a coupled coordination model based on coupling theory and quantitatively studied the coupled and coordinated development of Australia's energy, economy, and ecology [16]. Yu et al. (2019) studied the evolution of the coordinated development pattern of the 3E, and science and technology quaternary systems in the eastern region [17]. Most literature focuses on urban areas, with limited research on rural areas and few comprehensive assessments of the influencing factors [18,19]. We aim to explore these factors and provide a scientific basis for formulating policies to promote sustainable rural development, ensuring coordinated progress in the economy, environment, and society.

We conducted an in-depth study of the factors influencing the 3E system in rural China, aiming to improve the theoretical system of sustainable development, provide a scientific basis for targeted policy measures, and promote rural sustainability. We found the macro-level operation of the rural 3E system and explored the micro-level factors influencing it. The study helps fill gaps in domestic and international research and offers suggestions for sustainable rural development theory. It also addresses issues related to energy consumption structure, energy efficiency, and environmental pollution in rural areas, providing theoretical support for optimizing energy structure, improving efficiency, and reducing pollution. Additionally, it offers a scientific basis for policies to promote coordinated development of the economy, society, and environment in rural areas.

The paper is structured as follows: In Section 2, we review the literature; in Section 3, we present the theoretical foundation and 3E model; in Section 4, we detail the methodology; in Section 5, we report the results from the cluster analysis; in Section 6, we discuss factors through principal component and heterogeneity analyses; and in Section 7, we conclude with our findings and future outlook.

2. Literature review

2.1. Overview of energy-economic research

Scholars have extensively studied renewable energy supply and demand. Zhang et al. (2022) explored transition paths and policies for carbon neutrality [20]; Fang (2022) focused on the energy economy in relation to peak carbon and carbon neutrality [21]. Hassan et al. (2022) examined the role of energy efficiency, renewable energy, and technological progress in reducing ecological footprints across 16 OECD countries from 1990 to 2020 [22]. Energy economic security is crucial for national stability. Zhang et al. (2020) analyzed challenges to China's energy security and suggested strengthening security systems and promoting energy consumption and supply revolutions [23]. These studies highlight both traditional and renewable energy development, as well as their economic and environmental impacts.

The operation mechanism and efficiency of the energy market are key areas of energy economy research. Tang et al. (2024) analyzed China's energy economy using an index evaluation system, highlighting stable growth but regional and industrial differences, and offering policy recommendations for high-quality development [24]. Yang et al. (2023) examined urban waste logistics from a waste-energy-economy perspective, proposing improvements to energy efficiency and economic benefits through optimized waste collection [25]. Xie et al. (2022) studied the economic consumption of new energy in microgrids and proposed an optimal shared energy storage allocation scheme [26]. Li et al. (2021) investigated the green certificate market trading based on renewable energy economic dispatch [27], and another Li et al. (2021) empirically assessed the impact of energy structure and digital economy on carbon emissions, revealing the significant role of coal-based energy in driving emissions [28]. Nong (2019) explored the theoretical nature and path of modern energy economic development, emphasizing innovation-driven strategies for optimizing the energy structure and achieving coordinated development [29]. These studies illustrate the complexity and mechanisms of the energy market from various perspectives.

Energy economic policy plays a crucial role in the development of the energy economy. Liu et al. (2024) explored the role of carbon pricing and renewable energy policies in promoting energy system transformation, emphasizing the need for policy formulation to consider various factors' comprehensive impacts [30]. Xia et al. (2024) studied how transition climate risk affects carbon emission efficiency in energy companies from a policy perspective [31]. Chen et al. (2024) examined the policy mechanisms for wind and new energy power markets from an international benchmarking perspective [32]. Zheng et al. (2024) explored the relationship between local government responses and industrial upgrading using new energy vehicle policies as a case study [33]. Zhou et al. (2023) analyzed the impact of China's new energy demonstration city policy on the green innovation of new energy enterprises [34]. Hu et al. (2023) examined improvements to rural energy policy and legal systems, stressing their importance in promoting rural energy development and economic transformation [35]. Huang et al. (2021) discussed the energy revolution and China's energy security [36], while Xu (2020) analyzed China's energy development and economic efficiency from a macro perspective [37]. These studies provide valuable insights for formulating effective energy policies to promote sustainable energy economy development and achieve carbon neutrality.

2.2. Overview of energy-environment research

The relationship between energy and the environment has become a key research focus due to growing environmental challenges. For example, Wang et al. (2022) explored the economic scheduling of integrated energy in parks, considering demand response, comfort, and carbon trading [38]. Che et al. (2022) examined the impact of trade liberalization on the energy-economic efficiency of the logistics industry [39]. Gao et al. (2018) studied the tail efficiency of energy and environmental constraints during urbanization, concluding that the effects of these constraints on economic growth and energy consumption are becoming more evident, with the government needing to address these issues to promote balanced economic and environmental development [40]. These studies emphasize the importance of balancing environmental protection with economic growth, reflecting the trend towards more diverse and in-depth research in the energy-environment field.

Technological innovation is crucial for addressing energy and environmental issues. Zhang et al. (2023) examined the impacts of energy and power system transitions on China's environment, highlighting challenges and opportunities in the process [41]. Wang et al. (2020) studied energy and environmental efficiency in Chinese cities, stressing the role of technological innovation in improving efficiency [42]. These studies offer valuable insights for promoting technological innovation to achieve sustainable energy and environmental development.

Energy and environmental efficiencies are key indicators for assessing the relationship between economic development, energy consumption, and environmental impact. Scholars have studied this topic from various perspectives [43]. Zhao et al. (2022) explored the issue of non-differentiated model planning in distribution systems within an integrated energy environment [44]. Wang et al. (2020) examined industrial energy-environmental efficiency in China, focusing on technological heterogeneity [45]. Wen et al. (2020) analyzed the medium- and long-term trends of China's consumption and its impact on the energy environment, concluding that the transformation of consumption structure would increase pressure on the energy environment, necessitating government policies to optimize consumption and energy structures [46]. Huang (2018) studied the spatial correlation network of China's energy and environmental efficiency, identifying influencing factors across regions, which provides insights for policy formulation [47]. These studies offer diverse perspectives and methods for understanding energy-environmental efficiency.

Energy policies and talent mechanisms significantly impact environmental protection. Zhao et al. (2024) explored the cultivation of dual-carbon talents with an international perspective, highlighting its importance for global governance [48]. He et al. (2023) investigated the role of carbon trading policies in alleviating rural energy poverty and found positive effects on rural development [49]. These studies are key references for formulating effective energy policies that balance economic development and environmental protection.

2.3. Comprehensive overview

An overview of energy-economic and energy-environmental studies is provided, covering supply and demand, markets, policies, and the energy-environment relationship. However, research on 3E issues in rural areas is insufficient. While researchers examining energy economy focus on renewable energy, they overlook rural specifics, such as energy demand, access to renewables, and policy impacts. Additionally, environmental policy evaluations are lacking. Energy-environmental research mainly targets efficiency and innovation, but rural areas face challenges beyond energy-pollution conflicts, involving the balance between ecological protection and economic growth. Researchers should focus on improving efficiency, fostering economic and ecological balance, and exploring policy and technological innovations. We conclude that the existing research is narrow, and rural 3E issues require deeper analysis, considering rural specifics and the role of policies and innovation. Targeted recommendations will be provided.

3. Theoretical basis and evaluation system

3.1. 3E system theory

The 3E systems theory provides a comprehensive framework for studying the interactions and impacts between the energy, economic, and environmental systems. The theory emphasizes the interdependence and complexity of these systems, which have become increasingly interconnected as globalization and industrialization progress. This growing interdependence poses significant challenges: i) The energy system, a central component of the theory, covers the process of energy generation, conversion, transport, and use. Its primary objective is to meet the energy needs of social and economic development while ensuring environmental and resource sustainability. Various energy sources, including fossil fuels, nuclear energy, and renewables, play distinct roles in the energy system, each with specific characteristics, advantages, and disadvantages [50]. ii) The economic system, another key component of the theory, encompasses activities such as production, distribution, exchange, and consumption. Its goal is to achieve macroeconomic objectives, including economic growth, employment, price stability, and balance of payments. Within the 3E system, the economic system significantly impacts both the energy and environmental systems through factors like investment decisions, technological innovations, and policy formulation. iii) The environmental system addresses the sustainability of natural resources, ecosystem health, and the effects of human activities on the environment. The goal of the environmental system is to achieve environmental sustainability, maintain ecological balance, and ensure the long-term use of natural resources. Environmental systems are directly influenced by both energy and economic systems, particularly through issues such as environmental pollution, climate change, and resource overconsumption.

The core of the 3E systems theory lies in the study of the interactions and impacts between these three systems. These interactions can be positive, such as energy development promoting economic growth and environmental policies enhancing environmental quality, or negative, where environmental pollution hinders economic development and excessive energy consumption threatens environmental sustainability. Understanding and analyzing these interactions is essential for formulating effective policies and measures to achieve sustainable development. The 3E systems theory posits that energy consumption, economic development, and environmental protection are mutually constrained and reinforcing. Energy supply and demand directly influence economic development, which in turn affects energy supply and demand. Similarly, environmental protection and pollution control are closely linked to both energy consumption and economic development. To achieve coordinated development across the 3E systems, a holistic approach is required, integrating various factors and promoting sustainable development through effective policy measures and technological innovation.

3.2. Indicator construction for the 3E model in rural areas

In constructing a system of evaluation indicators for the 3E system in rural areas, the situation and characteristics of rural areas have been fully considered. It is hoped that the established system will comprehensively, objectively, and effectively reflect the three aspects of energy consumption, economic development, and environmental protection in rural areas, providing a scientific basis for policymakers and relevant departments.

Energy consumption indicators have been identified as a key component in evaluating energy use in rural areas. These indicators include rural electricity consumption, per capita use of renewable resources, and others. Rural electricity consumption reflects the supply and consumption of electricity in rural areas, while per capita renewable energy use reflects the extent of renewable energy usage [51]. Together, these indicators provide a comprehensive picture of energy consumption in rural areas.

Economic development indicators have been established as an important basis for evaluating the economic development level in rural areas. These indicators include per capita disposable income of rural residents, per capita output value of primary industry, and retail sales of social commodities in villages. Per capita disposable income reflects the living standard of rural residents, per capita primary industry output shows the effectiveness of agricultural production, and rural retail sales of social commodities indicate the activity level of the rural market. Together, these indicators reflect the economic development level in rural areas.

Environmental protection indicators are crucial in evaluating the ecological environment in rural areas. These indicators include effective irrigated area, food production, and chemical substance inputs. The effective irrigated area reflects the infrastructure of agricultural production in rural areas, grain output directly reflects the results of agricultural production, and chemical inputs indicate the environmental impact of agricultural production. These indicators collectively form the evaluation system for the ecological environment in rural areas.

The construction of these indicators is shown in the Figure 1, and the indicators are interrelated, constituting a complete evaluation system. This system provides a comprehensive understanding of energy consumption, economic development, and environmental protection in rural areas, offering strong support for policy formulation and implementation. In future development, the system will need to be optimized and improved based on the actual situation and needs, ensuring that it better serves the development of rural areas. The construction of specific indicators is illustrated in Figure 1.

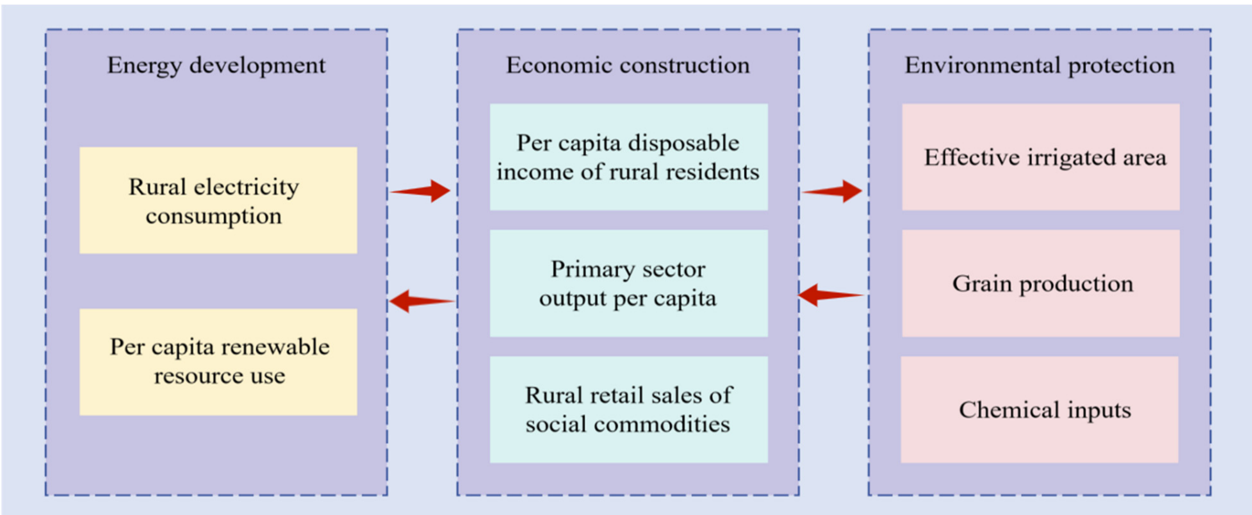


Figure 1. Evaluation model of energy-economic-environmental system (3E) in rural areas.

3.2.1. Construction of indicators for the energy development category

(1) Rural electricity consumption

Rural electricity consumption, as a critical indicator of energy use, directly reflects the energy demand in rural areas for both production and daily life. By analyzing rural electricity consumption data, insights are provided into the current status of rural energy consumption, emerging trends, and existing issues. Such analysis is essential for informing rural energy policy, optimizing the energy structure, enhancing energy efficiency, and advancing sustainable rural development.

(2) Per capita renewable resource use

The per capita renewable energy use indicator is a key metric for assessing the development and utilization of renewable energy in rural areas. It provides insight into the extent of renewable energy adoption, its efficiency, and its growth potential. Analyzing this indicator offers policymakers a solid foundation for designing more effective and targeted policies. Furthermore, increasing per capita renewable energy use is a crucial strategy for transforming the rural energy structure, reducing carbon emissions, protecting the ecological environment, and fostering green development in rural areas.

3.2.2. Construction of indicators for the economic development category

(1) Per capita disposable income of rural residents

Disposable income per rural inhabitant is a crucial indicator in assessing rural economic development. It serves as both a key measure of rural economic progress and a direct reflection of the living standards and economic well-being of rural residents. This indicator helps to gauge the income levels and quality of life in rural areas, as well as the overall development of the rural economy. By conducting thorough analyses of this indicator, a clearer understanding of the current state and future trends of rural economic development can be obtained, providing a solid foundation for the formulation and adjustment of rural economic policies.

(2) Primary sector output per capita

Per capita primary sector output is a vital indicator in assessing rural economic development. It reflects the efficiency of agricultural production in rural areas and indicates the scale of agricultural production. By thoroughly studying this indicator, the current state of rural agricultural production, existing challenges, and future development potential can be clearly understood. This provides valuable insights for formulating agricultural policies, optimizing the agricultural industry structure, and enhancing agricultural production efficiency.

(3) Rural retail sales of social commodities

Social goods rural retail sales serve as a crucial indicator of consumption levels and market dynamism in rural areas. This indicator reflects the strength of demand, consumption potential, and overall market activity in rural regions. By analyzing rural retail sales of social commodities, a clearer understanding of rural market supply and demand can be gained, which helps identify development opportunities and guide policies for the sustainable growth of the rural economy.

3.2.3. Construction of indicators in the category of environmental protection

(1) Effective irrigated area

Effective irrigated area is a critical indicator for assessing agricultural production conditions in rural China. It reflects the status of irrigation infrastructure and highlights the balance between agricultural productivity and the ecological environment. A thorough analysis of the effective irrigated area offers valuable insights into the current state of agricultural production and the environmental changes occurring in rural areas. This understanding provides a solid foundation for the formulation and adjustment of agricultural policies, ensuring that both agricultural development and ecological sustainability are adequately addressed.

(2) Grain production

Grain production is a fundamental indicator of agricultural capacity in rural areas, directly linked to food security and the broader agricultural development agenda in China. It reflects both the level of agricultural productivity and the efficiency of resource utilization. A detailed analysis of grain production provides insights into the strengths and weaknesses of agricultural output, highlights the impact of environmental factors on production, and enables the formulation of effective strategies to ensure food security and promote sustainable agricultural development.

(3) Chemical inputs

The use of chemical inputs in agricultural production has contributed to increased crop yields but also raised concerns about environmental pollution. The indicator of chemical inputs reflects the extent of chemical pollution in rural agricultural practices and highlights the environmental impact of farming activities. Studying this indicator provides valuable insights into the risks posed by agricultural practices to the environment and offers scientific data to inform the development of environmental protection policies. Additionally, it helps guide farmers in the rational use of chemical substances, reducing environmental pollution and promoting sustainable agricultural practices.

The construction of an evaluation index system for the 3E systems in rural areas enables a comprehensive assessment of the development status of energy, economy, and environment. It provides valuable insights for the formulation of targeted policies and measures to promote the coordinated development of 3E in rural areas. Further studies will explore the factors influencing the 3E model, laying a solid foundation for achieving sustainable development in rural areas.

4. Method

4.1. Data collection and processing

In this study, data from 31 provinces in China from 2010 to 2020 are selected, primarily sourced from the China Agricultural Statistics, China Energy Statistics Yearbook, China Statistical Yearbook, and China Rural Statistics Yearbook. The collected data include rural electricity consumption, per capita disposable income of rural residents, per capita primary industry output, rural retail sales of social commodities, effective irrigated area, grain production, and chemical substance inputs.

For data processing, the original data were cleaned, outliers were removed, and missing values were filled using the linear interpolation method. To account for differences in scale and value between indicators, the data were standardized and subjected to logarithmic transformation. Additionally, to mitigate the influence of the time span on the results, the annual fixed benefit method was applied.

4.2. Entropy weighting method to calculate weights

In constructing the evaluation index system for 3E in rural areas, the entropy weight method is employed to determine the weight of each index. This objective method of empowerment ensures that the weights are determined without the influence of human subjectivity. By using the entropy weight method, the weights calculated more accurately reflect the true status of the 3E systems in rural areas, providing a solid and scientific basis for policy formulation.

The entropy weighting method is used to calculate the weights of the evaluation indicators of the 3E system in rural areas in the following steps:

(1) Calculate the share X of the value of the ith indicator in the value of the indicator in year κ.

$$X_{ki} = x_{ki} / \sum_{k=1}^{m} x_{ki} \tag{1}$$

(2) Calculate the information entropy of the ith indicator E_ι.

$$E_i = -\frac{1}{\ln m} \sum_{k=1}^{m} x_{ki} \ln x_{ki} \tag{2}$$

(3) Calculate the information redundancy of the ith indicator D_ι.

$$D_i = 1 - E_i \tag{3}$$

(4) Calculate the ith indicator weight $W^{'}$.

$$W' = D_i / \sum_{i=1}^{n} D_i \tag{4}$$

The weights calculated using the entropy weight method provide a more accurate reflection of the real situation of the 3E system in rural areas, offering a scientific basis for policy formulation. Based on these weights, a comprehensive evaluation of the 3E system in rural areas is conducted, resulting in a final 3E score. This score serves as a crucial data foundation for subsequent research, helping to inform further analysis and recommendations for sustainable development in rural areas.

5. Results

5.1. Overall assessment

According to the data shown in Figure 2, the 3E system score in China, representing the combined indicators of energy, economy, and environment, has demonstrated a rising trend year by year from 2010 to 2020. This indicates a gradual improvement in the performance of China's regions in these three areas. The level of the 3E system score is not only crucial for assessing China's sustainable development, but also serves as an important benchmark for evaluating the progress of green development across regions.

However, despite the overall upward trend in 3E system scores, there are a few regions where scores have declined. This warrants attention, as such declines may signal underlying issues in the 3E development process. Possible problems in these regions could include inefficiencies in resource allocation, inadequate environmental protection measures, or an over-reliance on a singular economic development model. To better understand this situation, this paper will conduct a cluster analysis of the 3E system scores for the years 2010 and 2020. Cluster analysis is an effective data analysis method that groups regions based on their 3E scores. This allows for a clearer understanding of which regions are performing well in terms of 3E development and which regions face challenges. Such insights are critical for formulating targeted policies to address regional disparities in 3E development. When performing the cluster analysis, it is important to consider the unique characteristics of each region. For instance, some regions may exhibit high energy and environmental scores due to abundant natural resources, but their economic development may lag behind. In contrast, other regions may have strong economic growth but lower energy and environmental scores. These nuances must be taken into account when crafting policies to foster balanced development.

By comparing the 3E system scores from 2010 to 2020, regions can be categorized into different groups based on their scores, enabling an analysis of the trends in various regions. This categorization will provide valuable guidance for formulating more targeted, region-specific policies to promote the balanced and sustainable development of China's 3E system on a national scale.

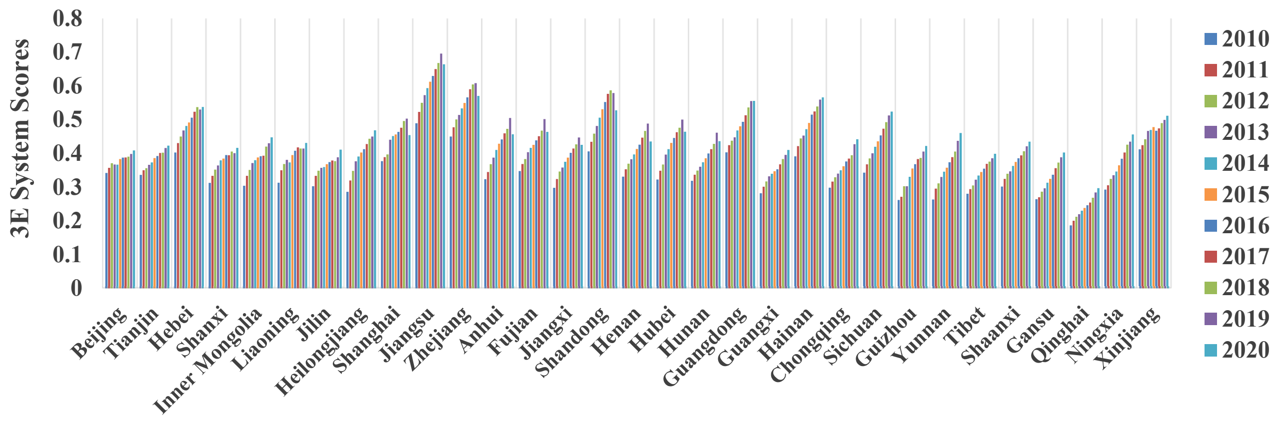


Figure 2. Rural 3E systems sub-region year-on-year trends, 2010–2020.

5.2. Cluster analysis

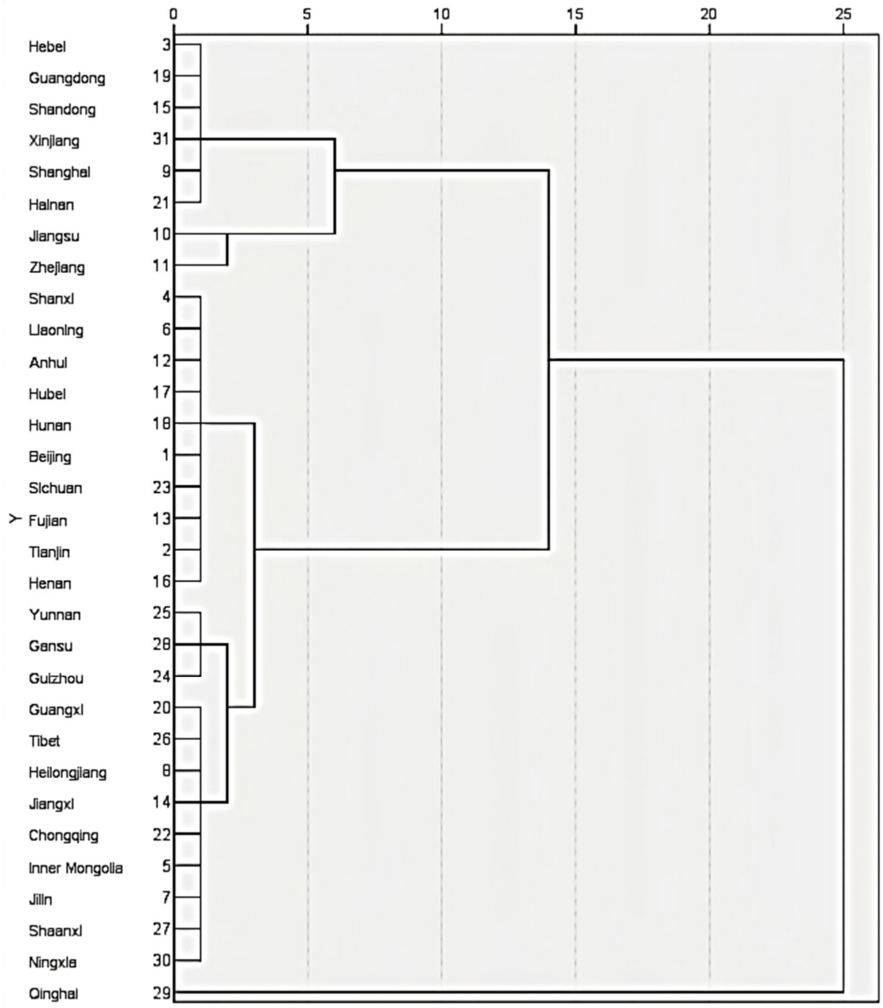


Figure 3. Cluster analysis of 3E systems in 2010.

In Figure 3, cluster analyses were conducted for each region to better understand the development status of the 3E system across China in 2010. The purpose of this cluster analysis is to categorize the regions according to their 3E performance and to provide valuable insights for policy formulation.

(1) Regions with a high level of development: These regions primarily include the eastern coastal areas and certain developed regions in central and western China, such as Guangdong, Shandong, and Shanghai. These areas have demonstrated excellent performance in 3E development and exhibit strong capabilities in coordinating energy, economic, and environmental goals. Years of rapid development have endowed these regions with not only a significant economic output but also impressive achievements in new industries, technological innovation, and environmental protection. The high level of development in these regions can be attributed to favorable geographical locations, policy support, and industrial restructuring. Moving forward, these regions are expected to continue playing a leading role in promoting coordinated regional development and contributing to the sustained growth of the national economy.

(2) Medium-level development regions: This category includes most of the central and western regions, such as Shaanxi, Gansu, and Tibet, as well as certain relatively developed areas. These regions show a more balanced level of 3E development and have the potential for further coordinated growth. Although there is a gap between these regions and the more developed ones, they possess advantages in terms of resource endowment, policy support, and industrial transformation. By leveraging these advantages, strengthening infrastructure, optimizing industrial structure, and improving public services, these regions are expected to make significant progress in development.

(3) Regions with lower levels of development: Represented by regions such as Qinghai Province, these areas face substantial development challenges and have relatively low levels of 3E performance. To achieve sustainable development, the government needs to increase policy support and address the specific bottlenecks hindering growth. Targeted development strategies should be formulated in the areas of energy, the economy, and the environment. Additionally, investments in public services, such as infrastructure, education, and healthcare, should be enhanced to improve the well-being of local populations and create a foundation for long-term development in these regions.

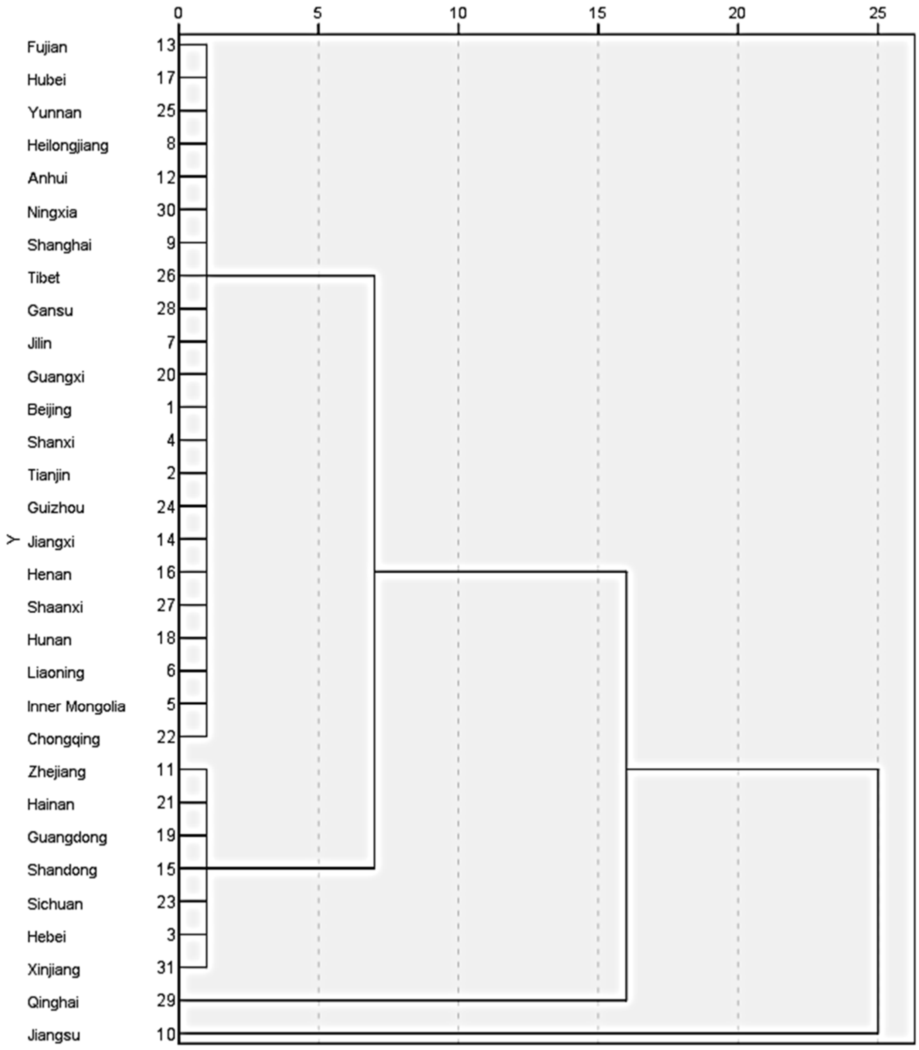


Figure 4. Cluster analysis of 3E systems in 2020.

The 3E system scores for 2020 were analyzed using cluster analysis, which categorized regions into three levels of development, as shown in Figure 4.

(1) High development level region: Jiangsu Province was identified as the region with the highest level of 3E development in 2020. The province demonstrated excellent coordination between energy, economic growth, and environmental protection, setting an example for other regions to follow.

(2) Medium-level development regions: These included regions in the eastern coastal areas and some developed central and western provinces, such as Fujian, Hubei, Anhui, and Shanghai. These regions maintained strong 3E performance and exhibited a solid capacity for further coordinated development. The experiences of these regions were found to offer valuable insights for promoting 3E development on a broader scale.

(3) Regions with lower levels of development: Qinghai Province was identified as a region with lower 3E development in 2020. Despite some improvements, the province's development in economic, energy, and environmental dimensions remained relatively underdeveloped compared to other regions, indicating significant room for progress.

The comparison between the cluster analysis results from 2010 and 2020 revealed a trend in the development levels of rural areas in China, highlighting the disparities between coastal and non-coastal regions. The results suggest that regions should tailor their development strategies based on their current state. Regions with high levels of development should be maintained as leaders in 3E coordination and continue to set examples. Medium-level regions should encompass accelerating development to join the ranks of high-level regions. Regions with lower levels of development should prioritize targeted reforms to enhance economic, energy, and environmental development. This analysis provides a foundation for policymakers to implement region-specific strategies and measures to promote coordinated 3E development across the country.

5.3. Subregional evaluations

In the previous section, a detailed cluster analysis of the 3E model scores was conducted, revealing a significant gap between coastal and non-coastal regions. This necessitated a separate evaluation of these two areas. In this paper, the 3E model scores of coastal and non-coastal areas were analyzed in depth. In non-coastal rural areas, the total 3E score varied from region to region, but with an overall upward trend. As shown in Figure 5, Beijing and Sichuan had higher total 3E scores in 2010, with Sichuan having the highest score in 2020. However, disparities between regions remained, such as Qinghai Province, which had a relatively low 3E score compared to others. In coastal areas, Figure 6 shows that overall development was better, with more regions at a higher level of development compared to non-coastal areas. The growth of coastal regions showed a broadly converging pattern. Moving forward, each region should develop targeted policies and strategies according to its specific conditions to accelerate rural development and close the development gap between regions. The overall 3E score trend will continue to play a key role in monitoring and assessing progress, providing useful guidance for policymakers and practitioners.

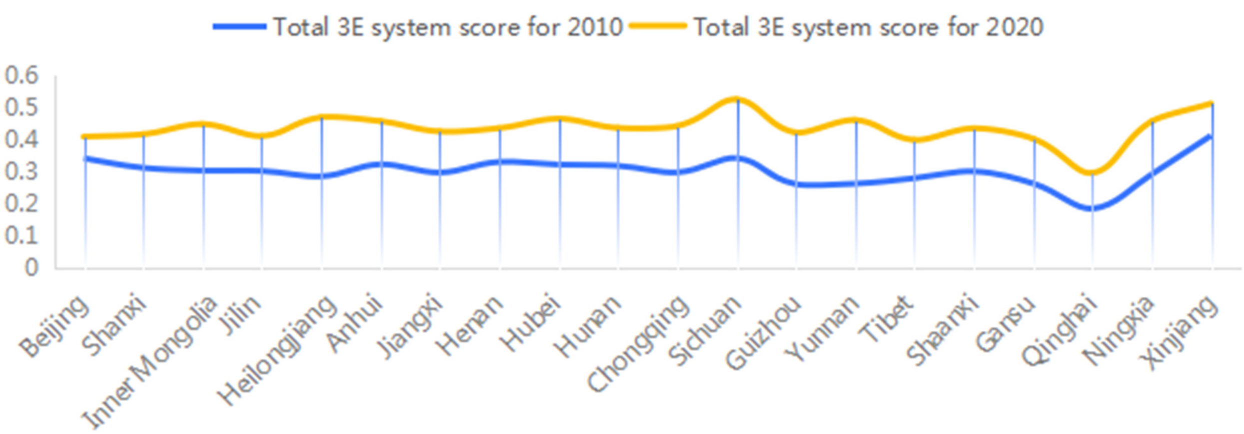


Figure 5. Evaluation of the 3E model for non-coastal rural areas.

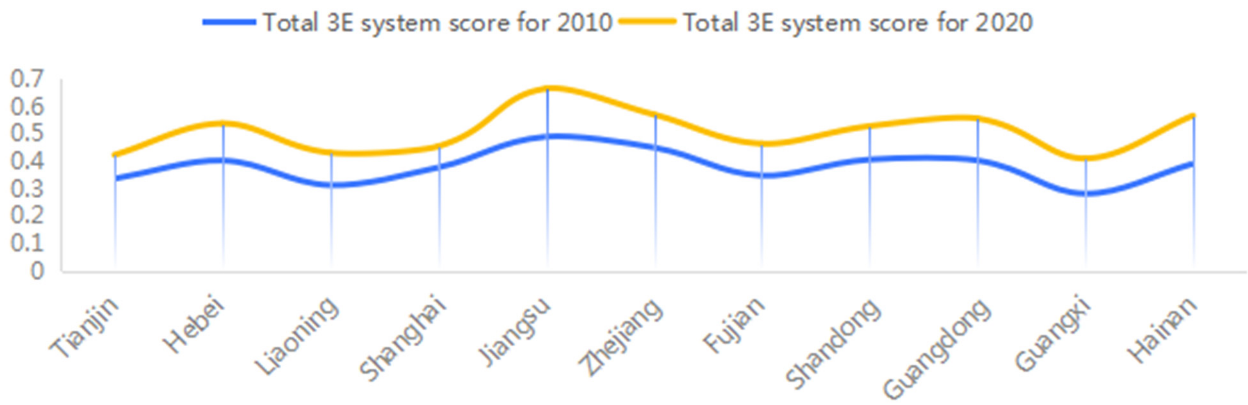
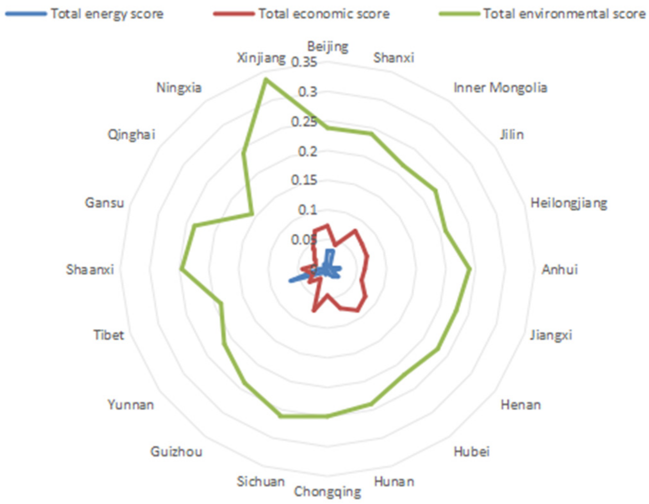


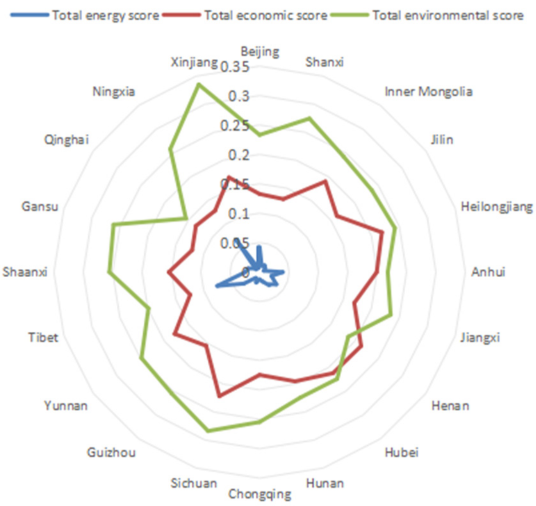
Figure 6. Evaluation of the 3E model for rural coastal areas.

To better analyze the development of 3E in rural areas, more specific analyses are conducted, as shown in Figure 7. First, overall, the total scores across the three dimensions exhibit a clear upward trend, indicating positive development. Second, in terms of the internal composition of the three dimensions, the development of the environment and the economy shows a good synchronization, while energy development lags behind. This suggests that, in rural areas of China, the development of the environment and economy are, to some extent, mutually reinforcing, but the sustainable development of energy requires further attention. Additionally, judging from the development of various types of regions, coastal regions outperform non-coastal regions in all three aspects of 3E. This difference can be attributed to the geographical advantages and policy support that coastal regions enjoy. Further sub-regional evaluation of the 3E model reveals that there are disparities in the development of each region in the three areas of 3E. For instance, in terms of energy development, most regions have considerable room for improvement. In the economic domain, some regions show faster development, with most coastal regions performing better than non-coastal areas. As for the environment, most regions demonstrate more balanced development. Based on the analysis above, policymakers should focus on increasing investment in energy infrastructure, improving energy efficiency, and promoting the optimization of the energy structure in regions lagging in energy development. Furthermore, the development and use of renewable energy should be encouraged to foster green energy development in rural areas. Regarding the development gap between coastal and non-coastal areas, policymakers should provide more support to non-coastal areas to improve their 3E development level. Furthermore, cooperation between coastal and non-coastal regions should be encouraged to share developmental benefits and promote the coordinated development of rural areas.

Between 2010 and 2020, China’s coastal areas experienced varying levels of development across the three dimensions of the 3E model. The rapid economic growth in these regions is reflected in a significant increase in the overall economic score, largely driven by national policy support, the expansion of global trade, and the inherent geographical advantages of coastal areas. These factors facilitated industrial upgrading and optimization of the economic structure. Moreover, coastal areas, as hubs of foreign investment and high-tech industry, benefited from increased capital inflows, further boosting their economic performance. In terms of environmental development, regions like Liaoning and Guangdong saw notable improvements, which can be attributed to their active environmental protection measures, stricter regulations, and investment in green technologies. However, regions like Zhejiang and Tianjin faced slower progress, possibly due to their reliance on heavy industry and fossil fuels, which hindered more rapid environmental improvements. The total energy scores also showed growth, particularly in regions like Jiangsu, Shanghai, and Fujian, where progress in energy structure optimization, improved energy efficiency, and the adoption of renewable energy were key factors. Despite overall positive trends, the development of coastal areas in the three 3E dimensions remained uneven, reflecting differences in resource endowments, industrial structures, and historical development paths. Moving forward, these regions need to continue their green development initiatives, balancing economic growth with environmental protection and enhancing energy structure adjustments to achieve long-term sustainability.



(a) 2010 non-coastal score



(b) 2020 non-coastal score

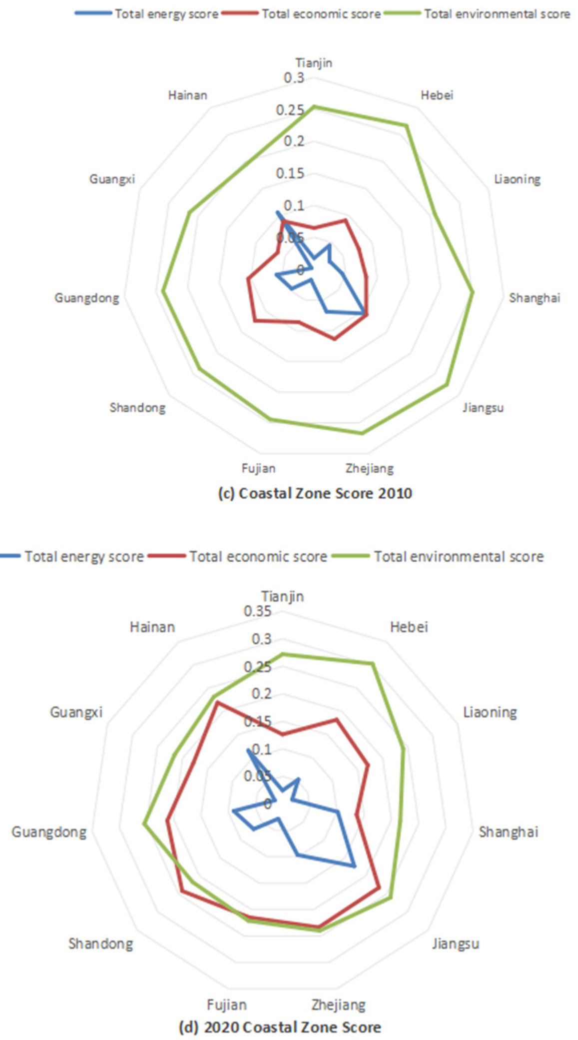


Figure 7. Energy, economic, and environmental evaluations of the 3E model for rural areas.

From 2010 to 2020, the total economic, environmental, and energy scores in non-coastal areas of China exhibited notable trends and causes behind their changes. The significant increase in the total economic score indicates an improvement in the economic environment of rural areas, driven in part by national policies such as poverty alleviation and rural revitalization strategies. These policies have provided financial support, infrastructure development, and industrial upgrading opportunities in rural areas. Additionally, the ongoing urbanization process has fostered greater connectivity between rural and urban areas, thereby diversifying local economies and boosting development.

In terms of environmental scores, significant improvements were observed in provinces like Gansu, Yunnan, and Shanxi, attributed to the regions' efforts in environmental protection and governance. Increased investments in pollution control, the implementation of stricter environmental regulations, and a focus on developing green industries have contributed to these gains. Furthermore, these areas have benefited from China's broader emphasis on ecological civilization, which has led to greater investments in ecological restoration and protection. However, regions like Beijing and Xinjiang showed less significant growth in environmental scores. This could be due to these regions having reached a relatively high level of environmental governance or facing more complex environmental challenges, such as smog control in Beijing or water scarcity in Xinjiang, which require long-term, in-depth solutions.

The increase in total energy scores in regions like Xinjiang, Beijing, and Tibet highlights their efforts in optimizing energy structures and advancing clean energy development. Xinjiang, an important energy base in China, has accelerated the development of renewable energy sources like wind and solar power. Beijing has led the way in promoting energy efficiency and transitioning to more sustainable energy consumption patterns. Moreover, Tibet's progress in developing hydropower reflects its unique geographical conditions, further contributing to the energy score improvement in the region.

The overall progress in economic, environmental, and energy scores in non-coastal areas is closely tied to the country's strengthening national capabilities and the implementation of targeted regional development strategies. Looking ahead, with continued focus and investment in these regions, further advancements in these areas are expected, contributing to the overall sustainable development of rural China.

In this article, the development of the 3E system in rural China from 2010 to 2020 has been analyzed in detail. Through the analysis of data, it has been shown that significant progress was made in the 3E aspects, although disparities between regions remain. The 2020 data were used to conduct a cluster analysis, revealing that Jiangsu Province stands out as a high-development area, with medium-development regions including the eastern coastal areas and certain central and western regions, while Qinghai Province was identified as a low-development region. The comparison of results from 2010 to 2020 further highlighted the trends and regional differences. It was found that coastal areas generally perform better across the 3E dimensions than non-coastal areas, likely due to their geographical advantages and stronger policy support. While some regions, particularly in the east, are seeing rapid economic growth and balanced environmental development, many regions face challenges, particularly in energy development. The findings suggest that targeted policies should be implemented to address the specific needs of coastal and non-coastal regions. Coastal areas should focus on optimizing their energy structure, promoting clean energy, and strengthening environmental protection. Non-coastal areas should prioritize improving energy infrastructure, attracting investment for industrial upgrading, and enhancing ecological restoration efforts. Ultimately, the implementation of differentiated policies and the establishment of a monitoring and evaluation system will be crucial for the continued sustainable development of rural areas and the realization of national rural revitalization goals.

6. Discussion

6.1. Selection of indicators

6.1.1. Explained variables

In this article, the development of 3E systems in rural areas is the focus. The 3E system development in rural areas is considered a complex and interrelated system, which is of great significance to the sustainable development of rural areas in China. To comprehensively assess the level of 3E system development in rural areas, an indicator system with multiple levels and dimensions was constructed. This indicator system is designed to comprehensively evaluate the 3E development of rural areas from various perspectives, in order to provide a better understanding of the development of 3E systems in rural areas of China. Therefore, the level of 3E is represented in this paper.

6.1.2. Explanatory variables

In this paper, the eight variables of total power of agricultural machinery (X1), the proportion of illiteracy (X2), the proportion of per capita disposable income of rural residents (X3), the food consumption expenditure of rural residents (X4), the number of rural self-employed people (X5), rural population (X6), the per capita consumption expenditure of rural residents (X7), and the local financial expenditure on education (X8) have been selected as the explanatory variables. These variables were chosen with the aim of deeply exploring their impacts on the 3E development level of rural areas from multiple perspectives, such as science and technology, talent and education level, and economic degree. The influence of these variables on the level of 3E development in rural areas is analyzed in depth.

(1) Gross power of agricultural machinery (X1). The total power of agricultural machinery is a key factor in rural development. With the advancement of China's agricultural modernization, the increasing popularity of agricultural mechanization has played a significant role in improving agricultural production efficiency and reducing production costs. The increase in the total power of agricultural machinery signals a transformation and upgrading of agricultural production methods, which in turn contributes to economic development in rural areas, thereby promoting the 3E development.

(2) Percentage of illiteracy (X2). The percentage of illiteracy reflects the quality of the population in a region. As the level of education rises, the illiteracy rate in rural areas gradually decreases, leading to a significant improvement in the cultural quality of the population. Reducing the illiteracy rate enhances the competitiveness of the rural labor market and injects new vitality into rural economic development, thus fostering the 3E development.

(3) Percentage of disposable income per rural resident (X3). The ratio of disposable income per rural resident serves as an important indicator of the economic development level in a region. An increase in the per capita disposable income ratio signifies a notable improvement in the living standards of rural residents, which contributes to higher consumption levels and improved quality of life, thereby promoting the 3E development.

(4) Rural food consumption expenditure (X4). Rural residents' food consumption expenditure is closely related to people's livelihoods. As the rural economy develops, the food consumption structure of rural residents gradually optimizes, and nutrient intake becomes more varied. This improvement benefits the physical health of rural residents and creates a robust population base for rural development, further promoting the 3E development in rural areas.

(5) Rural self-employment (X5). The number of rural self-employed individuals reflects the state of the rural employment market. As the number of rural self-employed persons increases, employment opportunities for rural residents expand, which supports the rational allocation of rural labor resources and raises the income level of rural residents, thereby driving the 3E development.

(6) Rural population (X6). The rural population serves as an essential foundation for rural development. As the rural population grows steadily, the human resource advantages of rural areas become more apparent, providing a stable labor force for rural economic growth, thus supporting the 3E development.

(7) Consumption expenditure per rural resident (X7). The per capita consumption expenditure of rural residents is an important indicator of the consumption structure. An increase in this ratio signifies the optimization of the consumption structure and improvement in the quality of life of rural residents, which contributes positively to the development of the 3E system.

(8) Local financial expenditure on education (X8). Local financial expenditure on education reflects the priority given to education by local governments. Increased investment in education can raise the educational level in rural areas, create favorable conditions for talent cultivation, and thus promote the development of the 3E system.

6.2. Data sources

The data used in this paper come from official releases by China's National Bureau of Statistics, the Ministry of Agriculture and Rural Affairs, and the statistical yearbooks of provinces and municipalities. The time frame of the data is from 2010 to 2020, covering rural areas in all provinces. During the data processing, we cleaned, sorted, and standardized the raw data to ensure the accuracy and consistency of the data. In addition, in order to eliminate the problem of heteroscedasticity in the data, we performed logarithmic transformation on some indicators.

6.3. Descriptive statistics

Before launching the regression analysis, descriptive statistical analyses of the indicators were carried out, aiming to grasp the basic characteristics and distribution of the data. By calculating the mean, median, standard deviation, and other statistical indicators, the concentration trend and degree of dispersion of each indicator were understood. For some variables, logarithmic treatment was implemented to reduce excessive differences between variables caused by unit differences. The results of the descriptive statistics are shown in Table 1, with no missing variables and complete data.

Table 1. Caption of the table.

Stats	Mean	P50	Sd	Min	Max
3E model	0.4077	0.3979	0.0836	0.1859	0.6960
X1	7.6286	7.8198	1.1212	4.5430	9.4995
X2	0.0613	0.0466	0.0636	0.0123	0.4431
X3	0.3889	0.3888	0.0565	0.2677	0.5420
X4	9.0903	9.1186	0.4146	8.0265	10.0190
X5	4.2923	4.4957	1.2403	0.7514	7.0934
X6	7.2025	7.3854	0.9467	5.3575	8.6629
X7	0.4576	0.4612	0.0700	0.2705	0.6623
X8	6.4385	6.5065	0.7272	4.1076	8.1635

6.4. Empirical analyses

6.4.1. Correlation test analysis

The correlation test is a commonly used statistical method to determine whether there is an association between two or more variables. It helps us understand the strength and direction of the relationship between the variables, further revealing potential links between them. The principle of the correlation test is to assess the association by calculating the correlation coefficient between variables. The correlation coefficient ranges from -1 to 1, indicating the strength and direction of the linear relationship between two variables. A correlation coefficient close to 1 suggests a strong positive correlation, while a coefficient close to -1 indicates a strong negative correlation. A coefficient close to 0 suggests no significant linear relationship. To test whether there is a correlation between each variable and the 3E model, this paper conducted a correlation analysis between each variable and the 3E model. The results show a significant relationship between each variable and the 3E model. As shown in Table 2, most variables are significant at the 10% level. This indicates that there is a correlation between the variables and the 3E model, making the study feasible for the next phase of analysis.

Table 2. Correlation statistics results.

	3E model	X1	X2	X3	X4	X5	X6	X7	X8
3E model	1								
X1	0.245***	1							
X2	–0.272***	–0.180***	1						
X3	0.558***	0.035	–0.433***	1					
X4	0.648***	–0.176***	–0.326***	0.603***	1				
X5	0.478***	0.682***	–0.414***	0.215***	0.218***	1			
X6	0.267***	0.885***	–0.276***	–0.033	–0.154***	0.798***	1		
X7	0.522***	0.262***	–0.398***	0.646***	0.725***	0.379***	0.187***	1	
X8	0.660***	0.497***	–0.435***	0.345***	0.545***	0.774***	0.664***	0.478***	1

(Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$ indicates significant at 10%, 5%, 1% level respectively.)

6.4.2. Basic regression results

In this paper, two basic regression analysis models are applied: The basic regression model (Eq 1) and the fixed effects model (Eq 2). The regression results are presented in Table 3. The basic regression model is a widely used method in regression analysis, while the fixed effects model is specifically designed for analyzing multiple time points or observations within the same data set. When there is high linear correlation between independent variables, i.e., multicollinearity, it can lead to bias in the estimation of regression coefficients and negatively affect the stability of the model. In this study, the regression analysis revealed that the signs of the X2, X6, and X7 variables did not align with the expected results, and several variable coefficients were not statistically significant. Therefore, it was initially concluded that there was a multicollinearity issue in the research data.

Table 3. Basic regression results.

Variant	(1) 3E model	(2) 3E model
X1	0.0129*	0.0108
	(–2.55)	(–0.84)
X2	0.0468	0.0578
	(–1.23)	(–1.7)
X3	0.0507	0.0196
	(–0.5)	(–0.07)
X4	0.104***	0.0319
	(–8.7)	(–0.77)
X5	0.00557*	0.00286
	(–2.4)	(–0.69)
X6	–0.0276*	–0.0965*
	(–2.41)	(–2.24)
X7	–0.0487	0.0507
	(–1.07)	(–0.51)
X8	0.0237**	0.0393**
	(–2.95)	(–2.86)
Year fixed effects		Yes
Firm fixed effect		Yes
Constant	–0.615***	0.240
	(–5.01)	(–0.51)
R^2	0.9144	0.9245
Sample size	341	341

(Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$ indicates significant at 10%, 5%, 1% level respectively.)

6.5. Multi-collinearity analysis

6.5.1. Tests for multiple covariance

In regression analysis, multicollinearity is a critical issue that can compromise the stability and prediction accuracy of the regression model. To detect multicollinearity, the Variance Inflation Factor (VIF) is commonly used. The VIF is calculated as $VIF = 1 / (1 - R^2)$, where R represents the correlation coefficient between the independent variables. A high VIF indicates the presence of multicollinearity between the independent variables. Typically, if the VIF exceeds 5 or 10, it is considered that a serious multicollinearity problem exists. Based on the results presented in Table 4, the VIF values for X1, X2, and X3 are all greater than 10, indicating a significant multicollinearity issue within the model.

Table 4. VIF test results.

Variable	VIF	1/VIF
X1	21.49	0.046523
X2	15.55	0.064297
X3	14.27	0.070084
X4	6.24	0.160163
X5	5.91	0.169287
X6	4.3	0.232786
X7	2.18	0.459428
X8	1.51	0.662333

6.5.2. Multicollinearity PCA correction (principal component analysis

(1) Feasibility test

Prior to conducting principal component analysis (PCA), the data were standardized to ensure that the sample's indicator data met the necessary requirements for PCA. The Kaiser-Meyer-Olkin (KMO) test was performed as an effective tool for assessing the adequacy of the correlation among variables. The KMO value ranges from 0 to 1, with higher values indicating a stronger correlation between the variables and providing greater support for the applicability of PCA. The results of the KMO test, as shown in Table 5, confirm that the data are suitable for conducting PCA.

Table 5. KMO and Bartlett's test.

KMO sample suitability quantity		0.612
Bartlett's test of sphericity	Approximate chi-square (math.)	2648.430
	Degrees of freedom (physics)	28
	Significance	0.000

When the KMO value is greater than 0.5 and the P-value is less than 0.05, the data are considered suitable for principal component analysis (PCA). Based on the test results, the KMO value is 0.612, and the significance P-value is 0.00, indicating that the correlation between the indicator variables is relatively strong. Therefore, the data are deemed appropriate for conducting PCA.

(2) Extraction of principal components

As can be seen from the data in Table 6, the contribution rate of the first principal component (Compl) has reached 48%, indicating that it accounts for 48% of the information from the original 8 indicators. Moreover, the cumulative contribution rate of the first two principal components exceeds 76%, meaning that these two components together capture 76% of the information from the original 8 indicators.

Table 6. Results of principal component analysis.

Principal component	Eigenvalue (math.)	Difference (the result of subtraction)	Contribution rate	Cumulative contribution
Comp1	3.8596	1.6221	0.4825	0.4825
Comp2	2.2376	1.5353	0.2797	0.7621
Comp3	0.7023	0.1244	0.0878	0.8499
Comp4	0.5779	0.2432	0.0722	0.9222
Comp5	0.3347	152152	0.0418	0.9648
Comp6	182587	8982193	0.0228	0.9868
Comp7	0.0843	0.0631	0.0105	0.9974
Comp8	0.0212	-	0.0026	1.0000

(3) Selection of principal components

This result shows that by using principal component analysis, the original 8 indicators can be simplified into 2 principal components while retaining most of the information from the original indicators, as shown in Table 7. This method of dimensionality reduction helps to better understand and analyze the data, revealing the intrinsic connections and patterns between the variables.

Table 7. Principal component selection.

Variant	Factor 1	Factor 2
X1	0.6568	–0.6291
X2	–0.6048	–0.2193
X3	0.5292	0.6390
X4	0.5129	0.7593
X5	0.8556	–0.3311
X6	0.7173	–0.6703
X7	0.7019	0.4986
X8	0.8832	–0.0372

(4) Principal component rotation

To better understand the meaning of these two principal components, the results of the principal component analysis were rotated for a more intuitive interpretation, as shown in Table 8. Assuming the original eight indicators are A, B, C, D, E, F, G, and H, the first principal component (Factor 1) can be interpreted as a combination of A, E, F, and H. This component reflects the level of scientific and technological human resources development in rural areas, comprising indicators like the total power of agricultural machinery, the number of self-employed individuals in rural areas, the rural population, and local financial expenditure on education. The second principal component (Factor 2) is a combination of C, D, and G, which reflects the economic level of rural residents. It is composed of the disposable income per capita of rural residents, food consumption expenditure, and per capita consumption expenditure. Through these two principal components, most of the information from the original eight indicators can be represented, allowing for a better analysis and processing of the data.

Table 8. Principal component rotation results.

Variant	Factor 1	Factor 2
X1	0.9218	–0.1374
X2	–2.2805	–0.5349
X3	–0.0727	0.8385
X4	–0.1700	0.9286
X5	0.8532	0.2255
X6	0.9948	–0.1362
X7	0.1518	0.8231
X8	0.6640	0.4851

According to the table, each principal component variable can be expressed as:

$$F1 = 0.9218X1 - 2.2805X2 - 0.0727X3 - 0.1700X4 + 0.8532X5 + 0.9948X6 + 0.1518X7 + 0.6640X8$$

$$F2 = -0.1374X1 - 0.5349X2 + 0.8385X3 + 0.9286X4 + 0.2255X5 - 0.1362X6 + 0.8231X7 + 0.4851X8$$

(5) Principal component regression

Linear regression analyses were performed on the dependent variables using the extracted principal components F1 and F2 as new independent variables. Based on the results of these regression analyses, the effectiveness of the model fit was assessed, and predictions for future outcomes were made. As shown in Table 9, the standard errors of the parameter estimates are small and within the acceptable range, indicating that the model is relatively stable. Additionally, the p-values of all parameters are less than 0.05, suggesting that the regression parameters are statistically significant. These findings indicate that the model is well-fitted and that the regression effect is significant. Therefore, the establishment of the principal component regression model is deemed feasible.

Table 9. Principal component regression results.

Variant	(1) 3E model
F1	0.0514*** (6.26)
F2	0.0466*** (6.91)
Year fixed effects	Yes
Firm fixed effect	Yes
Constant	0.4077*** (439.54)
R^2	0.8701
Sample size	341

(Note: *** p<0.01, ** p<0.05, * p<0.1 indicates significant at 10%, 5%, 1% level respectively.)

6.6. Heterogeneity analysis

According to the cluster analysis of the 3E system, a significant gap in the development level of 3E (environmental, economic, and social) between coastal and non-coastal cities in China has been identified. To further explore this phenomenon, this paper divides the 31 provinces into coastal and non-coastal cities. Equations (1) and (2) are applied to represent coastal and non-coastal cities, respectively, and the heterogeneity of the regression model is tested. The regression results are presented in Table 10.

Table 10. Heterogeneity regression results.

Variant	(1) 3E model	(2) 3E model
F1	0.1189***	0.0389***
	(5.02)	(4.88)
F2	–0.1143	0.0567***
	(–0.56)	(8.88)
Year fixed effects	Yes	Yes
Firm fixed effect	Yes	Yes
Constant	0.4264***	0.3946***
	(160.00)	(341.91)
R^2	0.8405	0.8970
Sample size	121	220

(Note: *** p<0.01, ** p<0.05, * p<0.1 indicates significant at 10%, 5%, 1% level respectively.)

The numerical results show that, for coastal areas, the coefficient of the first principal component related to the development level of scientific and technological talents is 0.12. This indicates that the development of scientific and technological talents has a significant positive impact on the 3E development in coastal areas. In contrast, the coefficient for the economic level of rural residents is −0.11, which is not significant.

In non-coastal areas, both principal components are significant. The coefficient for the development level of scientific and technological talents is 0.04, while the coefficient for the economic level of rural residents is 0.06. This suggests that in non-coastal areas, both the development level of scientific and technological talents and the economic level of rural residents have a considerable impact on the 3E development level.

Further analysis reveals that the development of scientific and technological talents in coastal areas plays a critical role in improving the 3E development. Specifically, for every 1 unit increase in the development level of scientific and technological talents, the 3E development level in coastal areas is expected to increase by about 0.12 units. However, the economic level of rural residents has a relatively smaller impact, likely because coastal areas already have a higher economic development level, and the economic status of rural residents is relatively better, causing its effect on 3E development to be less pronounced compared to that of scientific and technological talents.

In non-coastal areas, where economic development is lagging, there is a shortage of scientific and technological talents, and rural residents' economic levels are lower, the impact of these two factors on the 3E development level is more significant. Specifically, for every 1 unit increase in the development level of scientific and technological talents or the economic level of rural residents, the 3E development level in non-coastal areas will increase by approximately 0.04 units and 0.06 units, respectively. This highlights the importance of improving both technological capabilities and economic conditions to boost 3E development in non-coastal areas.

7. Conclusions and future perspectives

7.1. Conclusions

We draw the following conclusions regarding the 3E system: (1) A comparison of the cluster analysis results for 2010 and 2020 reveals an overall upward trend in the level of 3E development in rural areas of China, along with significant disparities between coastal and non-coastal areas. (2) An analysis of the 3E model scores for these areas indicates notable differences in development. Most areas exhibit considerable potential for improvement in energy development, while some areas show faster economic growth, and many areas demonstrate more balanced environmental development. (3) Principal component analysis reveals that the development level of scientific and technological talent, as well as the economic level of rural residents, significantly influences the level of 3E development in rural areas. (4) Heterogeneity analysis further shows that the development of scientific and technological talent has a greater impact on the level of 3E development in coastal areas, while in non-coastal areas, both scientific and technological talent development and the economic level of rural residents have a similarly significant influence on the 3E development.

7.2. Research implications

7.2.1. Theoretical implications

This study makes significant theoretical contributions. First, it enriches and expands the research on the 3E system by incorporating the development level of scientific and technological talents and the economic conditions of rural residents into the analytical framework of 3E development. This approach provides a new theoretical foundation and research perspective for future studies in this area, offering deeper insights into the sustainable development of rural areas in China. Furthermore, the study highlights the differential impact of scientific and technological talent development and the economic level of rural residents on the 3E development level, enhancing our understanding of the challenges related to rural sustainability. These findings offer valuable theoretical support for policymakers and researchers in addressing rural development issues.

7.2.2. Practical implications

This study also offers valuable insights for rural areas in China at the practical level. On one hand, local governments should prioritize the cultivation and introduction of scientific and technological talents when formulating policies to develop rural innovation. Strengthening the technological capabilities in rural areas will not only enhance the 3E development but also promote economic growth and social progress. On the other hand, improving the economic conditions of rural residents is equally important. Governments should ensure the basic livelihoods of rural populations and improve their quality of life through various policy interventions. These efforts will lay a solid foundation for the sustainable development of rural areas and contribute to the broader goal of building a modern socialist country.

7.3. Research limitations and prospects

This study has certain theoretical and methodological limitations. For example, the data selection was limited to rural areas, and urban areas were not included. In future research, the scope of the data could be expanded to include urban areas, allowing a more comprehensive exploration of the relationship between the development of scientific and technological talent, the economic level of rural residents, and the 3E development level. Additionally, the level of 3E development could be evaluated from more dimensions, which would improve the comprehensiveness and accuracy of the study. In conclusion, while valuable insights into 3E development in rural areas of China have been provided, further improvement and deepening are needed in subsequent studies. Through continued exploration and research, more targeted policy recommendations and theoretical support for the sustainable development of rural areas in China are expected to be offered.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Conceptualization, Y.Y. and Y.S.; methodology, Y.Y.; software, Y.S.; validation, Y.Y. and Y.Y.; writing—original draft preparation, Y.Y. and Y.S.; writing—review and editing, Y.Y. and Y.S. All authors agreed to the manuscript.

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